source of all energy, guides the energy-driven processes on earth and governs the climates. We have discussed how different environmental components affect growth, development and yield of sorghum, especially in the adverse climatic conditions of SAT. Several techniques have been formulated to evaluate cultivars germplasms and their responses to plant environments. There is a need to select cultivars adaptable to diverse environments. Simulation modeling could help predict the growth and development of crops under diverse climates and different environments. Simulation models can estimate the yield from a region with widely variable rainfall and a range of soil and crop management practices. This approach could be utilized to develop plant ideotype and predict crop growth and growth stages. The crop growing conditions of semiarid regions cannot be substantially improved although some improvement could be made by adopting good management practices. Plant productivity can also be improved by developing plants capable of withstanding unfavorable environments. More research effort is needed to improve crop productivity in unfavorable environments.

MINERAL NUTRITION OF SORGHUM [1]

INTRODUCTION

All living organisms require mineral elements to sustain life and to grow and develop, and each organism is different in its requirement for specific mineral elements. Sorghum is a cereal and cereal crops have mineral element requirements that are different from noncereal crops. This is specifically true for nitrogen (N), since cereals do not now have the capacity to fix their own N from the atmosphere. Even within the cereal crops, sorghum is different from the other species of this group. Compared to maize, sorghum may be considered to require lower amounts of mineral elements, because of different growth rates and amounts of dry matter produced.

Without adequate supply and balance of mineral elements, sorghum will not grow well and produce adequate or desired end-products (grain and/ or fodder). Environmental conditions, soil type, capital assets, cultural practices and other factors dictate the amount of mineral elements used for the production of sorghum crop. Conditions are unique to nearly every place where sorghum is grown. Therefore, general statements about mineral element requirements for the production of a particular sorghum crop are difficult to make. Many factors must be considered.

The objectives of this chapter are to discuss each mineral element separately and to give concepts about some of the aspects unique to each element relative to mineral nutrition of sorghum, and to plants in general, with the hope that this approach will help to understand specific peculiarities associated with the mineral element requirements of sorghum and to provide information whereby better decisions can be made about mineral element problems, applications and use.

MINERAL ELEMENT REQUIREMENTS

Many factors are involved in determining mineral element requirements for the production of sorghum. Some factors that must be considered are: 1- the amount of available and residual mineral elements in soils, 2- chemical and physical

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properties of soils, 3- environmental conditions of the soil and locality, and 4-yield and end-product desired.

Three of these factors can be controlled to some extent by the addition of fertilizers and amendments according to needs of plants and soils. Except for moisture (irrigation), pest control, and cultural practices, little can be done about the control of some of the other environments conditions. The amount of product desired can be programmed, and the amount of seed sown can be controlled but ultimate yields remain the effect of all factors combined.

In general terms, the amount of mineral element removed by a sorghum crop producing approximately 8,000 kg/ha grain are (in kg/ha): 250 Nitrogen (N), 160 Potassium (K), 45 Magnesium (Mg), 40 Phosphorus (P), 40 Sulfur (S).

The amount of calcium (Ca) and the micronutrients (manganese (Mn), iron (Fe), boron (B), copper (Cu), and Zinc (Zn) removed are considerably less. Some mineral elements will be recycled if the fodder is left or added to soils, if it is removed from the soil, higher amounts of these elements will also be required.

As sorghum plants grow, mineral elements are taken into plants at different rates and amounts. Young plants usually absorb relatively high amounts of the mineral elements, and with age some elements are transferred from one plant part to another. Mineral element concentrations in various plant parts vary with plant age (Table 8.1), as well as the total amounts of each element absorbed as plants age (Table 8.2), and the distribution of mineral elements in various parts at maturity are given as a reference for changes that may occur in sorghum plants grown in the field (under relatively optimum conditions). As each element is discussed, reference to these tables will be helpful to understand its uptake, accumulation and distribution in sorghum plants.

Nitrogen

Of all the mineral elements required for sorghum growth, N is one of the most abundant elements in the plant. It is usually added to soils to meet sorghum plant needs. Nitrogen for plant growth must be either applied, provided through atmospheric fixation, or obtained from residual sources in the soil. For maximum plant yields, N is usually applied with each sorghum crop and sometimes added more than once during the plant growth cycle or season. Nitrogen is usually the most expensive mineral element that is required for sorghum production.

