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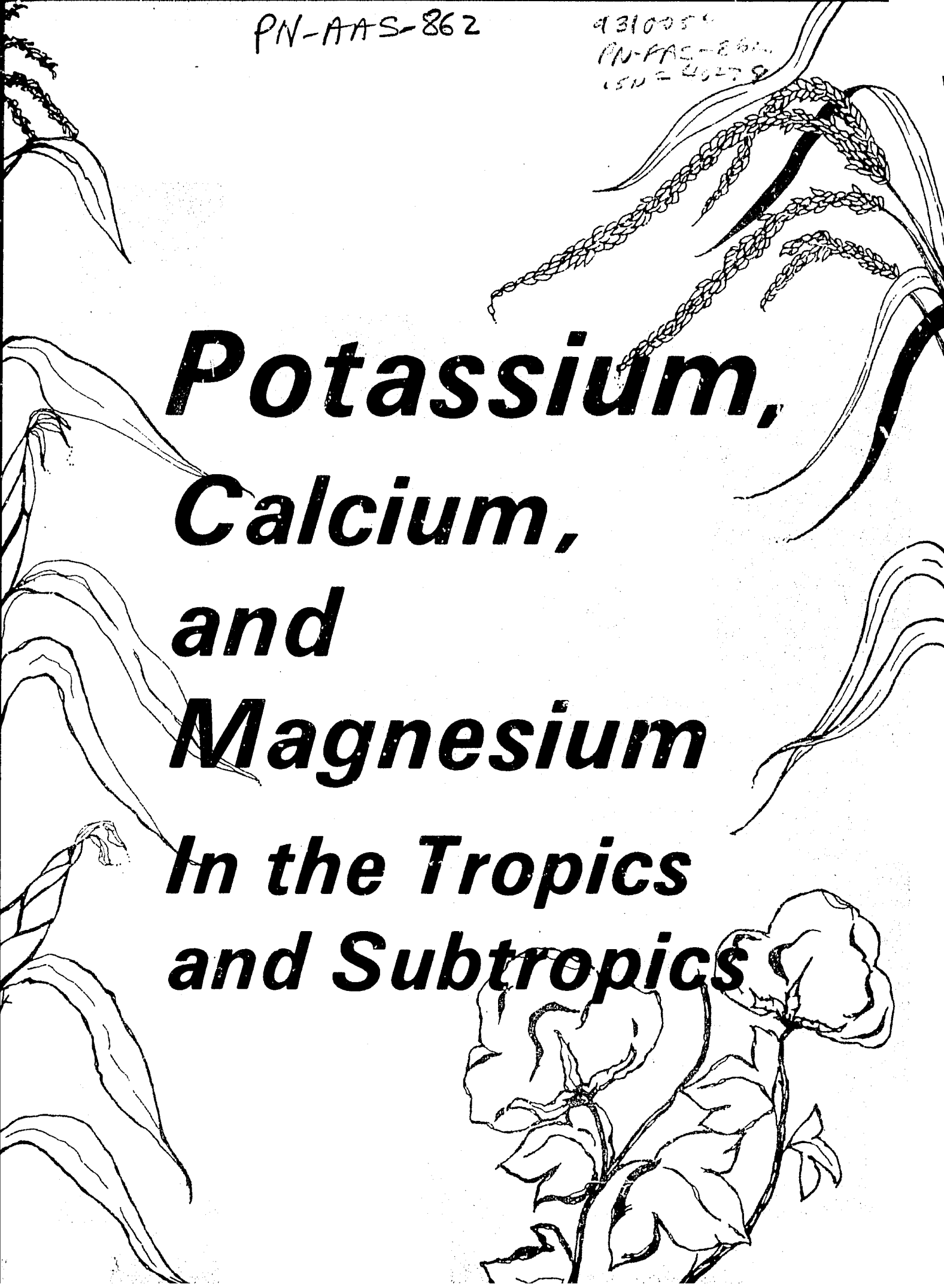

Potassium, Calcium, and Magnesium

In the Tropics and Subtropics

Abstract

The potential for increased food production in the world is undoubtedly greater than even the most optimistic surveys predict. Proper use of adequate amounts of potassium, calcium, and magnesium in fertilizers, soil amendments, crop residues and other byproducts, and minerals will be necessary if crop production potentials are to be realized. Use of these three plant nutrients with others will be an increasingly important part of the exploitation of natural resources as new lands of the tropics and subtropics are brought into production. Most of the increase in food production will come from more intensive use of lands already in production, however, and the soils of these lands will need larger amounts of all plant nutrients if high yields are to be reached and maintained.

This report is intended to point out some of the complexities of the soil and fertilizer problems involving potassium, calcium, and magnesium. It is hoped that the information it contains will be helpful in the research, education, and development that will be required to point the way to increased food and crop production on soils of the tropics and subtropics throughout the world.

Acknowledgment

Sincere thanks and appreciation are expressed to the International Fertilizer Development Center (IFDC) and the Potash and Phosphate Institute for having made this study possible. Appreciation is expressed also to all the persons and organizations that were visited in the different countries and who were so gracious and helpful in providing information and sharing data and experiences necessary for the preparation of this report.

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Symbols, Abbreviations, and Conversion Factors Used in This Report

Conversion Factors of Plant Nutrients

P_2O_5	x	0.4364 [a]	=	P
P	x	2.2914	=	P_2O_5
K_2O	x	0.8302	=	K
K	x	1.2046	=	K_2O
CaO	x	0.7147	=	Ca
Ca	x	1.3992	=	CaO
MgO	x	0.6030	=	Mg
Mg	x	1.6582	=	MgO
SO_3	x	0.4005	=	S
S	x	2.4971	=	SO_3

a. For most purposes these factors should be rounded off to the second decimal place.

Measures of Length

km ..... kilometer = 0.62 statute mile
m ..... meter = 3.28 feet = 39.37 inches
cm ..... centimeter = 0.3937 inch
mm ..... millimeter = 0.03937 inch

Measures of Volume

ml ..... milliliter = 0.001 liter
l ..... liter = 0.001 m^3 = 1,000 cm^3 = 1,000 ml

Measures of Mass

ton ..... metric ton = 1.102 short tons
kg ..... kilogram = 2.205 pounds (lb)
g ..... gram = 0.035 avoirdupois ounces
mg ..... milligram = 0.001 gram
bu ..... bushel (of wheat or soybeans = 60 lb; of maize = 56 lb)
quintal ..... 100 kg = 3.67 bu of wheat or soybeans and 3.94 bu of maize

Measures of Area

ha ..... hectare = 2.471 acres (A)

Units and Conversion Factors

Yields or Application Rates

kg/ha ..... kilograms per hectare = 0.892 pounds per acre (lb/A)
tons/ha ..... tons per hectare = 892 lb/A or 0.446 short tons per acre (st/A)
q/ha ..... quintals per hectare = 100 kg/ ha = 1.49 bushels (of wheat) per acre

Note: The bushel is a unit of volume, 35.24 liters.

Concentrations

meq/100 g ..... milliequivalents per 100 grams = (mg/100 g) divided by equivalent weight

Example: 39.1 milligrams K per 100 g (mg/100 g) = 1 meq K/100 g = 391 parts per million (ppm)

meq/100 ml ..... milliequivalents per 100 ml of soil sample
mg/100 g ..... milligrams per 100 grams = 10 ppm

Formula and Equivalent Weights

Element or Oxide	Symbol	Formula Weight	Equivalent Weight
Calcium	Ca	40.08	20.04
Potassium	K	39.10	39.10
Magnesium	Mg	24.32	12.16
Phosphorus	P	30.98	-
Sulfur	S	32.07	-
Calcium oxide (lime)	CaO	56.08	28.04
Magnesium oxide (magnesia)	MgO	40.32	20.16
Potassium oxide (potash)	K_2O	94.20	47.10
Phosphorus pentoxide (phosphate)	P_2O_5	109.95	-
Sulfur trioxide	SO_3	80.07	-
Calcium carbonate (limestone)	$CaCO_3$	100.09	50.05
Aluminum	Al	26.98	8.99

Acronyms and Other Abbreviations

CEC	cation exchange capacity
CIAT	International Center for Tropical Agriculture (Centro Internacional de Agricultura Tropical)
CPAC	Cerrados Agricultural Research Center (Centro de Pesquisa Agropecuária dos Cerrados)
DRIS	Diagnosis and Recommendation Integrated System
EUF	electro-ultrafiltration
FAO	Food and Agriculture Organization of the United Nations
IFDC	International Fertilizer Development Center
IPI	International Potash Institute
PPI	Potash and Phosphate Institute
Q/I	quantity/intensity
SSP	single superphosphate
TSP	triple superphosphate
TVA	Tennessee Valley Authority
UNIDO	United Nations Industrial Development Organization

Foreword

There is little hope of slowing the growth of population significantly before the year 2000. Most experts agree that, although the rate of growth of population is declining and may be as low as 1.7% annually through the rest of this century, the sheer numbers of growth are staggering. Some 6.35 billion people will inhabit this planet by the year 2000—an increase of 2 billion over those in 1980. The population is expected to be growing at the rate of 100 million people annually by the year 2000, compared with 78 million annually in 1980. This growth is not distributed uniformly over the earth, and the developing countries account for about 90% of the anticipated growth. The most seriously affected area is Asia, which has only 17% of the world's arable land but will have 57% of the world's population by the year 2000. Similar conditions, but on a smaller scale, exist for the Sahelian Zone of Africa and Central America and northeastern Brazil in Latin America, although land masses are much greater.

Global food production will have to be almost doubled by the year 2000, and developing countries must increase their food production at an annual rate of 4.0% through the 1980s and 3.8% through the 1990s if there is to be even slight improvement in the food supply. Food production in the developing countries increased at an annual rate of only 3.2% during the 1970s. The Food and Agriculture Organization of the United Nations (FAO) suggested that additional food be produced through a combination of increasing the productivity of land now under cultivation and bringing presently uncultivated land into production. It is estimated that one-third of the additional production must come from new lands and the other two-thirds from land now under cultivation.

The world now (1980) is cultivating only 1.4 billion of a total of 4.5 billion ha of potential agricultural land. The largest portion, about 40%, of the unused land lies in the vast forest and savanna areas of the tropics and is composed of acid, highly weathered, infertile soils classed as Oxisols and Ultisols. These soils cover some 1,600 million ha of which about half are potentially arable. The largest contiguous areas are in the interiors of Latin America and Africa, but there are smaller but important areas in Central America, Indonesia, and Malaysia. These soils are inherently low in fertility and are particularly low in the major mineral plant nutrients nitrogen, phosphorus, potassium, calcium, magnesium, and sulfur. It is becoming increasingly apparent that full production on these soils cannot be obtained with additions of only nitrogen or phosphorus or their mixtures. Equal attention must be given to supplying potassium, calcium, magnesium, and sulfur also.

Little research has been devoted to the need for potassium, calcium, and magnesium on the new lands, and extension workers usually ignore these nutrients in making fertilizer recommendations. Furthermore, the fertilizer sector, both domestic and international, has not yet decided how to supply the potassium, calcium, and magnesium that will be needed by the new lands as they are developed.

One of the objectives of this study is to assess the needs and demands for potassium, calcium, and magnesium on new agricultural lands that are expected to be developed in this decade and eventually by the year 2000.

Most of the increase in food production in the developing world must come from land that is now relatively productive because the physical and chemical properties of its soils can support high yields. The soil fertility of this land is now generally considered adequate, and fertilizers, particularly those supplying nitrogen and phosphorus, are used at moderate rates and the land is adequately watered by either irrigation or rainfall. This is the land that has been responsible for most of the increase in yield during the period known as the Green Revolution. As the yields continue to increase, however, these lands are subjected to increasing nutrient depletion, particularly of nitrogen, phosphorus, potassium, calcium, magnesium, and sulfur. Traditional fertilizer sources and management practices usually returned these nutrients in sufficient amounts to offset the pressures of increased yields. With the increasing use of high-analysis fertilizers, however, and the growing practice of removing crop residues from the field, the ability of the soil to supply crops with adequate amounts of nutrients has been lowered markedly. Reports of potassium deficiencies of major food crops are becoming increasingly common.

Until recently, in most developing countries potassium fertilizers have been applied almost exclusively to plantation or industrial crops such as sugarcane, cotton, oil palm, and rubber. Very little potassium has been recommended for food crops except in Brazil and India where use of potash on food crops has increased dramatically in the last decade. In some countries, such as Indonesia, China, Sudan, and Nigeria, the ratio (N + P):K has been 10 or even higher, in contrast to ratios N:P:K of 1:1:1 in South Korea, Japan, and several countries in Western Europe in which high-yield agriculture has been maintained for many years. NPK imbalances of the type that now exist in many developing countries cannot be tolerated if the required increases in food production from their lands are to be realized.

Recommendations for Research and Development

Although a great deal is already known about potassium, calcium, and magnesium in tropical and subtropical soils, more information is needed, particularly on the cation loading of low-exchange-capacity soils. These elements will take on increasing importance in the development of large regions that will be brought under cultivation and as the cultivation is intensified. Fertilization and liming practices devised to decrease the amounts of exchangeable aluminum, manganese, and iron, and to minimize their toxicities, also should be developed. Conventional fertilizer sources of potassium, calcium, and magnesium should be used as standards for comparison with the effectiveness of other sources of nutrients that result in high yields. Movement into, and loss of the nutrients from, the rooting zones of crops should be evaluated for each source, and each element should be evaluated both alone and with adequate amounts of other nutrients to take full advantage of their interactions. This research should proceed parallel with the development of the main soil types of the tropical and subtropical regions. Some specific areas needing research and development are discussed below.

Optimum Levels of Potassium, Calcium, and Magnesium

Levels of these elements under native soil conditions and those resulting from fertilization and soil amendments that produce maximum economic yields should be determined in long-term studies. The annual or periodic additions required to maintain high, profitable crop production should be established. Experience indicates that as soil nutrient levels and yields are increased, higher rates of nutrients than those initially applied are required to maintain yields and soil fertility. The effectiveness and efficiencies of different sources of these elements should be determined, and efforts should be made to use these elements as effectively as possible to increase the efficiency of the more expensive and energy-consuming nitrogen and phosphorus.

Soil test methods for determining the availabilities of potassium, calcium, and magnesium in the soils should continue to be evaluated and developed. Problems involving magnesium in some soils may be caused by high extractable aluminum (*50*), and soil test calibrations with the major crops should be part of the future research.

Fertilizers

Chemical Sources—Sources of nutrients with different solubilities should be evaluated, particularly the more slowly soluble materials. Frit-type materials that lower the rates of release of the nutrient elements might be developed, although these materials would be expensive in terms of energy, and their economics must be evaluated. The availabilities of the calcium and magnesium in different phosphate fertilizers, including finely ground rock phosphate and minigranules of the rock, should be measured. IFDC could make these and provide amounts for experimentation.

Multiple-Nutrient Fertilizers—Multiple-nutrient, high-concentration fertilizers containing N, P, K, Ca, Mg, and other nutrients should be developed for tropical soils to determine whether such materials are more effective than blends of single-nutrient materials in increasing soil nutrient levels and crop production. Multinutrient materials would be particularly helpful to the small farmer who does not understand fertilizer calculations but could easily apply the recommended amount of a stable multiple-nutrient fertilizer.

Particle Size—Fertilizer materials containing one or more nutrients could be produced in different particle sizes and with different degrees of hardness to control their rates of dissolution in the soil. Large particles of less soluble materials could decrease losses resulting from leaching, and might maintain higher soil nutrient levels over longer periods at the same rate of application.

Single or Multiple Coatings—Some study has already been made of sulfur coating of potassium fertilizer materials. A slow- or controlled-release material might be composed of multiple alternate layers of nutrient and coating in fairly large granules, or a multiple-nutrient granule might be impregnated with a chemical that would control the microbial oxidation of a binder, such as elemental sulfur, and hence the rate of dissolution of the granule.

Waxes, resins, membranes, and polyvinyl coatings or packets should be studied to evaluate the advantages of modifying the rate of dissolution and availability of pelletized nutrients over one or more growing seasons. Small Mylar packets of soluble nutrients have been used in some areas for fertilization of shrubs and trees, and these materials should be evaluated in the tropics.

Split and Timed Applications—Splitting and timing of applications of nutrients on high-value crops should be studied so that maximum efficiencies and economics can be obtained with proper combinations of sources, particle sizes, and coating of the nutrient materials. Where adequate labor is available, split applications of nutrients may be more economical than single applications of higher cost, slow-release materials.

Natural Byproducts—Byproducts containing potassium, calcium, and magnesium or their mixtures

should be used wherever possible. Gypsum produced in the manufacture of high-analysis phosphate fertilizers, and slags from steel manufacture and other processes may be valuable sources of plant nutrients. Gypsum not only provides calcium and sulfur as plant nutrients but also decreases saturation with aluminum in the soil profile. Gypsum also aids in the movement and distribution of potassium in soils high in clay (*23*). These effects of gypsum increase the rooting depth and the utilization of subsoil moisture, resulting in higher crop yields.

Research is needed on the amounts and availability of the potassium, calcium, and magnesium in the liquors now discarded in the production of sugar and alcohol. The proper amount and timing of application of these liquors, as well as the need for other nutrients, should be determined.

Where possible, crop residues should be used as sources of potassium as well as calcium and magnesium. Collection and use of residues on relatively small self-sufficient areas may be very practicable. In this research, plant analyses and total nutrient uptake will be useful in evaluating the relative efficiencies of the residues and conventional fertilizer materials.

Wood byproducts such as sawdust and ashes contain considerable amounts of potassium, calcium, and magnesium. In countries where these materials are available, study should be made of the availability of their nutrient contents. Other crop residues should be evaluated in these and similar studies.

A study should be made of the availabilities of the potassium, calcium, and magnesium in silicate minerals that are readily available in certain areas of interest. Some silicates have been shown to have marked beneficial effects on yield. These minerals should be compared with conventional fertilizer sources of nutrients, and the effects of particle size and treatment with chemical reagents to increase their availability should be determined.

Nutrient Needs Under Multiple and Mixed Cropping

The tropics and subtropics can support multiple, mixed, and intensive cropping. The amounts of potassium, calcium, and magnesium needed for cropping sequences devised for high production on the major soil types of the regions that will be developed for food production by the year 2000 should be determined. In some areas these studies will be related to production of biomass for use in the production of synthetic fuels.

Special attention should be given to the potassium, calcium, and magnesium needs of legumes which have the ability to fix atmospheric nitrogen. Legumes interplanted with other crops may have nutrient requirements different from those when the legumes are grown alone.

Nutrient Needs Under Minimum or Conservation Tillage Systems

Because of the erosiveness of tropical and subtropical soils, studies should be made of minimum or conservation tillage practices to determine the effects of those practices on the availabilities of potassium, calcium, and magnesium and the amounts of these elements required for profitable production of crops under these systems. A few data from studies in the tropics (*85*) indicate that the potassium and calcium soil-test levels needed for given yields are increased under no-till systems, in agreement with results of potassium-tillage systems in the temperate zone. Some of the effects of reduced tillage may include better moisture relations, lower soil temperature, increased bulk density, decreased porosity and aeration, less runoff, less soil erosion, and more efficient use of plant residues. Studies of the effects of tillage on the chemistry of soil potassium, calcium, and magnesium and the efficiency of these elements applied in fertilizers should be part of the research. Alternative methods of application and placement should be evaluated also.

Nutrient Needs of New Crop Hybrids and Varieties

As new crop hybrids and varieties are developed for tropical and subtropical regions, their responses to native and supplemental potassium, calcium, and magnesium should be determined. As germ-plasm more tolerant to excess aluminum and manganese is developed, soil pH would become less of a factor, and the levels, proportions, and the fertilizer sources of potassium, calcium, and magnesium for maximum crop yields should be evaluated.

Interactions of Potassium, Calcium, and Magnesium With Other Nutrients

To obtain high yields, farmers in the tropics and subtropics must take advantage of the interactions of potassium, calcium, and magnesium with other nutrients, with allowance for factors such as hybrid or variety, date of planting, placement of fertilizer, depth of planting, plant population, weed and pest control, supplemental irrigation, and proper harvesting of crops. These interactions can alter significantly the needs for potassium, calcium, and magnesium, and the response of crops to these elements. Investigators should evaluate these interactions so that the results can be explained to farmers and used to improve their yields.

Educational Efforts

IFDC is an outstanding international group active in the field of fertilizer use and development, and it is important that this group develop information on potassium, calcium, and magnesium in soils, fertilizers, and crops, and disseminate it in its workshops and seminars. With this information, participants from developing countries will be more aware of the importance of these nutrients in profitable crop production. These elements are an integral part of high-yield agriculture and must be included in IFDC's Outreach program.

General Considerations

FAO estimates that agricultural production will have to be increased 60% to meet the food requirements of the world's population in the year 2000 (*40*). Most of this increase is expected to result from an increase in production on present cultivated land, and the rest will be supplied by cultivation of some 200 million ha of new arable land, most of which is in the tropics (*40*).

Most of the increased production in the tropics will be obtained on low-base-status soils now classed as Oxisols, Ultisols, Inceptisols, and sandy Entisols (*159*). Of the 1,600 million ha of Oxisols and Ultisols in the forests and savannas of Latin America, Africa, and Asia, 680 million ha are potentially arable (*158*). In Latin America alone, the Cerrado region in Brazil and the Llanos region of Colombia and Venezuela contain some 200 million ha of these soils. The principal bases in soils are potassium, calcium, and magnesium, and these elements will take on increasing significance in world food production as the soils of the tropics are brought into production.

Each of these three elements has specific functions in plant nutrition, and together they play a complex role in soil fertility that depends upon the amounts and forms in which they are present or applied. They not only interact with one another, but they also alter the physical, chemical, and biological properties of the soil, and influence the availabilities to plants of other essential and nonessential elements.

Potassium is extremely important in regulating the osmotic functions of plants that influence a crop's water economy. It affects photosynthesis and the transport and deposition of photosynthate products that are vital to high crop yields. It interacts with calcium and magnesium and organic acids to maintain the electrolytic balance within plants. It is related to the uptake of nitrogen and N-fixation. It is required for the synthesis of protein and oil. It delays plant senescence and increases crop resistance to many diseases. In many crops the amount of potassium taken up is greater than that of nitrogen.

When limestone, which contains calcium and varying amounts of magnesium, is applied to very acid soils, it decreases the exchangeable hydrogen and the solubilities of aluminum, iron, and manganese, thereby decreasing the ability of the soil to adsorb applied phosphorus in less available iron, manganese, and aluminum compounds. At the same time, heavy applications of limestone may lower the solubilities of copper, boron, and zinc, and increase the solubility of molybdenum as the soil pH is raised. Liming changes the proportions, numbers, and activity of soil microbes that influence the rates of breakdown of soil organic matter and of mineralization of organically bound elements. Calcium and magnesium move downward in the soil, influencing rooting depths, and thus increasing the availability of soil moisture, especially during the dry periods of the rainy seasons in the tropics.

Potassium, calcium, and magnesium thus play key roles in world food production. This report will explore those roles and relate them to crops, soils, and fertilizers, with consideration of their availabilities and the need for further study. The relation of these elements to future food production on tropical soils will be discussed, as well as their general relation to fertilizer use, research, education, and development programs.

Roles of Potassium, Calcium, and Magnesium in Crops

Each nutrient element has a specific role to play in plant nutrition, but each is interrelated to some 15 other essential or nonessential elements and these relationships must be understood if they are to be of help in obtaining the required increase in food production.

Potassium

Potassium is taken up by plant roots as the ion K^+, and the total amount of potassium in crops is often as much or more than that of nitrogen. Potassium has specific metabolic, biochemical, and physical roles in plants, including:

1. Enzyme activation, stability, and configuration—potassium activates some 60 enzymes.
2. Stomate opening and closing.
3. Photosynthesis—chloroplast structure and photophosphorylation.
4. Osmotic regulatory functions—water uptake and loss.
5. Photosynthate transport and deposition.
6. Protein synthesis.
7. Neutralization of organic acids.
8. Photorespiration.

Concentrations of potassium in plants usually are high in tissues with high metabolic activity such as the meristems, and potassium is very mobile in plants. Through the interaction of these various roles, a crop with adequate potassium and other essential elements can produce very high yields.

