INFLUENCE OF POTASSIUM AND MAGNESIUM CONCENTRATIONS IN NUTRIENT CULTURE ON GROWTH AND COMPOSITION OF SORGHUM [*Sorghum bicolor* (L.) Moench] PLANTS

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Greenhouse experiments were conducted to evaluate the main effects and interactions between applied K and Mg on dry matter yield and nutrient contents of sorghum [*Sorghum bicolor* (L.) Moench] plants harvested at three different growth stages, using sand culture. Effects of variations in K/Mg ratio in the growth medium on yield were also evaluated. Nutrient treatments consisted of 7 levels each of K as KCl from 0-300 ppm in 50 ppm increments and Mg applied as $MgCl_2$ at 0-60 ppm in 10 ppm increments. A sorghum hybrid, 'RS 671' and its male and female lines, 'Tx 415' and 'Redlan,' respectively, were used. Whole plants were harvested at 25, 50 and 75 days after seedling emergence, and dried samples of top and root tissues were subjected to chemical analyses.

Variables measured included top and root dry weights at each harvest. Top tissue concentrations of N, P, K, Mg, Ca, Zn, Fe and Mn in the 50- and 75-day-old plants were also measured.

There was no yield response to applied K and Mg until 50 and 75 days after seedling emergence, respectively. At final harvest, maximum top dry matter yield occurred when K and Mg were supplied at a concentration of 195 and 38 ppm, respectively. Significant interaction effects were not observed.

Applied K increased K but decreased top tissue N, P, Ca, Zn and Mn concentrations. Since top dry matter yield increased with increased K rates, both N and P uptake increased with low but decreased with high K levels.

Magnesium concentration and uptake decreased at all rates of K, indicating a strong antagonistic effect of K on Mg absorption. Potassium application had no effect on Zn, Fe and Mn uptake. Applied K was negatively correlated with tissue N, P, Mg, Ca, Zn and Mn concentration but positively correlated with tissue K. Plant K concentration was negatively correlated with tissue N, Mg, Ca and Zn but had no relationship with Mn concentration.

Applied Mg decreased N in RS 671 at both harvests but had no effect on N content of the parent lines. At 75 days, applied Mg had a slight depressive effect on K and a synergistic effect on P absorption. Applied Mg increased tissue Mg concentration and uptake, decreased Ca concentration but had no apparent effect on Ca uptake. Magnesium had a synergistic effect on Zn and an antagonistic effect on Mn absorption. A positive correlation was observed between applied Mg and each of tissue P, Mg and Zn concentration but negatively correlated with tissue Ca and Mn. Plant Mg concentration was positively correlated with each of tissue N, P, Ca and Zn concentration but negatively correlated with tissue K. No relationship was observed between plant Mg and each of plant Fe and Mn.

Plant N concentration was positively correlated with tissue P, Mg, Ca, Zn, Mn and Fe but negatively correlated with K. Plant P was positively correlated with tissue Mg, Zn and Ca but had no relationship with tissue K, Fe and Mn. Plant Ca was positively correlated with plant

Zn, Fe and Mn concentration.

Significant negative K-Mg interactions were observed for Mg and Mn concentrations, but positive interactions were observed for Ca concentration and forage cation ratio. Plant N, P, Mg, Ca, Zn, Fe and Mn concentrations were each negatively correlated with yield. However, plant N concentration affected yield of the 50-day-old plants more than did the other nutrients. At 75 days, however, plant K and Ca contents affected yield more than did the other nutrients.

The wide variations in K/Mg ratio of the growth medium had no adverse effect on dry matter yield of sorghum plants.

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'Tunde

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INTRODUCTION

The provision of the appropriate amounts and desirable proportions of the various essential nutrient elements for the optimum yield of our food crops continues to create a challenge to plant nutritionists.

It has long been assumed that the ability of the soil to produce crops is dependent not only upon the proper supply of nutrients but also upon the maintenance of adequate balance between the various nutrient ions present in the growth medium. The response of a plant to one nutrient often depends upon the level of other nutrients in the growth medium, and the uptake of a given ion depends not only on its activity in solution but also on the activities of other ions and the relation that exists between solution ions and exchangeable ions.

In the tropics and especially Nigeria, potassium application to crops has received the least attention of the three major fertilizer elements. Several factors have contributed to the lack of awareness of potassium requirements. The traditional system of "shifting-cultivation" allows a piece of land to revert to its natural fertility after it must have been cultivated for a period of five or more years. This common practice of bush fallow would normally increase the supply of exchangeable potassium and magnesium in the topsoil resulting in the frequently reported non-response of crop to potassium application. With the rapid increase in population and thus a greater demand for food and land, the number of years for fallow is now being reduced resulting in a more intense cultivation of the soil. This leads to rapid depletion of potassium and some other essential elements and hence the necessity to

include potassium along with N and P in any fertilizer recommendation.

Magnesium deficient like the potassium deficient soils are mostly confined to humid areas of the world. Agboola and Corey (1973) conducted a nutrient survey on some intensively cultivated government farms in western Nigeria and suggested that the low yield of maize obtained was probably due to antagonistic effect of potassium on magnesium uptake. Frequent applications of nitrogen, phosphorus and potassium fertilizers without the addition of magnesium are assumed to result in a wider K to Mg ratio in the soil, which may lead to low yields. To obtain the high yields required to feed the growing population, it will be advisable to include magnesium along with N, P and K in any fertilizer recommendation. Apart from the increase in the uptake of some other nutrients and decrease in soil K to Mg ratio, magnesium application may reduce the degree of antagonism between potassium and magnesium.

In the Sudan and Guinea savannah vegetational zones of Nigeria, apart from the soil fertility problems, periods of drought are common and unpredictable. Under this climatic condition, guineacorn [Sorghum bicolor (L.) Moench] is usually more productive and reliable than maize (Zea mays L.). The purposes of the investigation reported here are therefore to:

1. Study the direct and interactive effects of applied potassium and magnesium on dry matter yield of sorghum.
2. Investigate the effect of the nutrients on the absorption and accumulation of potassium, magnesium and other nutrient elements; the relationships between the nutrients in the plant and how they affect dry matter yield.

3. Investigate to what extent differences in sampling dates affect the variables under investigation.
4. Study the effect of changes in K to Mg ratio of the growth medium on dry matter yield and nutrients contents of the crop.

REVIEW OF LITERATURE

It has long been recognized that a balance of nutrients necessary for plant growth is essential for optimum yield of any crop. If one of the essential nutrient elements is present in the medium in insufficient amounts, or in chemical combinations which render it poorly available for absorption, the lack of this element in the plant may bring about some disturbances in its metabolism. These metabolic disturbances manifest themselves in the development of visible symptoms such as yellowing or purpling of leaves, stunted growth and a subsequent reduction in yield or the total failure of the crop.

The supply of unbalanced nutrient elements in the medium may often lead to interaction in the medium or within the plant which may also lead to some modifications in the growth of the plant.

One of the major ways of investigating selective ion absorption is to study the mutual effects of ions on the absorption of each other. Epstein's (1962) studies have shown that the presence in any appreciable amount of any ion in the growth medium will affect the rate of absorption of most other ions. This is because cell permeability, enzyme activities, respiration and growth rates are all influenced by the ionic composition of the medium which in turn affect the rate of absorption of ions from it.

It has been postulated that the absorption of ions is mediated by "carriers" possessing specific active sites to which the ions are bound in their passage across cellular membranes. This carrier hypothesis has been able to explain many of the experimental results with regards to

the absorption of various cations and anions and the interrelationships among both the cations and anions. Ions in solution exhibit competitive (negative or antagonistic) effects and positive or synergistic effects (Epstein, 1972).

The cellular membranes through which ions are absorbed are impermeable to free ions. These ions are therefore transported across membrane through the attachment to binding sites of ion carriers. There are numerous types of binding sites with characteristic chemical affinities for various ions or groups of chemically similar ions. Ions of some elements that so closely resemble those of another, that the carrier sites cannot distinguish, compete for the carrier site and thus competitively interfere with each other's absorption if both are present in the solution.

Nitrogen Fertilization

Nitrogen (N) is known to be the most limiting factor for production of most crops on most soils, and the form mostly used by plants is the nitrate-nitrogen (NO_3^--N) form. In addition to its role in the formation of proteins, N is an integral part of the chlorophyll molecule. And, as a constituent of protein, enzymes and chlorophyll, N is involved in all processes associated with protoplasm, enzyme reactions and photosynthesis.

The deficiency symptoms include a general yellowing of leaves, or chlorosis, due to an inhibition of chlorophyll synthesis.

Many researchers have demonstrated the direct effect of N on both yield and N concentrations in different crops. Jordan, Laird and

Ferguson (1950) working on the growth rate and nutrient uptake of maize in a fertilizer experiment found the early uptake of N to be proportional to the applied N. An increase in the growth medium normally leads to an increase in the concentration of N in the plant (Krantz and Chandler, 1946, 1951; Grunes and Krantz, 1958; Ologunde,[1] 1974; Rabufetti and Kamprath, 1977).

The interactions of nitrogen with various nutrient elements in plants have also been demonstrated. Terman and Noggle (1973) and Terman, Noggle and Hunt (1977) observed an increase in phosphorus (P) concentration and uptake in young plants of corn with applied N. Cole, Grunes, Porter and Olsen (1963) found that pretreatment of corn seedlings with N increased growth rates, rate of P uptake per unit of root weight and translocation of P to the tops 5-10 fold.

The form of N applied to the growth medium had also been reported to affect the relationship of N with the other ions in plants. Blair, Miller and Mitchell (1970) used the NO_3^- and NH_4^+ sources of N and reported higher P concentrations in corn seedlings grown with NH_4^+-N than with NO_3^--N. Riley and Barber (1971) explained that the lower soil pH resulting with NH_4^+-N was closely correlated with higher P concentration and uptake by soybean (Glycine max L.). This finding was confirmed by Engelstad and Allen (1971).

An increase in applied N resulted in an increase in concentration of potassium (K) in Kentucky bluegrass and tall fescue (Hojjati,

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[1]Ologunde, O. O. 1974. Effect of nitrogen and population on yield and yield components of Zea mays L. M.S. Thesis, University of Missouri, Columbia.

Templeton and Taylor, 1977). Tyner and Webb (1946) had earlier noticed an antagonistic effect of N and K on each other. An increase in the level of N in the soil decreased the percentage content of K in the leaves. This effect was observed by many other researchers, but the decrease of K was attributed to dilution.

Krasaesindhu and Sims (1972) obtained a significant N x Ca interaction for both grain and straw yields of rice (Oryza sativa L.). Nitrogen content and Ca concentration of grains were greatly enhanced by both N and Ca fertilization. Hojjati, Templeton and Taylor (1977) recorded an increase in Ca concentration in herbages with increasing N fertilization. Data by Clark (1970) show a trend for increased sulfur (S) content in corn plants as N rates were increased. Rabufetti and Kamprath (1977) observed that N fertilization had a larger effect than S fertilization in determining total S accumulation in grain and straws of corn. A form of positive interaction between N and S was suggested to explain the result. Blanchar and Hossner (1968) and later Rehm and Caldwell (1970a,b) used different sources of N on corn and reported that a higher S content in plants receiving NH_4 ions than those receiving NO_3 ions. A form of competition between the NO_3^- and SO_4^{2-} ions was suggested to explain the physiological reaction.

Petterson, Dolar and Chesters (1969) observed a direct effect of N on magnesium (Mg) and manganese (Mn) and an inverse effect on boron (B) concentrations in the tobacco leaves. Mayland and Grunes (1974) concluded that N and Mg effects were additive in increasing forage Mg content and therefore reduced the incidence of tetany in animals. However, Hojjati, Templeton and Taylor (1977) observed this additive effect

of N and Mg in Kentucky bluegrass and tall fescue only at the early growth of these herbages. During the later growth of these herbages, high N decreased Mg concentration. This action of N on Mg may increase the likelihood of tetany due to the reduced availability of Mg to livestock.

Under the greenhouse conditions, Gupta, Macleod and Sterling (1976) found that the addition of 50 ppm N or more reduced B uptake and therefore alleviated B toxicity in wheat. In field experimentation, the B toxicity in wheat and barley at 2.24 kg B/ha as associated with reduced grain yields was insignificantly alleviated by the addition of N to the soil. Andersen (1971) observed that heavy applications of N increased the total uptake of added isotope strontium (^{90}Sr) and calcium (Ca) considerably, but the relative distribution of the two isotopes in grains and straw was affected differently. The concentration of ^{90}Sr in grain decreased with increasing N supply until the maximum yield was obtained.

Phosphorus Fertilization

Phosphorus (P) is absorbed mainly as the dihydrogen phosphate ion, $H_2PO_4^-$. P is a constituent of many compounds in plants, and as a constituent of nucleoproteins, it is involved with cell divisions and the transfer of hereditary characteristics by the chromosomes. It is also a constituent of the high-energy compounds ADP and ATP, which provide energy for synthesis of such compounds as sucrose, starch and proteins.

In many plant species P deficiency induces the formation of anthrocyanin pigments with the result that the leaves become purple in color. In P deficiency, the photosynthetic rate fell gradually, roots become elongated and chloroplasts become filled with starch (Gauch, 1972).

The interactions of P with other nutrient and especially the micronutrient elements have been studied intensively by many researchers. Garg and Welch (1967) found that P placed with corn seeds not only increased growth, P concentrations and uptake 2, 3 and 4 weeks after planting but also increased N concentration and uptake by corn seedlings. Hills, Sailsbery, Ulrich and Sipitonos (1970) found similar effects of P on NO_3^--N concentrations in sugarbeet seedlings (Beta vulgaris L.) growth both in culture solution and on the field.

Mahtab, Swoboda, Godfrey and Thomas (1972) studying the effect of phosphorus on phosphorus uptake concluded that P is a function of the clay and water contents of the soil and the applied P. At low moisture levels, the response of sorghum to P addition was not as great on coarse-textured soil as on fine-textured soils.

Estes and Bruetsch (1973) found that relatively high rates of P might interfere with plants' absorption and utilization of trace elements. Petterson, Dolar and Chesters (1969) had earlier shown that P had a direct effect on Ca, Mg and B and an inverse effect on Zn and Cu concentrations in tobacco leaves. Watanabe, Lindsay and Olsen (1965) working on nutrient balance involving phosphorus iron and zinc observed that an increase in applied P resulted in P-induced deficiency symptoms.

One suggested reason for this was as a result of high P concentration in the plant tissue which resulted in a P/Fe ratio greater than 60.

Many workers have suggested that P may interfere with the proper utilization of Fe in the plant (Brown, 1961; Wallace and Lunt, 1960; Watanabe et al., 1965). Brown and Ambler (1970) have shown that a high P concentration in the root may interfere with the Fe-stress response of a plant. Watanabe et al. (1965) stressed the importance of P/Fe ratio and reported that a ratio of P/Fe greater than 60 in maize tissues caused Fe-deficiency to occur in the plant. Estes and Bruetsch (1973) reported that reduced Fe translocation was the reason for the susceptibility of the susceptible corn hybrids. This was caused by relative high P concentrations in the tissue. They suggested that levels of P greater than 22 ppm in the nutrient solution would produce significant reduction in Fe concentration of the foliage.

The interaction of P and Al had been studied by many workers. Hartwell and Pember (1918) first suggested that P-deficiency symptoms in barley shoots could result from the internal precipitation of P and Al. Later, Wright (1943) and Wright and Donahue (1963) also reported that Al precipitated P within barley roots. Wallihan (1948), however, suggested that Al and perhaps P were held to the root surfaces by ionic exchange. More recent work by Clarkson (1966) with barley root suggested that the interaction between Al and P was an adsorption-precipitation reaction that occurred at the cell surface or in the free space of the root. The electron microprobe analysis of corn roots by Rasmussen (1968) and Rasmussen, Shull and Dryer (1968) revealed that Al precipitated on the surface of the epidermal cells of the roots. Naidoo,

Stewart and Lewis (1978) found that both Al and P coprecipitated in the outer cells of the root caps of snapbean and cotton.

Woolson, Axley and Kearney (1973) observed that the arsenic phytotoxicity and As in corn plant were altered by P additions. The percent of water-soluble As present in corn was found to be proportional to the added P and inversely proportional to time and to Fe and Al contents. However, Carrow, Rieke and Ellis (1975) observed that P had little or no effect on As toxicity in turfgrass even at very high P levels.

Andersen (1971) reported that heavy application of P decreased the concentrations as well as the total uptake of ^{90}Sr and ^{45}Ca, but the ratio of $^{90}Sr/Ca$ was little affected. Safaya (1976) working on P-Zn interaction in corn observed that the rate of Cu absorption was reduced with P and Zn as the plant aged.

Many investigators have reported the interaction between P and Zn in the soil resulting in antagonism which usually intensifies Zn deficiency symptoms in plants. A decrease in Zn concentrations with P has been reported (Burleson, Daccus and Gerard, 1961; Langin, Ward, Olson and Rhoads, 1962; Ward, Langin, Olson and Stukenholtz, 1963; Boawn and Leggett, 1963, 1964). Rudgers, Demeterio, Paulsen and Ellis (1970) reported that Zn deficiency symptoms were accentuated by P fertilization. Warnock (1970) reported Zn deficiency at high P and low Zn when P and Zn concentrations in the medium were 130 ppm and 2.5 ppm, respectively. In this corn plant, the distributions of Mn, Zn and Fe among leaf, stem and root tissues indicated that P and Zn fertilization altered the mobility

of the micronutrients within the plant. Since Zn-deficient plants accumulated a large excess of Fe, interference from the Fe was suggested as contributing to physiological malfunction within the Zn-deficient corn plant.

Safaya (1976) found higher concentration of P in tissues of Zn-deficient plants and observed that visual symptoms of Zn deficiency appeared when the level of applied P was raised to 75 µg P/g soil in maize. Wallace, Elgazzar, Cha and Alexander (1974) observed that at low level of Zn in solution culture, increasing P supply decreased the absolute uptake of Zn and its content in all plants' parts. However, at high level of Zn, increasing P resulted in the reverse actions and did not materially change the proportion of the total amount of it in roots compared with shoots.

Ward et al. (1963) and Olson, Stukenholtz and Hoover (1965) found that higher extractable K would only increase Zn uptake by corn if soils were relatively high in soluble P. Lessman and Ellis (1971) reported that the P levels of the soil and the amount of P applied were well correlated with reduced Zn utilization in plants.

Soil reactions and especially the pH of the soil are some of the important factors influencing Zn availability in soils. As soil pH increases, Zn availability decreases; thus, calcareous soils which inherently have high pH values have been noted to be deficient in Zn. Melton, Ellis and Doll (1970) reported that heavy application of P (500 pp2m) induced Zn deficiency especially on soils testing above pH 7.0. Pea growth was found to be reduced by both Zn deficiency (below 20 ppm-Zn in tissue) and toxicity (above 50 ppm-Zn in tissue).

Controversy still exists as to the nature of the interaction between P and Zn and its effects on plant growth. Adriano, Paulsen and Murphy (1971) observed that the most marked interaction at high P levels was between Fe and Zn which mutually antagonized each other during translocation more than absorption. Olsen (1972) suggested a P inactivation of Zn in soil, while Wallace et al. (1974) said it was either an effect of P on Zn uptake by plants in which P acts on the absorption site, or an effect of P on limiting Zn translocation or utilization in plants. Some other general explanations were:

1. Physical, chemical or microbial immobilization of Zn or P in the soil.
2. Precipitation of Zn by P inside the plant or at the root surface.
3. Disruption of plant metabolism resulting from imbalance of nutrients.

Potassium Fertilization

Plants require relatively large amounts of potassium (K). Along with Mg, K is required for the actions of some enzymes, especially fructokinase. Extracts of K-deficient pea roots showed considerably less pyruvate kinase activity than did those of K-sufficient plants (Evans, 1963). Recent investigations have established the involvement of K in starch synthesis (Nitsos and Evans, 1968, 1969). Potassium appears to play a role in translocation, since a deficiency of K is known to decrease translocation of labelled photosynthate from leaves to other portions of sugarcane plant (Hartt, 1969). And, more recently,

Humble and Hsiao (1969) reported that K was essential for stomatal openings.