The lithosphere contains relatively high N, but the soil portion of the lithosphere is very small compared to the whole. Most lithosperic N is unaccessible or unavailable for plant use. The portion of N potentially available for plant use in soils is found in various forms and is constantly changing. Even though atmospheric N may be fixed by microorganisms or plant-microorganism association, this source of N is not readily available to sorghum until the N is converted from organic to inorganic forms. The interconversions of the various forms of N [organic N, ammonium (NH_4^+), nitrate (NO_3^-), and gaseous N] and the use or loss of NH_4^+ and NO_3^- are continually changing. Because of the dynamic changes that occur in N in soils, the amount of available N can change extensively in a relatively short period of time. Nitrate levels in soils may be as high as 20 to 30 mM after a N fertilization, but normally range from 2 to 20 mM in soil solutions. Only about 50% of the N applied to soils is taken up and used by plants. The remainder is

Table 8.1 Mineral element concentrations in aboveground sorghum plant parts with age.

	Vegetative			Bloom/early grain fill - 12 leaf	
	Plant	Leaves	Stalk	Head	Plant
N *	20.4	28.6	11.0	23.3	17.9
P *	3.17	3.09	2.40	4.21	2.76
K *	40.2	14.4	20.8	8.9	19.8
Ca *	28.6	41.1	23.2	5.5	28.6
Mg *	2.18	2.54	2.87	3.45	2.82
S *	1.40	1.36	0.90	2.00	1.14
Si *	21.8	23.8	17.3	1.0	18.8
Mn **	41.2	39.8	40.4	28.6	39.6
Fe **	274	196	62	41	108
Cu **	7.4	8.4	7.9	10.7	8.4
Zn **	21.3	20.1	27.2	38.8	25.6
DMY ***	58	80	131	13	224
	Maturity				
	Leaves	Stalk	Grain	Whole Plant	
N *	19.6	6.0	13.7	13.0	
P *	1.80	1.12	2.96	2.29	
K *	10.0	24.6	5.7	11.1	
Ca *	58.4	25.3	1.3	18.4	
Mg *	2.30	2.56	2.16	2.28	
S *	1.20	0.87	1.03	1.03	
Si *	41.2	26.6	0.3	14.7	
Mn **	72.9	24.9	10.8	26.5	
Fe **	393	67	33	112	
Cu **	7.9	7.5	4.2	5.7	
Zn **	22.8	21.2	14.0	17.5	
DMY ***	88	106	249	443	

* mg/g dry weight; ** µg/g dry weith; DMY dry matter yiel (g/plant)

left for microorganism use, leaching, or other N reactions and processes that occur in soils.

Nitrogen deficiencies occur on essentially all soils, whether they be alkaline, neutral, or acid. The various reactions for and changes in N depend on many factors, but the presence and sustenance of microorganisms is important. Nitrogen in soils with adequate or high moisture will change more extensively than in drier soils.

Both NH_4^+ and NO_3^- (inorganic N) can be absorbed by plants, but NO_3^- is

Table 8.2 Proportion of mineral elements in sorghum plants with age.

	Stage of plant growth (contents as % of total at maturity)		
	Vegetative 12 leaf	Bloom/early grain fill	Maturity
Dry Matter	13	50	100
N	20	70	100
P	18	61	100
K	47	90	100
Ca	20	78	100
Mg	12	62	100
S	18	56	100
Si	19	64	100
Mn	20	76	100
Fe	32	49	100
Cu	17	73	100
Zn	16	74	100

usually found in higher proportions than NH_4^+ under most soil conditions. Ammonium at excessive concentrations can be toxic to plants. Most inorganic N is rapidly converted to an organic form once inside plant tissue, but NO_3^- is commonly noted in plant tissues.

Nitrogen concentrations in normal sorghum leaves range from about 15-30 mg/g (dry wt). Nitrogen is a constituent of numerours organic compounds in plants, specially amino acids (the building materials for proteins), nucleic acids, and other cellular compounds. Since enzymes (proteins) catalyze nearly every metabolic reaction in plants, N is indispensible to plant growth and development. Young plants accumulate relatively high concentrations of N, but N decreases in the various plant parts with age. Nitrogen is readily remobilized. It is transferred from one plant part to another, and accumulates extensively in kernels. Most of the plant N is absorbed during the vegetative and by early grainfilling growth stages.

Plants deficient in N usually are stunted, spindly and pale yellow in color. Symptoms appear first on older (lower) leaves and spread to the younger (upper) leaves. A uniform pale or deep yellow color develops near the tips and margins and progresses toward the base and midrib of the leaf. Necrotic spots normally develop when severe deficiency symptoms appear. Severe N deficient leaves turn brown, die and fall down (pendent) on the plant. Heads of N deficient plants are small, yields are reduced, and seed numbers are reduced. The vegetative stage of plants is shortened and plants usually mature earlier. Shoot/root ratios normally increase with N deficiency.