The biochemistry and physiology of potassium is covered in a book by the International Potash Institute (IPI) (*74*). Papers dealing with the role of potassium in plant physiology include those by Jackson and Volk (*79*), Peaslee and Moss (*135*), Estes et al. (*45*), and Tanaka (*176*) on photosynthesis and respiration, Evans and Wildes (*46*) on enzymatic activity, Fischer (*51*) on stomate activity, Marinos (*113*) on subcellular effects on shoot tissue, Hodges (*70*) and Mengel (*117*) on uptake mechanism, and Beringer (*12*) on the influence of potassium metabolism on crop yields.

Calcium

Plants take up calcium as the ion Ca^{2+}. The action of calcium in plants appears to involve activation and inhibition of enzymes; formation, activation, and stability of membranes; and contribution to the structure of cell walls. In general its roles are:

1. Metabolic control—activates or inhibits enzymes.
2. Membrane structure—controls root activity and selectivity, and rate of ion uptake.
3. Cell wall structure—stabilizes the cell and is laid down as calcium pectate in the middle lamella. Interacts with auxin during cell division and growth.
4. Interaction with other elements, decreasing the availability of most micronutrients, but increasing the availability of molybdenum.

Calcium is found in high concentrations in areas of rapid cell division and high metabolic activity, such as in meristematic tissue. It moves primarily in the xylem tissue but is considered to be relatively immobile in plants.

Calcium also assists in maintaining electroneutrality in plant tissue, but, in spite of its high concentrations, it may add little to crop yield because of its lack of mobility and its inability to substitute for potassium or magnesium in metabolic processes. On the basis of its total content, however, calcium often ranks third, below nitrogen and potassium, as a nutrient for most crops (Table A-1). In most soils calcium reaches roots primarily by mass flow (*8*), but concentrations of calcium in the solutions of some tropical soils may be so low that diffusion may be the dominant mechanism.

Hewitt (*69*), Nason and McElroy (*128*), and Foy (*56*) have discussed the role of calcium in plant nutrition, and Christiansen and Foy (*25*) have recently reviewed the function of calcium in plants. Tanaka and Hara (*177*) found that for optimum rates of photosynthesis in maize the calcium concentration of leaves should be between 0.4% and 0.9%. Hanger (*66*) has discussed the movement of calcium in plants, and this may be important in root growth on acid, high-aluminum soils, and Kirkby (*96*) has discussed the broad aspects of calcium nutrition and its importance.

Magnesium

Magnesium is taken up by plants as the ion Mg^{2+}. It occupies the center of the chlorophyll molecule and is involved directly in photosynthesis. Only 10%-20% of a plant's magnesium is associated with chlorophyll, however, and the element apparently has other roles in plant physiology and metabolism. Along with potassium and calcium, magnesium is associated with enzyme activity and the maintenance of the electroneutrality of plant tissue. The role of magnesium includes:

1. Formation of chlorophyll.
2. Activation of enzymes, especially those associated with energy transfer, including:
   a. Photosynthesis
   b. Glycolysis

c. Tricarboxylic acid cycle
d. Respiration
e. Sulfate reduction

3. Formation of cellular organelles.
4. Metabolism of carbohydrates.
5. Synthesis of proteins.

High concentrations of magnesium, as well as those of potassium and calcium, are found in meristematic tissue where rapid cell division takes place.

Plant magnesium needs and uptake are interrelated with those of potassium and calcium and can be affected by ammonium ions, as well as by exchangeable hydrogen and aluminum. Because of its role in phosphorylation reactions, magnesium is often associated with increased uptake and utilization of phosphorus.

The role of magnesium in plant nutrition was discussed thoroughly in 1959 by Gauch and Krauss (*60*) and more recently by Kirkby and Mengel (*97*). Papers on the behavior of magnesium in plants have been published by Nason and McElroy (*128*), Hewitt (*69*), Sutcliffe (*175*), Woodruff (*199*), Steucek and Koontz (*173*), and Marinos (*113*). Malavolta (*109*) has written a bulletin on the potassium, magnesium, and sulfur in soils of Brazil. Peaslee and Moss (*135*) and Tanaka and Hara (*177*) measured the magnesium concentrations involved in photosynthesis and found the critical concentration in maize to be 0.15% Mg.

Characteristics of Tropical and Subtropical Soils

The soils of the tropics and subtropics are as varied as are those of other areas, but many of the soils from which future food production will come have certain characteristics in common. Many are acid, very low in phosphorus, high in aluminum, iron, and manganese, and have a low base status, which means that their levels of available potassium, calcium, and magnesium are low or soon become low as crops are grown. Problems with these soils are usually further complicated by deficiencies of nitrogen, sulfur, and micronutrients, either initially or within a few growing seasons as the chemistry of the soil is modified by fertilization and liming.

Many of these tropical soils have been characterized in soil survey studies. Latin American surveys include studies by Muller and Van Buren (*123*), Kantor (*92*), Carmargo and Falesi (*24*), Lopes and Cox (*103, 104*), Lepsch et al. (*101*), and Buol and Cuoto (*22*). Many of the soils in Africa and Asia have been classified by workers at the Agricultural University and International Soil Museum in Wageningen and at the Royal Tropical Institute in Amsterdam. Early Belgian, British, and French overseas investigators worked on the characteristics of African soils (*136*). Most countries now have their own competent soil survey teams and surveys.

Tanaka and Yoshida (*178*) studied many of the soils on which rice is grown in Asia in an effort to identify the nutritional and fertility problems of rice culture.

Dudal (*39, 40*) of FAO has been a leader in correlating soil survey and classification data with agricultural development, and Isbell (*77*) has reported on the genesis and characteristics of tropical soils. Sanchez and his coworkers (*158, 159, 160*) have discussed the effects of the chemistry of tropical soils on their potentials in agriculture and food production and have identified the fertilizer roles of potassium, calcium, and magnesium in the soil.

Chemical analyses of soil profiles from several countries in Latin America, Asia, and Africa are shown in Table A-2. The "critical levels," those at which satisfactory yields can be obtained, shown in Table A-3 were established by crop responses to increasing applications of fertilizers. Comparison of the data in Tables A-2 and A-3 shows that many tropical soils are deficient in potassium, calcium, and magnesium. There are, of course, values other than "critical level" that may be considered, such as the cation exchange capacity (CEC) of the soil and the percent saturations, and relative amounts of potassium, calcium, and magnesium.

The availability of these elements in soils usually has little relationship to their total content which is dependent upon the parent material of the soil, the vegetation under which the soil was formed, the soil's topography and aspect, its weathering over time, and the current climate. In many soils the elements are present but unavailable because they are component parts of the primary and secondary minerals. The readily available portion of an element, such as potassium, over a season may be only 0.5%-1.0% of its total content of the soil. This portion is the exchangeable fraction and includes the water-soluble fraction since most analyses do not separate the exchangeable and water-soluble fractions. Another fraction of the nutrient is nonexchangeable or slowly available, a form that is released slowly as the exchangeable or readily available fractions are depleted. These several forms of potassium, calcium, and magnesium are in dynamic equilibrium and their amounts change as concentrations in the soil solution increase or decrease as a result of fertilization or crop uptake. This situation is particularly true of potassium and magnesium because these elements may be adsorbed by the clay fraction of the soil.

In low-base soils, as shown by the soil profile data, the amounts of exchangeable potassium, calcium, and magnesium decrease with increasing soil depth. The higher amounts in the surface soils correspond to a slightly higher CEC associated with the organic matter they contain and the recycling of the nutrients to the surface by the vegetation.

Mokwunye and Melsted (*122*) and Boyer (*18*) have reported the small amounts of exchangeable potassium, calcium, and magnesium in many African soils. Some of the surface soils of Sierra Leone contain as little as 0.17 meq Mg/100 g and this is decreased to 0.10 meq in the subsoil. In very acid soils, pH 3.9-4.1, of the Congo, exchangeable magnesium in surface soil ranged from 0.02 to 0.12 meq/100 g, and the exchangeable calcium ranged from 0.22 to 0.39 meq/100 g.

Some of the profile data were collected more than 10 years ago. With improved high-yielding crops and heavier applications of nitrogen and phosphorus in many areas, further stress has been placed on many of these soils that were already low or marginal in their contents of available potassium, calcium, and magnesium.

Many of the Oxisols and Ultisols are highly saturated with aluminum, a major factor, along with the low levels of potassium, calcium, and magnesium, in the fertility of the soils. High concentrations of aluminum are toxic to many crops, and these concentrations are usually associated with a soil pH below 5.5 and with deficiencies of calcium and magnesium.

These conditions can be corrected, however, by applications of lime and fertilizers.

Climate is a major factor in the development of the characteristics of a soil, and this is especially true of the tropical soils, as suggested in Figure 1. In some areas of the Amazon and the Congo the annual rainfall may be 2,500 mm or more. In some tropical regions the rainy seasons are interrupted by short dry periods and are often followed by a much longer very dry period that may last from one to several months. The short dry periods have major effects on the availability of soil moisture and the need for deeper penetration of crop roots.

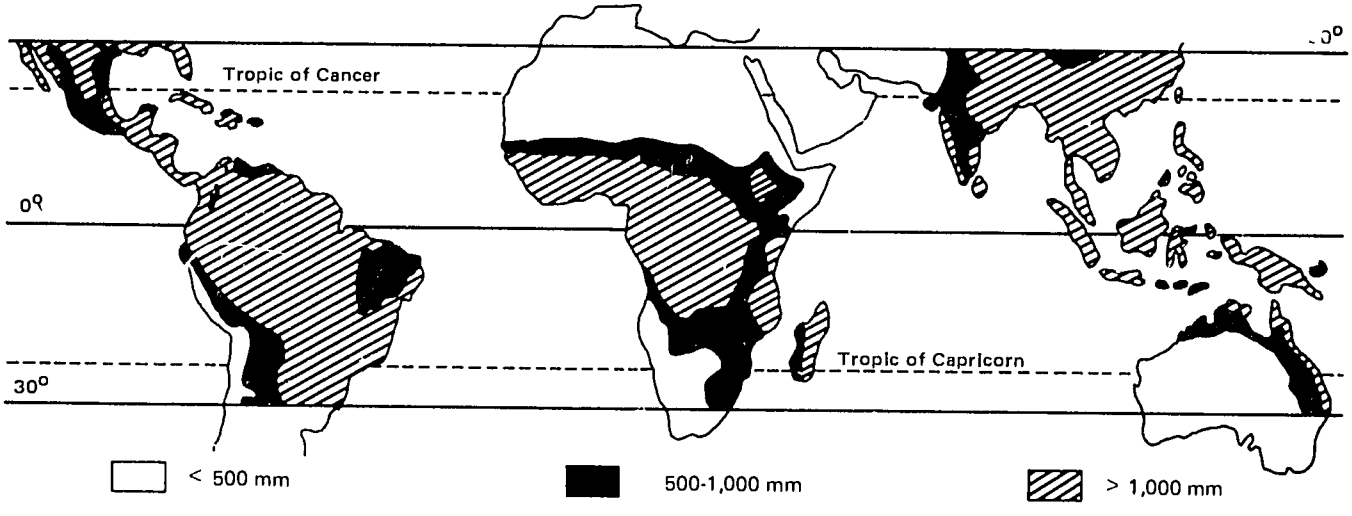


Figure 1. Mean Annual Rainfall of Tropical and Subtropical Areas (*77*).

Potassium, Calcium, and Magnesium Contents of Crops

Different crops take up different amounts of nutrients, depending upon the availability of the nutrients, the needs of the particular crop, and the physical, chemical, and biological conditions of the environment. These factors combine to determine the yield and the nutrient requirements. Amounts of nitrogen, phosphorus, potassium, calcium, magnesium, and sulfur taken up by typical crops are listed in Table A-1.

The amounts of potassium taken up by a number of crops are listed by Barber and Humbert (*9*). The calcium and magnesium contents of crops are reported by Jacob (*80*) and Boyer (*18*), and Malavolta (*109*) has summarized the amounts of potassium, calcium, and magnesium required by a number of crops in Brazil.

Most crops require relatively little calcium. Reviews of the calcium requirements of crops have been published by Boyer (*18*) and Jones (*82*).

In general, starch and sugar crops, such as cassava, potatoes, sweet potatoes, and sugarcane, have the highest requirements for potassium, calcium, and magnesium. Banana, coconut, oil palms, sisal or jute, coffee, and tea have very high requirements for these elements, but the relations between potassium and magnesium are especially important. Most forage crops, those that will be grazed or made into hay or silage, and horticultural crops have high requirements for these nutrients, followed closely by oil seed crops and grain crops, such as soybeans, maize, and sorghum. The cereal grains have relatively lower requirements than other crops, except at very high yields.

In meeting the needs of crops grown on low-exchange-capacity tropical soils, the nutrients removed by the harvested portion of the crop, the amounts of nutrients available from the soil, and the amounts lost by leaching and erosion must be considered. Higher yielding varieties exert increased nutrient stresses on soils, particularly for potassium and magnesium, and intensive cropping increases those stresses.

Under intensive or multiple cropping, as when two or more crops are harvested annually, nutrient demands on the soil are increased, so that soils that could supply nutrients for one crop per year with somewhat lower yields may become seriously stressed for nutrients, such as potassium, under higher yield levels and multiple cropping. Recent studies from India (*62*) demonstrate the increase of nutrient uptake under higher rates and combinations of fertilizer nutrients and with intensive crop sequences in a single year (Table 1). Applications of nitrogen and phosphorus increased the uptake of soil potassium by 25% and 317%. The applied potash increased nitrogen uptake by 14% and 21% and phosphorus uptake by 29% and 26%, with an apparent increase in the efficiency of utilization of each nutrient.

Table 1.
Uptake of Nitrogen, Phosphorus, and Potassium Under Intensive Annual Cropping in India (*62*)

Fertilizer Applied, kg/ha			Nutrient Uptake, kg/ha		
N	P_2O_5	K	N	P	K
Wheat, Soybean, Potato Sequence					
Control			164	9	88
204	200	0	293	17	110
204	200	200	333	22	204
Maize, Wheat, Cowpeas (Fouder) Sequence					
Control			46	8	47
320	190	0	166	34	196
320	190	132.5	201	43	238

Optimum Concentrations of Potassium, Calcium, and Magnesium in Crops

For a given crop there is an optimum concentration of each essential element that is needed for growth and development to produce maximum yields. Concentrations of these elements may vary somewhat with consequent lowering of yields, but maintaining high yields requires fairly close adherence to the optimum concentration.

The potassium concentrations of a number of crops are listed in Table 2 in which deficient, critical, and sufficient concentrations are indicated. The critical concentrations of calcium and magnesium of a number of crops are shown in Table 3.

Table 2.
Potassium Concentrations of Dry Matter of Crops, Grown Under Different Nutrient Conditions

Crop	Portion Sampled	K Concentration, %, Under Indicated Condition		
		Deficiency	Critical or Optimum	Sufficiency
Grains				
Maize (*83, 139*)	Ear leaf at silking	<1.7	1.9-2.0	1.9-3.0
Rice (*192, 195*)	Tillering, straw	<0.4	0.8-1.2	1.0-2.8
Sorghum (*83*)	Leaf at bloom stage	<1.4	-	1.4-1.7
Wheat, oats, barley (*195*)	Leaf at boot or early heading	1.25-1.49	-	1.5-3.0
Oil crops				
Oil palm (*192*)	Leaflets, frond 17	<0.6	1.5	1.5
Olives (*98*)	Leaves	0.30	-	1.1-1.5
Peanuts (*166*)	Stems and leaves	<1.7	-	1.7-3.0
Soybeans	Leaves at pod set	<1.7	-	1.7-2.5
Sugar crops				
Sugar beets (*181*)	Petiole, blade	0.1-0.6	1.0	1.0-11.0
Sugarcane (*71*)	Sheaths, internodes	0.3-1.5	1.0-2.3	1.0-6.0
Fiber crop				
Cotton (*157*)	Upper mature leaf	-	-	2.0-3.0
Forage crop				
Alfalfa (*114*)	Whole tops	<1.8	1.7-2.4	2.5-3.8
Vegetable crops (*61*)				
Potatoes	Petiole, early to late season	4-9	-	6-12
Snap beans	Petiole, 4th leaf	2	-	4
Sweet potatoes	Petiole, 6th leaf	3	-	5
Watermelons	Petiole, 6th leaf	3	-	5
Fruit trees and fruits				
Avocadoes (*98*)	Leaf	0.35	-	0.75-2.0
Bananas (*192*)	Leaf at shooting	<1.2	4.0	4.0-4.8
Citrus[a] (*42, 98*)	Leaves	0.7	1.2-1.3	1.2-1.9
Grapes (*95*)	Leaves	-	2.01	-
Mangoes	Leaves	0.45	-	0.45-0.65
Pears	Leaves	0.50	-	0.7-2.1
Peaches	Leaves	0.35	1.68	1.68-2.20
Pineapples (*192*)	Leaves, semimature	<0.5	3.5	3.5-4.2
Nut crops				
Almonds (*98*)	Leaves	0.50	1.7	-
Coconuts (*192*)	Palm leaflets, frond 9	0.35	1.1	-
Pecans (*98*)	Leaves	0.35	1.0	-
Walnuts	Leaves	0.50	1.0	-
Other crops (*192*)				
Cocoa	Leaves	0.6	2.0	-
Coffee	Leaves at flowering	0.7	2.2	-
Rubber	Basal leaf	0.6	1.5	-
Tea	5th leaf, new branch	0.5	1.4	-

a. Grapefruit, lemon, orange.

Table 3.
Calcium and Magnesium Concentrations of Dry Matter of Crops

Crop	Portion Sampled	Concentration, %, Under Optimum Conditions	
		Ca	Mg
Bananas (*109*)	At flowering	-	0.36
Beans, snap (*61*)	Young mature trifoliate	0.8	0.25
Cocoa (*109*)		-	0.45
Coconut palm (*33*)	Leaf of rank 14	-	0.30
Coffee		-	0.31
Cotton (*157*)	Leaves	1.00	0.30
Maize (*83*)	Ear leaf at silking	0.40	0.25
Oranges (*109*)		-	0.50
Peanuts (*166*)	Leaves, early pegging	1.25	0.30
Potatoes (*61*)	Petiole, young mature leaf	1.50	0.50
Rice (*195*)	Panicle differentiation	0.28	0.19
Sorghum (*83*)	Third leaf, heading	0.30	0.20
Soybeans (*166*)	1st mature leaf, early bud	0.36	0.26
Sugarcane (*71*)	Sheaths 3, 4, 5, 10	0.15	0.10
Sweet potatoes (*61*)	Mature leaf	0.70	0.40
Tomatoes	Leaf at first mature fruit	4.0	0.60
Wheat, oats, barley (*195*)	Above ground sampling at early heading	0.20	0.15

There is a definite interrelationship among the concentrations of potassium, calcium, and magnesium in the different portions of a crop. If one of these nutrients is deficient, another will be taken up by the crop to maintain the cation-anion balance or electroneutrality, but this behavior does not necessarily mean that the yield will be increased or even maintained. On the other hand, if a deficient nutrient is added, as by fertilization, both the yield and the concentration of that nutrient in the plant will increase until the critical or optimum concentration is reached. The yield will then level off, but the concentration may continue to rise. This relationship is illustrated in Figure 2 in which the yield of maize

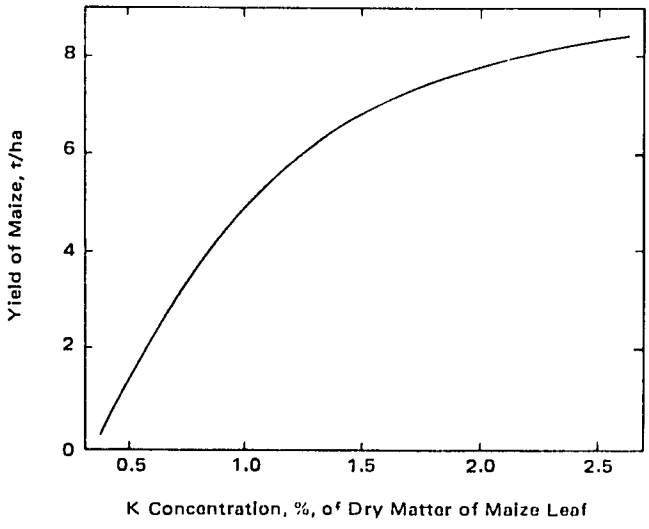


Figure 2. Relation Between Yield of Maize and Potassium Concentration of the Leaf *(105)*.

grain is plotted as a function of the potassium concentration of the leaf. When measuring the effect of a single nutrient it is essential that all other nutrients be adequate.

When potassium is the deficient cation and its availability is increased, concentrations of calcium or magnesium or both in the plant usually will be decreased on almost an equivalent basis (*123*), and this effect in the maize leaf is shown in Figure 3. Increasing the concentration of one element until the concentration of another element drops below its critical level may result in less than optimum yields because of competition between the two elements in the plant uptake and metabolism. This situation does not occur when adequate levels of all nutrients are maintained in the soil.

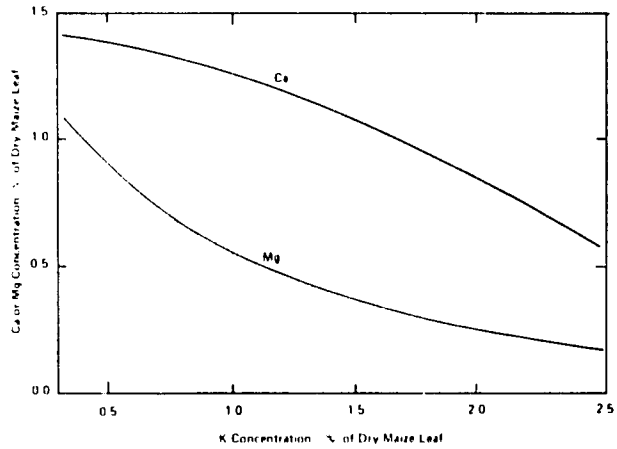


Figure 3. Relations Between Calcium and Magnesium Concentrations and Potassium Concentration of Maize Leaf *(105)*.

Other ions, such as ammonium, NH_4^+, may have antagonistic or competitive effects on the uptake of potassium, calcium, and magnesium (*14, 26, 44,*). The effects of ammonium nitrogen on magnesium and calcium are particularly pronounced because of the higher mobility of the ammonium. Ammonium nitrogen may slowly convert to nitrate nitrogen in acid soils, thereby adding to the problems in soils low in calcium and magnesium. Adams (*2*) notes, for example, that the adverse effect of diammonium phosphate on young seedlings when placed near the seed is due to an ammonium-induced calcium deficiency.

There is some evidence that once the critical concentration of a nutrient in a crop is reached, the critical concentration for that nutrient in the grain is reached also. Once the critical level in the grain is reached the yield can be increased, but the concentration of the nutrient in the grain will remain unchanged. When the yield is no longer increased by nutrient additions the nutrient concentration of the grain is again increased. Most of the investigation of

this concept has been concerned with nitrogen, but a few studies have been made with potassium.

There is considerable variation in the potassium concentration of each particular grain. For example, the grain of some maize hybrids may contain as little as 0.27% K and others may contain as much as 0.6% K. With increasing soil potassium or applications of potassium, soybeans in nontropical locations have shown increases in the potassium concentrations of the beans from 1.6% to more than 2.3%. Applications of phosphate may also increase the potassium concentration of soybeans. As soybean yields in Brazil were raised from 2,658 to 3,585 kg/ha by application of phosphate, the potassium concentrations of the beans were raised from 2.07% to 2.30%, and the potassium removed in the beans was 72 kg/ha or 20 kg/ton of beans at the higher yield (*67*). Most grains contain less calcium and magnesium than potassium.

Crop Response to Potassium, Calcium, and Magnesium

It is well known that crops grown on low-base tropical and subtropical soils respond to applications of potassium, calcium, and magnesium. Because of the similarity of most low-base soils, results from Latin America will be used as the basis for discussion of the problems and opportunities involving potassium, calcium, and magnesium on these soils in general. Much of the information will be from soils of the Colombian Llanos and the Cerrado of Brazil, which cover more than 200 million ha and which have considerable potential for future agricultural production. Other areas in Latin America that will eventually be developed include the Amazon regions of Bolivia, Brazil, Peru, and Venezuela.