The most characteristic general symptom of K deficiency is that of tip and marginal scorch of the most recently matured leaves (Gauch, 1972). However, in some plants, particularly legumes, the first sign of K deficiency is a white speckling of the leaf blades.

Many investigators have reported results indicating reciprocal or antagonistic relationships in plants between K and N, Ca or Mg (Boswell and Parks, 1957; Munson, 1968). Blevins, Hiatt, Lowe and Leggett (1978) studied the influence of K on uptake, translocation and reduction of nitrate by barley seedlings (Hordeum vulgare C.V. Compana) and observed that low K seedlings supplied with $Ca(NO_3)_2$ had lower levels of NO_3^- uptake, nitrate reductase activity and lower organic acid concentration than seedlings treated with 1 mM KNO_3. Schneider and Clark (1970) observed no significant effect of K application on the P content of pearl millet; however, all plots receiving K singly or in combination with Ca and/or Mg were significantly higher in NO_3^--N.

In their experiments to improve responses of corn (Zea mays L.) and snap bean (P. vulgaris L.) to different rates and sources of K, Terman, Allen and Bradford (1975) and Terman, Noggle and Hunt (1977) obtained marked responses to applied K. Marked reciprocal K-N, K-Ca and K-Mg relationships with yield response to rates of K were attributed to both dilution and ion antagonism. Antagonism was reported to be pronounced at higher K rates.

Hackett, Sinclair and Richards (1965) studied the influence of amine content on the balance between K and P in the nutrition of barley.

They observed that the severity of K-deficiency symptoms was strongly influenced by the external level of P, while the effect of P depended on the degree of imbalance between K and P in the nutrient medium. The more the disparity between the concentration of K and P in the nutrient solution, the more the intensity of K-deficiency symptoms.

Jones, Lutz and Smith (1977) reported that applied K increased K concentration of soybean nodules but had little effect on N, P, Ca, Cu, Fe, Mn and Zn concentrations and decreased Mg concentration. Rehm and Sorensen (1974) also reported that fertilizer K and S had no effect on P content of alfalfa tissue. They obtained no significant yield response to applied K.

Landua, Swoboda and Thomas (1973) reported a decrease in Mg content of coastal bermudagrass by the application of K; however, the K content of the grass was increased by K application.

An induced Ca deficiency has been attributed to high concentrations of K, Na or Mg in the growth media (Berry and Ulrich, 1970). They cultured sugarbeets in a modified Hoagland's nutrient solution and observed that the plant in low-K, Ca series developed severe K-deficiency symptoms and a much higher incidence of Ca deficiency in the high-K, Ca series. This indicated that in the Ca-K interaction, the low K supplied plants could not utilize completely the Ca supplied even when the culture solution contained high calcium.

Potassium was reported to increase boron (B) uptake and thus enhanced B toxicity symptoms in plants (Reeve and Shieve, 1944). This might explain why Hill and Morill (1975) obtained reduced peanut (Arachis hypogea L.) yields with high B and K applications. Ouellette (1963) and

Sinha (1961) reported that at very low B concentrations, K application could increase or cause B-deficiency symptoms which was mostly accompanied by a decrease in B uptake. The increase in B uptake due to the addition of K was explained as a depression in Ca activity (Reeve and Shieve, 1944), and the deficiency of B caused by K applications to soils poor in B content was attributed to physiological interactions (Sinha, 1961).

Sulfur Fertilization

All plant proteins have S-containing amino acids (cysteine, cystine and methionine), and S is also a constituent of the tripeptide, glutathione, since cysteine is one of the three amino acids (Gauch, 1972).

Sulfur is absorbed mainly in the form of sulfate ions (SO_4^{2-}) which is then reduced in plants and incorporated in organic compounds.

Sulfur-deficiency symptoms resemble those of nitrogen deficiency, but in contrast with N deficiency when older, lower leaves are affected, S affects only the uppermost, youngest leaves.

Relatively very little information is available on the interaction of S with other nutrient elements either in the growth medium or in the plants; however, competition between SO_4^{2-} and some other anions are reported. Rehm and Caldwell (1970) suggested physiological reaction to explain a competition between NO_3 and SO_4 ions when it was observed that plants that received NH_4 ions had a higher S content than those that received NO_3 ions (Blanchar and Hossner, 1968). Rehm and Sorensen (1974) observed that both S and K had no effect on the P content of

alfalfa and neither was any interaction effect between K and S observed even at high applied P.

However, Landua et al. (1973) observed an increase in S content of bermudagrass with applied S, but Mg content was decreased. The K content of the grass was increased by both S and K.

The possibility of correcting toxic levels of molybdenum (Mo) for animal nutrition was investigated by Gupta and MacLeod (1975) who found that the application of S to forage crops decreased Mo concentration in the forages. They recorded a significant interaction between Mo and S; the decreases in Mo concentrations of tissues with applied S were more marked when Mo was added than in the absence of Mo.

Singh (1970) observed that an application of 250 kg/ha S increased grain yield of peas by 100 percent as well as prevented the occurrence of chlorosis caused by lack of Fe. The occurrence of chlorosis was probably due to some nutrient imbalance. Although the chlorotic leaves in other treatments were observed to contain 40 percent more Fe than the green leaves, application of S corrected the imbalance of Fe which caused the inactivation of Fe by providing a more balanced nutritional condition.

Magnesium Fertilization

Each chlorophyll molecule contains one atom of Mg. This shows the importance of Mg in photosynthesis. Magnesium is also reported to be involved in the activation of many enzymes in plants.

Since Mg is readily mobile in plant, the mature leaves usually show signs of deficiency symptoms first. Diagnostic symptoms include

interveinal yellowing or interveinal chlorosis.

Both the synergistic and antagonistic effects of Mg on other nutrient elements have been reported in many crops. McLean and Carbonell (1972) reported that Mg content of both german millet and alfalfa tissues increased with increased Mg saturation in soil. They suggested that for most conditions, 6-10 percent Mg saturation would likely be adequate for maximum yields of crops. Adams and Henderson (1962) showed that exchangeable soil Mg below 4.0 percent was insufficient for maximum yields of Sudan grass and ladino clover. Similarly, Prince, Zimmerman and Bear (1947) had earlier indicated that alfalfa plants responded to Mg when exchangeable Mg was below 6.0 percent. For citrus, Martin and Page (1965) found that Mg deficiency occurred when the exchangeable level of Mg was 5-10 percent.

The depression of Mg uptake by plants from addition of K is widely known. Prince et al. (1947) noted that the most important single factor influencing the Mg uptake by alfalfa plants was the quantity of available K. They observed that the Mg content of the plant increased with cropping of soils low in Mg if K supply were permitted to decrease concomitantly. This suggested that additional Mg should be used when large amounts of K are applied to the soil. In Nigeria, Agboola and Corey (1973) reported a negative correlation between exchangeable Mg in soil and percent K in the corn tissue. The low K content in maize tissue despite the apparent high levels of exchangeable Mg in the soil was attributed to the antagonistic action of soil exchangeable K on Mg.

In culture solution, a decreased uptake of Mg with increased K supply had been reported (Martin and Page, 1965; Scharres and Mengel,

1958). This result would indicate a true K-Mg physiological antagonism since the medium was independent of the possible effects of colloidal complex of soil.

The Mg/K ratios had been reported to be a better estimate of Mg availability than the exchangeable Mg (Walsh and O'Donohoe, 1945; McColloch, Bingham and Aldrich, 1957). Lombin and Fayemi (1976) working with soils from some areas of western Nigeria observed a more significant correlation between Mg uptake by plant and K/Mg ratio than between any of the other soil variables studied. However, Hossner and Doll (1970) observed that the yield response of potato to Mg fertilizer was related to both levels of exchangeable soil Mg and to soil Mg/K ratio.

Calcium Fertilization

Calcium is known to be essential for the maintenance of selective ion transport in cellular membranes (Epstein, 1961; Rains, Schmid and Epstein, 1964). Epstein (1961) showed that in the absence of Ca, selectivity in absorption of K and Na by barley roots quickly broke down within minutes of the beginning of the experiment. However, Jones and Lunt (1967) observed that Ca requirements for corn root systems were low provided other essential ions were in balance and if no toxic ions were present.

Deficiency symptoms associated with Ca are "dieback" of the meristems and damaged root systems. Since calcium-deficient soils are acid, Ca deficiency is usually associated with toxic levels of hydrogen ions and ions of Al and Mn which tend to go into solution at low pH values.

The desirable effect of calcium fertilization is the increase in soil pH. This removes the toxic effect of hydrogen ions and heavy metals. The interaction of Ca and Mg in the nutrition of higher plants has been recognized by many investigators (Epstein, 1962; Durrant and Drycott, 1971; Tewari, Sinhar and Mandal, 1971; Troung, Andrew and Wilson, 1971; Fageria, 1974).

In their studies of the interaction of Ca and Mg in nutrition of intact sugarbeets, Mostafa and Ulrich (1976) observed that Ca interfered with Mg uptake but did not induce Mg-deficiency symptoms. This is in contrast to the induced Ca-deficiency symptoms when Mg interfered with Ca uptake at a similar Ca/Mg ratio even when the amount of Ca and Mg in the solution far exceeded the amount required for growth. This points to the fact that the Ca/Mg ratio in the nutrient solution is an important factor to consider in sugarbeet nutrition.

Short-term uptake tests disclosed that increasing levels of Ca in solution cultures decreased both Sr and Ba uptake by bush beans and decreased the proportions of the ions remaining in roots compared with that translocated to leaves (Wallace and Romney, 1971).

Cations such as Ca and Mg have been reported to protect roots from the toxicity effects of Al and Mn. Rhue and Grogan (1977) observed that an increase in Ca concentration decreased the severity of Al toxicity in roots of corn inbreds. However, they found marked differences among inbred lines in the ability of their roots to grow in the screening solutions at all levels of Ca.

Calcium has often been reported to increase the absorption of various cations and associated anions, and this stimulating effect of Ca

has been termed the "Viets effects." Pitman (1964) reported that the Ca enhanced Cl^- uptake in beetroot tissue. Calcium has been reported to increase the rate of SO_4^{2-} absorption. Leggett, Galloway and Gauch (1965) reported that the increase was caused by the effect of Ca on the turnover rate of carrier.

Calcium was reported to decrease the uptake of zinc (Schmid, Haag and Epstein, 1965) and Na (Handley, Metwally and Overstreet, 1965). Handley et al. (1965) explained that Ca may decrease uptake by stabilizing the membrane and thus causing a decline in permeability. The inhibitory effect of Ca on K absorption from dilute K concentrations has been attributed to a decrease in permeability of the cell membrane (Elzam and Hodges, 1967).

Micronutrients

Many studies have shown antagonistic relationships among micronutrients in a wide variety of crops grown in different soil environments. Singh and Steenberg (1974) reported that the uptake of Mn was reduced by Zn applications on maize cultivated in Zn-deficient soils. In rice (Oryza sativa L.) plants Mn toxicity was reduced by increasing the concentration of Zn in solution culture (Ishizuka and Ando, 1968).

A number of examples of Zn-induced Fe deficiencies (Watanabe et al., 1965) and Fe-induced Zn deficiencies (Rosell and Ulrich, 1964) have been reported. Mortvedt and Giordano (1971) demonstrated evidence for a marked Fe-Zn interaction in sorghum, when application of $ZnSO_4$ to the no-Fe check treatment reduced growth and Fe uptake, while high Fe application reduced Zn uptake in the presence or absence of Zn. In corn

Safaya (1976) observed that Fe concentration in plants decreased with Zn application. This antagonistic effect of Zn on Fe was manifested by reduced yields as the ratio of Fe/Zn in the plant tissue decreased below 1.5.

Iron-induced Mn deficiency (Hanger, 1965) and Mn-induced Fe deficiency (Knezek and Greinert, 1971; Vlamis and Williams, 1964) also occur. Gupta (1972) observed an increasing rate of added Mn to the soil decreased the concentration of Fe, Mo and Cu, but B was not affected.

Antagonistic relationships between Mo-Mn (Cheng and Ovelette, 1972; Mulder, 1954), Mo-Fe (Gerloff, Stout and Jones, 1959; Hanger, 1965), Cu-Zn (Gilbey, Greathead and Gartell, 1970; Hawf and Schmid, 1967) and Cu-Fe (Cheshire, Dekock and Inkson, 1967) have been reported. Singh and Steenberg (1974) concluded that though Zn, Fe and Mn ions in barley appeared to have limited influence on translocation within the plant, these ions exert strong synergistic effects at the site of transport. There appeared to be pronounced antagonism between the pair Mo-Zn, Mo-Fe and Mo-Mn in the metabolism of barley.

The application of chromium to soybeans grown in nutrient culture resulted in decreased concentrations and total uptake of Ca, K, P, Fe and Mn in tops and of K, Mg, P, Fe and Mn in roots of the crops. These effects were observed at Cr treatments as low as 0.5 ppm (Turner and Rust, 1971).

Anion-Cation Interactions

Many researchers have reported both antagonistic and synergistic effects of anions on each other or on cations in the growth media.

Harward, Jackson, Piland and Mason (1956) reported a negative interaction between Cl^- and NO_3^- in nutrient absorptions by plants. The stimulation of cation uptake, and especially K accumulation in higher plants by NO_3^- had been observed (Minotti, Williams and Jackson, 1969; Blevins, Hiatt, Lowe and Leggett, 1978).

Mattson (1966) contended that since the NO_3^- was the main anion taken up by the plants, its uptake and metabolism would control the uptake of all other anions and cations. Bar-Yosef and Kafkafi (1972) reported that high NO_3^- in soil solution could inhibit P uptake. Humble, El-Leboudi and Rendig (1965) had earlier observed a similar depressive effect on P uptake caused by high NO_3^--N concentration in the nutrient solution during a 24-hour uptake period. James, Weaver and Reeder (1960) observed that KCl fertilizer significantly reduced NO_3^- concentration of potato petioles. This interaction was explained by mutual antagonism between NO_3^- and Cl^- on nutrient uptake by plants. Fertilizer P was, however, observed to have a pronounced synergistic effect on Cl^- uptake.

Ionic Balance

When there is an excess of cations over anion uptake, organic acids and especially citrate and malate have been known to increase in the cells (Ulrich, 1941, 1942; Noggle, 1966; Osmond and Laties, 1969). Wit, Dijkshoorn and Noggle (1963) proposed that organic anion concentration of the plant tissue is regulated by growing plants. It was suggested that a given plant species regulates its organic salt content within a narrow range of values at optimal growth rates. At a normal

organic salt content, the value observed at optimal growth, was postulated as one of the conditions for good growth. A low organic salt content was never accompanied by an optimal growth. The concentrations of organic anions in plants are determined as the difference between the concentrations of cations (Na^+, K^+, Ca^{2+}, Mg^{2+}) and the concentrations of inorganic anions (Cl^-, NO_3^-, $H_3PO_4^-$, SO_4^{2-}). Wit et al. (1963) and Noggle (1966) observed a positive correlation between yield and concentrations of organic acids in cells. Watanabe, Olsen and Cole (1971) reported an increase in dry matter yield of barley as the organic anion concentration increased. However, with sorghum and pinto beans, the lowest yields were associated with the highest organic anion concentration which was found to be above the normal values, apparently because of some nutrient imbalance. With sorghum this nutrient imbalance was observed to be connected with low K/Ca ratios.

Follett and Reichman (1973) studied ionic balance in barley as influenced by P fertilization. They observed that P increased yields, decreased the organic anion concentration and the adverse effects of low water and temperature on the plant. Banwart and Pierre (1975) found that nitrogen fertilization increased the anion and N contents of corn, oats and orchardgrass.

MATERIALS AND METHODS

Experiments were conducted in the Agronomy greenhouse of the University of Nebraska-Lincoln between October 1978 through June 1979. Each plastic container of 5.5-liter capacity with drainage hole at the bottom was filled with 5 kg washed river sand. The sand was then thoroughly leached with distilled water before seeds were sown.

Treatments

Nutrient treatments were 7 rates each of potassium as KCl and magnesium as $MgCl_2$. Seventeen of the possible 49 K-Mg combinations were used (Table 1).

To each of the nutrient treatments were added 112 ppm NO_3^--N and 160 ppm Ca as $Ca(NO_3)_2$, 42 ppm NH_4^+-N as both $NH_4H_2PO_4$ and $(NH_4)_2SO_4$, 31 ppm P as $NH_4H_2PO_4$ and 32 ppm S as $(NH_4)_2SO_4$. Zinc sulfate ($ZnSO_4 \cdot 7H_2O$), copper sulfate ($CuSO_4 \cdot 5H_2O$), boric acid (H_3BO_3), manganese chloride ($MnCl_2 \cdot 4H_2O$) and molybdic acid ($H_2MoO_4 \cdot H_2O$ - assaying 85% MoO_3) were added to supply 0.05, 0.02, 0.5, 0.5 and 0.01 ppm Zn, Cu, B, Mn and Mo, respectively. Iron was supplied with FeHEDTA (Fe hydroxyethylenediamine-triacetate). The chelate stock solution was prepared by dissolving 6.99 g FeHEDTA in deionized water and bringing the solution to one liter volume. One milliliter of stock solution was used in each liter of nutrient solution.

Application of nutrient solution started 8 days after seedling emergence and continued on alternate days until harvest. All pots were flushed with distilled water 3 times during each experiment.

Table 1. Rates, coded values and combinations of potassium and magnesium used.

			POTASSIUM						
	Rates	(ppm)	0	50	100	150	200	250	300
		Codes	-3	-2	-1	0	1	2	3
	0	-3	X			X			X
	10	-2		X				X	
	20	-1			X		X		
MAGNESIUM	30	0	X			X			X
	40	1			X		X		
	50	2		X				X	
	60	3	X			X			X

X = Nutrient combinations used.

A sorghum [Sorghum bicolor (L.) Moench] hybrid, 'RS 671' and its male and female lines, 'Tx 415' and 'Redlan,' respectively, were used as the test crop.

Four seeds were sown about 2 mm deep in each pot followed by the application of deionized water. The seedlings were thinned to 2 plants per pot 5 days after emergence.

Throughout the duration of the experiment, the light period was maintained at 16 hours per day with day and night temperature at 28 C.

Plants were harvested at 25, 50 and 75 days after seedling emergence. On a given harvesting day, the height of each plant was measured. At the final harvest, stem diameter was also measured. Tops were separated into lower leaves, upper leaves and stem, except for the first harvest when the whole top was collected without separation. Leaf area of each plant was measured using LI-3100 area meter, followed by stem measurement. Fresh tissues were washed with distilled water and put in an oven for drying. Sheaths were included along with their respective leaves.

The roots were thoroughly washed and rinsed with 0.01 N HCl followed by distilled water and then put in the oven for drying.

Analytical Procedures

Plant materials were dried at 80 C for 72 hours in a forced-air oven. Each sample was weighed and ground in a Wiley mill to pass 2 mm mesh screen. The ground lower and upper leaves and the stem for each treatment were thoroughly mixed, and a sample from this mixture was taken to represent the top plant tissue. The samples were stored in

plastic cups before they were subjected to chemical analysis at the Soil Testing Laboratory of the University of Nebraska-Lincoln. Tissues obtained during the first harvest were not chemically analyzed because of their small sizes.

Total N was determined by a modified Kjeldahl procedure. For analyses for other nutrients, plant samples were dry ashed in an oven. Phosphorus was measured according to Barton's solution method as described by Jackson (1958). Potassium was determined by flame photometry and Mg, Ca, Zn, Fe and Mn were determined by atomic adsorption spectrophotometry. All concentrations of elements were expressed on the basis of dry plant material. Nutrient uptakes by sorghum tops were calculated.