Supraoptimal N may promote lush, green foliage and delay maturity. Ammonium is normally toxic at lower levels of N than NO_3^-. Excess NO_3^- causes leaf margins to appear water-soaked, turn dark green, and be somewhat leathery in texture before dying and turning dark brown or black.

Phosphorus

Although abundant amounts of P are usually absorbed and accumulated in sorghum, the actual amounts of P needed in metabolic reactions and structural components of cells are relatively small. Considerable amounts of P are normally added to soils on a consistent basis, usually annually or with each crop. Some estimates show that only about 10 % of the P added to soils is absorbed by plants. Therefore, extensive amounts of P become unavailable in the soil by absorption or fixation by various soil fractions and particles. Soil P concentrations of about 0.1 mM (near 3 µg/g) are considered adequate for plants. For plants fed adequate P, about 60 to 80% of the P inside plant tissues is considered to be in the organic form. Thus, considerable amounts of P inside plants are not performing essential functions at all times. The turnover rate of P in metabolic reactions is rapid, because P has a primary function in energy transfer reactions of the various metabolic pathways. P is involved with nearly every metabolic process in the plant, and P deficiency can directly or indirectly affect nearly every plant growth process, including energy transfer reactions.

Phosphorus interacts with many elements, so the availability and function of other elements is affected by P. P exists in 3 anionic forms (PO_4^{3-}, HPO_4^{2-}, and $H_2PO_4^-$. Young plants usually have relatively high P concentrations which decrease with age. Normal concentrations range from 2 to 4 mg/g. Phosphorus accumulates extensively in the kernels (as phytin). Phosphorus is readily remobilized from older to younger tissues and from vegetative tissue to the grain. As P is readily mobile, P deficiency symptoms appear first on the lower (older) leaves and progress upward toward the upper leaves. Most of the P absorbed by plants is taken up by the grain fill. As the plant matures, considerable amounts of P move from the vegetative parts to the grain. At maturity, over 70% of the above ground plant P is found in the kernels.

Phosphorus supply and availability for plants grown in low or P deficient soils may be altered greatly by mycorrhizae species associated with plant roots. These mycorrhizal associations with sorghum (and other plants) are not abnormal or exotic, because the greater part of the vegetation worldwide is infected with them. The two major classes of mycorrhizae fungi identified are: 1- ectohophic which forms external mycelia sheaths around roots and between cortical cells and are associated exclusively with 3 species; 2- vesicular arbuscular whose mycelia grow both internally and externally to root cells, extend extensively from roots into the surrounding soil and are found with roots of nearly all plant species. Four major genera of vesicular arbuscular mycorrhizae (VAM) fungi have so far been found to be associated with sorghum: *Glomus, Gigaspora, Acaulospora* and *Scherocystis*. In pot culture experiments, certain VAM fungi increased plant dry matter yield by as much as 220 % over plants grown without mycorrhizae. The VAM species showed differences in effectiveness for plant dry matter increases. Phosphorus concentrations increased by as much as 3-fold in sorghum grown with VAM fungi. VAM fungi have been known to enhance not only P absorption, but also K, S, Zn, Cu and Si absorption in plants. The magnitude of mycorrhizae response has usually been much greater for P than for the other elements. Even though VAM fungi contribute only about 10% to the total dry weight of roots, they have the potential of absorbing P at rates many times that of uninfected roots. Increased P uptake by plants associated with VAM cannot be accounted for by P diffusion in soils, because P diffusion in soils is so low. Mycorrhizae increase the effective soil volume from which roots can effectively absorb P and other mineral nutrients. The VAM fungi themselves also have the potential to make P more available for plant uptake.

Population densities of mycorrhizae are associated with levels of P in the soil. If soils are low in P, mycorrhizae densities are higher than in soils with higher levels of P. Supraoptimal levels of P appear to be toxic to mycorrhizae. Increases in productivity of crops like sorghum grown in soils with low or deficient levels of P may be greatly enhanced if adequate mycorrhizae infection with highly efficient strains are obtained. Even though genotypes differ in their ability to tolerate low P, tolerance to low P may be associated with root mycorrhizae.

Phosphorus deficiency occurs frequently when plants are grown on acid and tropical soils. These soils (usually otisols and oxisols) generally have high fixation capacities for P because of high Al and Fe oxide concentrations. Phosphorus does not readily move in soils because of its high reactivity with soil particles. For the most part, plant roots must grow to where P is located to adequately supply plant needs. Because of the low P mobility in soils, considerably more P is added to soils than is absorbed by plants.