Factors Affecting the Availability of and Crop Responses to Nutrients

Many factors influence the availabilities of potassium, calcium, and magnesium to growing plants. The soil-forming factors—parent material, topography, climate, vegetation, and age—determine the characteristics of a soil and, hence, the relative availability of each nutrient at a given time. Most tropical soils are fairly highly weathered, but soils of recent volcanic or alluvial origin are exceptions.

The factors that influence the availability and uptake of potassium have been reviewed recently (*126*), and these factors influence the behavior of calcium and magnesium also. In general, the availability of a nutrient in a soil is influenced by:

1. The types and amounts of primary and secondary minerals present.
2. The amounts of exchangeable and slowly available nonexchangeable forms of the nutrients.
3. The relative amounts of potassium, calcium, and magnesium.
4. The availabilities of nutrients other than potassium, calcium, and magnesium.
5. The rainfall and amount of soil moisture.
6. The type and extent of the root system of the crop.
7. The method of clearing the land, as from tropical forests.
8. The amounts and forms of potassium, calcium, and magnesium added in residues, fertilizers, liming materials, and soil amendments.

Among the factors that can change the need for or response to potassium, calcium, and magnesium are:

1. Level of exchangeable forms and relative availability of nonexchangeable forms.
2. Ability of the soil to adsorb or "fix" the cation.
3. Soil pH and amounts of exchangeable aluminum, manganese, iron, and sodium.
4. Soil temperature.
5. Soil moisture.
6. Tillage practices.
7. Soil compaction.
8. Amounts of other nutrients applied.
9. Relative amounts of potassium, calcium, and magnesium.
10. The crop species.
11. The variety or hybrid of the crop species.

No attempt will be made to discuss all these points which are listed only to point out the complexity of nutrient availabilities and factors influencing the responses to them.

Response to Potassium

Potassium and other nutrients are applied to soils to increase the yield and quality of a crop and to increase the food supply and the farmer's profit. If the farmer is short of capital, he adds the amounts of nutrients to produce the highest return per dollar spent for fertilizer. If he has adequate funds and nutrients are readily available, he selects rates that will produce the highest return or profit per unit area. If production of food is the major consideration, combinations of nutrients are selected that will produce the maximum possible yield.

Several review papers on potassium in tropical soils (*75*) have been published recently, including those on soils of Latin America (*35, 111, 146, 154, 158a, 170, 192*), India (*13, 140*), and Africa and Asia (*93, 94*).

Areas deficient in potassium have been established by means of soil classification data and agronomic tests. Areas of Colombia that are very deficient in potassium are shown in Figure 4 (*116*). The eastern Colombia or Llanos region, which covers some 20 million ha and extends into Venezuela, is very low in potassium and responsive to potash applications. It is expected that this area will be developed agriculturally in the next 20 years and will be one of the major areas of future agricultural development.

Another tropical area that is typically low in and responsive to potassium is the Cerrado region of Brazil which covers more than 183 million ha, of which 50 million ha can be developed rapidly (Figure 5). This area is now being developed at about the rate of 1 million ha/year, and this development will be accelerated as more emphasis is placed on agriculture in Brazil. Emphasis on the use of biomass for the production of alcohol will add impetus to the development, and although this activity is competitive with the use of resources for production of food,

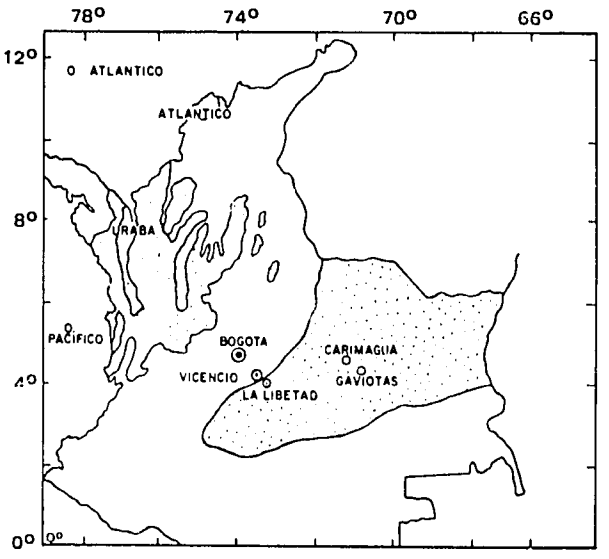


Figure 4. Potassium-Deficient Areas (Dotted) of Colombia (*116*).

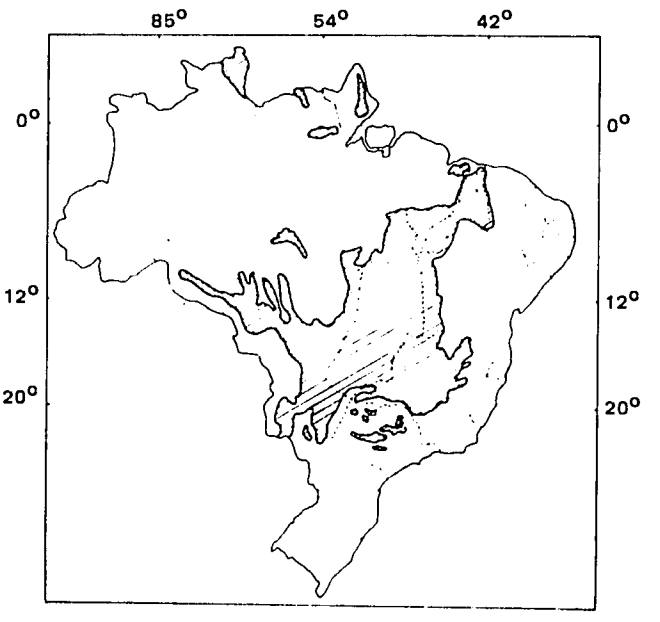


Figure 5. The Cerrado Region of Brazil (Shaded, 183 million ha) is Typically Low in Potassium, Calcium and Magnesium (*31*).

it will aid in retaining capital that would otherwise be used to purchase foreign oil. The overall effect thus should assist in the development of food production.

The potassium status of soils in China is shown in Figure 6 (*94*) and that of soils in India is shown in Figure 7 (*94*).

In general, the critical exchangeable soil potassium concentrations, at which deficiencies occur, range from 0.15 to 0.45 meq/100 g, as shown in Table A-3. These are levels below which responses to applied potassium would be expected but at which maintenance amounts of the nutrient should be applied to maintain the productivity of the soil. The critical levels appear to increase with increased CEC of the soil, but they also differ with the crop, as will be discussed later.

Ritchey et al. (*148*) found good responses of maize to potash applications on soils testing 0.06 meq K/100 g (Figure 8). Mathematical treatment of the data indicated that the level of soil potassium that produced the maximum yield was 96.7 ppm or 0.25 meq/100 g. In a subsequent paper Ritchey et al. (*150*) calculated that the maximum yield was obtained when the maize leaf contained 2.11% K. Applications of 75 kg K_2O/ha on maize produced initial and residual responses that netted a return of CR $18.67/CR $1.00 invested.

With single rates of application as high as 600 kg K_2O/ha, good residual effects were obtained 4 years later during the 1978/79 season as shown in Figure 9. Yields following the lower single rates of application decreased relative to the higher rates in successive seasons and produced a typical sigmoid yield curve. Maintenance rates of crop residues or of KCl applied annually at 100 kg K_2O/ha banded alone or added to the residual treatments produced high yields, the highest yield being 7 tons/ha, nearly 6 tons/ha more than the control.

De Souza et al. (*171*) measured the exchangeable potassium in these plots by the ammonium acetate method and by Mehlich's double acid method and found a high degree of correlation between the results of the two methods.

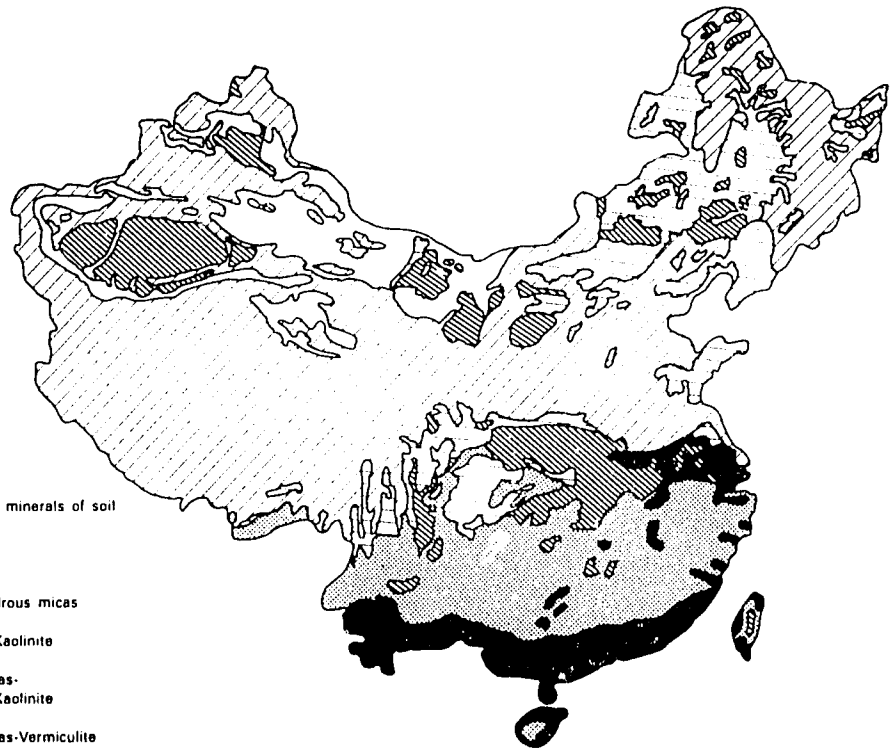
Soybeans grown on the same plots in the 1977/78 season utilized the residual treatments applied in the previous 2 years. Control plots produced only 65% of the maximum yield, whereas a maintenance application of 50 kg K_2O/ha applied the previous year for maize produced 97% of the maximum yield (Table 4).

A pictorial view of the response of cassava to rates of 0, 60, and 120 kg K_2O/ha with N 50 and P_2O_5 50 kg/ha, obtained from an FAO study in northeast Brazil, is shown in Figure 10.

Research results such as these produce soil test calibration data from which a potassium soil test can be used to predict the response to added potash and the amount that should be applied for a given test. An example of a potassium soil test calibration curve developed for cotton, beans, and sugarcane is shown in Figure 11 (*183*). A similar potassium calibration curve for soybeans at Campinas in the State of Sao Paulo has been developed (*184*).

Recent results from the Amazon Basin have indicated marked responses to applied potassium when three crops were grown annually on land cleared from forest (*158a*). Each of the crops—rice, corn, and soybeans or rice, peanuts, and soybeans—required from 96 to 120 kg K_2O/ha or from 288 to 360 kg K_2O/ha annually for maintenance of high production.

In some countries the response to potassium is not as straightforward as in the results presented above.

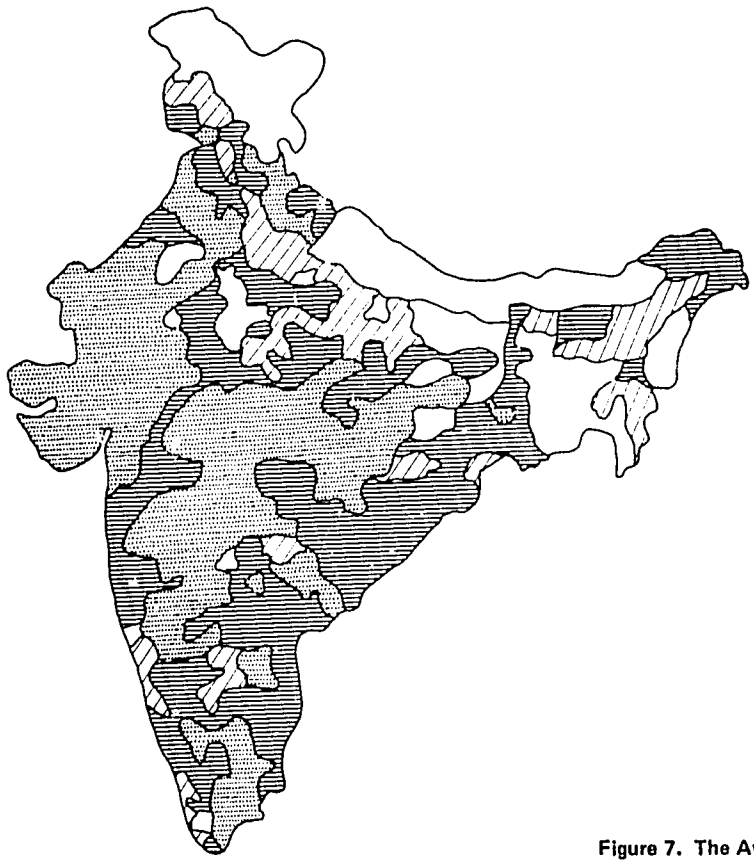


Legend

Symbols	Nutrient grade	Slowly available potassium *		Predominant clay minerals of soil
	very low	<8	I	Kaolinite
	low	8-20	II	Kaolinite-Hydrous micas
	medium-low	20-40	III	Vermiculite-Kaolinite
	medium	40-60	IV	Hydrous micas-Vermiculite-Kaolinite
	medium-high	60-90	V	Hydrous micas-Vermiculite (Chlorite)
	high	90-140	VI	Hydrous micas-Montmorillonite
	very high	>140	VII	Hydrous micas

*mg K_2O /g, soluble in boiling N NHO_3

Figure 6. Potassium Reserves of the Soils of China *(94)*.



Symbol	Avail. K status	
	Low	= < 5 mg K/100 g*
	Medium	= 5-17 mg K/100 g*
	High	= >17 mg K/100 g*

* soluble in N ammonium acetate

Figure 7. The Available Potassium Status of the Soils of India *(94)*.

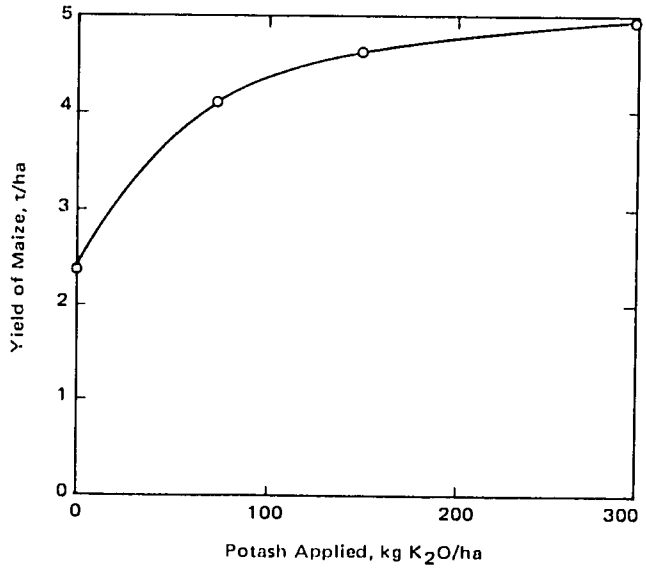


Figure 8. First-Year Response of Maize to Potash on a Dark Red Latosol of the Brazilian Cerrado *(30)*.

For example, in the Sierras of Peru, Ryan and Perrin (*156*) found that with average weather and soils testing 22, 127, and 232 ppm K (0.06, 0.32, and 0.59 meq/100 g) the recommended amounts of K_2O were, respectively, 190, 115, and 35 kg/ha, and the higher testing soils produced the highest yields. Differences in the price of potash and the unit value of the crop produced little variation in the most profitable rate of application of K_2O, which was about 126 kg/ha. The soils, the crop, the higher altitude, and the relatively cooler climate may explain the differences from the results given above from studies in Brazil.

The tendency of Latin American soils with high potassium concentrations to produce high yields without application of fertilizer potash has been observed also on nontropical soils. Thus, Tejeda-Sanhueza (*179*) working on NP fertilizer studies on wheat in Chile found that when the yields on the control plots were related to the soil test values, the highest correlation obtained was with the soil test potassium values, even though the test values were well above those usually considered to indicate response to potassium fertilizers. The exchangeable potassium values ranged from 208 to 780 ppm (0.52-1.99 meq/100 g). None of the other soil test measurements correlated well with the yields.

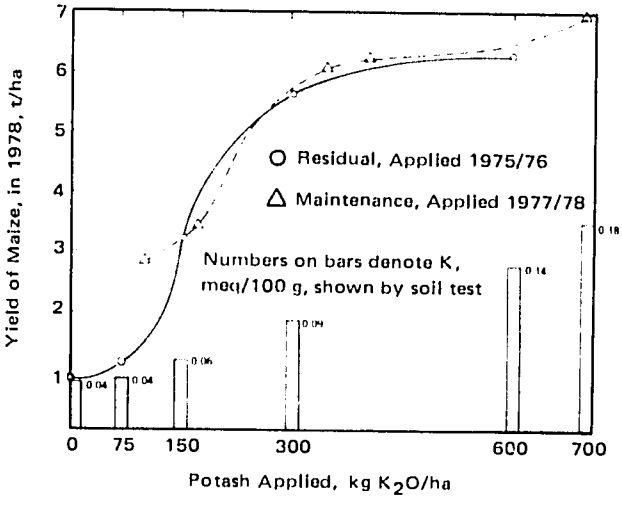


Figure 9. Response of Maize to Residual and Maintenance Rates of Potassium *(201)*.

Table 4.
Effect of Residual Potassium on Soybean Yield (*32*)

K_2O Applied, kg/ha, Broadcast 1975/76	1976/77	Soybean Yield, kg/ha, 1977/78
0	0	1,700
0	100	2,388
75	0	2,136
75	100	2,437
150	0	2,548
150	100	2,564
600	0	2,624

Different crops show different critical soil levels of exchangeable K, which is to be expected because of the differences in soil, climate, crop requirements, and conditions under which they are grown. Some soils with higher amounts of exchangeable K may not release the nutrient rapidly enough to maintain an adequate concentration of potassium in the soil solution. Thomas (*180*), Skogley (*165*), Grimme (*65*), Nemeth (*130*), and Kemmler (*94*) have pointed out the fallacy of assuming that higher exchangeable potassium levels always indicate high potassium availability or predict a lack of response to applied potash. The labile or readily available potassium should be determined, as well as the soil's buffer capacity or ability to release nonexchangeable potassium at a useful rate. Mielniczuk (*118, 119*) has prepared a bulletin and paper on soil potassium and forms of potassium in Brazilian soils. On many soils in Colombia and Brazil a simple extraction appears to do as well in estimating the availability of potassium (*5*), as the quantity/intensity, Q/I, approach of Beckett (*11*). On low-exchangeable potassium soils that show little crop response to applied potassium, however, or on high-exchangeable potassium soils that show responses to applied potassium, the Q/I approach of the electro-ultrafiltration (EUF) method of Nemeth (*129, 130*) may be superior. The more acidic extractants apparently do well in measuring the amounts of

Figure 10. Response of Cassava to Potassium Applied With Nitrogen and Phosphorus on a Potassium-Deficient Soil in a Northeast Brazilian FAO Study (*21*).

nonexchangeable potassium that become available in highly weathered soils, but it should be noted that in Venezuela the use of Olsen's sodium bicarbonate-extractable potassium method was ineffective in predicting responses to applied potash.

Low-exchange-capacity soils that are fertilized to increase the exchangeable potassium to high levels tend to be rapidly depleted by continuous cropping to their equilibrium level of exchangeable potassium. The exchangeable potassium then becomes constant, usually at a considerably lower yield level, unless adequate amounts of maintenance fertilizer potassium are applied. Evidence suggests that on many soils in which the crop has to depend on nonexchangeable potassium as its source of potash, lower yields are to be expected (*65*) because the rates of release of

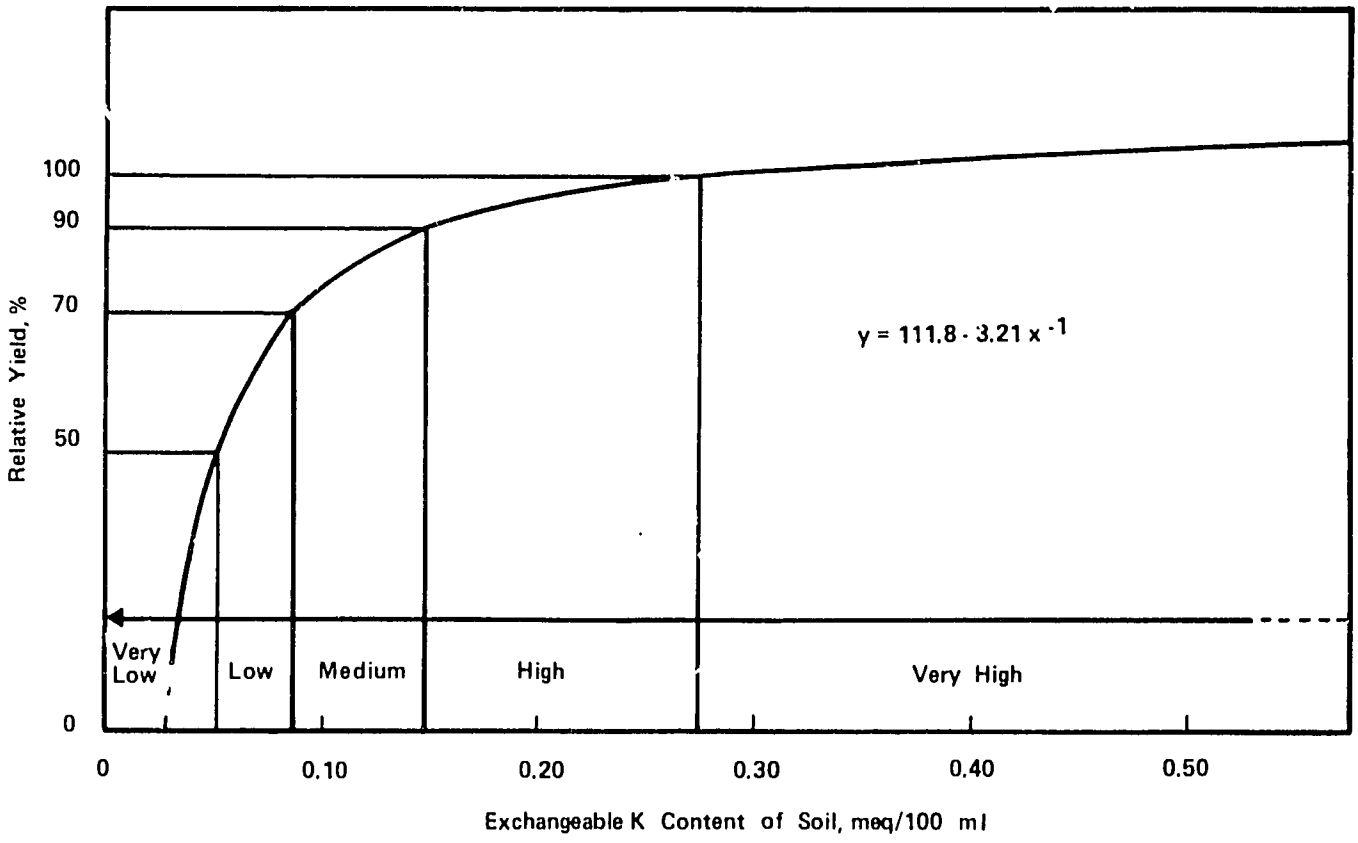


Figure 11. Relation Between Exchangeable Potassium Content of Brazilian Soils and Relative Yields of Cotton, Beans, and Sugarcane (*183*).

potassium apparently are inadequate to sustain high yields. Basic soil chemistry studies are needed to explain the differences among the potassium-supplying powers of different soils.

Long-term trials including potash are particularly important in developing countries (*158a*). Newly cultivated soils may test relatively high in potassium, but with applications of adequate nitrogen and phosphorus and removal of several crops the need for additional potassium becomes apparent. In a long-term rice research project at Maligaya in the Philippines (*193*), a soil that initially tested 178 ppm K (0.46 meq/100 g) showed profitable responses by the third season to applications of 60 kg K_2O/ha with applications of nitrogen and phosphorus, and the interactive response to potash continued to increase in successive seasons, as shown in Figure 12. The effect of the decrease of 127 ppm K or 0.32 meq K/100 g in the soil test without application of potassium decreased the yield of rice more than 2 tons/ha by the tenth year.