Statistical Analysis

There were 17 K-Mg treatments, 3 sorghum lines and 3 harvests resulting in a total number of 102 treatments. These were arranged in a randomized complete block design, with 2 replications. The experiment was repeated twice. For each measured variable, the means of the 2 experiments were used for statistical analysis.

Quadratic multiple regression equations were developed from the experimental data to measure the effect of K and Mg on the selected dependent variables using the following model:

$$Y = b_0 + b_1K + b_2Mg + b_3K^2 + b_4Mg^2 + b_5K\,Mg$$

where

Y = Dry matter yield, nutrient concentration, nutrient uptake, plant height and diameter

K = Coded rate of K application

Mg = Coded rate of Mg application

b_0 = Y value when all the X's are zero (intercept)

b_1 = Linear regression coefficient for K

b_2 = Linear regression coefficient for Mg

b_3 = Quadratic regression coefficient for K

b_4 = Quadratic regression coefficient for Mg

b_5 = Regression coefficient for K-Mg interaction

All the regression data are presented in forms of regression coefficients.

All hypotheses were tested at the 5% probability level.

RESULTS AND DISCUSSION

The main objective of this study was to determine what effects various levels of potassium and magnesium in the growth medium would have on growth and nutrient contents of sorghum grown in a sand culture.

Dry Matter Yields and Other Yield Variables

Top tissue. Regression coefficients showing the effect of nutrient K and nutrient Mg on top dry matter yield are shown in Table 2. Applications of K had no effect on dry matter accumulation in the 25-day-old plants (Fig. 1). Averaged over the lines and hybrid dry matter accumulation in the 50-day-old plants increased curvilinearly with increased K applications; however, differences were noted among hybrid and lines. While dry matter yield of RS 671 increased directly in proportion to the amounts of K in the growth medium, that of Redlan increased curvilinearly and Tx 415 showed no response.

At 75 days after seedling emergence, dry matter yield increased curvilinearly with increasing K in the growth medium. Figure 3 shows that within each level of applied Mg, increasing the amounts of nutrient K from 0 to 200 ppm increased yield. A further increase in K concentration in the growth medium resulted in a yield decrease.

The effect of Mg application on the dry matter yield of RS 671 at the 75-day-sampling period was mainly linear, while both Redlan and Tx 415 responded curvilinearly (Table 2). Averaged over lines and hybrid, dry matter yield increased with increase in added Mg up to 40 ppm (Fig. 2).

Table 2. Regression coefficients and R^2 values showing the effect of potassium and magnesium concentrations in nutrient solutions on dry weight of top tissues of a sorghum hybrid and its parent lines at three harvest dates.

Variable	Intercept	K	Mg	K^2	Mg^2	K x Mg	R^2
First Harvest (25 days)							
RS 671	0.371	0.002	0.001	0.001	0.003	-0.004	0.19
Redlan	0.257	0.004	0.008	-0.005	-0.002	-0.002	0.35
Tx 415	0.190	-0.003	-0.008*	0.003	0.003	-0.001	0.55
Hybrid & Lines	0.282	0.001	0.008	-0.001	0.0009	-0.002	0.24
Second Harvest (50 days)							
RS 671	5.63	0.421*	-0.061	-0.170	0.007	-0.060	0.84
Redlan	4.14	0.200*	-0.057	-0.134*	-0.069	-0.011	0.80
Tx 415	3.50	0.184	-0.020	-0.049	-0.039	-0.028	0.38
Hybrid & Lines	4.42	0.268*	-0.056	-0.111*	-0.042	-0.033	0.80
Third Harvest (75 days)							
RS 671	25.7	1.88*	0.87*	-1.16*	-0.46	-0.07	0.88
Redlan	23.6	1.72*	1.13*	-0.89*	-0.67*	0.14	0.90
Tx 415	19.2	1.54*	0.55*	-0.78*	-0.48*	0.09	0.90
Hybrid & Lines	22.7	1.64*	0.79*	-0.93*	-0.53*	0.06	0.92

*Indicates a significant difference at the 0.05 level of probability.

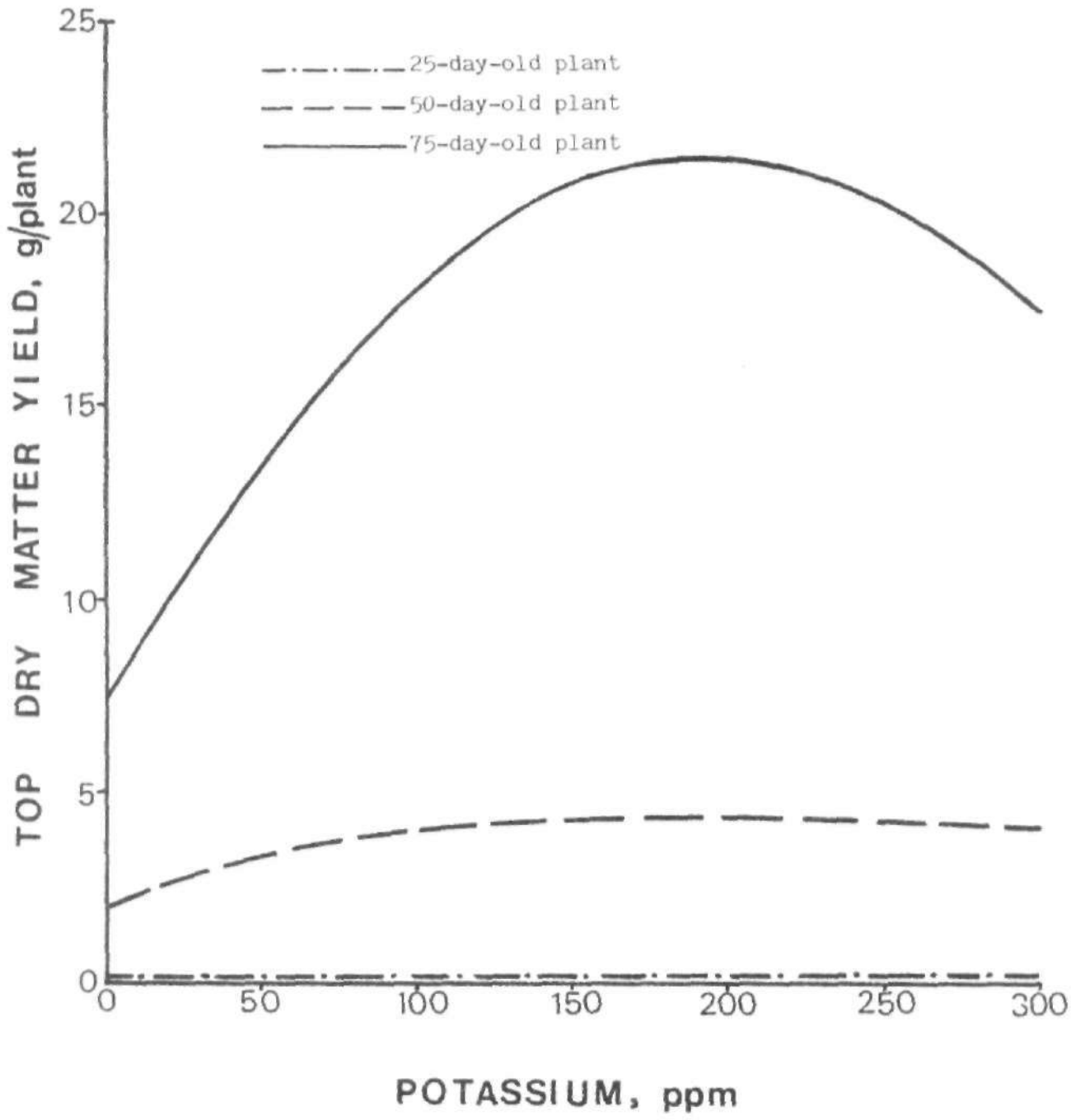


Fig. 1. Top dry matter yield of sorghum plants at 3 harvest dates in response to rates of applied potassium in nutrient solution (average for 3 lines).

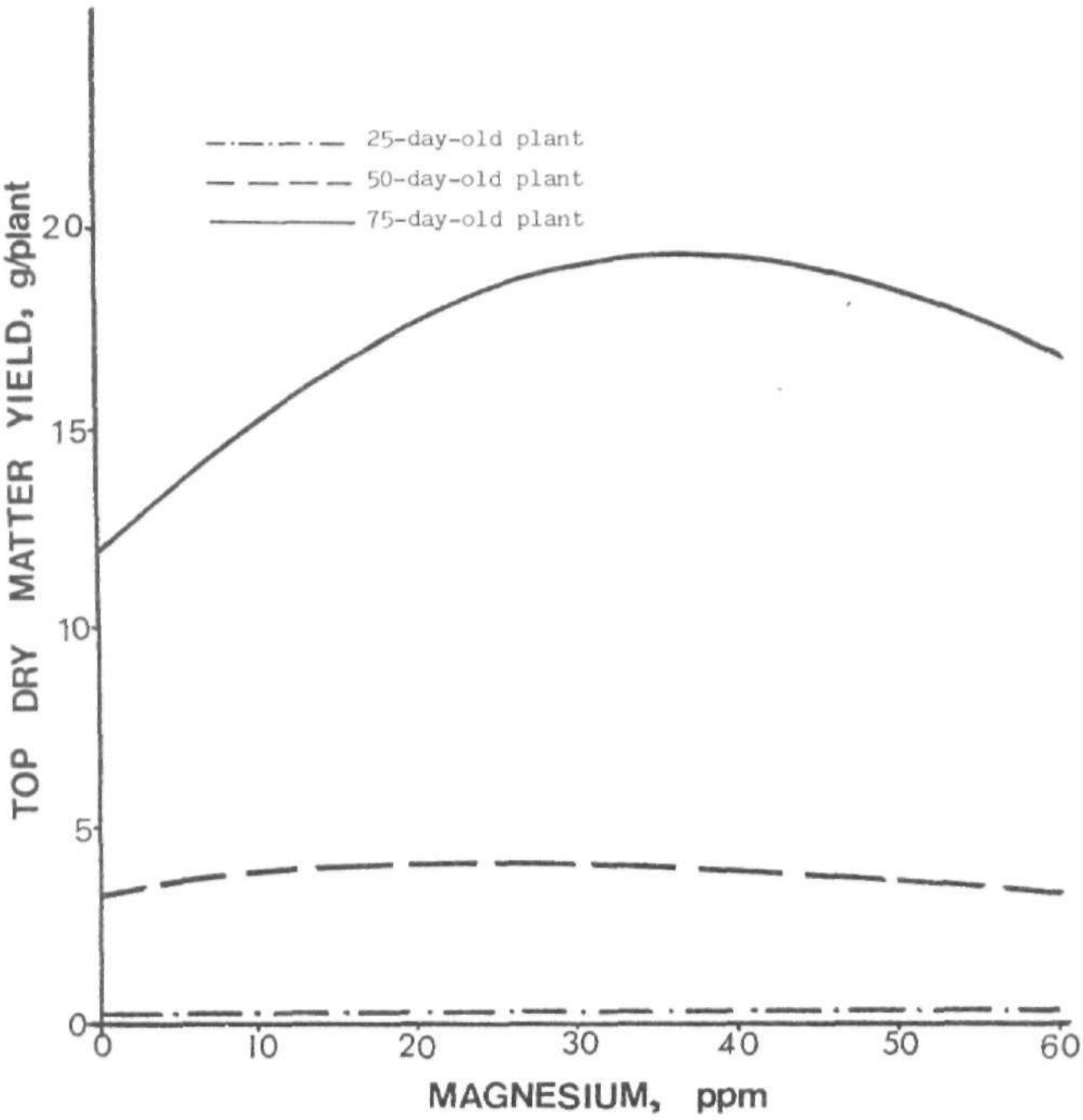


Fig. 2. Top dry matter yield of sorghum plants at 3 harvest dates in response to rates of applied magnesium in nutrient solution (average for 3 lines).

Table 2 shows that the interactive effect of K and Mg was not significant, indicating that the effect of K was not modified by the rate of Mg application and vice versa. Figure 3 illustrates this effect. The optimum levels of K and Mg in nutrient medium required for maximum growth seem to decrease and increase, respectively, as plants get older. The calculated optimum rates of K and Mg required for maximum dry matter production at the 75-day-sampling period were 195 (0.50 meq/100 g) and 38 (0.31 meq/100 g) ppm, respectively. The corresponding values for the 50-day-old plants were 210 and 32 ppm.

The dry matter accumulation in the plants was observed to be increasing in spite of the considerable reductions in the concentrations of Ca and Mg in the top tissue due to application of low levels of K and Mg (Tables 11, 13). This suggests that the three exchangeable cations, K, Mg and Ca, carry out at least, in part, certain non-specific functions which can be performed by one cation in the absence of another. It might also be noted that the Mg and Ca concentrations in K- and Mg-deficient plants are abnormally high due to inability of plant's selectivity function to operate normally (Fig. 31, 42, 43). As deficiencies are removed, plants are better able to select nutrients for uptake. Another factor is that as plants grow better, formation of organic components (proteins, carbohydrates, etc.) occurs much more rapidly. Thus, the decrease in top tissue nutrient concentrations may simply be a dilution of them in a greater amount of organic materials (larger plant).

Reports on the response of dry matter yields of sorghum to K and Mg applications are rather limited, and reports on some other crops are inconsistent. Terman et al. (1975, 1977) observed a positive response

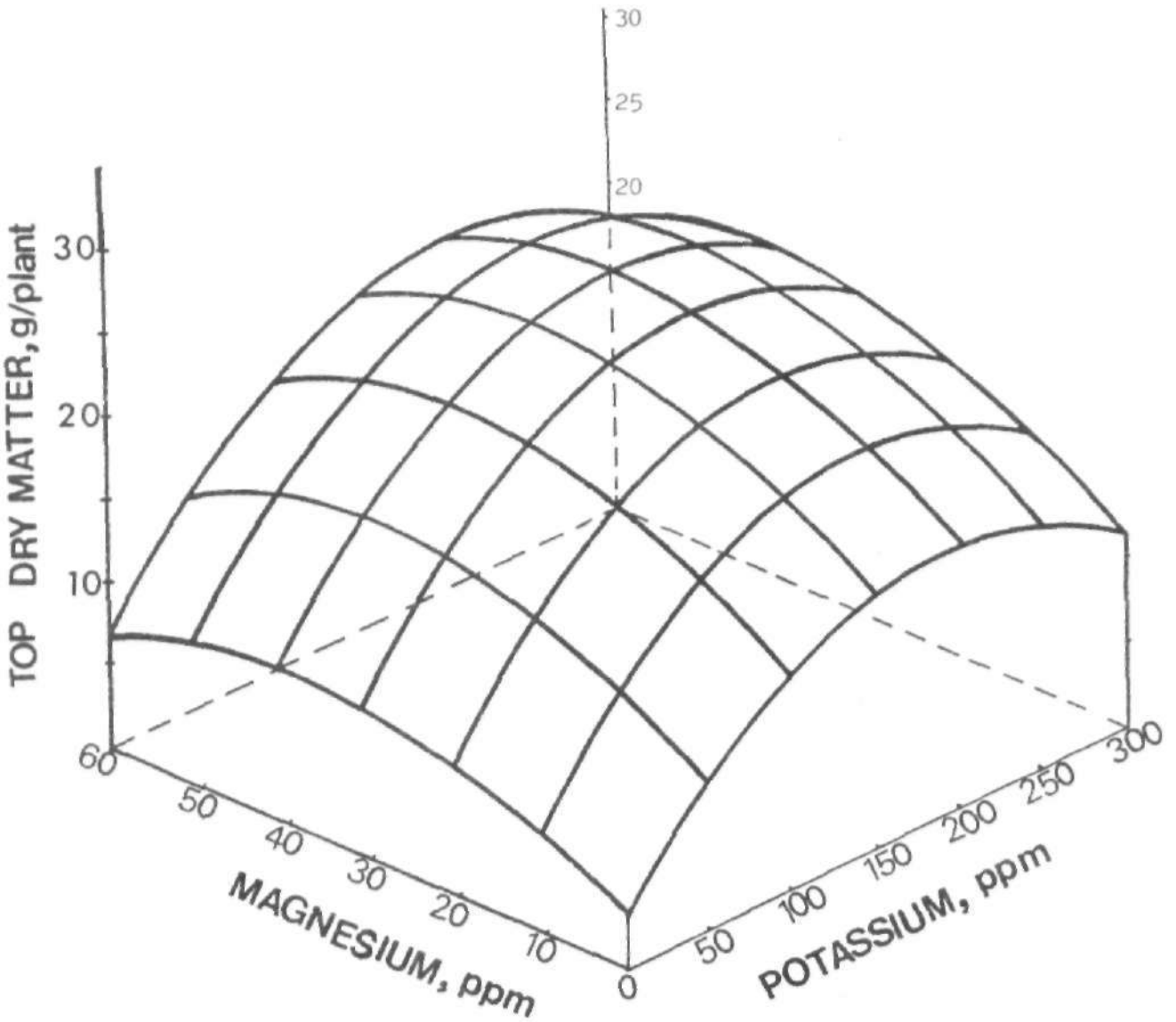


Fig. 3. Predicted response surface of top dry weight of sorghum plants to increasing levels of potassium and magnesium concentrations in nutrient solution at 75 days after seedling emergence (average for 3 lines).

of snap beans and corn yields to K application. Omar and Kobbia (1966) observed significant increase in yield of lucerne to K rates, but Mg application was reported to have no effect. However, Rehm and Sorensen (1974) reported that the crop did not respond to K application. Smith (1979) reported a decrease in dry weight of switchgrass due to K application, and Hill and Morrill (1975) and Herbert (1970) suggested a strong K-Ca antagonism to explain the reduction in yield of groundnuts due to K application. As demonstrated in this study, the response of sorghum plant to K and Mg applications depends among other factors on the age of the plant. Sorghum plant did not show any response to K and Mg application until 50 and 75 days after seedling emergence, respectively. Omar and Kobbia (1966) harvested their crop after only 6 weeks in the greenhouse, a period not long enough to demonstrate Mg response in the crop.

Some other factors, such as initial soil K and Mg levels and rate of release from soil minerals, are important considerations. Results obtained by Heathcote and Stockinger (1970) indicated that responses of corn, cotton and groundnuts to K application increased with time and intensity of cropping following a long fallow period in Nigeria. The practice of bush fallow would normally increase the supply of exchangeable K and Mg in the topsoil which should result in a lack of response of a crop to K application immediately following a long fallow period. Classen and Wilcox (1974) reported that K addition increased corn growth only when NH_4^+-N as against NO_3^--N was used as the nitrogen carrier.

Although the interactive effect of K and Mg was not significant, reports of K-Mg interactive effect on yield of some other crops have

been consistent. Stilwell (1972) and Kansal and Sekhon (1974) reported that in 'low K' soils, application of K with or without Mg was beneficial to wheat yield. However, in 'high K' soils, application of Mg was detrimental to yield. Bedi and Sekhon (1977) indicated that where the exchangeable cation ratios (K/(Ca + Mg + K) in equivalents) was less than 0.025, K fertilizer increased the dry matter yield of corn. In soils where the ratio exceeded 0.05, the application of one or both K and Mg reduced yield.

The increase in dry matter production due to increased K in the growth medium has been attributed to both morphological and physiological interrelationships. Cooper, Blaser and Brown (1967) observed that as applied K increased, alfalfa plants developed larger leaves, more epidermal cells per leaf area, more stomates with larger aperture and higher net photosynthesis. Tables 22 and 23 show low but significant correlation between applied K and total leaf area of sorghum plants both at the 50- and 75-day-sampling periods. Stem length and diameter were each correlated with K concentration in the growth medium resulting in the increased total dry matter yield as K in the growth medium increased.