Phosphorus deficiency in plants is relatively common during cool weather. In the temperate zones, seeds are planted and seedlings are small during much of the cool weather. As a result, small plants with their relatively small root systems, cool root environments, and fairly high P demand often show P deficiency symptoms during the early plant growth stages. Phosphorus deficiency tends to decrease tillering and may be the result of decreased phytohormones needed to assure the formation and development of new tillers. Shoot growth appears to be affected more by P deficiency than root growth, thus shoot/root ratios generally decrease as plants become P deficient. Grain development and filling are inhibited by P deficiency, so kernel quality if usually poor.

Deficiency of P is characterized by stunted, spindly, dark green leaves which have overtones of dark red coloration. Older leaves show the red pigmentation first, and this pigmentation progresses upward toward the younger leaves. Leaf tips and margins show the redness first which progresses toward the base and midrib. A characteristic symptom of P deficiency on leaf sheaths is also the upward progression of red coloration. At times the dark red coloration of P deficiency will occur in streaks in the interveinal tissue leaving green veins. As the deficiency becomes more severe, the red pigmentation will become uniformly distributed over the leaf. If the deficiency continues sufficiently long, leaves turn brown and die. In young plants, leaves often appear to be more erect and sometimes "leathery". Roots often turn dark brown, purple or black.

Excess P can depress plant growth and interact with other elements (especially Fe, Cu, and Zn) to cause deficiencies of other elements. Reduction of root growth by excess P has been noted. Supraoptimal P has also been shown to cause a unique "red-speckling" on the tips and margins of older leaves of many sorghum genotypes. This "red-speckling" decreases progressively from older to younger

leaves. This disorder appears at the tips and margins and progresses toward the base and midrib of leaves. The amount of P in the soil or growth medium to induce this disorder is relatively low (often less than 1 μg/g). This disorder is not induced in older plants as readily as in younger plants, but if sufficient P is added, it can be induced an older leaves as well.

Potassium

Potassium is one of the most abundant mineral elements in sorghum plants. Depending on plant age, plant part and conditions, other mineral elements to approximate K in plant composition are N, Ca and Si. Because K accumulates in sorghum plants at relatively high concentrations, considerable amounts of K must be added to soils or soils must be adequately supplied with available K. Neutral to alkaline pH soils normally contain high amounts of residual K. Potassium normally has to be added to acid soils because of its depletion by leaching from the relatively high amounts of rainfall.

Even though some soils contain considerable amounts of K, most of it is associated with nonexchangeable fractions. Exchangeable K levels in soils vary, but are usually at about 2 to 5 μg/g soil and represent about 1 to 4% of the total soil K. Factors such as source of parent material, type of clay, amount of fixation and organic matter affect the amount of soluble or exchageable K available for immediate plant uptake and use. The nonexchangeable fractions of soil K are structural K (soil minerals) and absorbed K (on clay and organic matter colloids). Even though the amount of exchangeable (free) K may be low, many soils have the potential to make considerable amounts of K available. However, the rate of K availability may be limiting and insufficient for immediate plant needs, and additional soluble K may be required for optimum growth. Of the K applied to soils, only about 30 to 50% is absorbed by plants.

Potassium is absorbed by plants readily as K^+ and this is the active form inside plants. Concentrations of K in plants are usually around 20 to 50 mg/g (dry weight). Inside the plant, K does not form stable complexes, is not bound tightly by and is not an integral part of organic molecules. Potassium functions primarily in osmoregulatory processes like cell turgor, stomate opening and closing, and protein configuration and conformation. Potassium functions as a catalyst of numerous enzymes; over 70 enzymes have been identified that require K for maximum activity. In the metabolic processes or enzymes requiring K, relatively high concentrations are reported for optimum activity. *In vitro* experiments often report 40 to 80 mM K for maximum activity of enzymes and 100 to 200 mM K are not uncommon in cellular cytoplasm and vacuoles. Potassium has been associated with cellular electronegativity. That is, if excess anions appear in the cells from NO_3^- absorption and organic acid synthesis, K^+ is the usual counter-ion associated with these compounds. Potassium has also been associated with the circulation of organic and aminoacids in the transport systems of plants. Potassium is highly remobilized and readily moves during plant development from older to younger tissues if the need arises.

Young sorghum plants accumulate high K in the leaves which decreases with age. Although kernels contain considerable K, most of the plant K in older plants remains in the stalks. Potassium deficient plants lose stalk strength and are prone