In recent studies (*193*) it was found that potassium measured by the EUF method predicted the availability of the soil potassium for rice better than the exchangeable potassium measured by the ammonium acetate method. When the EUF potassium value was 30 ppm K or 0.077 meq K/100 g before wetland preparation, maximum rice yields were obtained. This value is much lower than those found to be adequate for most upland crops. It is not known whether that level will be adequate for hybrid rice developed in China which is reported to require more potassium than other rice.

Potassium Soil Tests and Potash Recommendations—As pointed out above, potash recommendations are based on soil-test and crop-response data. Recommendations for crops in several countries are given in Table A-4. It is apparent that corrective applications of potash, followed by annual maintenance applications adjusted to the crop yield and the soil-test level, are required for maintenance of high yields (*158a*).

Many countries periodically revise their potash recommendations to fit changing conditions. Sri Lanka, for example, has recently increased its potash recommendations for low-country, dryland, and wetland rice and has virtually doubled the amounts of potash previously recommended for dryland rice and increased that of wetland rice by 30%.

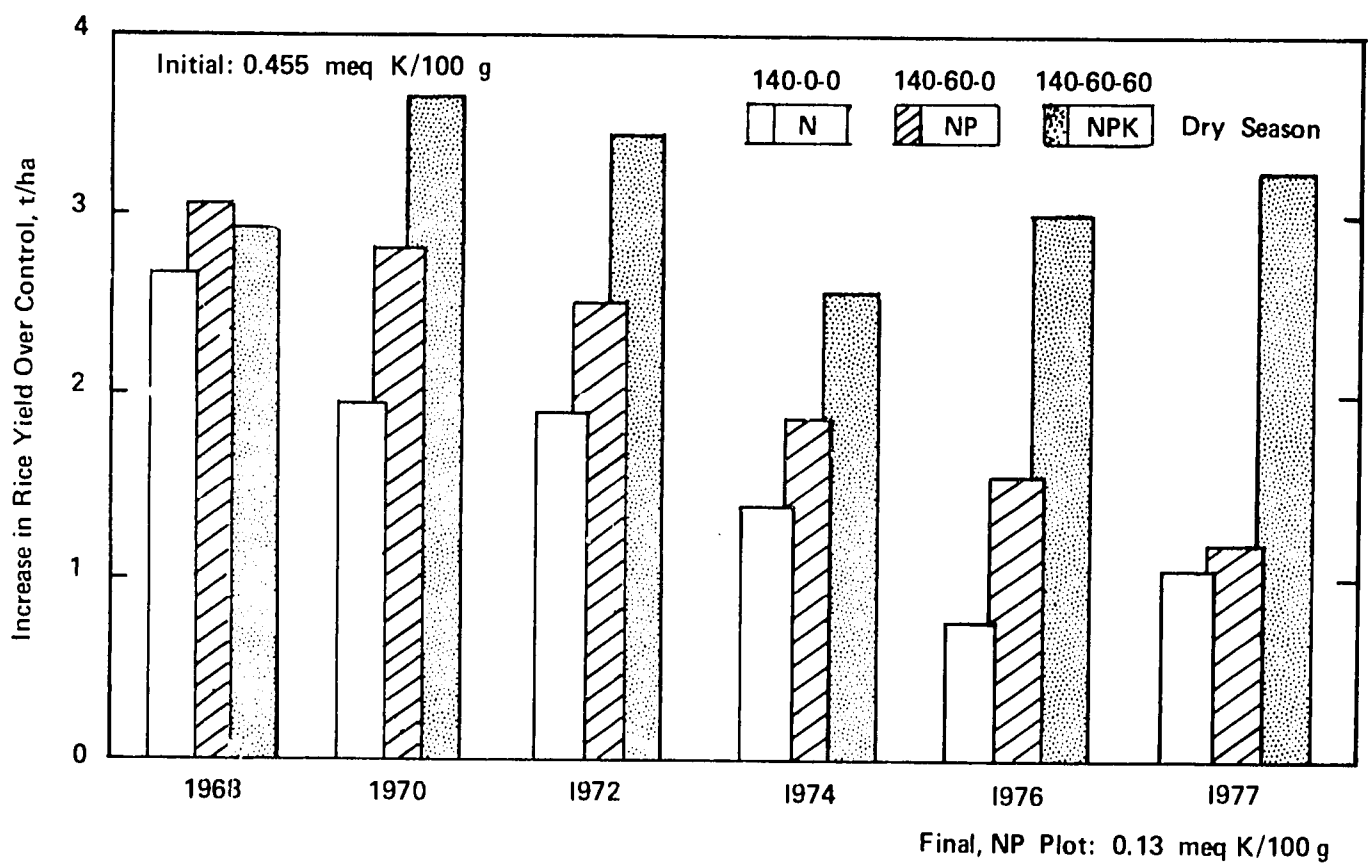


Figure 12. Response of Rice to Fertilizer in Long-Term Test in the Philippines (*193*).

For low-country dryland rice the new fertilizer recommendation is N 95, P_2O_5 45, K_2O 40 kg/ha; and for wetland rice N 95, P_2O_5 45, K_2O 60 kg/ha (*200*).

Response to Calcium

In many acid, low-base soils, calcium is important as a nutrient, and some soils in the tropics contain as little as 0.05 meq Ca/100 g. Of samples of the "Cerrado" soils of Brazil that were analyzed, 89% contained less than 1 meq Ca/100 g (*110*). Some subsoils contain as little as 0.008 meq Ca/100 g and are extremely deficient in calcium. The critical level for calcium is considered to range from 2 to 4 meq/100 g, as shown in Table A-3.

The importance of calcium for plants was discussed recently by Foy (*56*). Calcium is extremely important for root growth, and without adequate calcium roots simply will not grow (Figure 13). If the concentration of calcium is not adequate, roots do not penetrate the soil sufficiently to have access to other nutrients and soil moisture, even though these may be present in adequate amounts. Ritchey et al. (*149*) have recently devised a wheat seedling root-growth test for use in Brazil to screen soils for adequate exchangeable calcium levels.

For some crop species or varieties that have a high tolerance for aluminum the supply of calcium plays a major role in the response to phosphate fertilizers or lime, as shown in the research at the Carimagua Station by the International Center for Tropical Agriculture (CIAT) workers in the Llanos region of Colombia (*172*). For some species, applications of 200 kg Ca/ha as $CaCO_3$ produce the maximum response. The calcium needs can be met adequately by sources such as calcium phosphates or $CaSO_4$ (gypsum) if there is not a need to raise the soil pH.

Pearson (*134*) reported on studies by Baver and Ayres on sugarcane in Hawaii that showed responses to applications of calcium. In general, there was a yield response to applied calcium when the soil contained less than 448 kg/ha of exchangeable calcium or 1 meq Ca/100 g to a depth of 30 cm.

Boyer (*18*) reported that the soil level of calcium required by plants may be at least 0.35 meq Ca/100 g or 70 ppm, and there are indications that for some crops it is even higher.

Pearson (*134*) noted that the studies of Abruna and his coworkers in Puerto Rico with green beans on a number of different soils showed that the relative yield of beans was related to the ratio Ca:Mn in the bean leaves. Relative yields ranged from about 25% to 100% as the ratio Ca:Mn varied from 50 to 250. The optimum ratio of Ca to Mn in tissue was estimated to be 213 from mathematical treatment of these data.

Considerable study is needed to determine the calcium needs and responses of crops in the tropics. The calcium supplied by all sources must be taken into account, and it should be borne in mind that the calcium needs usually are confounded with soil pH and with toxicities of aluminum, iron, and manganese. Sources of calcium in phosphate fertilizers must be considered as well as the relationship of calcium with potassium and magnesium.

Because of the interrelationships of calcium with other elements, responses to application of calcium may be decreased by a lack of certain other nutrients. Research on *Brachiaria decumbens* at the CIAT station in Carimagua, Colombia, illustrates this relationship (Figure 14). It is apparent that calcium was added with the two sources of phosphate. The calcium applied with the phosphate fertilizer increased both the yield and the calcium concentration of the forage, but the potassium concentration decreased as the yield increased, and by the fourth cut the deficiency of potassium was serious. The potassium stress

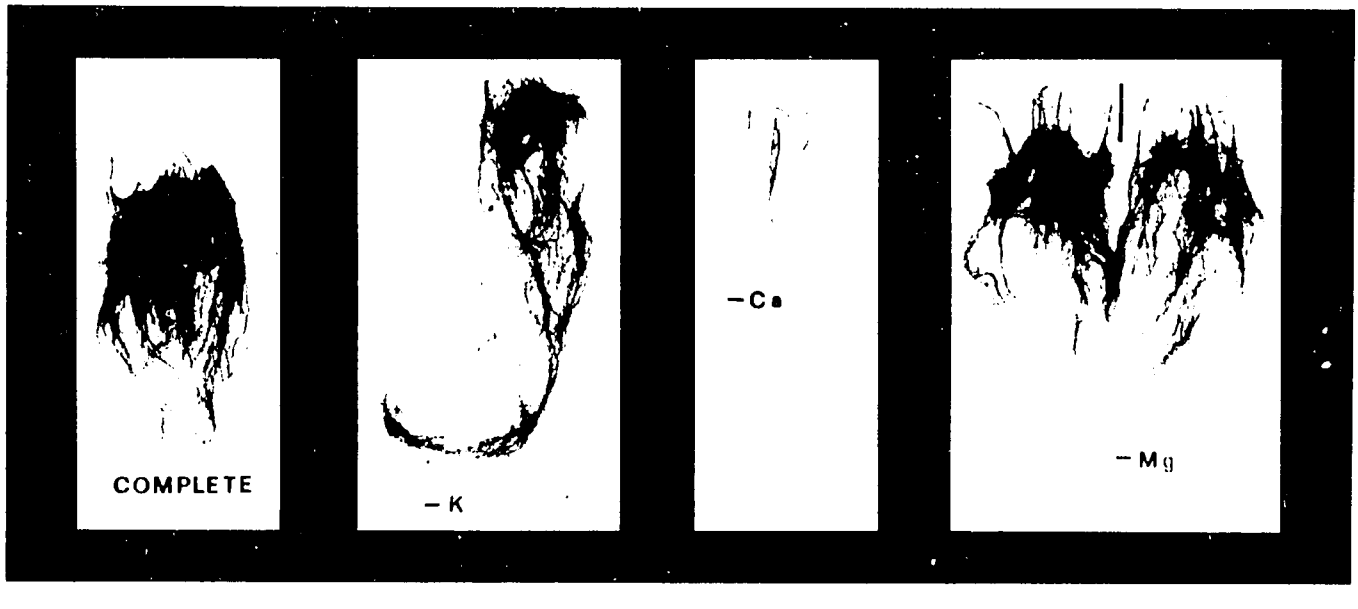


Figure 13. Effect of Deficiency of a Nutrient Element on Growth of Cacao Roots *(205a)*.

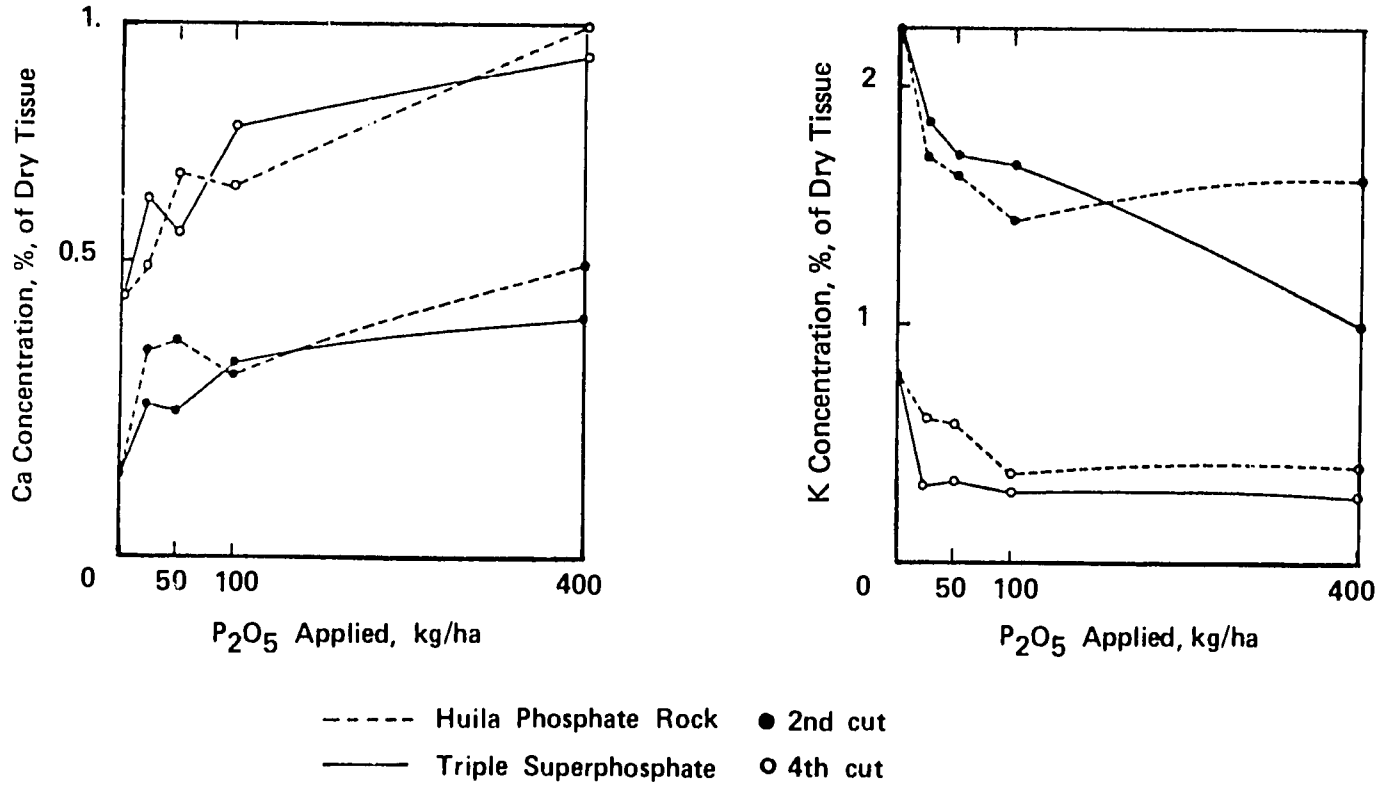


Figure 14. Effect of Phosphate Source and Rate on the Calcium and Potassium Concentrations of the Dry Tissue of Two Cuttings of *Brachiaria decumbens* Grown on a Colombian Oxisol *(29)*.

undoubtedly limited the response to the added calcium and to phosphorus which was the nutrient actually under study. The inverse relationship between the calcium and potassium concentrations in the forage of the second and fourth cuts is noteworthy.

Recent studies in the Amazon Basin indicate that for sustaining continuous crop production 3 tons of lime per hectare is applied every 3 years (*158a*).

Large applications of calcium as lime often decrease the availability of micronutrients such as zinc (*195*), and Brown (*20*) has recently discussed the role of calcium in the micronutrient stresses in plants.

Response to Magnesium

Crop responses to magnesium are much easier to measure than those to calcium because the effects of magnesium are less often confounded with those of liming, although liming can increase the uptake of magnesium as soil pH is increased (*50, 84*). In some soils, however, liming may increase the fixation of magnesium (*174*) and decrease the amount of measurable exchangeable magnesium. The critical soil level of magnesium varies much less than that of calcium and ranges only from 0.2 to 1.0 meq Mg/100 g, as shown in Table A-3.

Many tropical soils are deficient in magnesium, as shown by the amounts of exchangeable magnesium in Table A-2. Boyer (*18*) has published a bulletin which covers magnesium in tropical soils, and Baker (*6*) has discussed the soil chemistry of magnesium and the factors that affect responses of crops to magnesium.

Studies with soils of the Llanos of Colombia, the Amazon region of Peru, and the Cerrado region of Brazil have shown crop responses to magnesium. The results with three pasture species on soils from the Carimagua Station in the Llanos of Colombia, summarized in Table 5, show the responses to small applications of magnesium and point up the differences in response of the three species.

On the same soils at Carimagua, rates of K_2O as high as 200 kg/ha increased yields of some varieties of cassava but produced magnesium deficiencies and decreased yields of other varieties. The 20 kg of magnesium/ha used in the study summarized in Table 5 apparently was not adequate to meet the demands of some cassava varieties when the potassium availability increased.

Table 5.
Response of Pasture Grasses to Magnesium (*28*)

Mg Applied, kg/ha	Yield of Dry Matter, kg/ha, First Cut		
	Zornia Sp 728	*Desmodium ovalifolium*	*Pueraria phaseoloides*
0	2,436	675	229
20	3,151	1,552	739

Ritchey and his coworkers (*152*) at the Cerrado Center in Brazil found that maize did not respond to magnesium the first year when it was applied as a mixture of dolomitic lime with calcitic lime. When soybeans were planted on these plots the following season, however, there was significant response to magnesium, as shown in Table 6. The yield at the lowest rate of magnesium was only 73% of the optimum, but by increasing the rate of magnesium to 97 kg/ha the yield was increased about 37%.

Table 6.
Response of Soybeans to Residual Magnesium on a Dark Red Latosol (*32*)

Mg, kg/ha, Applied in 1975/76	Yield of Soybeans, kg/ha, 1976/77 Season
7	1,957
27	2,163
97	2,677
345	2,564

Villachia (*188*) observed significant crop responses to magnesium on soils cleared from the jungle in the Peruvian Amazon. The exchangeable magnesium was initially 0.21 meq/100 g and the ratio of exchangeable Mg to K was 1.94. Mathematical treatment of the data on soybeans indicated that the maximum yield was obtained with application of 21 kg Mg/ha. With applications of 3.6 tons of lime and 83 kg K/ha, addition of 18 kg Mg/ha increased the yield of soybeans 652 kg/ha.

When the potassium deficiency on these low-magnesium soils is corrected by application of potassium fertilizers, magnesium deficiencies appear and limit the yields unless proper amounts of magnesium are applied also. In dealing with these low-exchange-capacity soils the ratio Mg:K is significant and should be watched closely. For the conditions of the above study the critical ratio Mg:K was 1.2:1.

In the Amazon Basin long-term application of 25 kg Mg/ha/crop or 75 kg Mg/ha annually is required for sustained production growing three crops per year (*158a*). The Mg needs, of course, are soil and site specific.

Fairly large amounts of magnesium are required by some crops. Coomans and Ochs (*33*) found that, with adequate potassium, 0.9 kg of kieserite ($MgSO_4$) per palm per year was required for the most profitable yield of coconuts on low-magnesium soils, but that over a 10-year period there was no response to magnesium in the absence of applied potassium.

Adams and Henderson (*4*) found that on soils in the southern United States, crops responded to magnesium when the magnesium saturation was less than 4%.

Several sources of magnesium seem to be effective. The magnesium applied in dolomitic limestone has been found effective, but the solubilities of different dolomitic limestones vary considerably. Other than dolomitic limestone, the two important sources of fertilizer magnesium are kieserite, $MgSO_4 \cdot H_2O$, and potassium magnesium sulfate, $K_2SO_4 \cdot 2MgSO_4$. Use of the potassium magnesium sulfate appears to be on the increase in Latin America, probably because potassium and sulfur are supplied with the magnesium.

Magnesium deficiencies can be apparent even with very high yields. In a nontropical area in Kentucky (United States), with adequate nitrogen, phosphorus, and potassium, a maize yield of 12,042 kg/ha was obtained on a soil with an exchangeable magnesium soil test of only 0.11 meq/100 g. Application of 112 kg Mg/ha applied as MgO increased the grain yield by 1,380 kg (*210*). On the basis of a maize leaf nutrient ratio analysis often referred to as Diagnosis and Recommendation Integrated System (DRIS) (*10*), indications are that at a grain yield of 13,422 kg/ha there was a tendency for potassium and magnesium to be limiting the yield (*207*).

These results show that, although fairly high yields can be obtained with relatively low levels of soil-test magnesium, very high yields on low-base soils demand careful attention to the magnesium status. It is of interest that magnesium levels in soils with low availabilities of magnesium do not differ markedly between humid and tropical regions. In the tropics, however, greater losses from leaching are encountered, which may increase the amount of maintenance magnesium required.

Complex Relationships Involving Liming and Fertilization

The liming of "sour" or acid soils is as old as permanent agriculture, and a number of liming materials have been used, but the reasons for the positive, neutral, or negative responses to lime are complex and still imperfectly understood (*49, 53*). Among the benefits usually attributed to lime are:

1. Adds calcium and sometimes magnesium to the soil and raises the soil pH.
2. Decreases the toxicity of aluminum, iron, and manganese.
3. Decreases the leaching of applied potassium.
4. Decreases the sorption or fixation of fertilizer phosphorus.
5. Lowers the availability of boron, manganese, and zinc in some soils.
6. Increases the availability of soil molybdenum.
7. Increases microbial activity and the release of nutrients such as nitrogen, phosphorus, and sulfur from soil organic matter.
8. Improves the soil environment for bacteria associated with the symbiotic fixation of nitrogen.
9. Increases crop yields as a result of the action of one or more of the benefits listed above.

The individual actions seem clear, but their interactions must be considered to explain the complex situations encountered in many of the tropical and subtropical soils. Emphasis here is placed on the first two actions.

There have been many reviews on liming of tropical and subtropical soils (*1, 3, 88, 89, 90, 99, 133, 134, 167, 187*), and these are the basis for the following discussion.

Addition of Calcium and Magnesium

The amounts of calcium and magnesium added by liming depend upon the rate of application and the composition of the liming agent, usually limestone. The penetration of the calcium into the soil is illustrated in Figure 15 which presents data from the Cerrado Agricultural Research Center in Brazil.

Some fertilizer phosphates supply much exchangeable calcium. Studies in Colombia and Brazil show the amounts and beneficial effects of calcium that is added by application of different fertilizer phosphates, and the results of one such study at CPAC are shown in Figure 16. The applied phosphate may supply enough calcium to meet the needs of the crop.

Results of similar studies showed that increasing the rate of application of single superphosphate (SSP) from 200 to 2,000 kg P_2O_5/ha raised the soil pH only from 4.4 to 4.6, but that the same increase in the rate of application of thermophosphate raised the soil pH from 5.0 to 7.3.

Decrease of Exchangeable Aluminum and Aluminum Saturation

Aluminum toxicity and its relation to soil pH and liming has been studied both in the southeastern

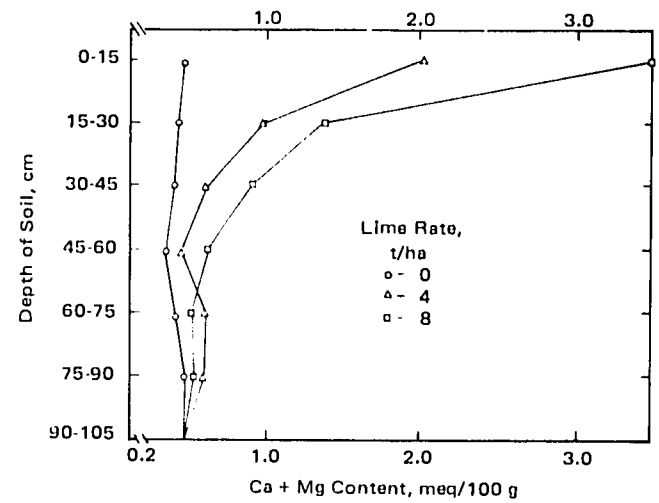


Figure 15. Effect of Lime on the Calcium and Magnesium Contents and Distribution in a Dark Red Latosol After Six Successive Crops *(31)*.

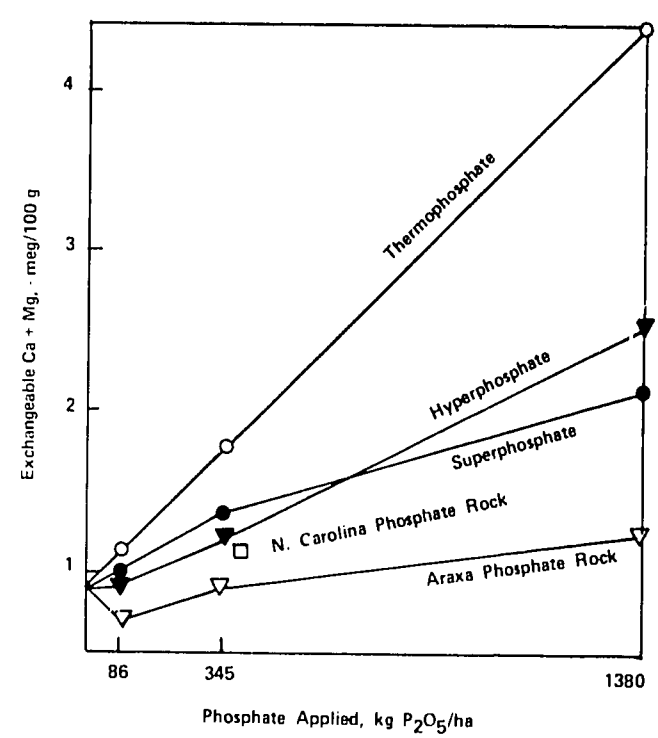


Figure 16. Effects of Different Phosphates on the Exchangeable Calcium Plus Magnesium on Cerrado Soils *(30)*.