Root tissue. Like the top tissue, Table 3 shows that the root dry weight was not affected by K and Mg application until 50 and 75 days after seedling emergence, respectively. Figure 4 shows the depressing effect of K on dry matter accumulation in roots when the concentration was above approximately 200 ppm in the growth medium at both harvests. However, differences due to hybrid and lines were observed. Root dry weight of RS 671 increased curvilinearly with K additions, while the dry

Table 3. Regression coefficients and R^2 values showing the effect of potassium and magnesium concentrations in nutrient solution on dry weight of roots of a sorghum hybrid and its parent lines at 3 harvesting dates.

Variable	Intercept	K	Mg	K^2	Mg^2	K x Mg	R^2
First Harvest (25 days)							
RS 671	0.102	0.001	-0.001	-0.0004	-0.0003	-0.0009	0.11
Redlan	0.064	0.0001	-0.001	-0.002*	-0.0002	-0.0000	0.37
Tx 415	0.055	0.0005	-0.005*	0.001*	0.0004	-0.0003	0.70
Hybrid & Lines	0.077	0.0006	-0.002	0.0006	-0.0009	-0.0004	0.39
Second Harvest (50 days)							
RS 671	1.563	0.105*	-0.024	-0.058*	-0.012	-0.018	0.81
Redlan	0.724	0.043*	-0.023	-0.018	-0.019	-0.012	0.66
Tx 415	0.998	0.026	0.005	-0.026	-0.018	-0.004	0.33
Hybrid & Lines	1.095	0.058*	-0.014	-0.034*	-0.016	-0.012	0.81
Third Harvest (75 days)							
RS 671	8.1	0.69*	0.32	-0.31*	-0.24*	0.01	0.79
Redlan	4.7	0.28*	0.27*	-0.15*	-0.19*	0.04	0.77
Tx 415	6.1	0.49*	0.19	-0.27*	-0.21*	0.05	0.81
Hybrid & Lines	6.3	0.48*	0.26*	-0.24*	-0.21*	0.03	0.83

*Indicates a significant difference at the 0.05 probability level.

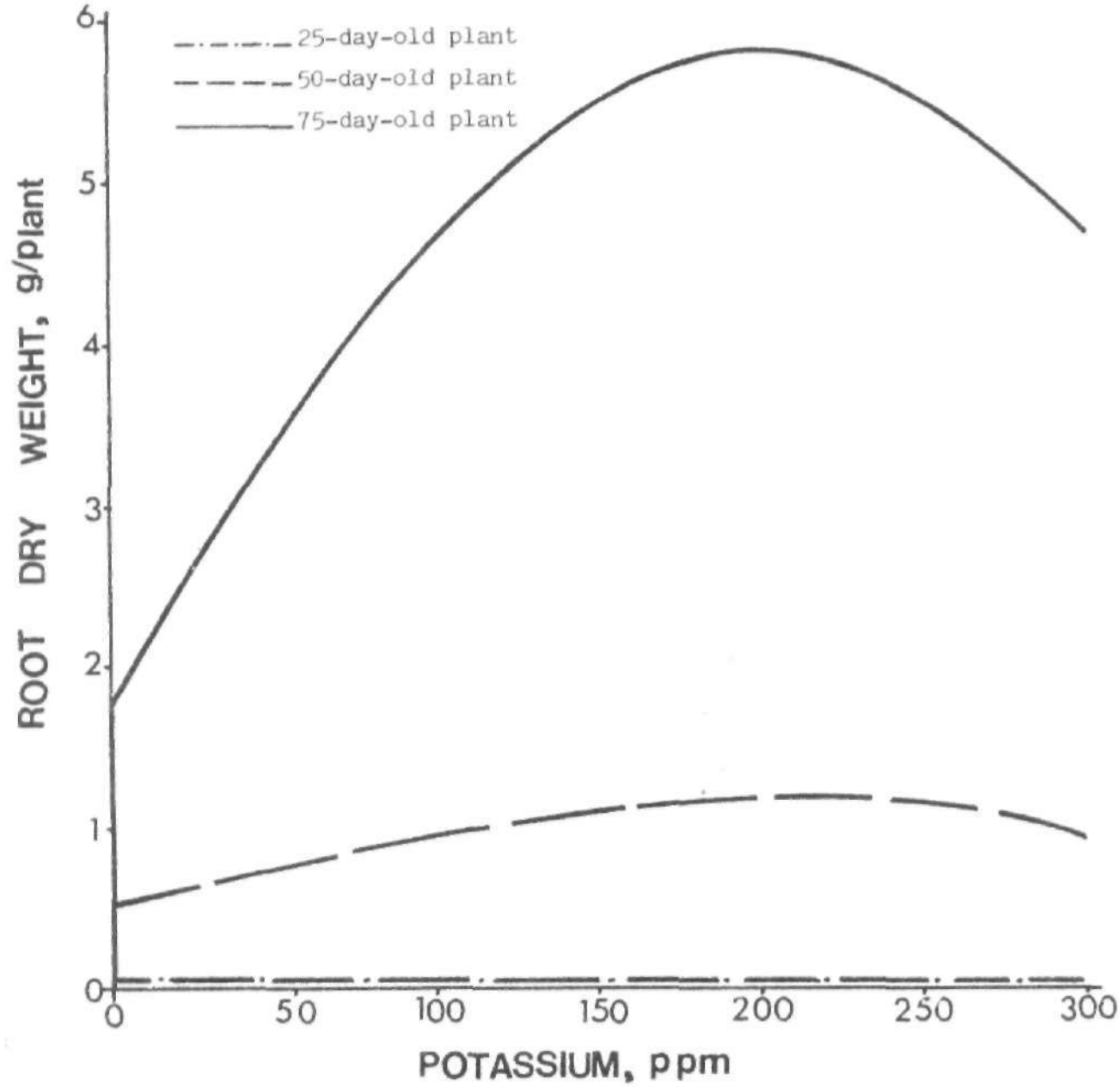


Fig. 4. Root dry weight of sorghum plants at 3 harvest dates in response to rates of applied potassium in nutrient solution (average for 3 lines).

matter accumulation in root of Redlan increased directly in proportion to K additions. Dry matter accumulation in roots of Tx 415 was not affected by K applications. At 75 days after seedling emergence, root dry weight in the lines and hybrid increased curvilinearly with K additions (Fig. 6). The increase in root dry weight with low levels of K applications tends to support the results of Keisling et al. (1979), who reported that a decrease in K supply resulted in an observable loss of vigor in the root system of bermudagrass.

Effects from Mg application were observed only at 75 days after seedling emergence, when rates above 40 ppm resulted in a marked decrease in root weight (Fig. 5).

There was no interaction between the effects of the two nutrients on root dry weight (Fig. 6). Averaged over the lines and hybrid, the calculated optimum levels of K and Mg required for maximum dry matter accumulation in roots were 192 and 32 ppm, respectively, for the 50-day-old plants. The corresponding values for the 75-day-old plants were 200 and 36 ppm, respectively.

Stem Diameter and Length

Stem diameter and length were measured to give an indication of how K and Mg applications affected the development of the plant. Table 4 shows the effect of the two nutrients on stem diameter and length of the 75-day-old plants. Stem diameter of the lines increased curvilinearly with increased K and Mg concentrations in the growth medium (Fig. 7); the hybrid, however, responded curvilinearly to K application, but Mg application had no effect. Table 4 shows also that application of

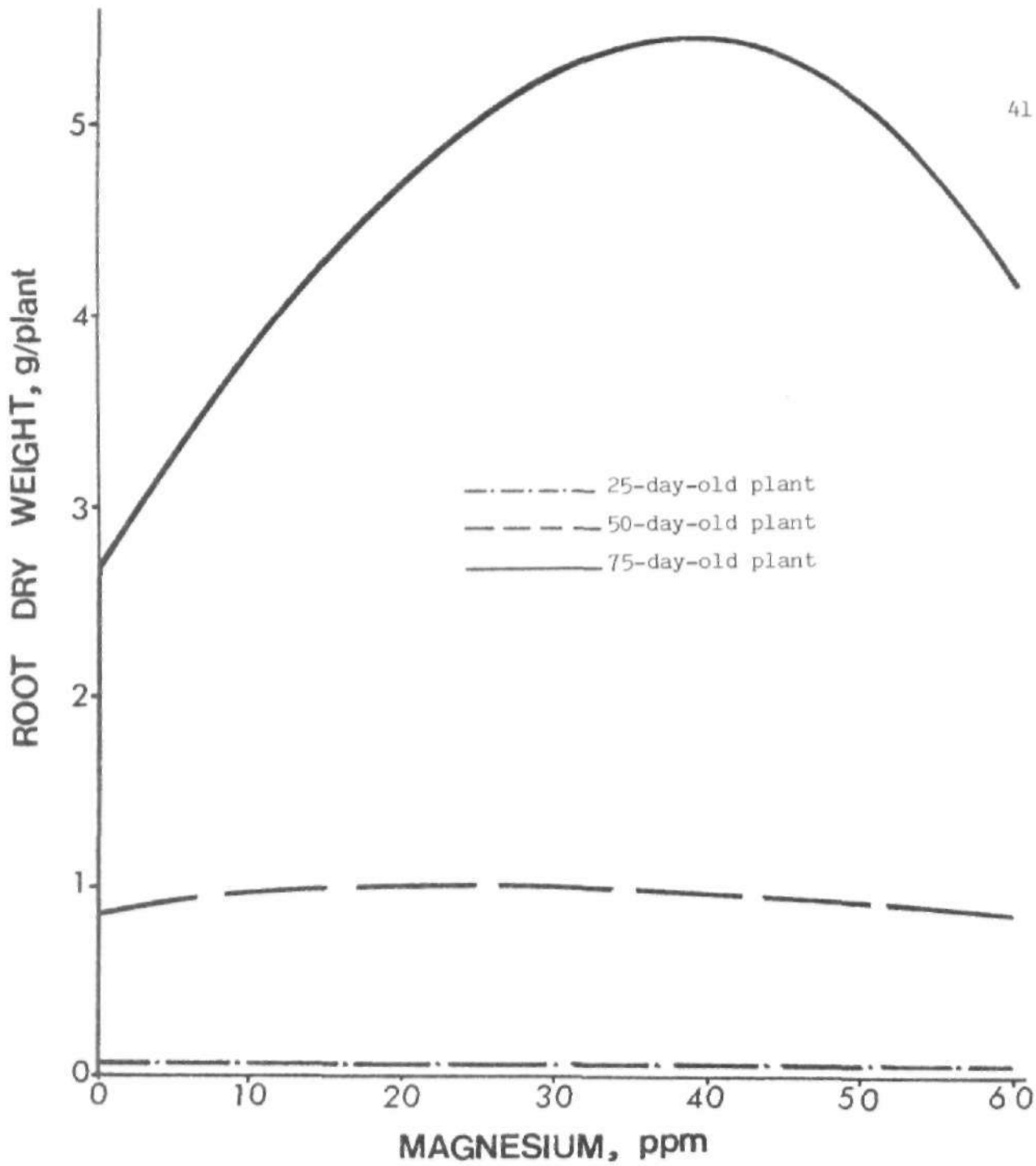


Fig. 5. Root dry weight of sorghum plants at 3 harvest dates in response to rates of applied magnesium in nutrient solution (average for 3 lines).

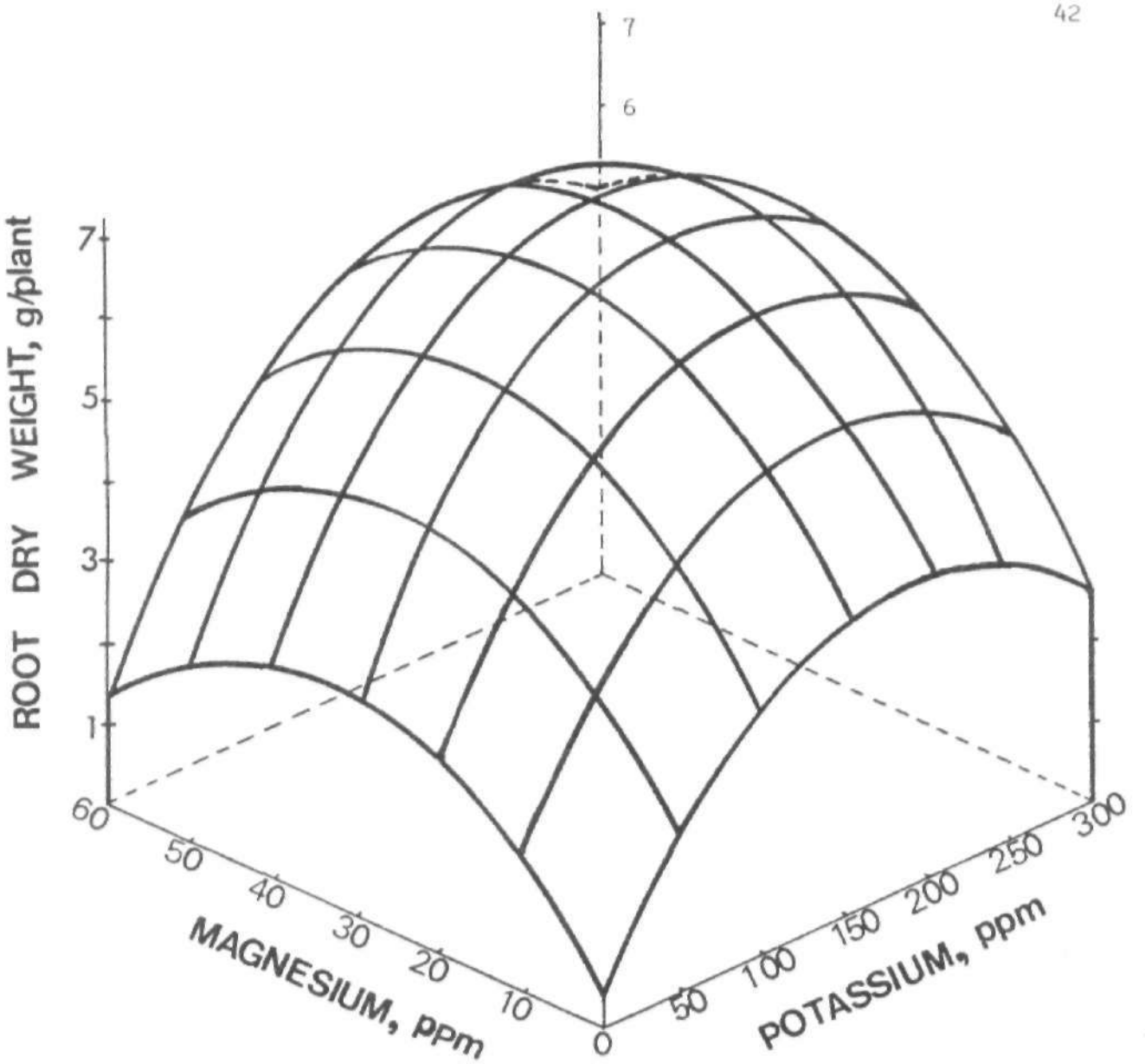


Fig. 6. Predicted response surface of sorghum root dry weight to increasing levels of potassium and magnesium concentrations in nutrient solution at 75 days after seedling emergence (average for 3 lines).

Table 4. Regression coefficients and R^2 values showing the effect of potassium and magnesium concentrations in nutrient solution on stem diameter and stem length of a sorghum hybrid and its parent lines at 75 days after seedling emergence.

Variable	Intercept	K	Mg	K^2	Mg^2	K x Mg	R^2
Stem Diameter							
RS 671	1.30	0.08*	0.02	-0.03*	-0.01	-0.005	0.87
Redlan	1.07	0.04*	0.02*	-0.02*	-0.01*	-0.001	0.85
Tx 415	1.46	0.10*	0.02*	-0.04*	-0.02*	-0.005	0.95
Hybrid & Lines	1.27	0.07*	0.02*	-0.03*	-0.02*	-0.001	0.93
Stem Length							
RS 671	39.6	6.13*	3.40*	-0.58	-0.24	-0.02	0.88
Redlan	62.8	7.02*	4.06*	-1.81*	-1.93*	0.89	0.87
Tx 415	17.7	1.32*	0.89	-0.78*	-0.14	0.18	0.65
Hybrid & Lines	40.0	4.82*	2.77*	-1.06*	-0.77	0.35	0.90

*Indicates a significant difference at the 0.05 probability level.

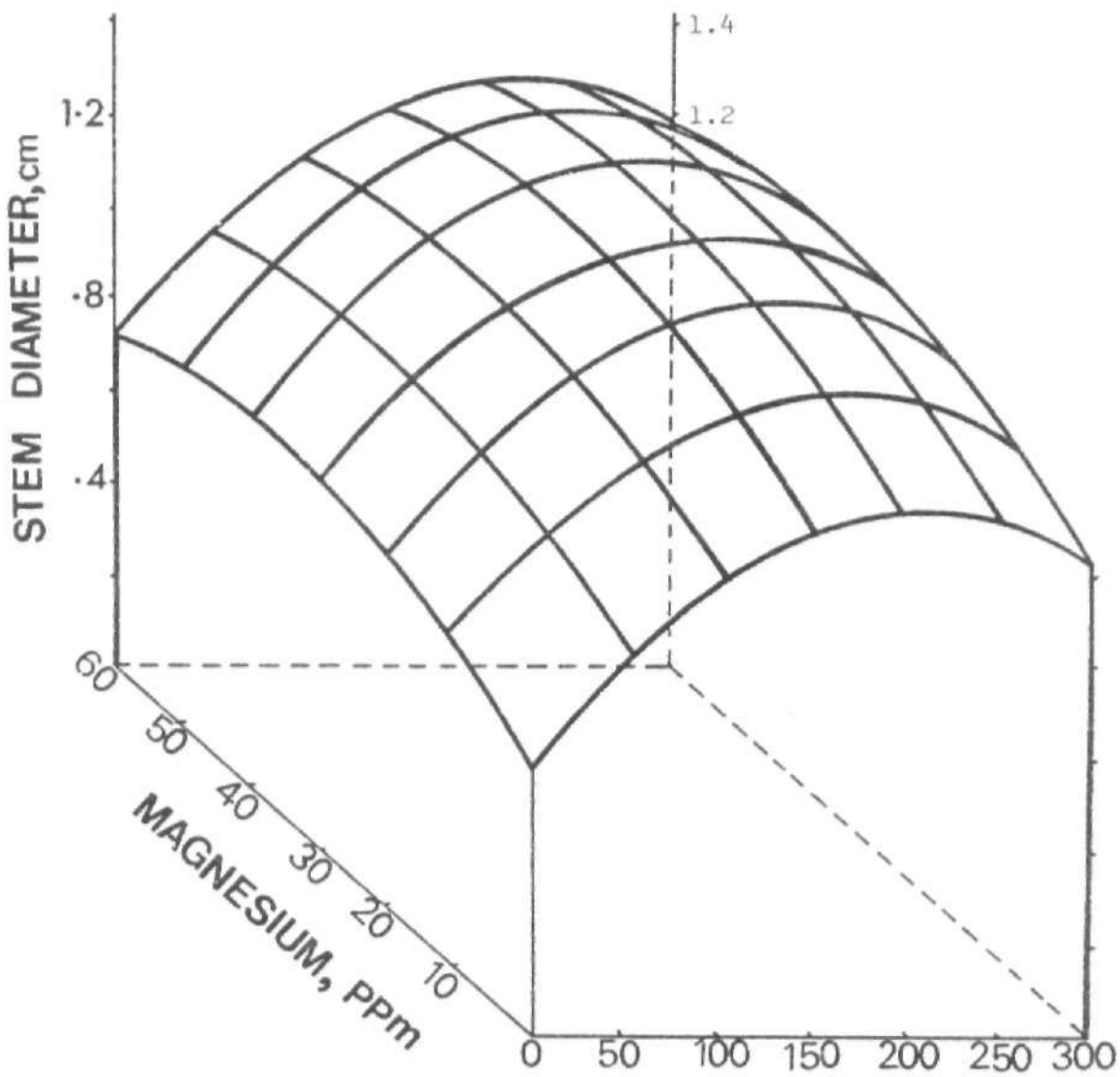


Fig. 7. Predicted response surface of stem diameter of sorghum to increasing levels of potassium and magnesium concentrations in nutrient solution at 75 days after seedling emergence (average for 3 lines).

both K and Mg affected the growth rate of the plant (Fig. 8). Differences among lines and hybrid were also observed. Figure 9 shows that the stem length of RS 671 developed directly in proportion to the amounts of K and Mg applied, that of Redlan (Fig. 10) showed a curvilinear relationship with the applied nutrient elements. Tx 415, however, responded curvilinearly to only K application, while application of Mg had no effect (Fig. 11).