United States and in the tropics. In work on soils in Brazil, Mohr (*121*) found little correlation between soil pH and exchangeable aluminum and suggested that aluminum toxicity be discussed in terms of percent aluminum saturation, **M**; his factor could be used to calculate the amount of liming agent required. The factor **M** is determined by the equation:

$$M = 100A/T$$

in which **A** is exchangeable aluminum in meq/100 g and **T** is the total CEC of the soil in meq/100 g, defined as the sum of the exchangeable Ca, Mg, K, Na, Al, and H; **T** was later modified to include only Ca, Mg, K, and Al.

On the basis of Mohr's results, it was recommended that soils be limed to decrease the solubility of the aluminum, and for Brazilian soils 1.5 tons/ha of limestone be used initially per meq/100 g of exchangeable aluminum. Limestone, however, is usually less than 100% effective because of variations in its composition, solubility, and particle-size distribution, and 2 tons/ha of limestone per meq/100 g of exchangeable aluminum is now recommended for soils in the State of Rio Grande do Sul in Brazil.

Several investigators (*87, 100, 115, 144*) reached conclusions similar to those of Mohr on the importance of liming to neutralize exchangeable aluminum. Foy (*57*) has discussed the effect of aluminum on mineral nutrition of plants, and the Colombian Society of Soil Science devoted its first colloquium (*169*) to the subject of acidity and liming in the tropics. Based on research in the United States, Shoemaker, McLean, and Pratt (*163*) developed a buffering method, commonly known as the SMP method, for determining the lime requirements of soils that contain much exchangeable aluminum. This method, however, overlimes many of the low-base-status soils.

The general relationships among lime rate, soil pH, percent aluminum saturation, and exchangeable manganese for a Colombian Ultisol are shown in Figure 17. Liming a soil to pH 5.5 to decrease aluminum toxicity also decreases the toxicities of manganese and iron (*89*).

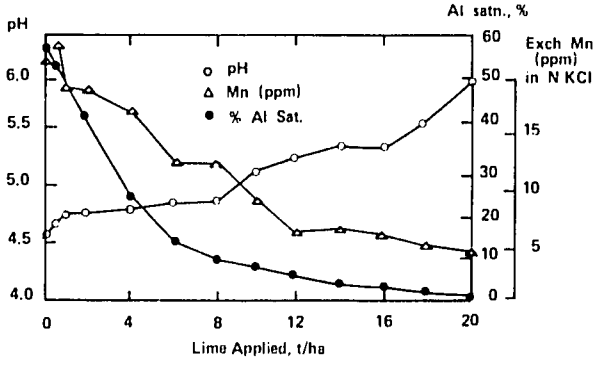


Figure 17. Effect of Lime on the pH, Aluminum Saturation, and Exchangeable Manganese in a Colombian Ultisol After 60 Days of Incubation (*28*).

Kamprath (*89*) has suggested that to obtain maximum yields Al saturation should be less than 10%-20% for maize, and generally less than 10% for soybeans, green beans, sugarcane, and cotton. For 90% of the maximum yield, the soil pH should be 5.0-5.3 for maize, 5.6 for soybeans, and 5.3-6.0 for cotton.

Lime recommendations vary with region, soil, and crop. In Colombia, for example, it is recommended that 1 ton of liming material be applied for each meq/100 g of exchangeable aluminum. In Brazil the liming material required to neutralize exchangeable aluminum is often estimated by the relationship:

$$\text{meq } CaCO_3/100 \text{ g} = 2 \times \text{meq exch Al}/100 \text{ g}$$

The importance of soil calcium and magnesium levels in relation to the aluminum level is well known, and some Brazilian states estimate the lime requirement from the relationship (*143*)

$$L = 2Al + (2 - Ca - Mg)$$

in which L is the lime required, in tons/ha of $CaCO_3$, and the symbols Al, Ca, and Mg are the amounts of the exchangeable elements, in meq/100 ml.

Kamprath (*89*) reports that the amounts of liming material required to decrease aluminum saturation to 10% range from 1.5 to 3.3 tons per meq/100 g of exchangeable aluminum; the actual amount of the liming material depends on its calcium carbonate equivalent (Table 7) and its relative effectiveness which increases as its particle size is decreased. Particles smaller than 60-mesh are considered 100% effective, those between 20- and 60-mesh are 60% effective, and those between 8- and 20-mesh are 20% effective.

Table 7.
$CaCO_3$ Equivalents of Liming Materials

Liming Material	Chemical Formula	$CaCO_3$ Equivalent, %[a]
Calcite	$CaCO_3$	100
Magnesite	$MgCO_3$	119
Dolomite	$CaCO_3 \cdot MgCO_3$	109
Calcium hydroxide	$Ca(OH)_2$	136
Calcium oxide	CaO	179
Magnesium oxide	MgO	248

a. Neutralizing value, tons $CaCO_3$, equivalent to 100 tons of the liming material.

Limestone usually contains some magnesium. Brazilian agricultural publications report that calcite contains 0.6%-3.0% Mg and dolomite contains 7.8%-12.0% Mg.

Calcium phosphate fertilizers, particularly when applied at higher rates, also decrease the exchangeable aluminum and the percent aluminum saturation. Data from the studies mentioned earlier that show

the effects of phosphorus sources on the content of exchangeable calcium and magnesium (Figure 16) also show how these sources decrease the exchangeable aluminum (Figure 18). Some of the beneficial effects of such phosphates may be due in part to the calcium and magnesium they supply and to the decrease in aluminum saturation they effect.

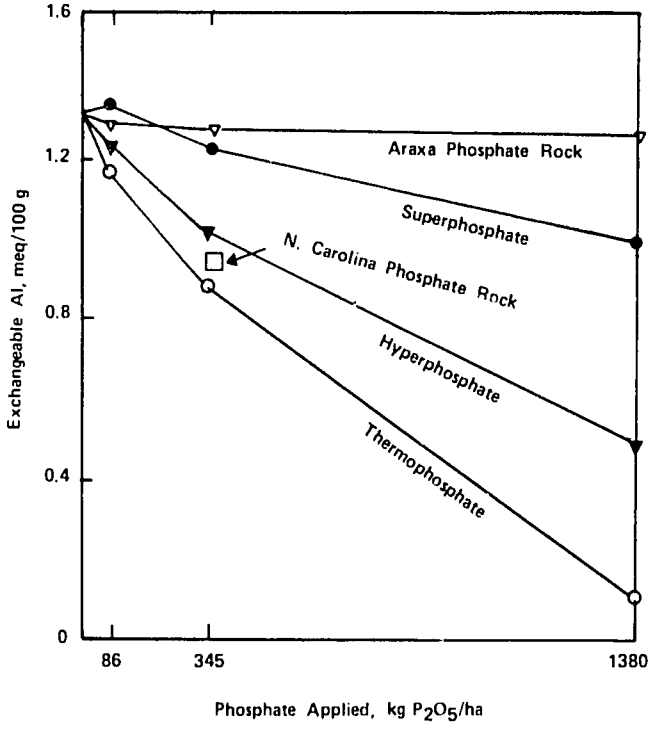


Figure 18. Effects of Different Phosphates on the Exchangeable Aluminum of Cerrado Soils *(30)*.

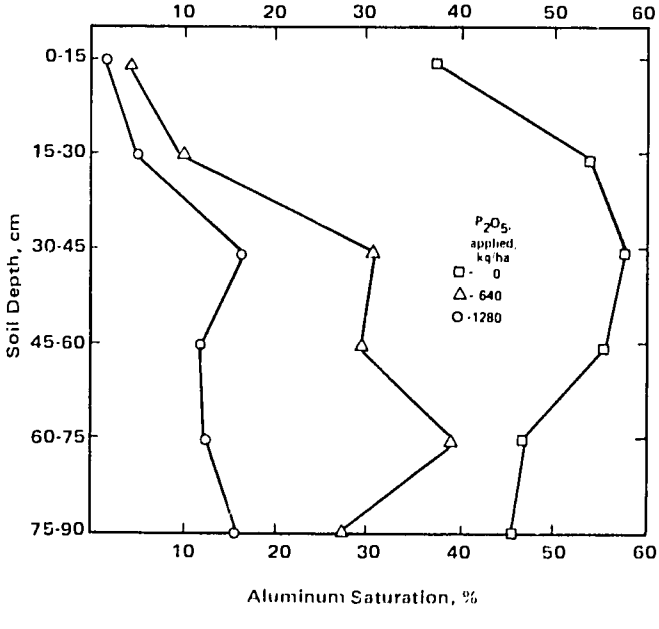


Figure 19. Effect of Single Superphosphate on the Aluminum Saturation in a Soil Profile *(31)*.

Field studies in Brazil show that SSP decreases aluminum saturation down the soil profile (Figure 19). Much of the decrease in aluminum saturation is due to the calcium sulfate in single or ordinary superphosphate (*145*) which moves down in the soil and complexes the aluminum. These results show that SSP has multiple purposes in many tropical soils by supplying phosphorus, calcium, and sulfur and decreasing aluminum saturation.

A North Carolina rock phosphate that contains P_2O_5 30.7%, CaO 49.4%, and MgO 0.6% would have a liming value of 0.68 kg $CaCO_3$ equivalent per kg of rock, or 2.22 kg $CaCO_3$ equivalent per kg of P_2O_5 (*71a*).

Effects of Rooting Depth and Soil Moisture on Response of Crops to Lime and Fertilizer

The use of lime and fertilizer to increase crop yields is well known, but the reports in the literature on the effects of the treatments are often conflicting. The reasons for the differences in response are complex, and on tropical soils crops may not respond to lime unless other essential nutrients are applied also. The response of maize to several rates of lime, each of which was incorporated in two depths of soil, is shown in Figure 20.

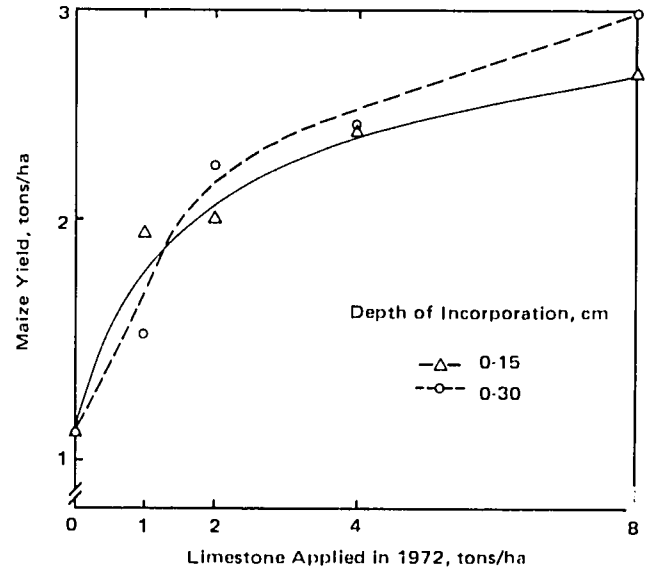


Figure 20. Effect of Rate and Depth of Incorporation of Limestone on Yield of Maize *(31)*.

Higher rates and greater depths of incorporation of single applications of lime produced higher yields fairly consistently, particularly during the first 2 years of the study, and the highest rate, 8 tons/ha, at the deepest incorporation, 30 cm, gave the highest yield of maize, more than 7 tons/ha in some seasons. The relative yield for lime rates at the two depths of incorporation are shown in Figure 21.

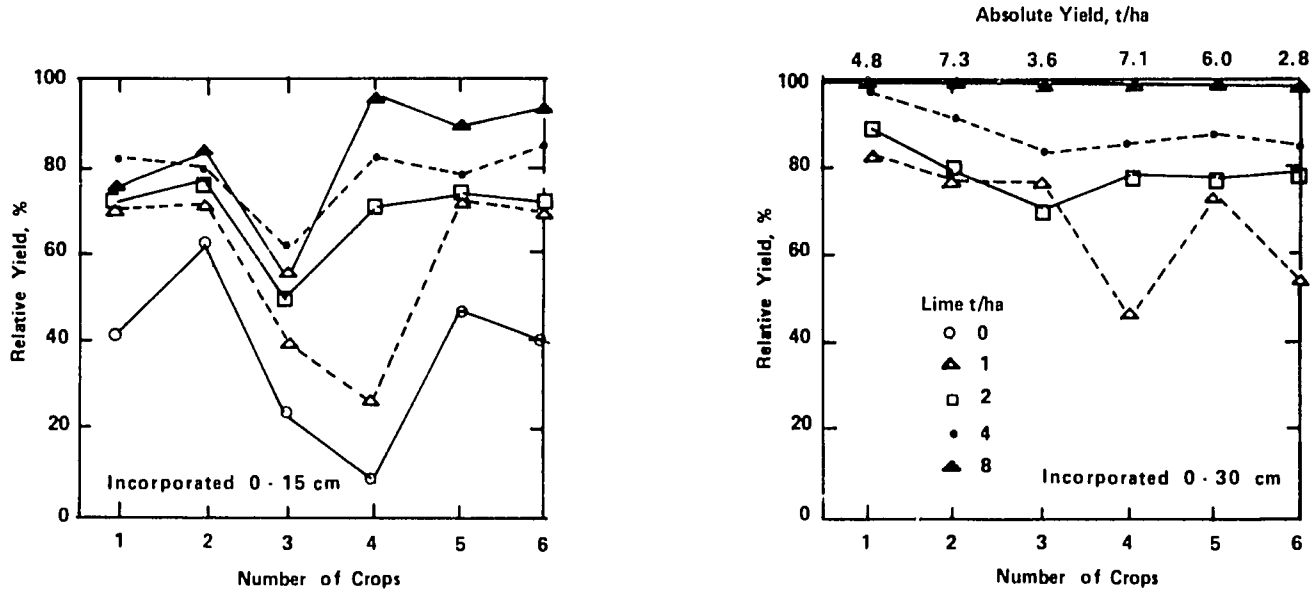


Figure 21. Effect of Amount and Depth of Incorporation of Initial Application of Liming Material on Six Successive Crops *(31)*.

The greater effects of the larger applications of lime and the deeper incorporation were accompanied by a greater decrease of the percent aluminum saturation and maintenance of this condition for a longer time, as shown in Figure 22.

Bouldin (*15a*) and Pearson (*133*) have reviewed the influence of deeper incorporation of lime on crop yields (Figure 23). Gonzalez-Erico et al. (*63*) report that tests with maize on Oxisols of central Brazil showed that deep incorporation (15-30 cm) of a single application of 4.0 tons/ha of lime produced 2.5 tons/ha more grain over three successive crops than shallow incorporation (0-15 cm) of the same amount of lime.

Evidence from CPAC indicates that the benefits of the deeper incorporation come largely from the greater rooting depths of crops treated with larger amounts of calcium and magnesium and from the resultant decrease of aluminum saturation. The greater rooting depth increases the availability to the crop of the soil moisture which is so necessary during the dry periods or "veranicos" that occur during the rainy season. Higher rates of either lime or phosphate increase the calcium content of the

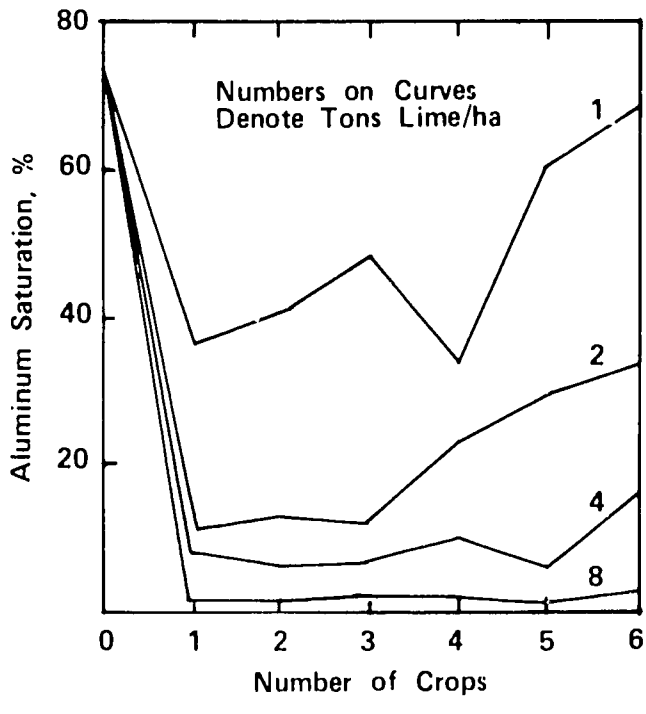


Figure 22. Effect of Initial Application of Liming Material on Aluminum Saturation of the Soil Over Six Cropping Seasons *(31)*.

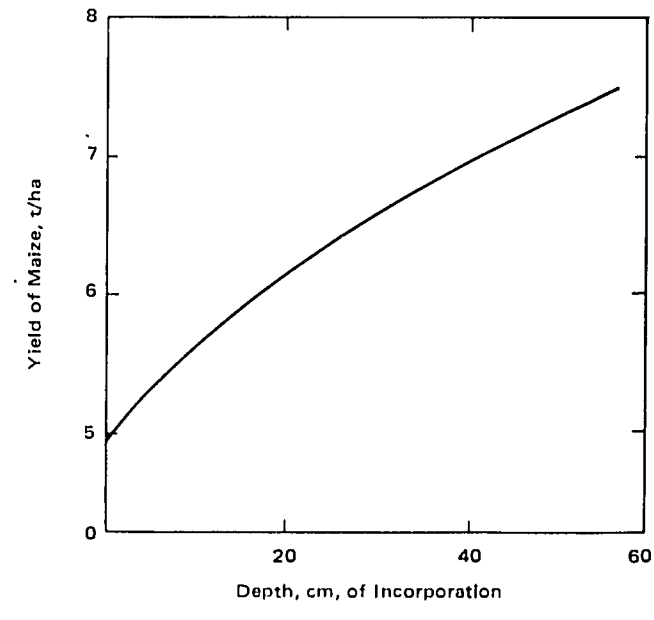


Figure 23. Effect of Depth of Incorporation of Liming Material on Yield of Maize *(15a)*.

soil and decrease the aluminum saturation. Liming also increases the penetration of roots into the soil with resultant increased access to subsoil moisture. The use of deep incorporations of lime and the use of calcium leaching to obtain the same results is discussed by Ritchey et al. (*152*).

Bouldin (*15a*) calculated the depth of soil, initially at field capacity, required to supply 6 mm of water per day to a crop for different periods of consecutive rainless days for two tropical soils, and his data in Table 8 demonstrate the need for changes in subsoil chemistry that affect rooting depth to ensure the productivity of soils that are being developed for agriculture in the tropics.

These data help explain why Brazilian agronomists obtain increased responses to rates of lime greater than those needed to decrease aluminum saturation in the plow layer or to raise the pH to 5.5. Results with both cotton and soybeans indicate increasing response in successive seasons to single higher applications of lime (*209*).

Table 8.
Rooting Depth Needed to Provide 6 mm Per Day of Water to a Crop During Rainless Periods (*15a*)

Consecutive Rainless Days	Frequency of Occurrence in Brasilia	Depth of Soil, cm, Reduced to Wilting During the Rainless Period: Dark Red Latosol (Brazil)	Catalina Clay (Puerto Rico)
8	3 per year	40	2
10	2 per year	50	33
13	1 per year	65	43
18	2 years in 7	90	60
22	1 year in 7	110	78

In a study of the effects of dolomitic limestone on soybean yields, Van Raij et al. (*185*) found that yields increased in successive seasons. The maximum yields as a function of pH were estimated from mathematical treatment of the data and were found to occur at pH 5.97 the first year, pH 5.92 the second, and pH 6.7 the third, even though aluminum saturation of the surface soil was zero in all years. The effect of exchangeable calcium and magnesium was estimated similarly, and the maximum yield of beans was found to be obtained with 2.62, 3.06, and 4.20 meq (Ca + Mg)/100 g, respectively, the first, second, and third seasons. It was concluded from these investigations that the Shoemaker, McLean, and Pratt, or SMP, buffer (*163*) provides a more reliable indicator of the lime required to bring the soil to pH 6 for this crop than the KCl-extracted exchangeable aluminum. Plant analysis data from the first year's study indicated that foliar potassium was decreased by liming and probably was deficient. Leaf magnesium concentrations were increased by applying lime, and those of aluminum, manganese, and iron were decreased. Iron and manganese contents of the leaf were relatively high in the first season in plots treated with 4.5 tons/ha of lime.

Leaching Studies

Calcium and magnesium move downward in the soil, increasing their exchangeable levels and decreasing the exchangeable aluminum and aluminum saturation when the source of calcium and magnesium is either lime or a calcium phosphate fertilizer; both lime and phosphates increase crop yields. The soil chemistry and the interactions involved are still being studied, both in the field and in the laboratory.

After applying KCl at rates as high as 600 kg K_2O/ha and cropping with maize, De Souza et al. (*171*) measured the potassium in the profile. They found significant movement of potassium only with the 600 kg K_2O/ha treatment on a soil that had initially contained only 25 ppm or 0.06 meq K/100 g (Figure 24). The surface 10 cm of the soil had a CEC of 2.4 meq/100 g.

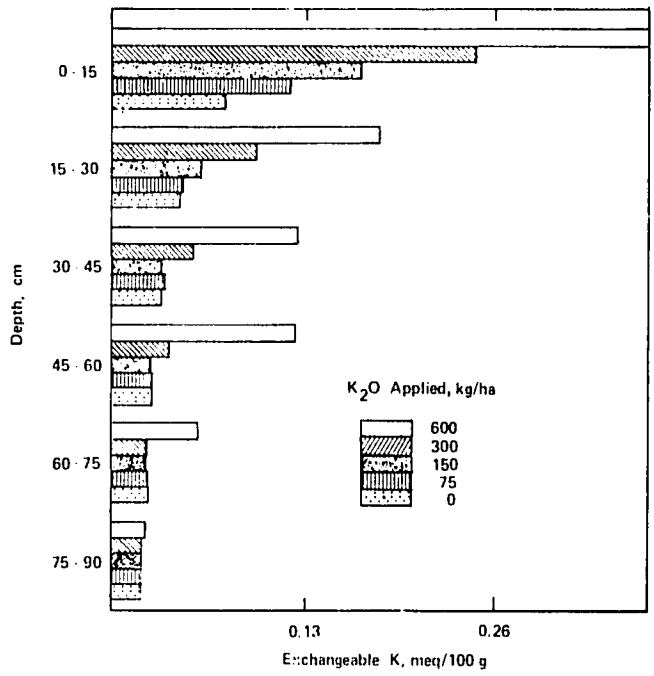


Figure 24. Effect of Applications of Potash on the Distribution of Exchangeable Potassium in the Profile of a Dark Red Latosol (*32*).

Results of extensions of these studies, included in Figure 9, showed that excellent residual effects of potassium were obtained 4 years after the initial applications, even with the downward movement of potassium, calcium, and magnesium in the soil. With these low-base-status soils that contain mostly kaolinitic clays and receive 1,000-2,400 mm of rainfall per year, these elements would be expected to move downward in the soil. There is evidence from these studies that when an additional 100 kg K_2O/ha was

applied the second year as a maintenance dressing it further increased yields even on plots to which 600 kg K_2O/ha had been applied previously.

Ritchey (*146*) constructed laboratory columns of these soil profiles and added one of three sources of calcium, equivalent to 2,000 kg Ca/ha, to each column and leached the columns with 1,200 mm of water, an amount equal to the average annual rainfall at the Cerrado Center. He then determined the distribution of calcium in the columns with the results shown in Figure 25.

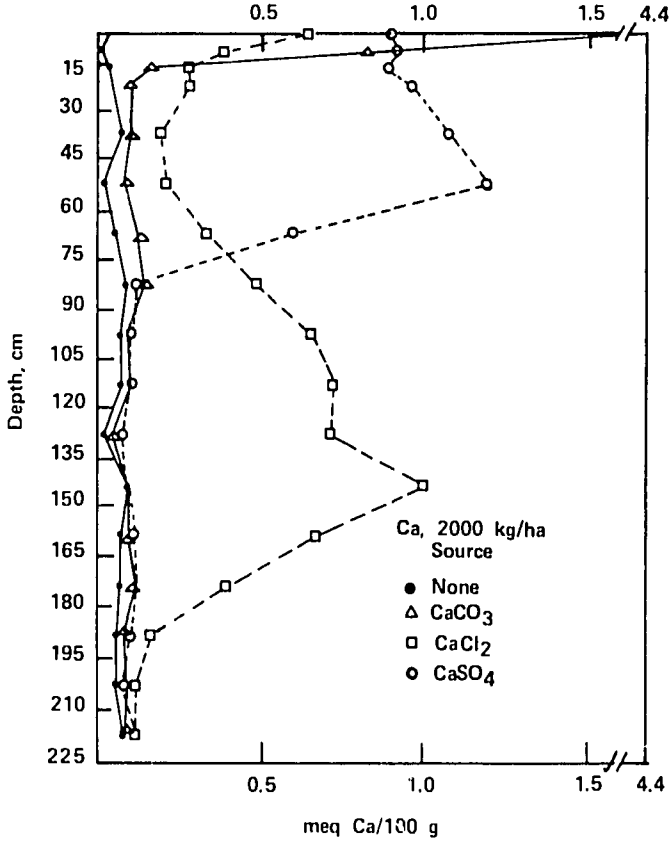


Figure 25. Effect of Associated Anion on the Distribution of Calcium in a Reconstituted Column of a Dark Red Latosol (*32*).

With the highly mobile chloride anion, calcium moved deeper in the column, the highest concentration being at the depth of 150 cm. The calcium sulfate, which has a less mobile anion, also moved, but the highest calcium concentration was at 45 to 60 cm. As mentioned earlier, $CaSO_4$ applied in SSP has been effective in previous studies in increasing exchangeable calcium and decreasing aluminum saturation (Figure 19). The carbonate caused the greatest increase in the surface exchangeable calcium, but calcium moved only to 20-25 cm deep.

Calcium sulfate has also been used on fine-textured soils to increase the movement of potassium into the rooting zone of fruit crops (*23*).

On soil columns similar to those discussed above, Ritchey (*146*) applied 8 tons/ha of dolomitic lime and triple superphosphate (TSP) or SSP to supply 1,300 kg P_2O_5/ha, and leached the columns with 1,200 mm of water. As shown in Figure 26 the SSP, which contains $CaSO_4$, showed the deepest movement of calcium and magnesium in the profile.

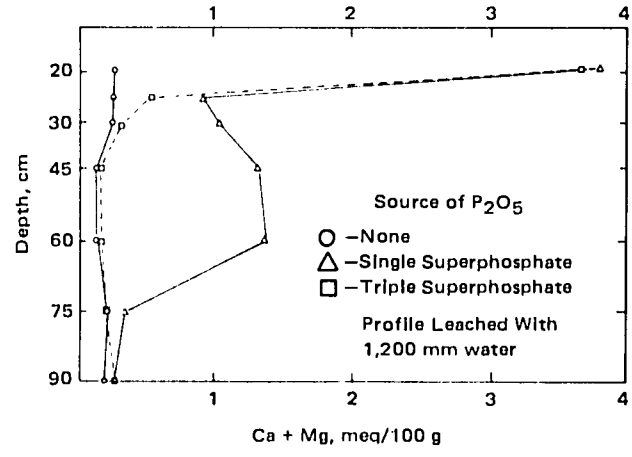


Figure 26. Effect of Dolomitic Limestone (8 t/ha) and Superphosphate (1,380 kg P_2O_5/ha) on the Distribution of Calcium and Magnesium in a Dark Red Latosol (*32*).

Results of field studies in Brazil (*146*) indicate that yields on some soils are higher with SSP than with TSP, presumably because of the lower aluminum saturation and the deeper rooting. Sulfur would also contribute to the yield. These results should be helpful in separating the effects of calcium nutrition from the toxicity effects of aluminum and manganese. These effects, of course, would be confounded with those of sulfur.

When forested jungle soils are cleared and the vegetation is burned, potassium, calcium, and magnesium in the ash are added to the soil, but under cropping and heavy rainfall the amounts of the bases are rather rapidly decreased by leaching and uptake of nutrients by crops. Villachia (*188*) at the Yurimagus Experiment Station in the Peruvian Amazon observed the changes in successive seasons in the amounts of soil potassium, calcium, and magnesium in a cleared area that had been treated with lime and fertilizer. For example, in a soil that was limed twice between March 1975 and August 1976, the level of exchangeable calcium was decreased by 0.5 meq/100 g or 224 kg Ca/ha. In a 4-year period, exchangeable calcium in unlimed and unfertilized plots decreased nearly 0.9 meq/100 g (403 kg Ca/ha), and magnesium decreased from 0.40 to 0.08 meq/100 g, a very deficient level.

Levels of exchangeable potassium were as high as 0.57 meq/ 100 g of soil 1 month after clearing, but after one crop of upland rice they had decreased to 0.28 meq/100 g. Even with a complete treatment by the eleventh month after clearing, crop removal and leaching had lowered the exchangeable potassium to

0.18 meq/100 g, below the 0.2 meq/100 g tentatively set as the critical level for these soils.

When 4 tons/ha of liming material was applied, the level of exchangeable calcium was decreased 1.9 meq/100 g or 850 kg/ha in 10 months, but some of the calcium lost from the surface soil presumably would be redistributed in the profile.

Villachia (*188*) found that through the application of lime and N 160, P 70, K 125, Mg 30, Cu 3, Zn 1, and B 1 kg/ha, the differences among the clearings that had been open for different periods of time could practically be ignored for maize; yields of about 5 tons/ha could be obtained fairly uniformly. Crops of maize and soybeans removed 76 to 278 kg K/ha, 13 to 49 kg Ca/ha, and 10 to 22 Mg/ha, depending on the season.

The relation between the amounts of potassium and those of magnesium is brought out by Villachia's research. Potassium applications totaling 375 kg/ha for soybeans, rice, and maize increased the exchangeable potassium by 0.144 meq/100 g. The three crops had taken up 261 kg K/ha, and the difference between the potassium applied and that removed by the crops was 114 kg/ha or 0.24 meq/100 g. On the other hand, the mean exchangeable magnesium decreased by 0.143 meq/100 g over the same period, almost exactly the amount by which the exchangeable potassium was increased and equivalent to the amount of anion that was associated with the applied potassium. These results demonstrate the lack of wisdom in applying an excess of only one nutrient on a soil with a low CEC. Such a treatment upsets the nutrient relationships and ultimately results in lowered yields.

The effect of leaching in the field depends on several factors, including drainage, vegetative cover, nutrient content of the soil, and the amount of nutrients, particularly nitrogen, applied in fertilizers and soil amendments. Boyer (*18*) reported that a soil in Senegal that had 128 mm of drainage lost Ca 30.7 and Mg 13.3 kg/ha. A soil in the Ivory Coast that had 500-600 mm of drainage lost Ca 110 and Mg 86 kg/ha. The effect of cover was shown by the fact that in Senegal the leaching losses were only Ca 18 and Mg 2.6 kg/ha under fertilized grass but on a bare soil the losses were Ca 56 and Mg 23 kg/ha.

Maintaining a high level of fertility increases losses of nutrients from the soil, but the fraction lost relative to that taken up by crops may actually decrease in successive seasons because of increased crop growth and greater rooting depth. Results of Godefroy et al. from the Ivory Coast reported by Boyer (*18*) showed that 38% of a low rate of lime was lost by leaching, but that only 25% of an application nearly six times greater was lost.

Decreasing Leaching Losses

In a review of losses of potassium by leaching, Munson and Nelson (*127*) suggest methods of decreasing losses of potassium by leaching from tropical soils. The major factors that influence the movement of applied potassium in the soil were shown to be the CEC of the soil; the soil pH or reaction; the method of placement and rate of application of potassium; the chemical source, particle size, and coatings of potassium fertilizers; combinations and sources of other nutrients applied with the potassium fertilizers; and the intensity, duration, and frequency of the rainfall.

Liming decreases losses of potassium by leaching in many soils because of increases in the CEC of the soils that result from pH-dependent charges and the fact that K^+ can replace Ca^{2+} on the exchange complex more easily than H^+ or Al^{3+}. These charges are associated with the soil organic matter.

Broadcasting on the surface of soils, and cultivation to provide slight mixing increases the contact of potassium with the soil and decreases the rate of leaching. The proper rate of application depends on the CEC of the soil. Banding and broadcasting of potassium are of equal value for low rates of application, but for rates above 300 kg K_2O/ha broadcasting has the advantage of greater contact of fertilizer with the soil.

In comparing sources of potassium in most soils the general order of retention of potassium would be approximately

$$K_2CaP_2O_7 > KPO_3 = K_3PO_4 > K_2HPO_4 > KH_2PO_4 > K_2SO_4 > KCl = KNO_3$$

The Tennessee Valley Authority (TVA) has produced a number of potassium phosphates, some of which are slowly soluble (*43*). These materials have been tested agronomically in TVA's program and have been found to resist leaching of potassium, the effect depending upon their composition and particle size. TVA has experimented also with sulfur-coated KCl and K_2SO_4.

Several coatings have been used to control the rate of release of potassium in the soil, and some were quite effective in improving the release of available potassium over an entire season. There has been little study of these materials in tropical areas, but materials should be developed for long-term tests so that the economics and possible advantages of controlled- and slow-release materials can be evaluated and their effectiveness compared with that of splitting and timing of applications of highly soluble potassium fertilizers.

Interactions

The interrelationships of potassium, calcium, and magnesium in soil fertility are complex. While much could be said about nutrient interactions, only a few examples will be given and emphasis will be placed on potassium. In addition to interactions among nutrients themselves, there are interactions of nutrients with crop species as affected by soil characteristics and nutrient supplies and needs, as well as by management practices.

Nutrient Interactions

Munson (*124, 125*), Loue' (*106, 107*), and Usherwood (*182*) have discussed interactions of potassium, calcium, and magnesium with emphasis on their interactions with nitrogen.

It is often difficult to find responses to potassium under low-yield conditions if other nutrients are limiting or if there are toxicities. Under such conditions growth is so slow that, unless potassium is seriously limiting, many soils will release potassium at a rate adequate to meet the needs of the crop. When higher yielding varieties or hybrids are introduced with adequate nitrogen and phosphorus, however, the more rapid growth markedly increases the rate of uptake of potassium and the potential for response to applied potash. This is illustrated in Figure 27 with results with rice in Brazil. With application of 30 kg N/ha the yield was 5.5 tons/ha and there was little response to potash, and a potassium soil test calibration with that rate of nitrogen would lead to erroneous conclusions. When 90 kg/ha of nitrogen was applied, however, the response to potash was practically linear up to the highest application listed and the yield was increased to about 8.7 tons/ha. Relationships such as these are important in calibrating potassium soil tests for fertilizer recommendations, and adequate rates of potassium or other nutrients should be applied to bracket the response range.

Potassium requirements are very high during the early growth of some crops, particularly when other nutrients are available in adequate amounts. For example, when phosphorus is deficient, increasing the application of phosphate can alter the rate and total uptake of potassium markedly. The effect of increasing the amount of phosphorus applied with a constant amount of nitrogen on the rate and total uptake of potassium by wheat over an entire season is shown in Figure 28 (*86*). The maximum uptake of potassium by wheat usually occurs at heading. In this example, increasing the application of phosphorus increased the uptake of potassium from 175 to more than 500 kg/ha and hastened the apparent maturity of

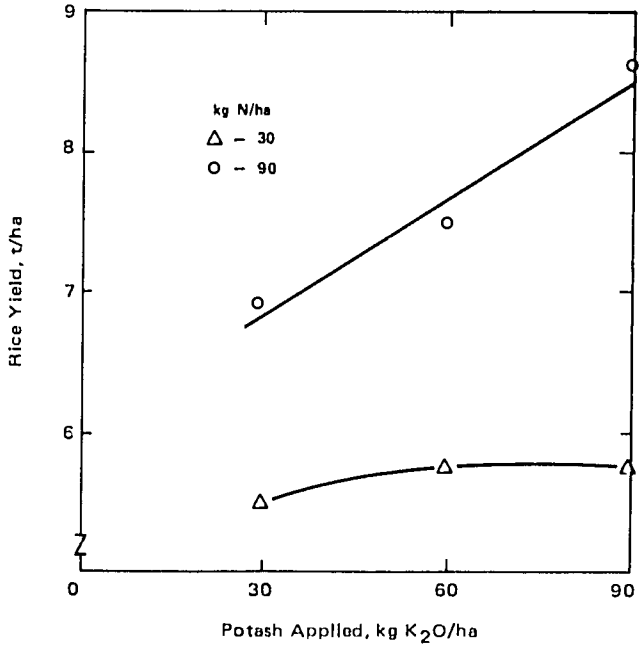


Figure 27. Response of Rice to Potash Under Two Levels of Nitrogen (*108*).

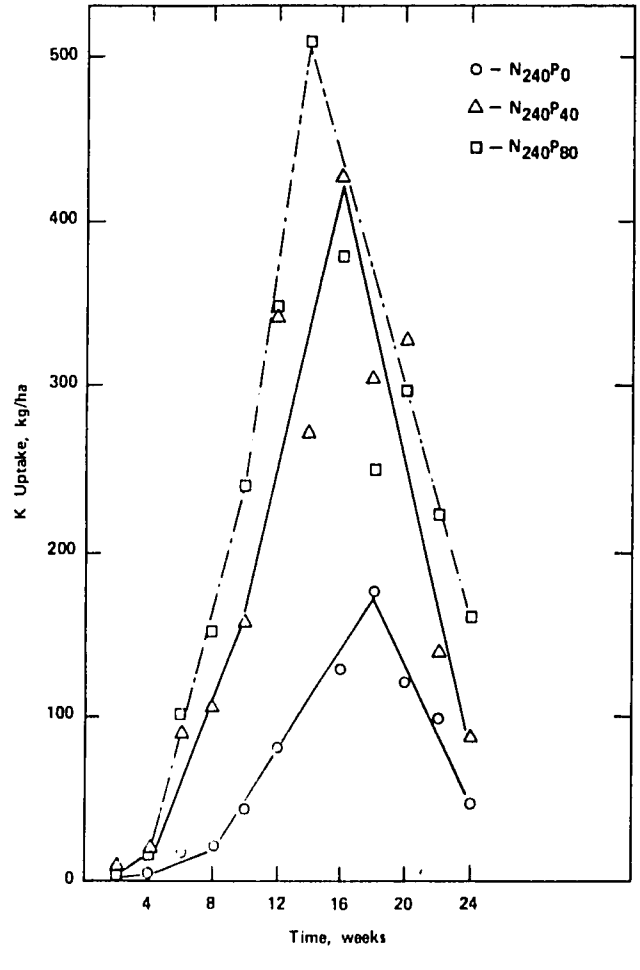


Figure 28. Effect of Phosphorus on Uptake of Potassium by Wheat on Soil Supplied With a Uniform Rate of Nitrogen (*86*).

the crop by moving the maximum uptake earlier in the season, thereby increasing the daily rate of uptake of potassium. This increased uptake in the earlier stage indicates an effect on the rate of maturation of the crop that could be important to food production in tropical areas where multiple cropping is practiced. It should be noted that about 40% of the potassium taken up was removed with the grain. If the straw were removed also, the removal of potassium would be increased markedly, thereby increasing the amount of maintenance potash required by the system.

Fox and his coworkers at the University of Hawaii have evaluated relationships of nitrogen and potassium on bananas over several years (*54*). On a soil with a high potassium content, nitrogen gave a good response the first 2 years, but thereafter production and bunch weight declined when potassium was not added (Figure 29). The interrelationship between the bunch weight of bananas and exchangeable potassium for different levels of leaf nitrogen is shown in Figure 30. With high levels of leaf nitrogen the relationship is essentially linear for soils containing as much as 2 meq K/100 g, indicating the relatively high requirement for potassium of well-fertilized bananas.

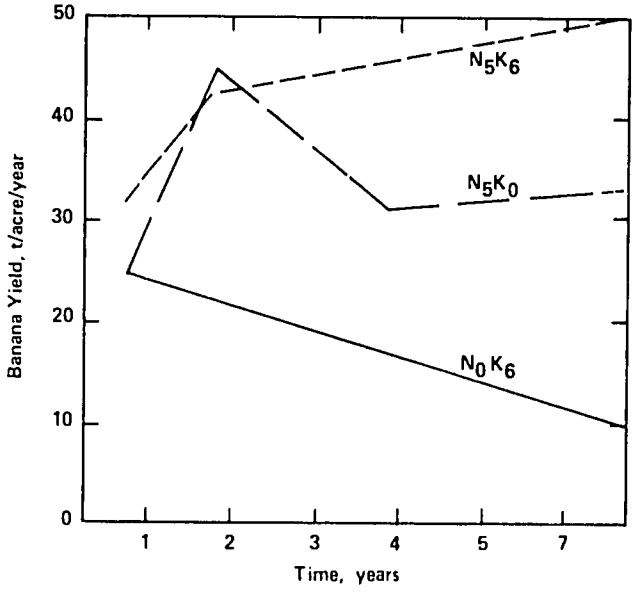


Figure 29. Response of Bananas to Nitrogen and Potassium Over Seven Growing Seasons *(54)*.

With oil and coconut palms on low-exchange-capacity soils, the initial need is often for potassium, followed by need for magnesium as production is increased. Sometimes the effects are additive, but interactions may be encountered. Important effects such as bringing palms into production much earlier than normal may result from proper nutrient combinations and rates, which can be very important in developing countries.

The source of nitrogen has a definite influence on the uptake and requirements of potassium, calcium, and magnesium, with the greatest effects on potassium and magnesium. With crops such as rice that can readily utilize ammonium nitrogen there probably are fewer problems than with upland crops. If the conversion of ammonium nitrogen to nitrate is slow, however, as on acid soils, large amounts of ammonium nitrogen may depress the availabilities of potassium and magnesium. Crops supplied with nitrate nitrogen usually take up larger amounts of potassium, calcium, and magnesium than those supplied with ammonium nitrogen.

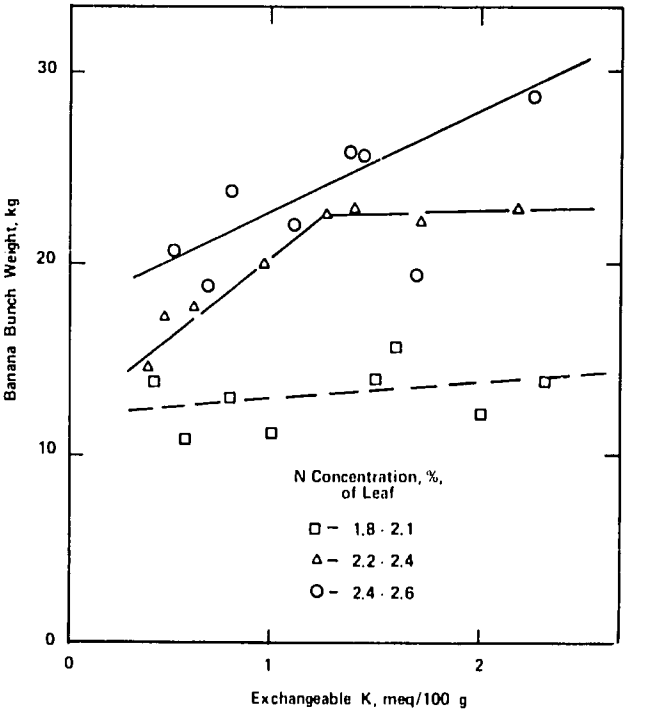


Figure 30. Relation Between Banana Bunch Weight and Exchangeable Potassium as Affected by Increasing Concentrations of the Leaf Nitrogen *(54)*.

Wilcox (*197*), working with soils in greenhouse studies at the Centro Nacional de Pesquisa de Arroz e Feijao, Goiania, Brazil, found that ammonium nitrogen induced toxicity symptoms in beans that were not treated with $CaCO_3$. Best growth of tomatoes was obtained with nitrate nitrogen and $CaCO_3$. All crops treated with ammonium nitrogen showed stunted growth and ammonium toxicity symptoms on a Glei Latosol. Application of KCl decreased the adverse effects of ammonium nitrogen, but when $CaCO_3$ was applied the ammonium nitrogen was more effective than nitrate nitrogen. In tests with beans and tomatoes (*197*), the proper combination of nutrient sources produced yield differences nearly as great as the maximum response to fertilizer

as shown in Table 9. Changes in soil pH did not appear to be a major factor in comparison with the form and amount of the nutrients supplied. These differences should be studied under field conditions.

Table 9.
Comparison of Maximum Response of Vegetable Crops to Fertilizer With Maximum Differences of Response to Different Combinations of Fertilizer Materials on Two Soils (*197*)

	Difference in Response, g/pot			
	Beans		Tomatoes	
	Glei Latosol	Red Latosol	Glei Latosol	Red Latosol
Maximum response to fertilizers	1.68	2.42	1.84	2.19
Maximum difference between sources	1.55	2.20	1.83	2.09

Lime-nutrient interactions are important, as shown by Mielniczuk's results on soybeans (*205*) that are summarized in Table 10. On a soil with an initial extractable P content of 2.4 ppm and a soil pH of 4.4, the yield of beans was only 72.5 kg/ha. With application of either 12 tons of lime and 200 kg P_2O_5/ha or 18 tons of lime and 100 kg P_2O_5/ha the yields of beans were more than 2,500 kg/ha. Economics would determine which combination of lime and P_2O_5 is the most profitable.

Van Raij and Machado (*209*) worked with cotton in Brazil and found little response to lime without potassium, but with adequate potassium the response to lime was linear up to an application of 6 tons/ha. Combinations of 60 kg K_2O/ha applied in the row and 60 kg K_2O/ha broadcast produced the highest yields, with improved maturity of the fiber and better micronaire and fiber quality.

Crop Species, Varieties, and Hybrids

The adaptation of plants to mineral stress in problem soils was the topic of a workshop in 1976, and workers at the international centers around the world are seeking crop species or varieties that are tolerant to aluminum and utilize nutrients efficiently, especially potassium, calcium, and magnesium. For species that are tolerant to aluminum, calcium can be treated as a nutrient, but soils also need some lime to minimize adsorption of phosphorus. Work on the CIAT Beef Project at the Carimagua Station in the Colombian Llanos has shown how plant species can be classified according to their relative nutrient efficiencies or requirements, and such a classification is shown in Table 11.

From this classification the potassium, magnesium, phosphorus, and sulfur requirements for establishment and maintenance of the grasses and legumes were estimated with the results shown in Table 11. Similar requirements are being developed for cassava and other crops at CIAT.

Some maize hybrids are much more efficient in utilizing nutrients than others. Munson (*124*) reports that in Tennessee (United States) Freeman found that two different maize hybrids yielded 1,506 and 4,267 kg/ha of grain without applied potassium. With application of a total of 363 kg K/ha over three seasons, the yields were 6,840 and 8,911 kg/ha, respectively. Both hybrids thus showed marked response to the applied potassium; the increases in grain yield were 5,334 and 4,644 kg/ha, respectively. The profitability of the higher yielding hybrid is obvious, however, even though the lower yielding hybrid was slightly more responsive. Similar relations are expected to exist on tropical soils.