Chemical Constituents

Nitrogen. The effects of nutrient K and nutrient Mg on N content in top tissue of the plant are shown in Table 5. Within any Mg level, application of K resulted in a curvilinear decrease in N concentration in the 50- and 75-day-old plants (Table 5). At these growth stages of the plant, the decrease in N concentration resulting from Mg application where present was predominantly linear (Fig. 13). However, differences in N concentration due to line differences were observed. Nitrogen concentration in RS 671 decreased directly with Mg additions during the second and third harvests (Fig. 14), but application of Mg had no effect on the N concentration in Redlan (Fig. 15) and Tx 415 (Fig. 16) at the third harvest.

Top tissue N uptake increased with increase in K and Mg concentrations in the growth medium (Table 6). Figure 17 illustrates that the plant N uptake increased markedly from the first increments of added K or Mg until the N uptake was sufficient to achieve near maximum dry matter yield. Thereafter, increasing the concentration of K in the growth medium resulted in a decrease in N uptake in both the 50- and

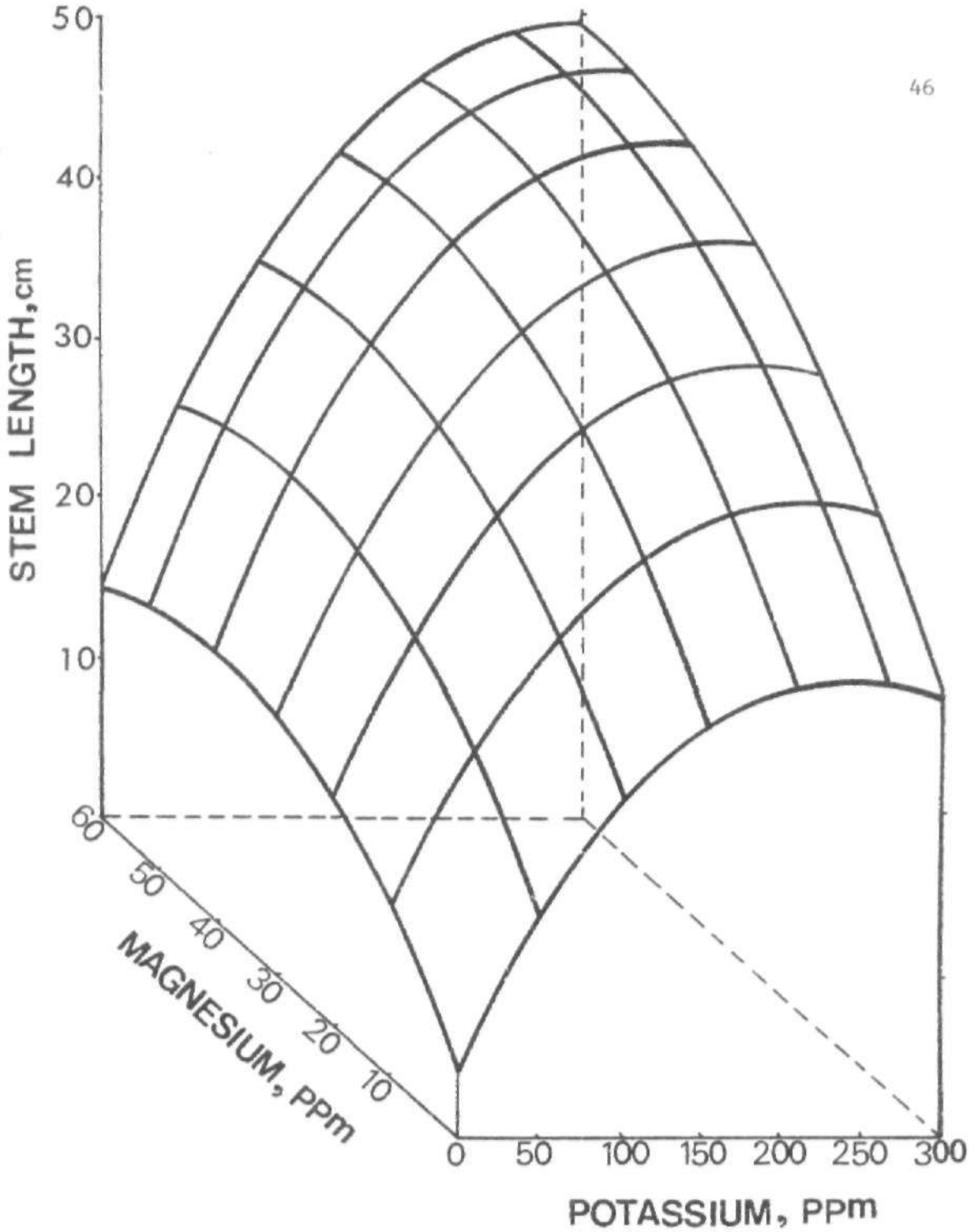


Fig. 8. Predicted response surface of stem length of sorghum plants to increasing levels of potassium and magnesium concentrations in nutrient solution at 75 days after seedling emergence (average for 3 lines).

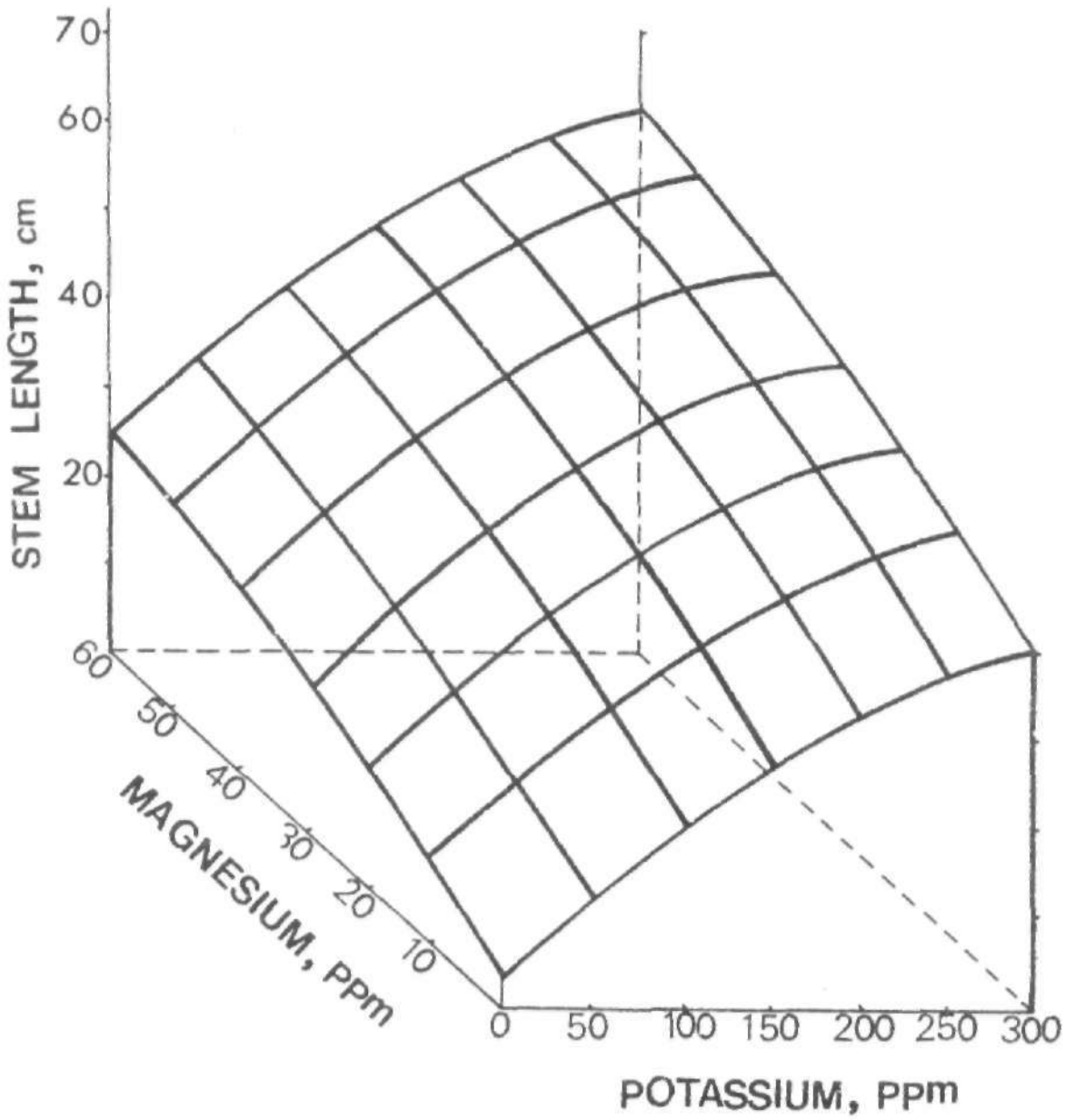


Fig. 9. Predicted response surface of stem length of 'RS 671' to increasing levels of potassium and magnesium concentrations in nutrient solution at 75 days after seedling emergence.

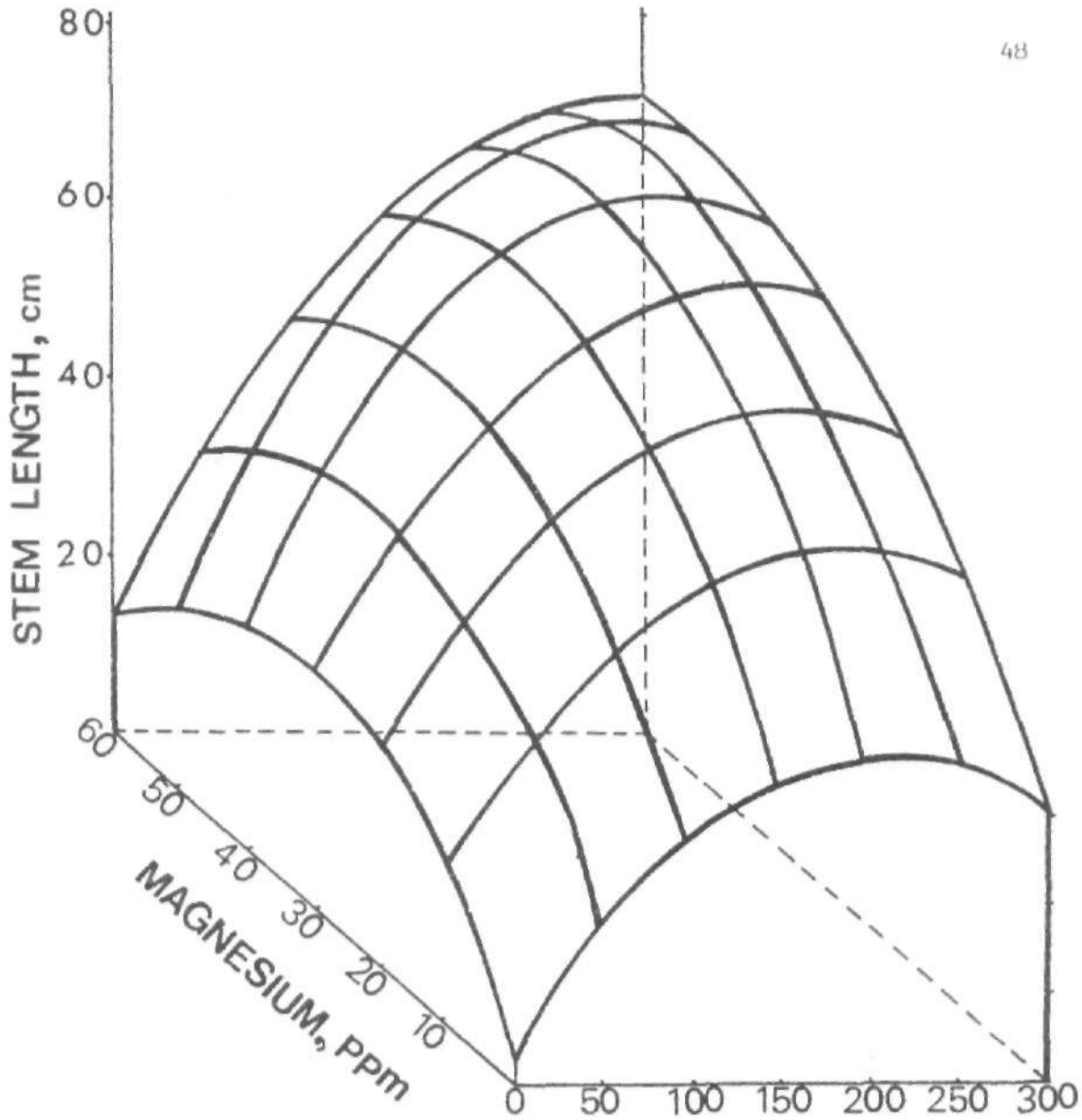


Fig. 10. Predicted response surface of stem length of 'Redlan' to increasing levels of potassium and magnesium concentrations in nutrient solution at 75 days after seedling emergence.

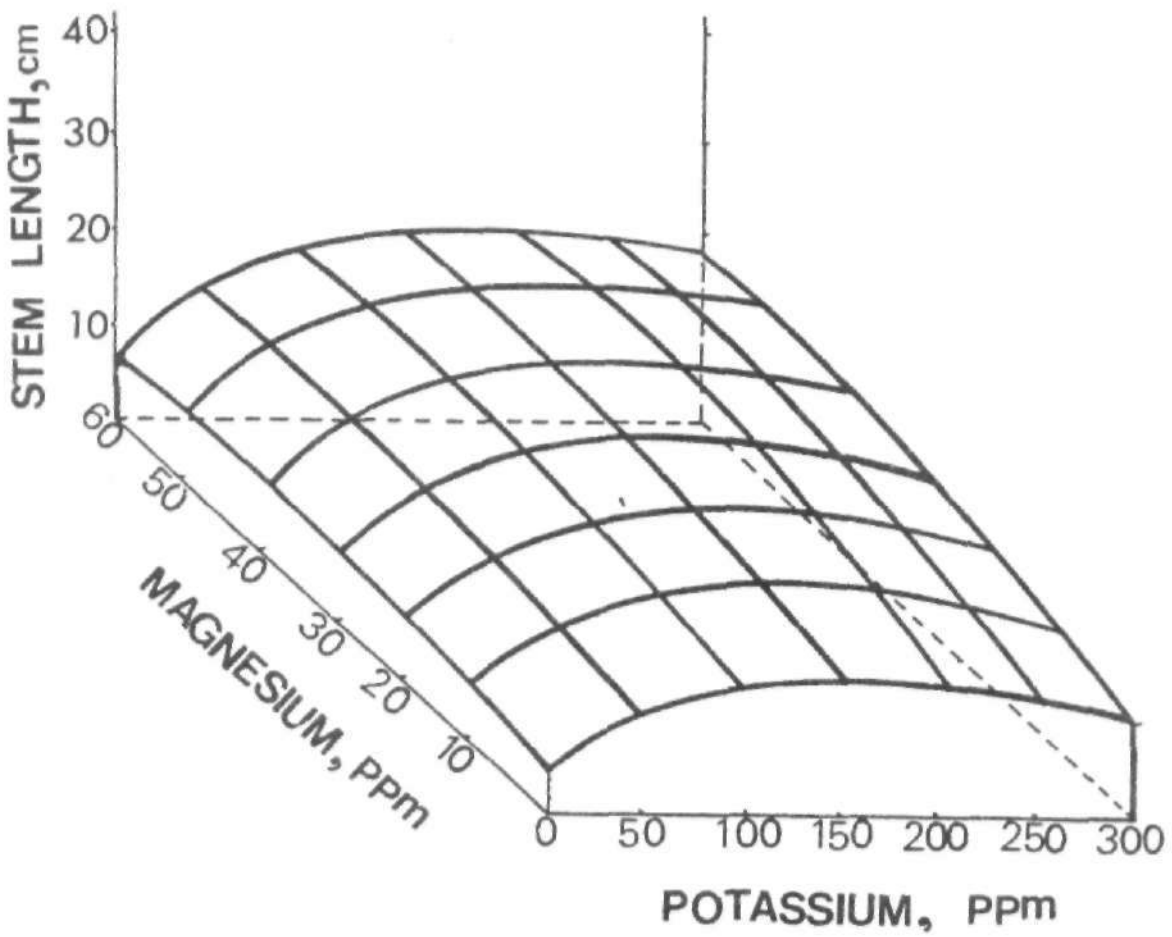


Fig. 11. Predicted response surface of stem length of 'Tx 415' to increasing levels of potassium and magnesium concentrations in nutrient solution at 75 days after seedling emergence.

Table 5. Regression coefficients and R^2 values showing the effect of potassium and magnesium concentrations in nutrient solution on nitrogen concentration of top tissue of a sorghum hybrid and its parent lines at 50 and 75 days after seedling emergence.

Variable	Intercept	K	Mg	K^2	Mg^2	K x Mg	R^2
Second Harvest (50 days)							
RS 671	3.16	-0.42*	-0.34*	0.029*	0.012	0.014*	0.80
Redlan	3.27	-0.039*	-0.007	0.024*	0.006	-0.000	0.73
Tx 415	3.55	-0.037*	-0.037*	0.008	-0.002	0.012	0.58
Hybrid & Lines	3.32	-0.039*	-0.025*	0.021*	0.005	0.008	0.75
Third Harvest (75 days)							
RS 671	2.34	-0.111*	-0.049*	0.047*	-0.001	0.029*	0.84
Redlan	2.20	-0.179*	-0.007	0.060*	0.004	-0.001	0.84
Tx 415	2.58	-0.167*	-0.033	0.070*	0.002	0.019	0.78
Hybrid & Lines	2.38	-0.146*	-0.030	0.057*	0.002	0.018	0.84

*Indicates a significant difference at the 0.05 probability level.

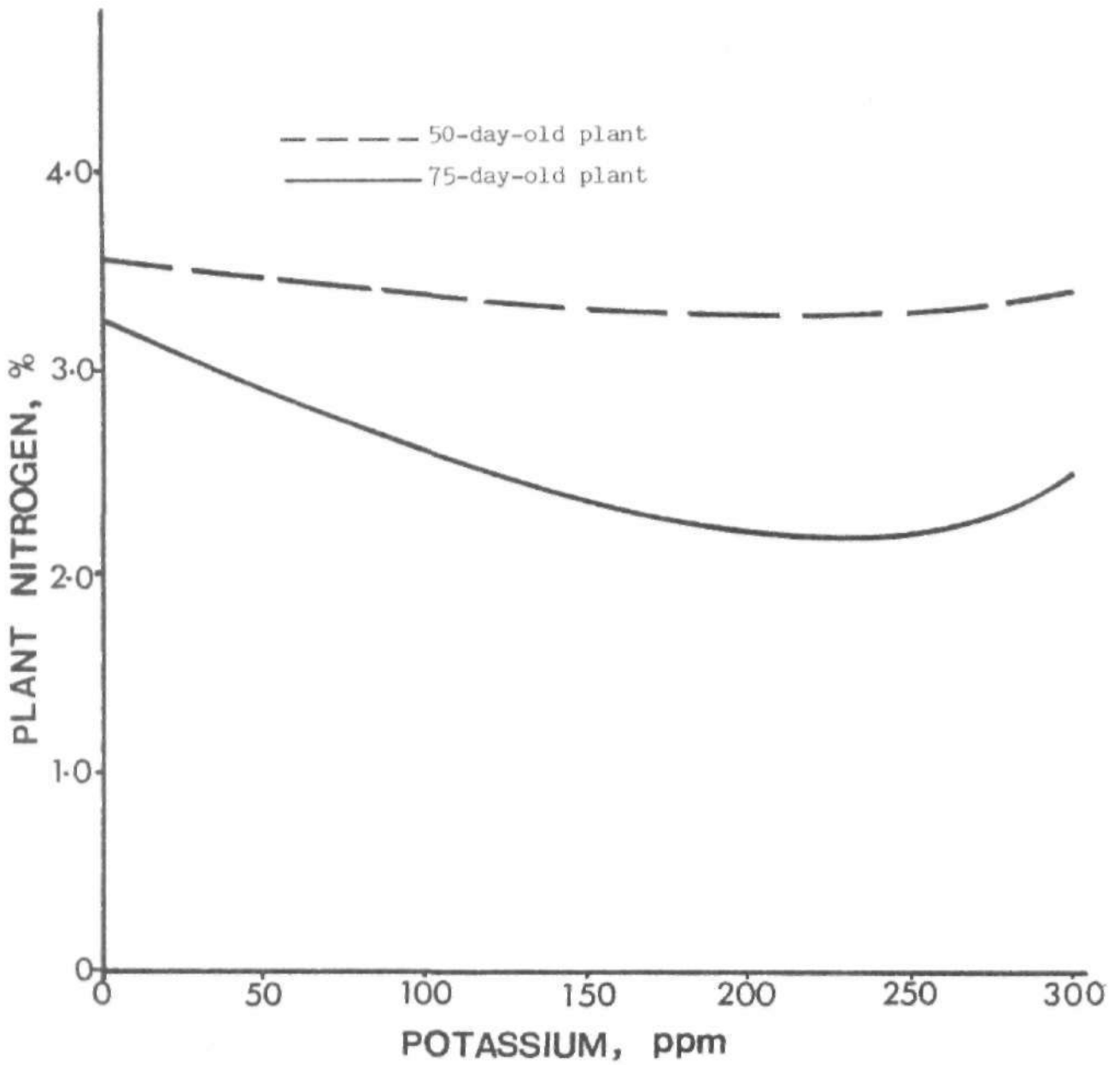


Fig. 12. Nitrogen concentration in top tissue of sorghum plants at 50 and 75 days after seedling emergence in response to rates of applied potassium in nutrient solution (average for 3 lines).

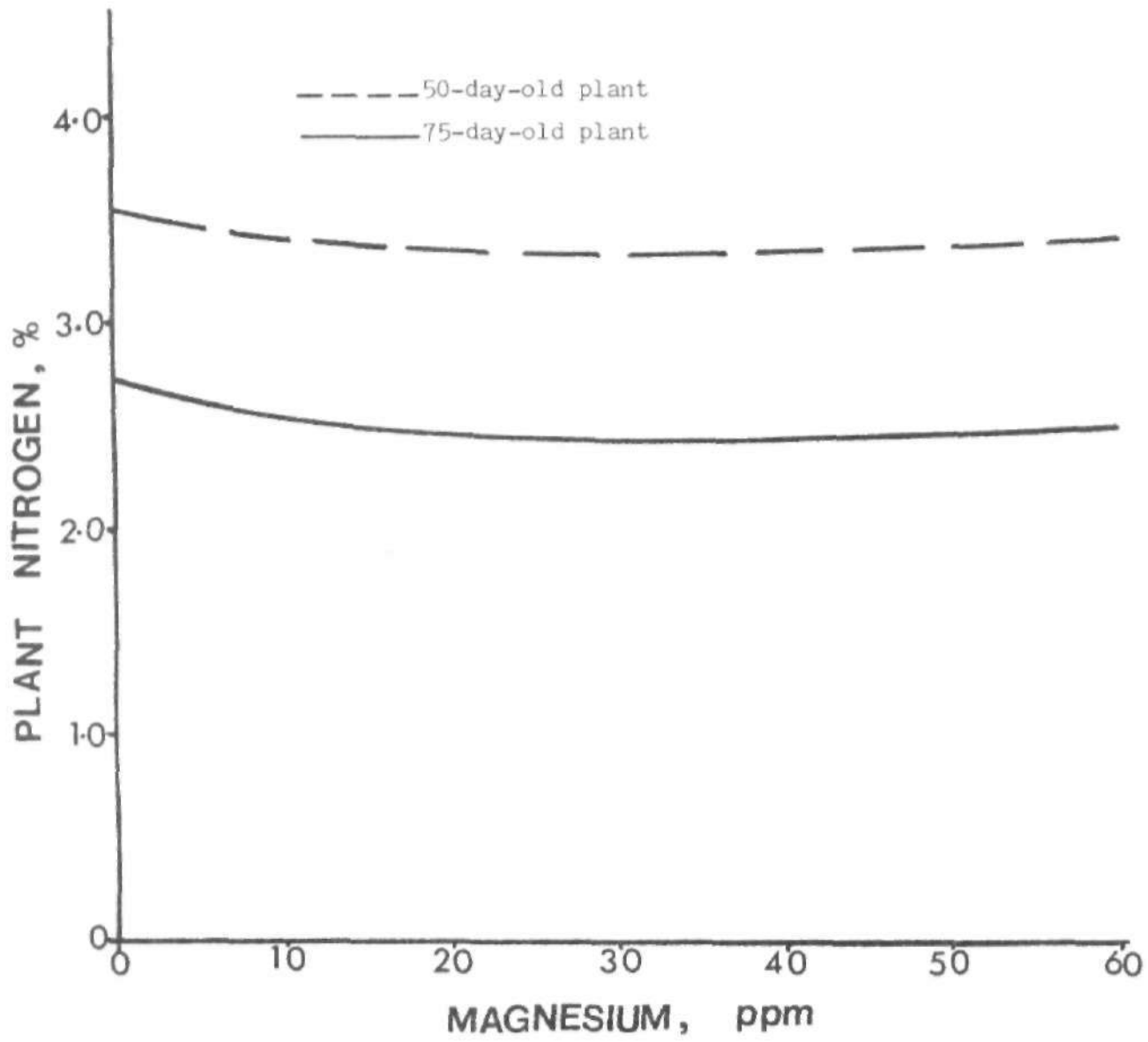


Fig. 13. Nitrogen concentration in top tissue of sorghum plants at 50 and 75 days after seedling emergence in response to rates of applied magnesium in nutrient solution (average for 3 lines).

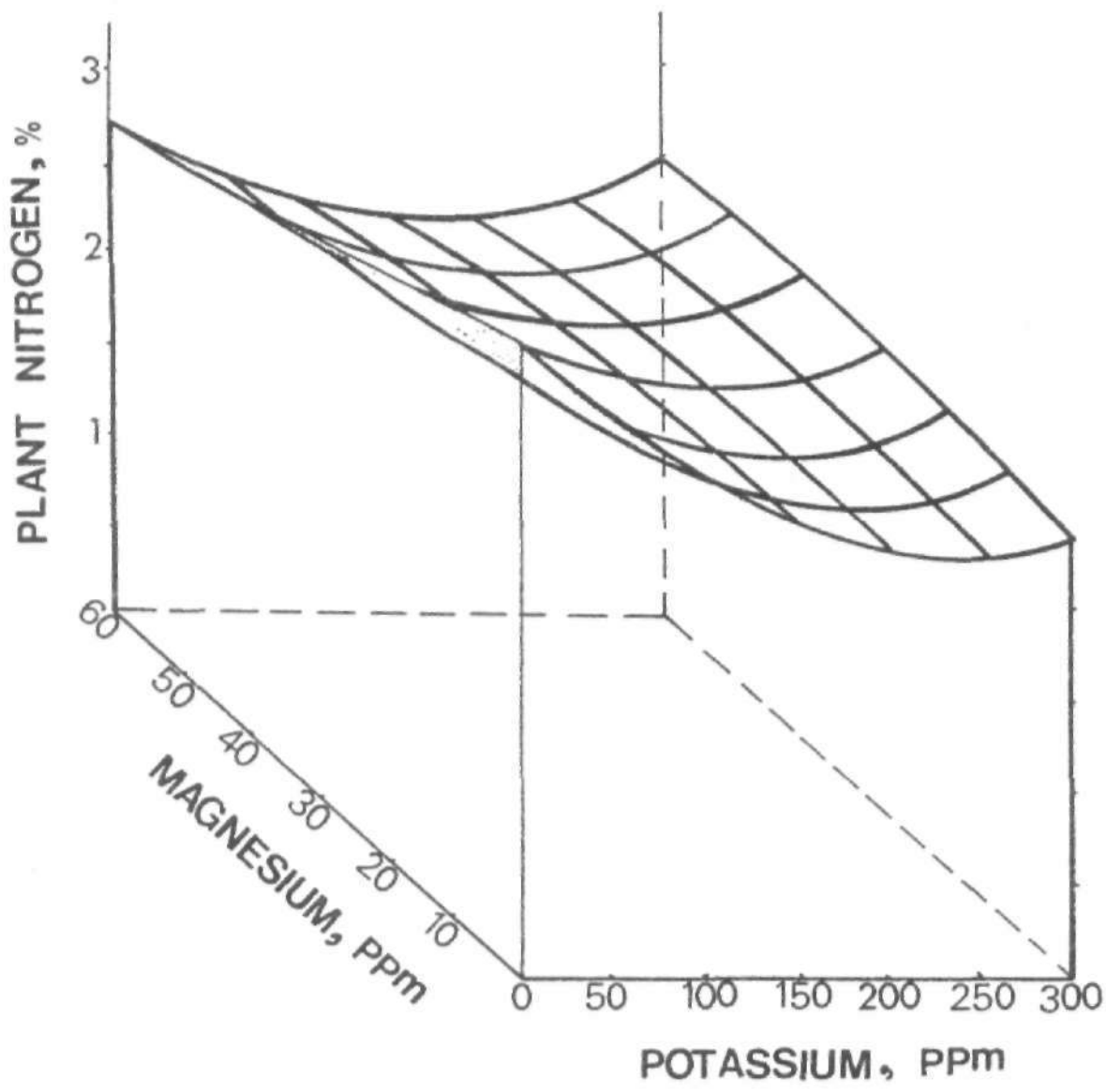


Fig. 14. Predicted response surface of nitrogen concentration in top tissue of 'RS 671' to increasing levels of potassium and magnesium concentrations in nutrient solution at 75 days after seedling emergence.

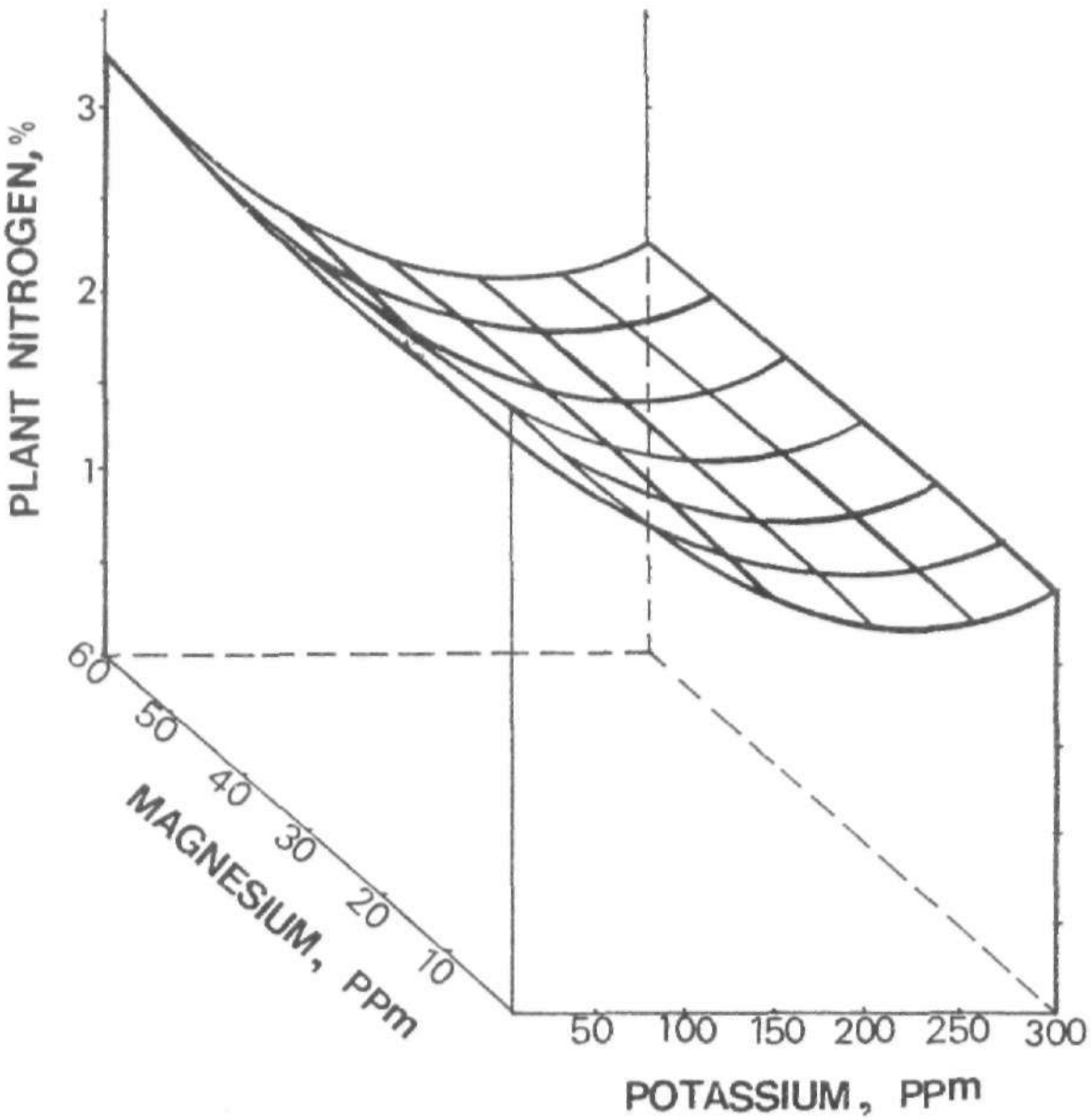


Fig. 15. Predicted response surface of nitrogen concentration in top tissue of 'Redlan' to increasing levels of potassium and magnesium concentrations in nutrient solution at 75 days after seedling emergence.

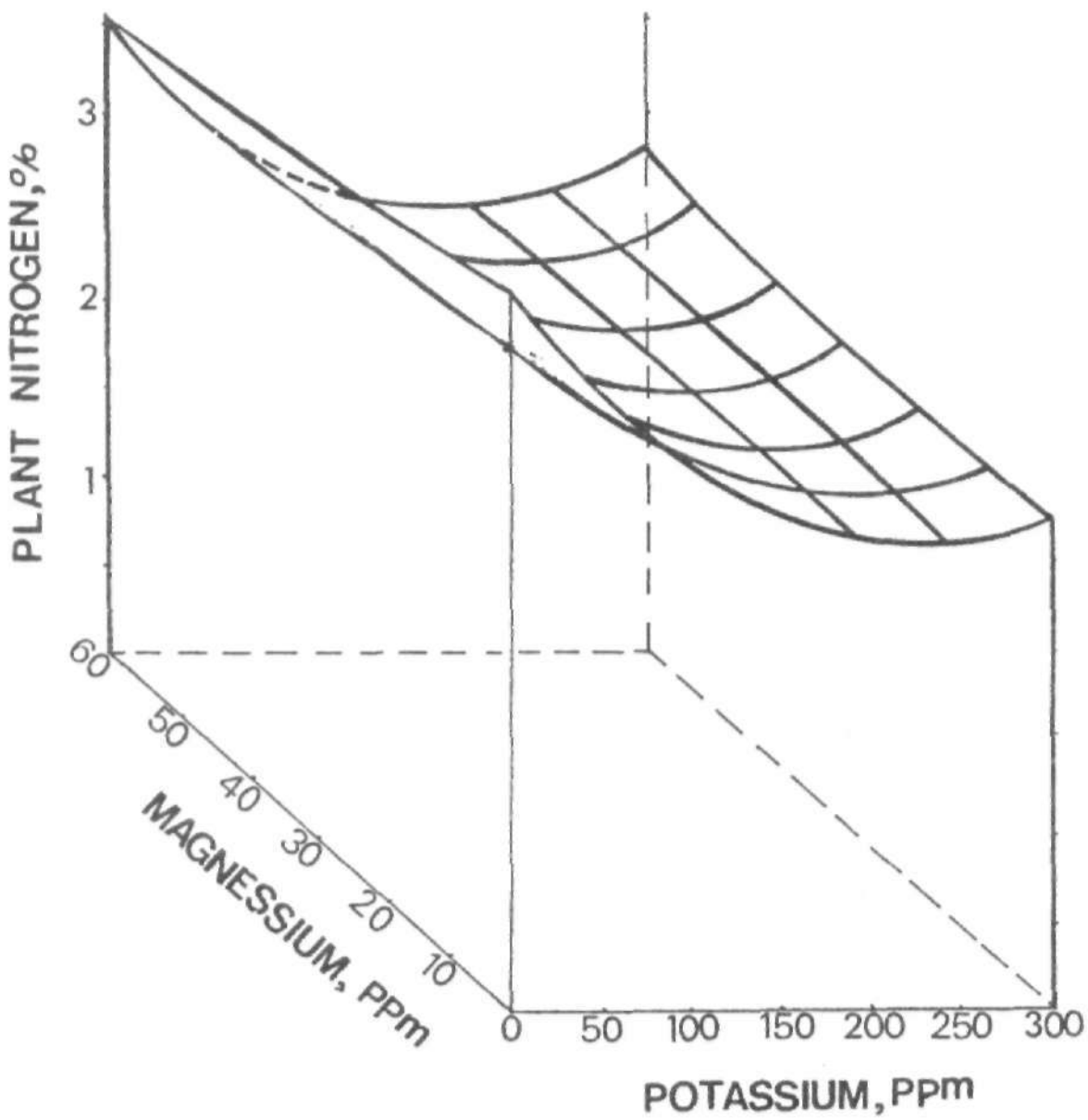


Fig. 16. Predicted response surface of nitrogen concentration in top tissue of 'Tx 415' to increasing levels of potassium and magnesium concentrations in nutrient solution at 75 days after seedling emergence.

Table 6. Regression coefficients and R^2 values showing the effect of potassium and magnesium concentrations in nutrient solution on nitrogen uptake in the top tissue of a sorghum hybrid and its parent lines at 50 and 75 days after seedling emergence.

Variable	Intercept	K	Mg	K^2	Mg^2	K x Mg	R^2
Second Harvest (50 days)							
RS 671	170.5	9.46*	0.14	- 4.57*	- 0.68	-0.18	0.74
Redlan	127.3	4.60*	- 1.49	- 3.63*	- 1.96*	-0.46	0.85
Tx 415	118.3	4.73	- 1.49	- 1.69	- 1.69	-0.71	0.38
Hybrid & Lines	136.4	6.18*	- 1.39	- 3.13*	- 0.90	-0.49	0.77
Third Harvest (75 days)							
RS 671	594.1	43.9*	18.0	-19.2*	-10.3	2.9	0.83
Redlan	512.2	35.4*	28.0*	-13.1*	-14.8*	4.5	0.90
Tx 415	494.3	34.2*	13.0	-17.0*	-12.8*	3.1	0.88
Hybrid & Lines	535.7	37.4*	19.9*	-16.9*	-12.4*	3.5	0.93

*Indicates a significant difference at the 0.05 probability level.