Baligar and Barber (*7*) have recently evaluated the uptake of potassium, calcium, magnesium, and phosphorus by maize hybrids. The rates of uptake of

Table 10.
Effects of Lime and Phosphate on Yields of Soybeans and pH, Exchangeable Aluminum and Manganese, and Average Phosphorus Content of the Soil (*205*)

	Soybean Yield, kg/ha, at Indicated P_2O_5, Rate, kg/ha					Average Effect of Lime on Soil		
							Exchangeable	
Lime, t/ha	0	100	200	300	400	pH	Al, meq/100 ml	Mn, ppm
0	725	1,717	1,732	2,195	2,485	4.4	3.25	45.6
6	1,512	2,260	2,355	2,477	2,442	5.4	0.29	16.1
12	1,785	2,412	2,557	2,300	2,505	6.4	0.00	8.7
18	1,927	2,517	2,320	2,390	2,500	6.8	0.00	6.1
25	1,527	2,422	2,492	2,795	2,407	6.9	0.00	5.7
				Average P Content, ppm				
	2.4	5.5	9.6	16.0	19.9	-	-	-

Table 11.
Requirements of Fertilizer Nutrients of Grasses and Legumes on the Llanos Soils of Colombia[a] (*208*)

Species	Relative Nutrient Requirement				
	P	K	Mg	S	Lime
M. minutiflora	1	1	1	1	1
B. humidicola	1	2	2	2	1
B. decumbens	2	2	2	2	1
A. gayanus	2	2	2	2	3
H. rufa	3	3	2	2	2
P. maximum	4	3	3	3	1
B. radicans	3	3	2	2	1
Z. latifolia	1	1	2	2	1
S. guianensis	1	1	2	2	1
S. capitata	1	1	2	2	1
D. ovalifolium	2	2	3	2	1
P. phaseoloides	3	2	4	3	1

Nutrient	Requirement	Rate of Nutrient, kg/ha, at Indicated Requirement			
		1	2	3	4
K_2O	Establishment	20	30	40	50
	Maintenance	10	15	20	25
Mg	Establishment	10	15	20	25
	Maintenance	4	8	12	16
P_2O_5	Establishment	40	60	80	100
	Maintenance	10	15	20	25
S	Establishment	10	15	20	25
	Maintenance	4	8	12	16

a. A higher number denotes higher requirement.

potassium and phosphorus by maize genotypes were different, but those of calcium and magnesium were similar. The type of root system has a major effect on the uptake of potassium and phosphorus, both of which reach roots primarily by diffusion in the soil moisture.

Recent reports (*206*) from China indicate that newly developed hybrid rice not only gives higher yields than other varieties under the same levels of NP fertilization, but also requires 25% more potash than the older varieties.

Clark (*27*) has discussed the influence of crop genotype on the uptake of calcium and magnesium, as well as the different responses to these nutrients of specific hybrids or varieties. The relationships are very complex and may be associated with aluminum or micronutrients or both.

Selection of species for higher nutrient efficiencies should be linked with high yields of marketable products if increased food production is to be obtained. High yields cannot be obtained unless adequate nutrients are present in the soil or provided through supplemental applications.

Mineral Sources of Potassium, Calcium, and Magnesium

Some of the many minerals that contain potassium, calcium, and magnesium are listed in Table 12. Silicate minerals that contain these plant nutrients are listed in Table 13. These are included because silicates have been found effective in increasing the yields of some crops (55).

Potash

The present major mineral source of potash in the world is sylvinite, a mixture of KCl and NaCl, but considerable amounts of carnallite, langbeinite, and kainite also are mined and refined. Potash is recovered from brines at Searles Lake in California and the Great Salt Lake in Utah in the United States and from the Dead Sea in Israel and Jordan. Other deposits are deep and must be mined. The distribution of potash deposits throughout the world is shown in Figure 31.

The British Sulphur Corporation conducted a survey of world potash resources in 1975 (*199a*), and Singleton (*164*) extrapolated the supply and demand of potash up to the year 2000. Sheldrick and Stier (*162*) estimate the total recoverable potash reserves of the world to be 13 billion tons of K_2O and the total resources to be 140.4 billion tons; Von Peter (*189, 190*) estimates the recoverable world reserves to be 50 billion tons of K_2O. More deposits of potash have since been discovered, and it seems safe to say that potash reserves are adequate for the long term, even though it may not be practicable to develop all the known deposits. The cost of developing a mining and refining complex and establishing the transportation and distribution system for readily recoverable deposits has increased rapidly in recent years.

Latin America has many potash deposits. Sheldrick and Stier (*162*) list potash deposits in Brazil, Chile, Mexico, and Peru, and other reports mention potash deposits in Argentina, Bolivia, Colombia, and Peru; little is known, however, about the quality and size of most of these deposits. IFDC's report on Bolivia contains information about the location and extent of the Salars potash deposit in that country. Potash has been discovered in the north-central part of Brazil, but little is known about the deposit. It is understood that the development of the potash deposits near Sergipe in northeast Brazil is underway.

Large amounts of potash will be required for the development of Latin America's tropical agricultural land. Early estimates based on a relatively moderate level of production indicated that Latin America will need some 4.4 million tons of K_2O annually for their main crops (*111*), but with new land being developed and with new research information on fertilization, the annual potash requirements are expected to be much higher.

Potash deposits have been discovered recently in Thailand, and IFDC in consultation with the World Bank has made a study of the development of fertilizer production in Thailand and present information on the extent of the potash deposits and the potential for their development (*72*).

Africa has potash deposits in the Congo, Morocco, and Ethiopia. Production in the Congo was started, but mining difficulties closed the operation. Little is known about the other deposits or their potential.

Calcium and Magnesium

The major source of agricultural lime is limestone, a more or less pure calcium carbonate that contains 21% to 40% Ca. Deposits of limestone are widely distributed throughout the world.

Gypsum, hydrated calcium sulfate, is another source of calcium, and the mineral contains more than 22% Ca. Deposits of gypsum are rather widely distributed throughout the world, and calcium sulfate is a major component of single or ordinary superphosphate. Unlike calcium carbonate, calcium sulfate is a neutral salt and does not change the pH of the soil to which it is applied.

The major source of magnesium is dolomitic limestone, a mixture of the carbonates of calcium and magnesium in which the magnesium content ranges from 1.3% to 13.0%. This form of magnesium is often applied in liming programs. Other minerals from which agricultural magnesium is obtained are langbeinite, carnallite, and kieserite (Table 12); brucite, olivine, and serpentine (Table 13) are other mineral sources of magnesium, but most mining and refining of magnesium compounds is carried out in connection with the mining of potassium minerals.

There are large deposits of limestone in Latin America and along the Gulf Coast of Mexico. Colombia has a reserve of 24.5 billion tons of limestone (*112*) that is fairly evenly distributed over the country except in the Llanos Orientales where it will be needed for the development of the Oxisols in that savanna. The lime probably will be barged up the river from the ocean and then delivered by truck when the transportation system is developed.

Peru has excellent deposits of dolomitic limestone in many areas of the country, but much remains to be done in developing these sources and establishing the necessary transportation and distribution systems for their exploitation.

Brazil has large deposits of limestone that are well distributed over the country (*19*). Some of the

Table 12.
Mineral Sources of Potassium, Calcium, Magnesium, and Sulfur

Mineral	Formula	Composition, %[a]			
		K_2O	CaO	MgO	S
Alunite	$KAl_3(OH)_6(SO_4)_3$	11.4	-	-	15.5
Anhydrite	$CaSO_4$	-	41.2	-	23.5
Aphthitalite	$K_3Na(SO_4)_2$	42.5	-	-	19.3
Arcanite	K_2SO_4	54.0	-	-	18.4
Brucite	$Mg(OH)_2$	-	-	69.1	-
Calcite	$CaCO_3$	-	56.0	-	-
Carnallite	$KCl{\cdot}MgCl_2{\cdot}6H_2O$	16.9	-	14.5	-
Dolomite	$CaMg(CO_3)_2$	-	30.4	21.2	-
Epsomite	$MgSO_4{\cdot}7H_2O$	-	-	16.3	13.0
Gypsum	$CaSO_4{\cdot}2H_2O$	-	32.6	-	18.6
Hanksite	$KCl{\cdot}9Na_2SO_4{\cdot}2Na_2CO_3$	3.0	-	-	18.4
Kainite	$KCl{\cdot}MgSO_4{\cdot}3H_2O$	18.9	-	16.2	12.9
Kalinite	$K_2SO_4{\cdot}Al_2(SO_4)_3{\cdot}24H_2O$	9.9	-	-	13.5
Kieserite	$MgSO_4{\cdot}H_2O$	-	-	29.1	23.2
Langbeinite	$K_2Mg_2{\cdot}(SO_4)_3$	22.6	-	19.4	23.2
Leonite	$K_2Mg(SO_4)_2{\cdot}4H_2O$	25.7	-	11.0	17.5
Magnesite	$MgCO_3$	-	-	47.8	-
Niter	KNO_3	55.7	-	-	-
Polyhalite	$K_2SO_4{\cdot}MgSO_4{\cdot}2CaSO_4{\cdot}2H_2O$	15.6	18.6	6.7	28.3
Picromerite[b]	$K_2SO_4{\cdot}MgSO_4{\cdot}6H_2O$	23.4	-	10.0	15.9
Sylvinite	$KCl{\cdot}NaCl$	35.4[c]	-	-	-
Sylvite	KCl	63.1	-	-	-
Syngenite	$K_2SO_4{\cdot}CaSO_4{\cdot}H_2O$	28.7	17.1	-	19.5

a. These figures are given for pure minerals. Natural minerals usually contain lower concentrations.
b. Schoenite is a variety with the same formula. In India these minerals contain 22%-24% K_2O and 9%-12% MgO (*186*).
c. The mineral as mined contains 15%-30% K_2O.

deposits are not dolomitic, however, and magnesium will have to be supplied by imported dolomite or other fertilizer magnesium sources. Malavolta (*108*) estimates that Brazil uses some 6 million tons of agricultural lime annually.

No survey was made of sources of lime in Africa and Asia, but it is assumed, on the basis of the plate tectonic concept of geology, that there are deposits of limestones in western Africa similar to those in eastern Latin America.

Many silicate minerals contain substantial amounts of calcium and magnesium, as shown in Table 13. When finely ground these minerals readily provide calcium and magnesium to growing plants, and some tests show the silicate minerals to be as effective sources of nutrients as more soluble compounds of the same nutrients.

Table 13.
Silicate Minerals Containing Potassium, Calcium, and Magnesium

Mineral	Formula	Composition, %[a]		
		K_2O	CaO	MgO
Orthoclase	$KAlSi_3O_8$	16.9	-	-
Microline	$KAlSi_3O_8$	16.9	-	-
Leucite	$KAl(SiO_3)_2$	21.5	-	-
Enstatite	$MgSiO_3$	-	-	40.1
Hypersthene	$(Fe,Mg)SiO_3$	-	-	40[b]
Diopside	$CaMg(SiO_3)_2$	-	25.9	18.5
Wollastonite	$CaSiO_3$	-	48.3	-
Tremolite	$CaMg_3(SiO_3)_4$	-	13.4	28.8
Olivine	$(Mg,Fe)_2SiO_4$	-	-	49[b]
Monticellite	$CaMgSiO_4$	-	35.9	25.6
Forsterite	Mg_2SiO_4	-	-	57.3
Muscovite	$H_2KAl_3(SiO_4)_3$	11.8	-	-
Biotite	$HK(Mg,Fe)_2Al_2(SiO_4)_3$	10.2	-	19[b]
Phlogopite	$H_2KMg_3(SiO_4)_3$	12.0	-	31.0
Serpentine	$H_4Mg_3Si_2O_9$	-	-	43.6
Talc	$H_2Mg_3(SiO_3)_4$	-	-	31.7

a. These figures are given for pure minerals. Natural minerals usually contain lower concentration.
b. Maximum value.

Figure 31. Location of World Potash Reserves.

1. Canada—Saskatchewan
2. Canada—New Brunswick
3. United States—North Dakota and Montana
4. United States—New Mexico
5. United States—Utah
6. United States—California
7. Brazil—Sergipe
8. Brazil—Amazon area
9. Peru—Sechura Desert
10. Bolivia—Salars
11. Chile—Guano and Salars
12. Argentina—Mendoza

12a. Argentina

13. United Kingdom—Cleveland
14. Spain—Catalonia, Navarra
15. France—Alsace
16. Italy—Sicily
17. Federal Republic of Germany

17a. Democratic Republic of Germany

18. Israel and Jordan—Dead Sea
19. Congo—Pointe-Noire
20. Ethiopia—Danakil
21. U.S.S.R.—West Ukraine
22. U.S.S.R.—Byelorussia
23. U.S.S.R.—Urals
24. U.S.S.R.—Siberia
25. China—Lake Ch-erh-han
26. Thailand—Khorat Plateau
27. Australia—Lake McLeod
28. Morocco

Fertilizer Potassium, Calcium, and Magnesium

Many fertilizer compounds are excellent sources of potassium, calcium, and magnesium. Many of these compounds that are available commercially, either alone or in mixed fertilizers, are listed in Table 14.

The chief source of fertilizer potassium is muriate of potash, KCl, which probably accounts for 95% of the total. Other principal sources are potassium sulfate, K_2SO_4, and potassium magnesium sulfate, $K_2SO_4 \cdot 2MgSO_4$; only small amounts of potassium nitrate, KNO_3, are produced. These are all excellent sources of potassium; they are highly soluble, which is advantageous on most soils, but on low-exchange-capacity tropical soils that receive 2,000-3,000 mm of rain annually, less soluble or controlled-release materials would be desirable.

There are many good sources of fertilizer calcium, including calcium ammonium nitrate, calcium nitrate, calcium sulfate or gypsum, and phosphate fertilizers themselves. Most phosphate fertilizers—single or ordinary superphosphate, triple or concentrated superphosphate, fused calcium magnesium phosphate or thermophosphate—are effective sources of calcium. Calcium is supplied also by rock phosphate itself; for example, North Carolina rock phosphate contains 35.3% Ca and 0.6% Mg (*71a*).

The fertilizer sources of magnesium available commercially are magnesium sulfate, potassium magnesium sulfate, magnesium oxide, and magnesium hydroxide. The amounts of magnesium supplied by fertilizers throughout the world are difficult to

Table 14.
Fertilizer Sources of Potassium, Calcium, Magnesium, and Sulfur

Fertilizer	Chemical Formula	Composition, %[a]			
		K_2O	CaO	MgO	S
Potassium Sources					
Potassium chloride	KCl	63.5	-	-	-
Potassium sulfate	K_2SO_4	54.0	-	-	18.4
Potassium nitrate	KNO_3	46.4	-	-	-
Potassium magnesium sulfate	$K_2SO_4 \cdot 2MgSO_4$	22.7	-	15.6	23.2
Monopotassium phosphate	KH_2PO_4	34.5	-	-	-
Potassium metaphosphate	KPO_3	39.8	-	-	-
Potassium polyphosphate[b,c]	$K_4P_2O_7+K_3PO_4$	60.6	-	-	-
Dipotassium phosphate	K_2HPO_4	59.5	-	-	-
Calcium Sources					
Limestone (Calcite)	$CaCO_3$	-	56.0	-	-
Dolomite	$CaMg(CO_3)_2$	-	30.4	21.9	-
Gypsum	$CaSO_4 \cdot 2H_2O$	-	32.6	-	18.6
Basic slag	Indefinite	-	42-50	2-8	-
Rock phosphate[d]	$3Ca_3(PO_4)_2 \cdot CaF_2$	-	55.6	0.1-1	-
Rhenania phosphate[b]	$CaNaPO_4+Ca_2SiO_4$	-	50.9	-	-
Ordinary superphosphate[b]	$Ca(H_2PO_4)_2 \cdot H_2O+CaSO_4$	-	28.9	-	8.2
Triple superphosphate	$Ca(H_2PO_4)_2 \cdot H_2O$	-	22.2	-	-
Calcium nitrate[e]	$Ca(NO_3)_2$	-	34.1	-	-
Calcium ammonium nitrate[b]	$(Ca,Mg)CO_3+NH_4NO_3$				
Calcitic	$CaCO_3+NH_4NO_3$	-	31.0	0.0	-
Dolomitic	$CaMg(CO_3)_2+NH_4NO_3$	-	21.2	15.2	-
Calcium cyanamide	$CaCN_2$	-	70.0	-	-
Magnesium Sources					
Kieserite (Magnesium sulfate)	$MgSO_4 \cdot H_2O$	-	-	25.8	20.5
Potassium magnesium sulfate	$K_2SO_4 \cdot 2MgSO_4$	22.7	-	19.4	23.2
Fused calcium magnesium phosphate	Indefinite	-	32.0	18.0	-
Calcined brucite[f]	$MgO \cdot xH_2O$	-	-	70-85	-

a. Most compositions listed are maximum values; commercial forms are seldom pure.
b. A physical mixture of variable composition.
c. Usually supplied as an aqueous solution containing about 27% K_2O.
d. The formula given is that of fluorapatite, once considered the major constituent of rock phosphate.
e. Usually occurs as $Ca(NO_3)_2 \cdot 4H_2O$ which contains 23.7% CaO.
f. Brucite is $Mg(OH)_2$.

determine, and no survey of the consumption of magnesium was made.

For low-base-status tropical soils, fertilizer materials should be selected that will provide suitable amounts of potassium, calcium, and magnesium, as well as other nutrients. A Colombian fertilizer company is now offering a six-nutrient fertilizer containing nitrogen, phosphorus, potassium, calcium, magnesium, and sulfur. For acid, low-base soils, sources of nutrients should be selected that would aid in decreasing the exchangeable aluminum, iron, and manganese. Thus, because of the ability of the calcium sulfate in SSP to provide calcium and sulfur which move down in the soil and decrease saturation with aluminum, SSP would be preferred over TSP on many tropical soils when lime is not available. The use of TSP with added gypsum, however, might be more economical because of the lower cost of transportation of the separate ingredients than that of the equivalent amount of SSP.

In 1978 Brazil used 1,274,736 tons of SSP which contained 255,202 tons of calcium, thereby improving the calcium status of many of the soils.

It is virtually impossible to obtain data that could serve as the basis of reasonable estimates of the amounts of calcium and magnesium used in agriculture throughout the world. There are some figures on the amounts of limestone used and on potash materials that contain magnesium, but these data apply to developed countries, and figures for developing countries, even on the amounts of limestone used, are very scarce.

On the other hand, potash production and consumption are fairly thoroughly documented. As shown in Table 15, a total of 24.3 million tons of K_2O was consumed in the world in 1980, 1.5 times that consumed in 1970. Of the 1980 amount, Latin America used 7.7% of the total, Asia 10.1%, and Africa 1.6%.

Table 15.
Historical Consumption of Potash[a]

	Consumption, '000 tons K_2O	
	1970	1980
World	16,403	24,256
Latin America	646	1,858
Asia	1,252	2,445
Africa	237	398

a. FAO (*48a*).

In an analysis of potash consumption during the early 1980s, the UNIDO/FAO/World Bank Working Group (*73*) estimated the annual rate of increase to be 5.3% for the first 6 years of the decade. Developing countries are expected to increase their demand for potash by 2 million tons during that period and to account for 17% of the world consumption by 1985. Most of the increased potash consumption, however, is expected to occur in the developed countries, and their consumption is expected to increase at an annual rate of 4.8%.

By the year 1990 the world consumption of potash is expected to be 1.6 times that in 1980, and Latin America should be using more than 9% of the total, Asia 9%, and Africa 1%. Potash consumption thus is expected to increase most rapidly in Latin America, particularly in Brazil. Colombia also is expected to increase markedly its consumption of potash.

Reported consumptions of potash in 1970 and 1980 for individual countries in Latin America, Asia, and Africa are listed in Table A-5. The production of potash by major producing areas of the world in 1970 and 1980 is listed in Table 16.

Table 16.
World Production of Potash[a]

	Production, '000 tons K_2O	
	1970	1980
Canada	3,178	7,337
Chile	16	23
China	5	20
Congo	123	0
Finland	1	0
France	1,842	1,933
Germany, D.R.	2,419	3,422
Germany, F.R.	2,405	2,701
Israel	576	787
Italy	155	95
Netherlands	1	0
Peru	1	0
Spain	524	691
United Kingdom	-	307
U.S.A.	2,259	2,052
U.S.S.R.	4,087	8,064
Total	17,592	27,432

a. FAO (*48a*).

From their analysis of the available data, Sheldrick and Stier (*162*) predicted in 1978 that the supply of potash would balance the demand until 1982. Because of the current world economic situation, the supply-demand situation should be in balance until the mid-1980s. World production is already being increased. World economic problems, governmental policies, and lack of and competition for funds slow the production, distribution and use of potash.

Potash production undoubtedly will have to be increased before the mid-1980s to meet the growing needs and demands. FAO projections indicate that production of food will have to be increased on present arable land, and another 200 million ha will have to be brought into production before the year 2000 to feed a hungry world. This will require large amounts of potash because the soils of most of the new land being brought into production are the low-base-status Oxisols and Ultisols.

Fertilizer, of course, is absolutely essential to the production of food. As an example, the average yield of cereal grain per hectare in a country is fairly definitely proportional to the average amount, in kg/ha, of the three major nutrients, N, P_2O_5, and K_2O, applied in that country. This relationship is shown in Figure 32. The yields of cereal grain in the 37 countries that use less than 85 kg/ha of the major nutrients could be increased markedly if the applications of the major nutrients were raised to the average of 214 kg/ha.

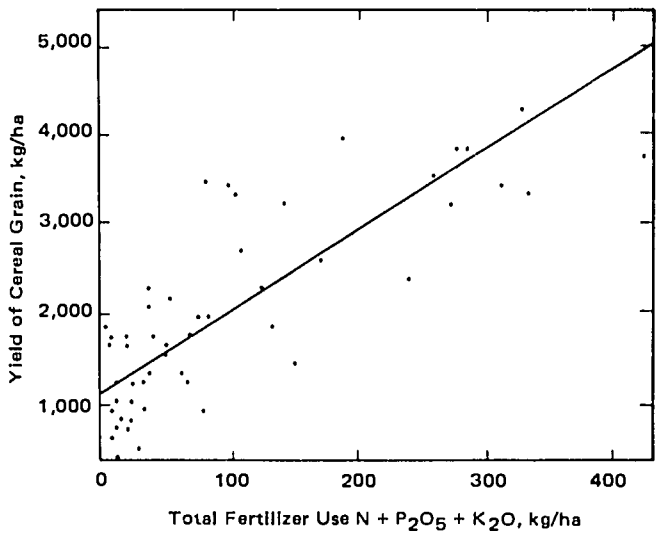


Figure 32. Response of Cereal Grains to Increasing Fertilization in Various Countries *(48)*.

Study of the data on which Figure 32 is based would be useful in determining the reasons for low yields in certain countries, and in suggesting suitable corrective measures. In many areas of the world, increased use of potash would increase the efficiency of the fertilizer nitrogen and phosphorus, and greater responses to potash will be obtained by application of adequate amounts of calcium, magnesium, and other essential nutrients.