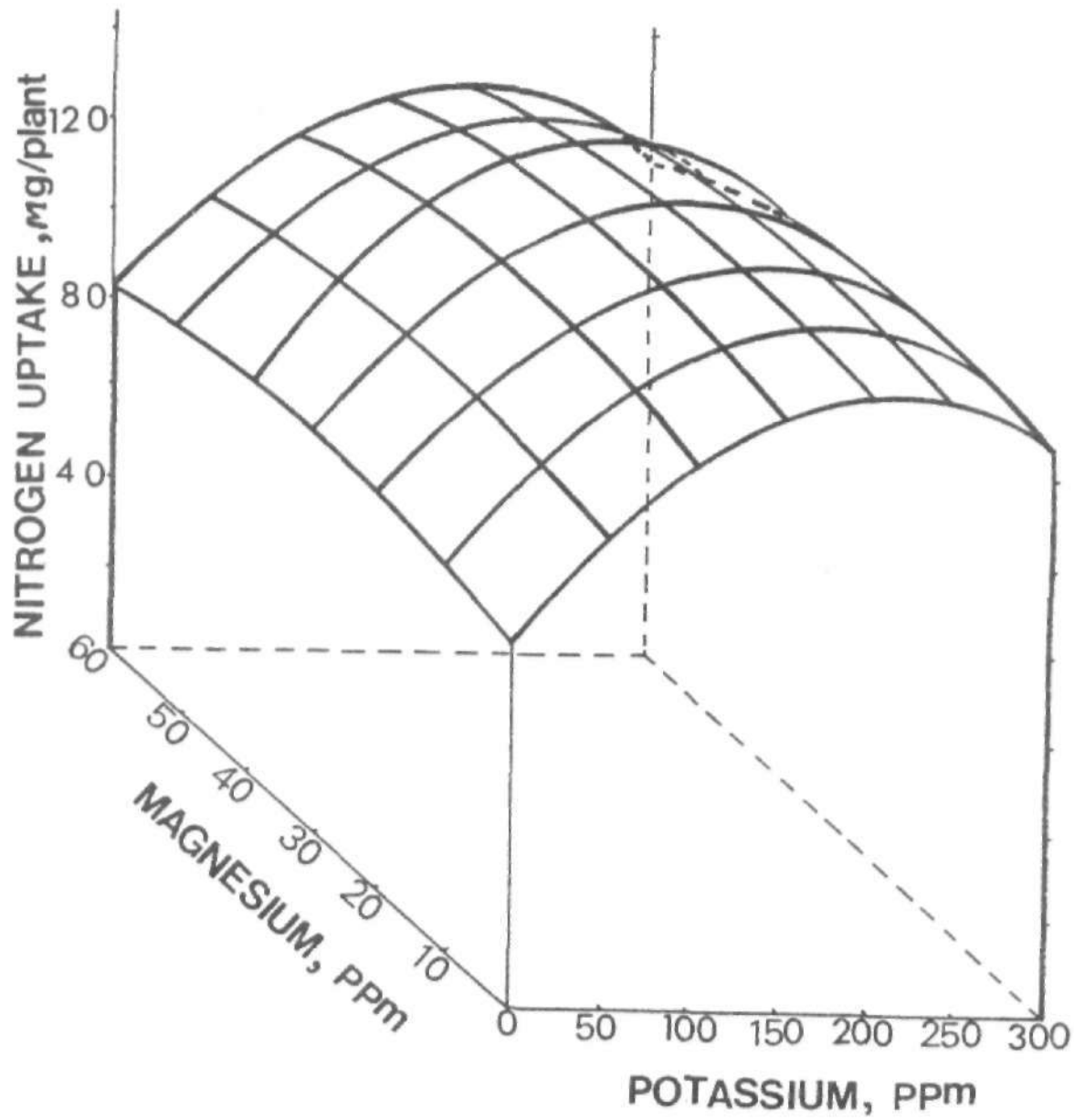


Fig. 17. Predicted response surface of nitrogen uptake by top tissue of sorghum plants to increasing levels of potassium and magnesium concentrations in nutrient solution at 50 days after seeding emergence (average for 3 lines).

75-day-old plants. Averaged over lines and hybrid, the maximum N uptake occurred when K was applied at a rate of 200 ppm and Mg at 20 ppm for the 50-day-old plants. Additional application of K over 200 ppm resulted in a decrease in uptake, whereas Mg application over 20 ppm had little or no effect on N uptake. It was observed that the optimum K concentration in the growth medium for maximum top tissue yield was also close to 200 ppm, suggesting that yield was closely related to N uptake.

This trend was maintained in the 75-day-old plants when application of K also increased the top tissue N uptake curvilinearly. The decrease in N uptake resulting from high concentrations of Mg became apparent at this growth stage of the crop (Fig. 18). Nitrogen uptake by Tx 415 was reduced by high concentrations of Mg in the growth medium, while Redlan, although showing increase at low Mg rates, also showed a marked decrease in uptake at high Mg rates. The increase in N uptake due to K and Mg applications was due to dry matter yield response to low levels of these applied elements. The decrease in N concentration as K and Mg applications increased could therefore be attributed to a dilution effect. True antagonisms between K and N and Mg and N occurred only at high concentrations of applied K and Mg. However, plant growth was also reduced at these high levels, so low N uptake could simply mean less plant demand for N. Terman et al. (1977) observed marked reciprocal antagonism between K and N. Shear, Crane and Myers (1953) reported that by increasing Mg in the rooting medium, the N content in leaves of Tung trees was lowered by about 12%.

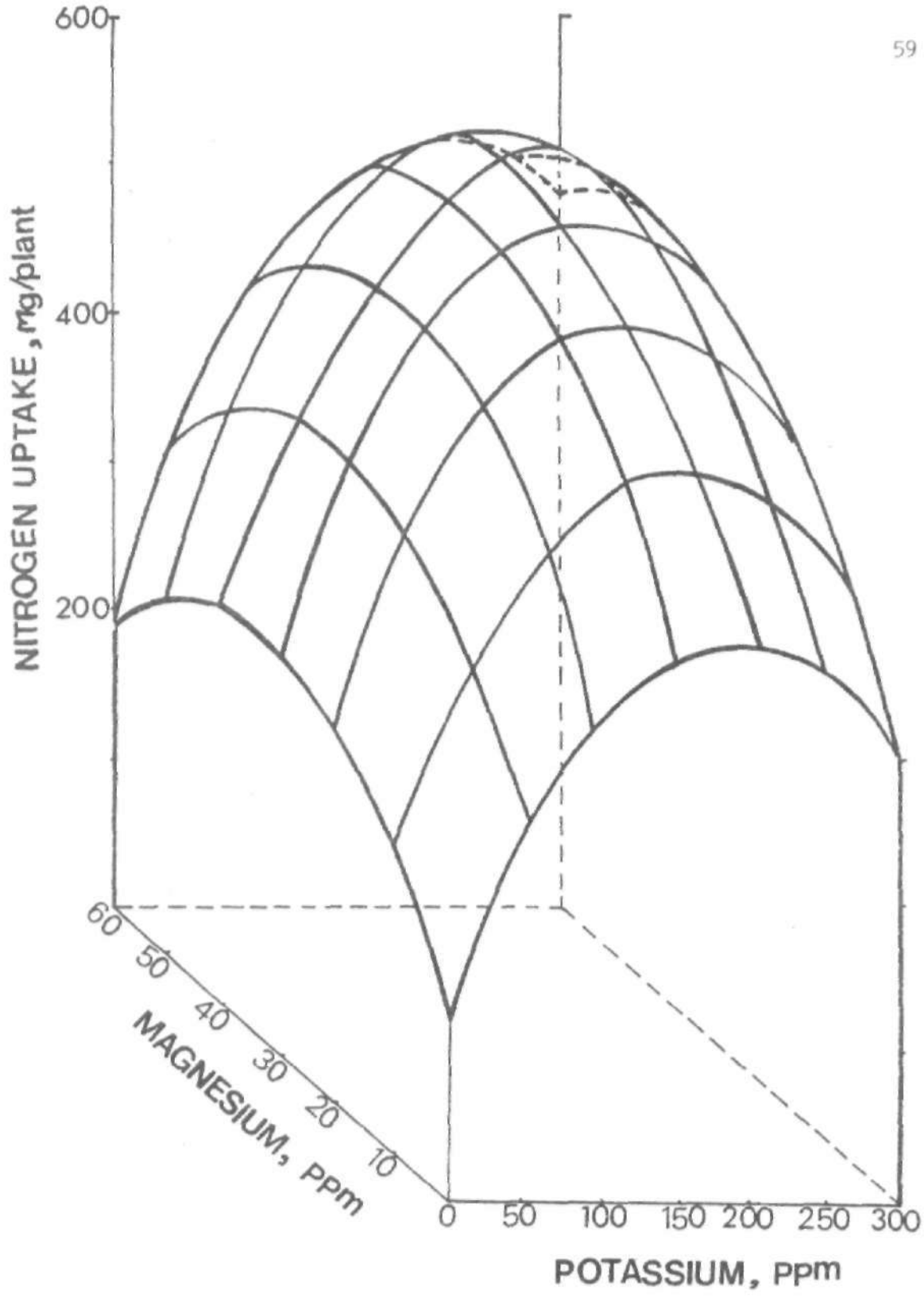


Fig. 18. Predicted response surface of nitrogen uptake by top tissue of sorghum plants to increasing levels of potassium and magnesium concentrations in nutrient solution at 75 days after seedling emergence (average for 3 lines).

Phosphorus. Regression coefficients showing the effect of K and Mg applications on P concentration in top tissue of sorghum plants are shown in Table 7. The average of the lines and hybrid showed a curvilinear decrease with increase in K application at the 50-day-sampling period. At 75 days after seedling emergence, however, plant P decreased directly in proportion to the amounts of K added (Fig. 19).

Application of Mg had essentially no effect on P absorption at 50 days after seedling emergence. However, increasing additions of Mg to the 75-day-old plants resulted in a linear increase in top tissue P concentration (Fig. 20). This occurred in spite of a decrease in dry matter yield at high rates of Mg.

Figure 21 shows no interactive effect of the applied nutrients on top tissue P concentration.

The data presented in Table 8 indicate the tendency for high levels of K additions to cause a reduction in P uptake especially in the young plants. As the plants became more mature, a positive curvilinear relationship between P uptake and K application was observed (Fig. 22). Like N uptake, the increased dry matter production at low applications of K and Mg was also responsible for this increase in P uptake. At high levels of K and Mg applications, top dry matter yield was decreased; and since uptake is a product of dry matter yield and nutrient concentration, the P uptake also decreased. The result suggests that the decrease in P content in response to K application was due mainly to dilution. However, data in Tables 7 and 8 show an increase in P concentration and uptake, respectively, with Mg additions, indicating that the effect of Mg on P absorption was synergistic.

Table 7. Regression coefficients and R^2 values showing the effect of potassium and magnesium concentrations in nutrient solution on phosphorus concentration of top tissue of a sorghum hybrid and parent lines at 50 and 75 days after seedling emergence.

Variable	Intercept	K	Mg	K^2	Mg^2	K x Mg	R^2
Second Harvest (50 days)							
RS 671	0.60	-0.063*	0.009	0.021*	0.002	0.008	0.82
Redlan	0.84	-0.076*	0.022*	0.010*	-0.004	-0.003	0.94
Tx 415	0.90	-0.052*	0.005	0.010	0.001	0.009	0.76
Hybrid & Lines	0.78	-0.064*	0.012	0.014*	-0.000	0.005	0.89
Third Harvest (75 days)							
RS 671	0.60	-0.040*	0.032*	0.016*	-0.008	-0.005	0.68
Redlan	0.60	-0.037*	0.035*	0.003	-0.005	-0.001	0.89
Tx 415	0.74	-0.047*	0.038*	0.010	-0.011	-0.003	0.65
Hybrid & Lines	0.64	-0.041*	0.035*	0.010	-0.008	-0.003	0.77

*Indicates a significant difference at the 0.05 level of probability.

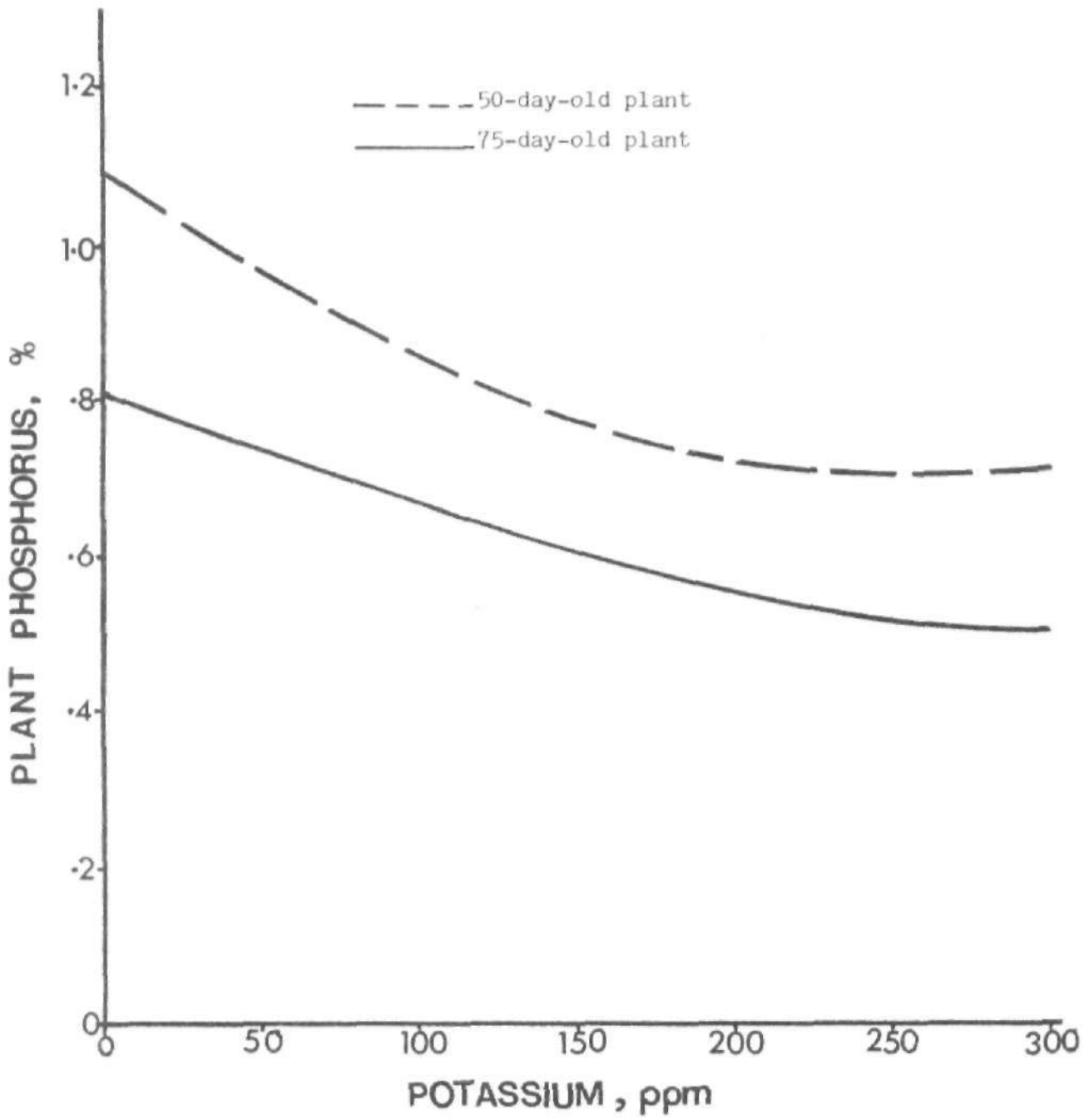


Fig. 19. Phosphorus concentration in top tissue of sorghum plants at 50 and 75 days after seedling emergence in response to applied potassium in nutrient solution (average for 3 lines).

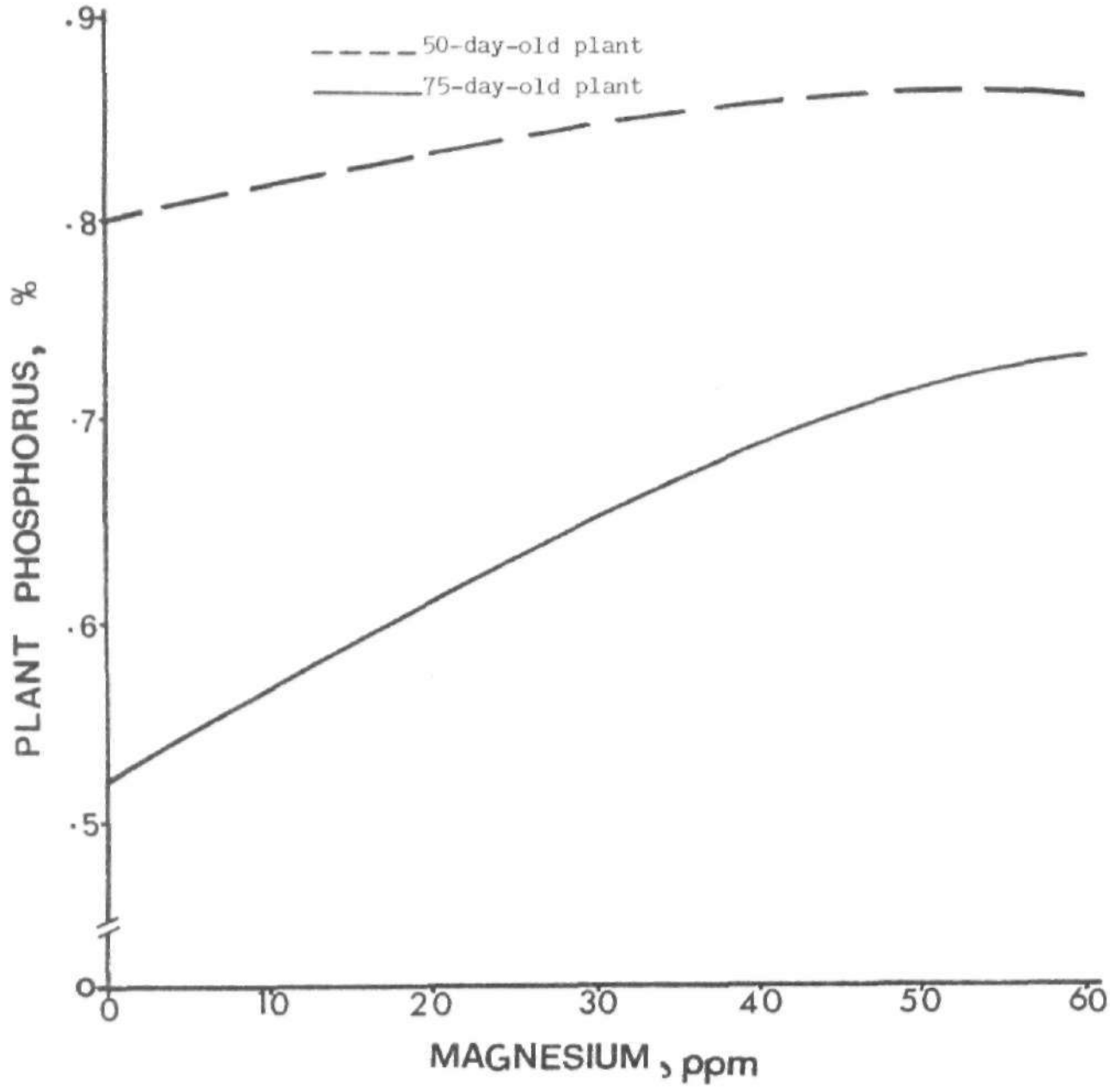


Fig. 20. Phosphorus concentration in top tissue of sorghum plants at 50 and 75 days after seedling emergence in response to rates of applied magnesium in nutrient solution (average for 3 lines).