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Appendix Tables

Table A-1.
Nutrient Contents of Crops[a]

Crop		Yield t/ha	Nutrient Content, kg/ha N	P	K	Ca	Mg	S
		Cereals						
Maize:	Grain	5.0	115	28	35	2	10	11
	Total	15.0	170	35	175	27	39	19
	Grain	12.5	168	42	53	-	20	17
	Total	25.0	298	55	247	-	73	37
Sorghum:	Grain	2.5	40	6	8	5	6	4
	Total	5.0	65	10	48	16	12	7
	Grain	8.9	134	29	28	-	16	25
	Total		280	44	186	-	50	43
Wheat:	Grain	3.0	75	15	12	3	9	5
	Total	8.0	125	22	92	16	14	14
	Grain	5.4	106	21	25	-	13	6
	Total		153	26	150	-	26	23
Rice:	Grain	3.0	46	8	13	2	5	4
	Total	8.0	84	14	89	21	9	9
	Grain	7.8	86	23	26	-	9	6
	Total		125	30	137	-	16	14
Barley:	Grain	5.4	123	20	32	-	9	11
	Total		168	27	139	-	19	22
		Protein and Oil Crops						
Soybeans:	Beans	3.0	200	26	57	10	10	6
	Total	9.0	300	40	115	70	35	23
	Beans	4.0	269	24	78	-	19	13
	Total		363	31	132	-	30	28
Sunflowers:	Seed	3.9	140	29	36	-	13	7
	Total		197	34	120	-	47	18
Peanuts:	Nuts	3.0	142	15	30	5	10	8
	Total	9.0	323	31	170	118	31	24
Oil Palms:		24.6	73	12	92	-	21	-
	Total		193	36	249	-	61	-
Coconut:	Nuts, husk		35	8	71	1	4	-
	Foliage, total		74	16	113	12	18	-
Field beans:	Beans	1.0	37	4	22	4	4	10
	Total	3.0	102	9	93	54	18	25
Peas:	Peas		25	4	9	4	2	2
	Total		80	8	60	25	8	15
	Peas	2.8	103	12	29	-	7	7
	Total		184	17	98	-	20	11
		Sugar and Starch Crops						
Sugarcane:	Stalks[b]	103	76	14	110	30	29	25
	Stalks	224.0	179	44	311	-	45	60
	Total		403	76	567	-	112	96
Sugar beets:	Beets	67.0	140	7	232	-	30	11
	Total		286	20	511	-	89	50
Potatoes:	Tubers	40.0	80	5	100	3	3	3
	Total		200	8	220	52	17	11
	Tubers	56.0	194	36	261	-	17	17
	Total		302	44	508	-	57	25

(Continued)

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Table A-1.
Nutrient Contents of Crops[a] (Continued)

Crop		Yield t/ha	Nutrient Content, kg/ha N	P	K	Ca	Mg	S
Cassava:	Roots	19.0	39	4	32	12	6	2
	Total		113	11	79	62	18	8
	Roots	45.0						
	Total		202	32	286	131	108	15
Sweet potatoes:	Roots	33.6	82	19	157	-	9	-
	Total		175	34	290	-	20	-
		Horticultural Crops						
Onions:	Bulb	37.0	66	14	77	4	5	22
	Total		133	22	177	16	18	34
Cabbage:	Heads	84.0	140	17	128	-	9	64
	Total		280	31	249	-	36	64
Tomatoes:	Fruit	41.0	72	18	130	7	7	9
	Total		84	21	185	31	8	28
		Stimulants						
Cacao:	Beans	1.0	20	6	30	3	4	-
Coffee:	Beans	2.0	33	3	52	7	3	3
	Total		253	19	232	143	33	27
		Forage Crops						
Grasses		13	200	30	200	50	50	20
		25	300	70	500	150	100	75
Clover-grass		13.4	336	44	335	-	34	34
Alfalfa		22.4	672	58	558	280	59	57
		Fruit Crops						
Bananas:	Fruit	30.0	142	18	365	10	-	-
	Total		627	69	1,390	278	-	-
Papaya:	Fruit	2.0	74	8	15	10	11	-
Oranges:	Fruit	6 boxes per tree	150	24	240	90	24	15
		Fiber Crops						
Cotton:	Lint	1.68	105	43	49	-	12	8
	Total		201	71	141	-	39	34
Sisal:			122	25	216	266	-	-

a. Most of these data are from Malavolta (*109*) and The Potash & Phosphate Institute, U.S.A.
b. Programa Nacional De Melhoramento Da Cana-De-Acucar, Relatorio Anual, 1976, Brasil.

Table A-2.
Some Chemical Characteristics of Soils From Latin America, Asia, and Africa

Country	pH		Clay, %	Exchangeable Content, meq/100 g					
	H_2O	KCl		CEC	K	Ca	Mg	Na	Al
LATIN AMERICA									
Argentina (*91*)									
N.W. (1 0-40 cm				12.8	1.44				
(2) 0-27 cm				47.8	2.35				
Pampas (*154*)	6.6			15.5	1.39	8.00	0.50		
	6.5			18.0	1.40	10.49	0.50		
Pampas (S.E.)									
Solonetz Solodizado (*37*)	5.8			34.8	2.70	14.6	4.7	0.4	
N.E., Misiones—Virgin—lateritic	4.5			21.9	0.12	5.0	3.0	0.12	
Upland—laterite	-			19.9	0.10	4.5	2.5	0.10	
Bolivia									
Santa Cruz—sugarcane plantation (*123*)									
Reclaimed forest	6.2	5.4			0.77	4.69	2.96	0.88	0.05
1 year in cultivation	6.5	5.6			0.24	1.25	0.66	0.22	0.05
3 years in cultivation	5.0	3.9			0.13	0.16	0.30	0.20	1.39
Brazil (*143*)									
Haplustoxic Tipico 0-10 cm	4.8	4.2		10.4	0.18	0.2	0.1	0.04	7.8
Umbriustoxic Tipico 30-60 cm	4.5	4.1		14.6	0.01	0.2	0.2	0.04	2.5
Dark red latosol 0-10 cm	4.9				0.10	0.4[a]			1.9
Red-yellow latosol 0-20 cm	5.0				0.06	0.05[a]			0.4
	5.3				0.14	3.2[a]			0.7
Dark-red latosols, dystrophic clayey forests, 20 sites	4.7	5.8			0.16	1.2[a]			0.7
Idem, dystrophic, loamy cerrado, 157 sites	4.0	5.6			0.07	0.6[a]			0.7
Vegetation (*103, 104*)									
Campo Limpo, $\bar{x}$-64 profile	4.87	4.16	33	1.08	0.08	0.20	0.06		0.74
Campo Cerrado, $\bar{x}$-148 profile	4.94	4.25	36	1.19	0.10	0.33	0.13		0.63
Cerrado, $\bar{x}$-245 profile	5.00	4.25	34	1.43	0.11	0.45	0.21		0.66
Cerrado, $\bar{x}$-45 profile	5.14	4.32	32	1.81	0.13	0.69	0.38		0.61
Forest, $\bar{x}$-16 profile	5.28	4.35	37	3.00	0.17	1.50	0.55		0.78
Colombia (*153*)									
Carimagua oxisol	4.9	3.9		4.70	0.10	0.53	0.93		2.35
Carimagua oxisol					0.08	0.06	0.04		
La Libertad					0.11	0.16	0.08		
El Pinal					0.07	0.08	0.04		
Peru									
Typic Tropaqualf (*22*)									
(Amazon jungle) 0-8 cm	5.6		18	0.2		10	1.9	0.1	0.2
(Yurimaguas) 8-15 cm	5.1		24	0.1		9.4	2.4	0.1	1.2

(Continued)

Table A-2.
Some Chemical Characteristics of Soils From Latin America, Asia, and Africa (Continued)

Country	pH		Clay, %	Exchangeable Content, meq/100 g					
	H_2O	KCl		CEC	K	Ca	Mg	Na	Al
LATIN AMERICA (Continued)									
Peru (Continued)									
Typic Paleudult									
(Amazon jungle) 0-4 cm	4.2		11		0.1	0.2	0.2	trace	2.0
(Yurimaguas) 4-16 cm	4.3		15		0.1	0.2	0.1	trace	2.9
Yurimaguas (*188*)	4.7			3.46	0.06	0.8	0.3		1.8
Surinam (*81*)									
Clay, 85%-90%, kaolinite		3.8-4.5		1.6	0.01-0.15	0.3-2.0	0.1-1.0	0.05-0.10	
AFRICA									
Botswana (*76*)									
(Savanna)—extensive grazing, 0-12 cm	6.9	5.2	40	21.2	1.4	10.9	3.8	0.1	
12-40 cm	6.4	4.9	49	19.5	1.0	10.1	3.8	0.1	
Ethiopia (*161*)	5.7	4.4	48.9	4.1	0.02	2.85	0.9		0.4
Ivory Coast (*161*)									
Ferraltitic tertiary sand, 0-15 cm	5.05	4.05		3.35	0.06	0.37	0.09	0.01	
Kenya (*91*)									
Eldon-Vulkanit Katena P-9, 0-10 cm	5.2			14.74	0.42	9.2	4.0		
10-37 cm	5.0			10.34	0.10	5.2	4.5		
Cherangani-Basement Katena P-14, 0-20 cm	4.9			1.89	0.14	0.4	1.1		
20-60 cm	4.6				0.02	0.2	0.4		
Field sample number									
SF-1, Humic Acrisol	6.6	5.6		33.2	2.08	16.0	4.3	0.60	
SF-2, Pellic Vertisol	7.4	6.1		80.4	0.35	33.6	15.7	0.75	
SF-3, Luvic Phaeozem	6.2	5.1		31.6	2.88	12.8	5.5	0.40	
SF-4, Rhodic Ferrasol	6.0	5.0		21.6	1.61	7.2	4.2	0.34	
SF-5, Ferralitic Arenosol	5.6	4.6		5.20	0.17	1.2	0.2	0.34	
SF-6, Chromic Luvisol	6.5	5.6		21.0	2.26	10.4	5.5	0.50	
SF-7, Mollic Andosol	6.9	6.4		84.6	1.65	30.4	3.95	0.43	
SF-8, Dystric Planosol	5.6	4.3		17.4	0.56	2.8	4.2	0.75	
SF-9, Vertisol	7.5	6.5		58.2	4.41	34.4	4.2	0.85	
SF-10, Andosol (allophanic)	5.4	4.5		49.2	0.30	1.2	0.6	0.25	
SF-11, Nitosol	5.3	3.4		27.4	1.38	[illegible]	5.5	0.34	
Namibia (*76*)									
Eutric Regosol, 0-5 cm	7.7	6.0	1	0.6	0.1	0.4	0.1	trace	
5-20 cm	7.4	6.0	2	0.6	0.1	0.4	0.1	trace	

(Continued)

Some Chemical Characteristics of Soils From Latin America, Asia, and Africa (Continued)

Country	pH		Clay, %	Exchangeable Content, meq/100 g					
	H_2O	KCl		CEC	K	Ca	Mg	Na	Al
AFRICA (Continued)									
Niger (*203*)									
Profile No. 941, 0-5 cm	6.65			21.1	0.2	14.5	6.6	0.2	
Profile No. 952, 0-25 cm	4.04			25.7	0.1	12.3	5.2	0.1	
Profile No. 944, 0-5 cm	6.02			1.3	0.2	0.6	0.2		
Nigeria (*76*)									
Plinthic Acrisol, 0-20 cm	5.9	4.9	7	5.8	0.1	1.6	0.3	0	
20-38 cm	5.5	4.4	6	3.8	0.1	0.8	0.0	0	
IITA experiment station, 0-10 cm	5.7	4.8	9	4.7	1.5	0.1	0.4	0.2	
10-28 cm	5.8	4.9	10	4.3	1.5	0.1	0.4	0.4	
ASIA									
Bangladesh (*203*)									
EP-1	5.6	6.5	23.8	11.0	0.15	5.5	1.1	0.53	
EP-3	6.0	6.8	23.2	10.0	0.30	5.1	0.9	0.47	
EP-6	5.7	6.7	16.3	6.0	0.06	2.0	0.5	0.15	
EP-9	5.4	6.4	25.2	6.7	0.10	0.4	0.2	0.08	
EP-17	4.9	6.3	44.0	14.4	0.14	3.1	1.7	0.38	
EP-20	5.2	6.5	9.8	3.6	0.04	0.2	0.1	0.10	
EP-21	6.4	6.6	23.9	16.7	0.12	9.5	3.3	0.68	
EP-33	5.1	6.3	16.1	6.0	0.11	0.8	0.4	0.09	
EP-35	8.0	7.1	31.1	20.1	0.36	33.1	3.1	2.87	
EP-41	5.7	6.5	16.7	8.4	0.12	1.9	0.4	0.16	
EP-46	7.4	7.4	31.0	12.2	0.62	8.7	7.5	5.07	
EP-47	7.4	7.3	33.5	19.1	0.55	17.1	8.8	4.58	
EP-50	7.8	7.4	56.2	26.9	0.44	20.7	7.8	1.99	
EP-51	8.2	7.5	16.2	13.1	0.16	22.2	2.6	1.85	
India									
Vertisol (*161*)	8.1	6.4	55.2	111.8	0.27	92.0	19.4		0.2
Lateritic Soil-Rice-Fe Toxicity (*178*)	5.8			3.2	0.05	0.86	0.28	0.20	
Indonesia Tropical Rainforest (*203*)									
Ultisol, 0-30 cm	4.68	3.73		10.8	0.07	1.5	0.53		4.0
Oxisol, 0-10 cm	5.05	4.29		20.3	0.14	5.6	0.94		0.6
30-35 cm	4.71	3.51		14.6	0.01	1.1	0.02		3.6
Malaysia (*76*)									
Orthic Ferrasol, 0-8 cm	4.7		58	23.6	0.5	1.3	0.6	0.1	
8-23 cm	4.1		62	10.5	0.1	1.0	0.2	0.1	
Albic Arenosol, 7-0 cm	4.0	2.6		15.9	0.6	1.7	4.4	0.8	
0-8 cm	4.1	3.0		7.2	trace	trace	0.3	trace	

(Continued)

Table A-2.
Some Chemical Characteristics of Soils From Latin America, Asia, and Africa (Continued)

Country	pH		Clay, %	Exchangeable Content, meq/100 g					
	H_2O	KCl		CEC	K	Ca	Mg	Na	Al
ASIA (Continued)									
Thailand (*176*)									
Eutric Gleysol									
Alluvial, 0-13 cm	5.0	4.1	73	30.3	0.6	15.1	3.9		
Rice, 3,000 kg/ha, 70-80 cm	6.2	5.1	70	27.2		19.8	4.4	0.2	
Udic Pellustert, 0-10 cm	8.0	6.7	49	55.4		47.6	3.0		
Sulfic Tropaquert, 0-15 cm	4.1	3.5	67	34.4	0.2	7.8	3.7	0.2	
27-48 cm	3.6	3.1	61	30.4	0.1	6.8	3.4		
Korea (*178*)									
K deficient on iron toxic rice sites, 2	6.40	4.4		7.0	0.20	1.8	1.3	0.17	
3	6.35	5.1		3.8	0.22	1.7	0.9	0.15	
7	6.60	4.4		4.8	0.12	1.8	1.5	0.10	
8	6.10	4.5		6.5	0.22	3.4	1.1	0.25	
12	5.20	3.4		16.0	1.00	1.8	4.1	1.55	
Japan (*178*)									
Rice soil akagar type III	5.00			40.1	0.48	4.5	2.2	0.26	
Taiwan (*178*)									
Rice soil	6.35			7.9	0.20	12.5	2.5	0.44	
Philippines (*178*)									
K deficiency riverside bolsol	7.4			40.9	0.18	47.0	4.5	0.30	
Sri Lanka (*178*)									
Rice soils, Fe toxicity site	5.18			9.5	0.17	2.0	1.2	0.26	
K deficiency site	5.18			5.2	0.15	1.5	1.2	0.17	

a. Ca + Mg.

Table A-3.
Suggested Critical Levels of Exchangeable Soil Potassium, Calcium,and Magnesium[a]

	Critical Level, mg/100 g or mg/100 ml		
	K	Ca	Mg
LATIN AMERICA			
Brazil			
General			
Goias	0.13	5.0[b]	
Minas Gerais	0.15	4.0	1.0
Parana	0.30	4.0	0.8
Sao Paulo (*59*)	0.40	5.0[b]	
Rio Grande do Sul and Santa Catarina	0.15		
Malavolta et al. (*110*)	0.40	5.0[b]	
Mielniczuk, J. (*118*)	0.16		
Industry	0.40	2-4	0.4-0.8
Crops			
Maize (*151*)	0.13		
	0.15		
Rice—traditional	0.26		
Rice—irrigated (*108*)	0.15		
Sugarcane (*183*)	0.21		
Soybeans (*184*)	0.22		
Coffee	0.15	2.5	0.5
	0.30[c]	2.7	0.9
Cotton (*183*)	0.16		
Beans (*183*)	0.18		
Alfalfa & silage, Rio Grande do Sul and Santa Catarina	0.20		
Colombia			
General			
Corn and rice	0.15		
Litoral Atlantico	0.35		
Alto Magdalena	0.25		
Valle del Cauca	0.25		
Cotton (*58*), Litoral Atlantico	0.45		
Valley de Cauca	0.35		
Potatoes	0.30		
Costa Rica			
General	0.20	4.0	1.0
Soybeans	0.40		
Maize and rice (*34*)	0.20		
Cuba (*18*)			0.4
El Salvador	0.32-0.40		
Guatemala	0.38		
Mexico	0.68		3.67
Panama	0.13		
Peru (*188*)	0.25[d]		0.2
ASIA			
Bangladesh, rice (*94*)	0.45		
China, rice (*94*), NH_4OAC	0.38		
HNO_3	1.92		
Formosa, pineapple (*16*)	0.17		
India			
General (*155*)	0.19		
Intensive production	0.30-0.50		
Tea	0.26		

(Continued)

Table A-3.
Suggested Critical Levels of Exchangeable Soil Potassium, Calcium,and Magnesium[a] (Continued)

	Critical Level, mg/100 g or mg/100 ml		
	K	Ca	Mg
ASIA (Continued)			
India (Continued)			
Potatoes (*64*)			
Alluvial soils	0.268		
Acidic brown hill	0.31		
Wheat—irrigated black soil (*138*)	0.25		
Indonesia			
Rice (78)			
Soil Type			
Alluvial	0.34		
Latosol	0.34		
Regosol	0.24		
Podzol	0.11		
Mediterranean	0.14		
Malaysia, rubber (*38*)			0.30
Philippines (*16*)	0.24		
Sri Lanka, rice (*94*)	0.45		
Rice (*132*)	0.25		
Taiwan (*198*), pineapple	0.36		
Rice	0.21		
AFRICA			
Botswana (*120*)	0.4		
Congo (*18*)		3.5[b]	
Dahomey (*16*)	0.15		
Ivory Coast (*16*)	0.15		
Bananas (*36*)		6[b]	
Kenya (*91*)	0.4	3	1
Madagascar, cassava (*16*)	0.60		
Nigeria (S.W.), maize (*102*)			0.4
Tomatoes (*168*)	0.31		
Yams (*131*)	0.20		
South Africa, sugarcane (*17*)	0.31		
	0.30		
Uganda			
General			
Foster (*52*)	0.46		
General			
Tropical soils (*16*)	<0.18		
2-3 meq of bases (*18*)		≧0.35	0.30
West Germany (*21*)			
Sands and loamy sands	0.51		0.82[d]
Loamy clays and clays	0.85		1.64[e]
			2.06[f]
Hawaii, sugarcane (*16*)	0.30		
Kentucky (*210*)	0.32		0.33
Alabama, peanuts (*3*)		0.75	

a. Maximum values of medium range of soil test values.
b. Ca + Mg.
c. Based on conventional ratio K:Mg:Ca of 1:3:9 or the ratio (Ca + Mg):K of 12.
d. <10% clay.
e. 10%-25% clay.
f. >25% clay.

Table A-4.
Potash Status of Soils and Recommended Rates of Application of Potash[a]

Soil Status	Exchangeable K, meq/100 g	Application, kg K_2O/ha, for Indicated Crops[b]				
		Grain	Protein and Oil	Sugar/ Starch	Fruit Crops	Fiber Crops
Minas Gerais						
Low	0.08	60-90	60	90-180	90	120
Medium	0.09-0.15	45-60	40	60-120	60	80
High	>0.15	30	20	30-60	30	40
Panama						
Low	<0.10	45-60	60	60-150	60	75
Medium	0.10-0.30	30-40	45	80-120	45	60
High	>0.30	15-30	15-30	30-60	30	30
Rio Grande do Sul & Santa Catalina						
Low	0.05-0.20	40-50	40-50	70-90	120	-
Medium	0.11-0.31	20-40	20-30	40-50	80	-
High	0.15-0.31	10	10	11-30	30	-
Sao Paulo						
Low	0.04-0.10	-	120	120	-	120
Medium	0.10-0.22	-	60	60	-	60
High	0.15-0.24	-	30	30	-	30
Colombia						
Low	<0.15	42-70	36-42	56-120	56-83	-
Medium	-	-	-	-	-	-
High	>0.15	12-30	12-25	35-70	42-68	-
Costa Rica						
-	-	20-31	-	-	-	-
Guatemala						
-	-	32	-	-	-	31
El Salvador						
-	-	31	-	-	-	-
Honduras						
-	-	19-55	-	32-49	-	-
Nicaragua						
-	-	26-31	-	47-130	-	-
Panama						
-	-	-	-	87-227	-	-
Peru						
-	0.06	-	-	163-190	-	-
-	0.32	-	-	115-143	-	-
-	0.59	-	-	35-123	-	-

a. The values given are orders of magnitude only. Applications should be based also on factors other than the exchangeable potassium content of the soil. Coffee, in particular, does not lend itself to generalizations.
b. Grain: barley, maize, rice, sorghum, wheat; protein and oil: beans, peanuts, peas, soybeans; sugar and starch: sugarcane, potato; fruit crops: banana, cassava; fiber crops: cotton, sisal.

Table A-5.
Consumption of Potash in 1970 and 1980[a]

	K_2O, Tons Actual Consumption	
	1970	1980
LATIN AMERICA		
Argentina	7,143	6,000
Bahamas	0	400
Barbados	2,500	3,000
Belize	500	100
Bolivia	11	1,200
Brazil	305,852	1,306,600
Chile	13,169	13,100
Colombia	31,806	75,500
Costa Rica	6,000	20,000
Cuba	145,400	187,300
Dominica	0	1,400
Dominican Republic	12,864	13,000
Ecuador	6,487	17,600
El Salvador	7,687	5,000
Guadeloupe	4,400	1,100
Guatemala	5,775	18,000
Guyana	2,051	1,000
Haiti	90	100
Honduras	7,500	7,300
Jamaica	9,626	5,600
Martinique	7,000	3,200
Mexico	25,789	74,800
Nicaragua	2,549	9,200
Panama	3,000	14,000
Paraguay	3,249	1,600
Peru	5,000	11,100
Saint Kitts	1,500	1,200
Saint Lucia	1,000	1,300
Saint Vincent	800	1,000
Surinam	60	200
Trinidad	2,500	2,900
Uruguay	5,778	3,600
Venezuela	19,091	50,500
Virgin Islands	300	0
Total	646,477	1,857,900
ASIA		
Afghanistan	0	300
Bangladesh	10,700	29,200
Burma	1,434	3,100
China	29,000	382,800
Cyprus	2,644	1,000
India	197,700	617,000
Indonesia	6,471	87,000
Iran	427	0
Iraq	1,000	4,500
Israel	10,855	22,300
Japan	610,500	512,000
Jordan	515	1,400
Kampuchea	561	0
Korean DPR	17,400	52,200
Korean Republic	82,998	183,000
Laos	23	0
Lebanon	7,000	6,600
Malaysia	75,700	194,900
Mongolia	0	0
Nepal	214	1,100
Oman	0	600
Pakistan	1,225	9,600

(Continued)

Table A-5.
Consumption of Potash in 1970 and 1980[a] (Continued)

	K_2O, Tons Actual Consumption	
	1970	1980
Philippines	38,000	55,800
Qatar	0	0
Saudi Arabia	0	3,400
Singapore	1,000	2,100
Sri Lanka	30,700	46,000
Syrian Arab Republic	1,040	2,500
Taiwan	60,000	95,600
Thailand	15,000	35,400
Turkey	11,500	49,000
United Arab Emirates	0	600
Vietnam	38,900	46,000
Total	1,252,507	2,445,000
AFRICA		
Algeria	26,000	35,800
Angola	2,000	3,800
Botswana	0	0
Burundi	65	100
Cameroon	4,859	11,000
Central African Rep.	300	0
Chad	0	100
Congo	4,000	200
Dahomey (Benin)	3,000	1,000
Djibouti	0	1,100
Egypt	1,909	7,500
Equatorial Guinea	0	0
Ethiopia	1,500	200
Gabon	0	0
Gambia	0	600
Ghana	645	5,000
Guinea	1,000	100
Ivory Coast	11,844	23,500
Kenya	3,100	9,000
Lesotho	0	0
Liberia	0	500
Libyan Arab Republic	462	3,600
Madagascar	3,900	2,800
Malawi	1,016	2,900
Mali	0	3,400
Mauritania	0	200
Mauritius	9,578	13,400
Morocco	16,000	40,800
Mozambique	1,344	1,400
Niger	22	400
Nigeria	1,065	25,000
Reunion	5,500	3,300
Rwanda	0	0
Senegal	1,430	5,000
Sierra Leone	160	300
Somalia	300	0
South Africa	96,100	139,700
Sudan	0	0
Swaziland	1,471	3,300
Tanzania	3,000	3,300
Togo	51	1,100
Tunisia	2,100	4,600
Uganda	1,000	100
Upper Volta	0	2,800

(Continued)

Table A-5.
Consumption of Potash in 1970 and 1980[a] (Continued)

	K_2O, Tons Actual Consumption	
	1970	1980
Zaire	1,200	2,000
Zambia	6,099	10,800
Zimbabwe	25,000	28,800
Total	237,020	398,500
World total	16,403,700	24,256,300

a. Tennessee Valley Authority. 1982. Unpublished FAO data.