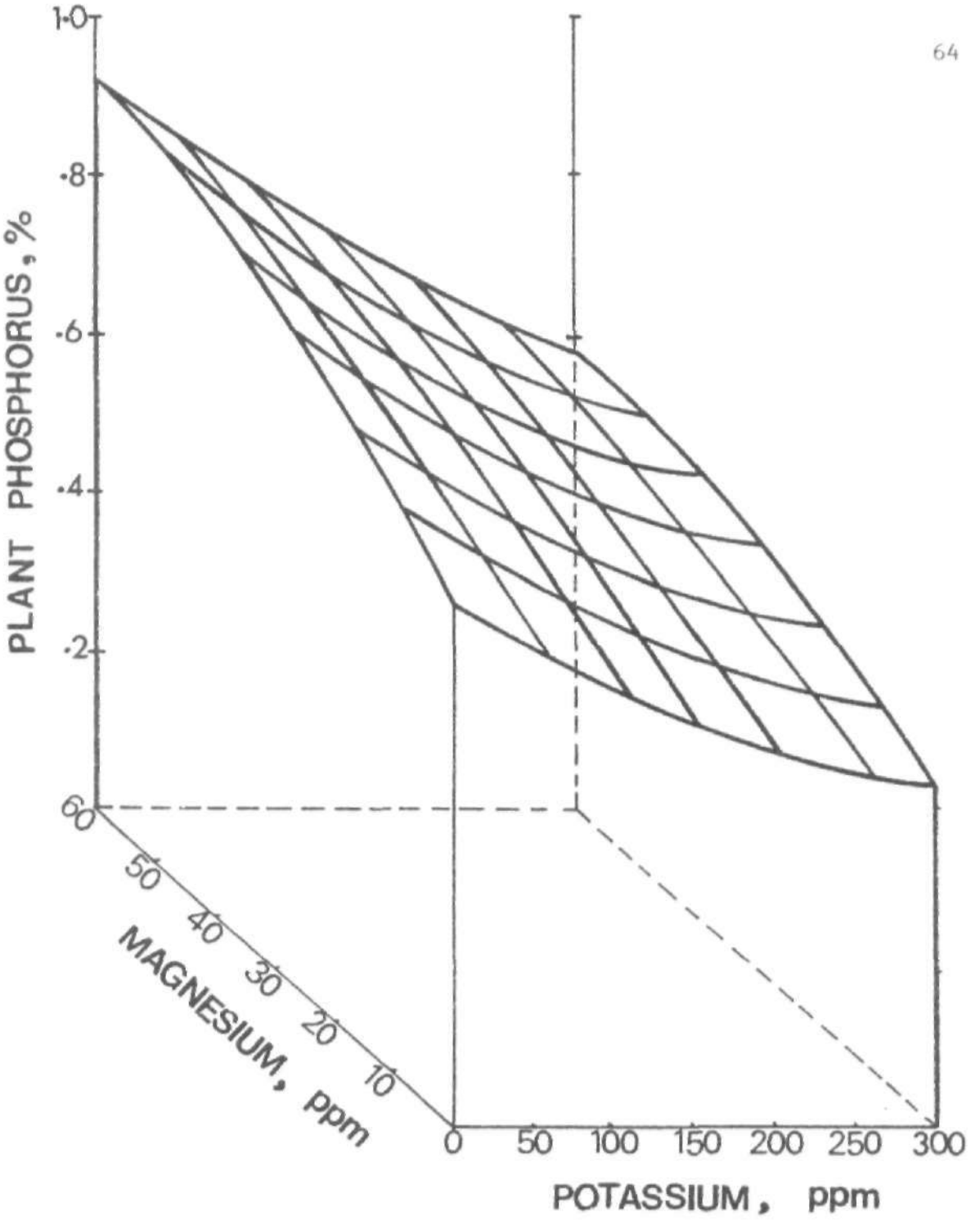


Fig. 21. Predicted response surface of phosphorus concentration in top tissue of sorghum plants to increasing levels of potassium and magnesium concentrations in nutrient solution at 75 days after seedling emergence (average for 3 lines).

Table 8. Regression coefficients and R^2 values showing the effect of potassium and magnesium concentrations in nutrient solution on phosphorus uptake by top tissue of a sorghum hybrid and its parent lines at 50 and 75 days after seedling emergence.

Variable	Intercept	K	Mg	K^2	Mg^2	K x Mg	R^2
Second Harvest (50 days)							
RS 671	37.7	0.32	0.78	-0.54	-0.21	0.15	0.46
Redlan	32.3	- 1.05	0.74	-0.81*	-0.65	-0.25	0.65
Tx 415	29.7	0.04	0.45	-0.35	-0.46	0.14	0.28
Hybrid & Lines	33.3	- 0.23	0.64	-0.56*	-0.45	0.03	0.64
Third Harvest (75 days)							
RS 671	146.7	10.0*	7.4*	-4.3*	-2.6	1.2	0.82
Redlan	132.2	6.5*	10.7*	-4.0*	-4.0*	1.8*	0.90
Tx 415	132.7	7.3*	5.1*	-4.7*	-3.6*	1.0	0.83
Hybrid & Lines	137.8	8.0*	7.7*	-4.4*	-3.4*	1.4*	0.92

*Indicates a significant difference at the 0.05 probability level.

The significant K-Mg interactive effect indicates that P uptake by Redlan was affected more by increased K applications when Mg in the growth medium was also increased.

Reports on interactions between K and P and Mg and P are few. However, Heathcote and Stockinger (1973) suggested that the application of high levels of K in coarse-textured soils of low cation exchange capacity might affect the uptake of some other nutrient ions such as P, Ca and Mg. Jones, Lutz and Smith (1977) observed that applied K increased K concentration of soybean nodules but had no or little effect on P concentration, and Rehm and Sorensen (1974) observed no effect of fertilizer K on P content in alfalfa tissue.

Potassium. Potassium application increased K concentration in top tissue of sorghum plants at both sampling periods (Table 9). This is in accord with the common observation that concentration of a nutrient in the plant increases with application of that particular nutrient. Figure 23 shows a near linear response of K concentration to K application at the two harvests.

Within K rates, the addition of Mg had no effect on K concentration in the top tissue of the 50-day-old plants (Fig. 24). At 75 days after seedling emergence, however, Mg in growth medium decreased top tissue K concentration directly in proportion to amounts added.

Averaged over lines and hybrid, the interactive effect of the added nutrient was not observed (Fig. 25). However, the data in Table 9 show that the presence of Mg in the growth medium inhibited K absorption in the 75-day-old RS 671 and Redlan. The significant K-Mg interaction indicates some Mg antagonism for K absorption in both RS 671 and Redlan.

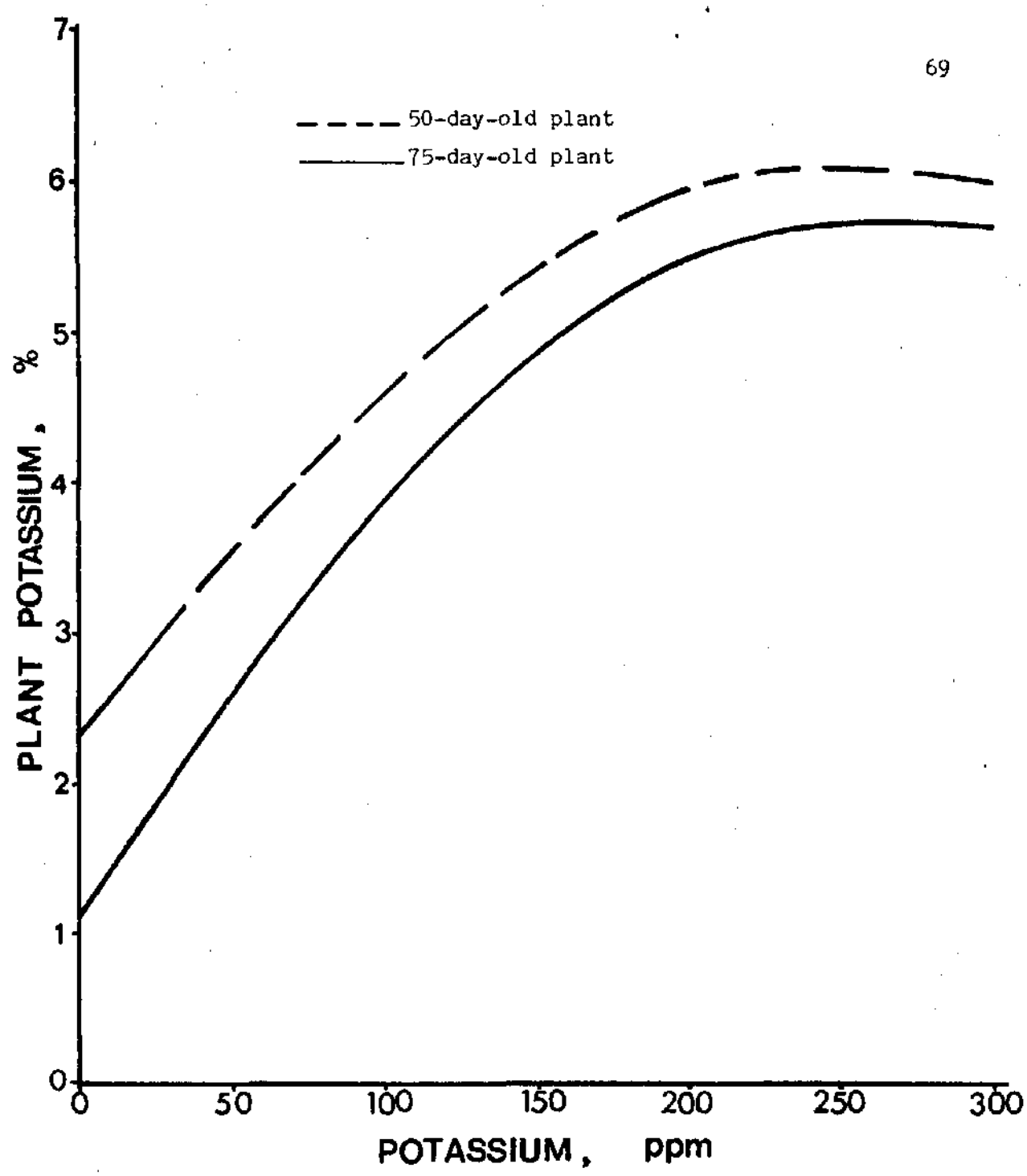


Fig. 23. Potassium concentration in top tissue of sorghum plants at 50 and 75 days after seedling emergence in response to rates of applied potassium in nutrient solution (average for 3 lines).

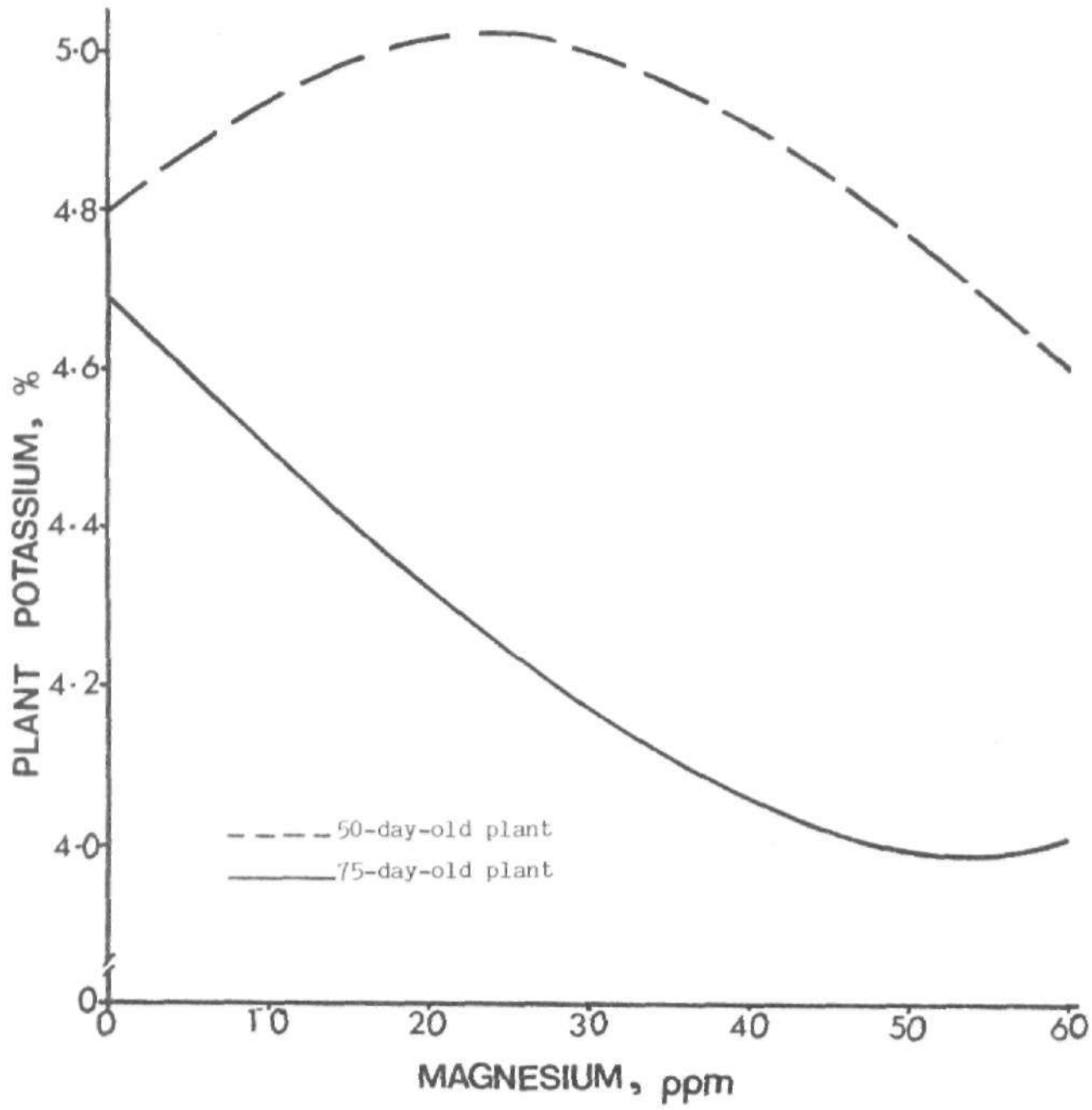


Fig. 24. Potassium concentration in top tissue of sorghum plants at 50 and 75 days after seedling emergence in response to rates of applied magnesium in nutrient solution (average for 3 lines).

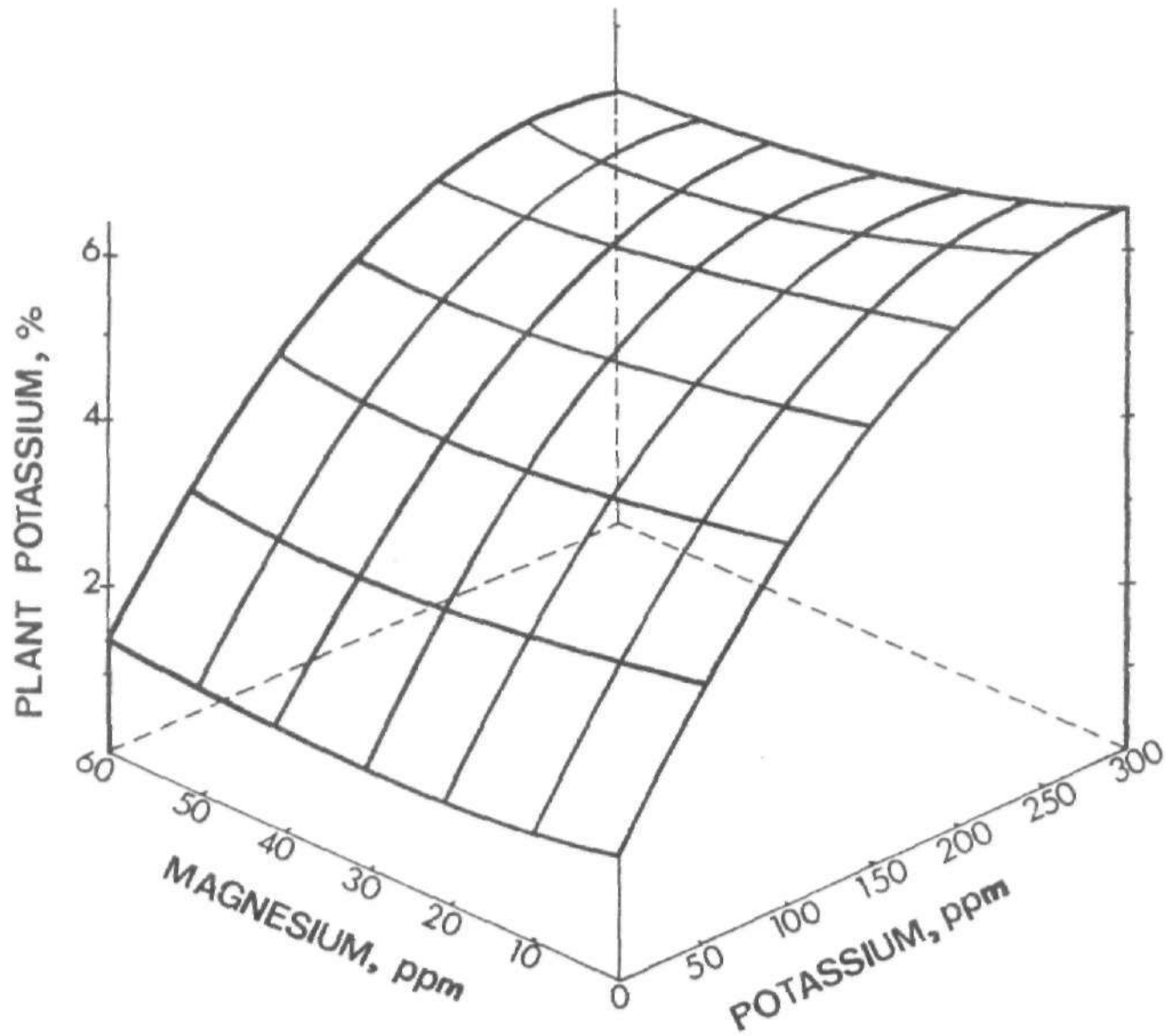


Fig. 25. Predicted response surface of potassium concentration in top tissue of sorghum plants to increasing levels of potassium and magnesium concentrations in nutrient solution at 75 days after seedling emergence (average for 3 lines).

As expected, a curvilinear relationship between K and top tissue K uptake was observed at both the 50- and 75-day-sampling periods (Table 10). Successive additions of K to a growth medium with no or low levels of Mg resulted in an increase in K uptake. However, when the Mg concentration was increased above 20 ppm level, application of K above 200 ppm resulted in a sharp decrease in K uptake. This further suggests that high concentration of Mg in a growth medium disturbs K uptake. Although the effect of Mg application was not apparent on K uptake in the 50-day -old plants (Fig. 26), its effect especially when applied at high concentrations was apparently detrimental to K uptake in the 75-day-old plants (Fig. 27).

The apparent lack of K-Mg interactive effect on K uptake was probably due to the complementary main effect of the applied nutrients on dry matter yield.

Much evidence of reciprocal antagonism between K and Mg is found in the literature (Prince et al., 1947; Scharres and Mengel, 1958; Martin and Page, 1965; Bedi and Sekhon, 1977). However, Omar and Kobbia (1966) reported a depressive effect of K on Mg absorption but found no antagonism by Mg for K absorption in lucern. This might be due to the fact that they harvested their crop 42 days after planting.

Magnesium. The regression coefficients showing the effects of K and Mg applications on Mg concentration in top tissue of sorghum plant are shown in Table 11. Within any Mg rates and at any sampling period, application of low to medium rates of K reduced Mg concentration in top tissue of the plants (Fig. 28). The decrease in Mg absorption with K

Table 10. Regression coefficients and R^2 values showing the effect of potassium and magnesium concentrations in nutrient solution on potassium uptake by top tissue of a sorghum hybrid and its parent lines at 50 and 75 days after seedling emergence.

Variable	Intercept	K	Mg	K^2	Mg^2	K x Mg	R^2
Second Harvest (50 days)							
RS 671	240.1	39.9*	- 2.1	- 6.6*	- 0.7	-1.0	0.91
Redlan	197.2	23.5*	- 4.8	- 9.4*	- 2.1	-1.3	0.88
Tx 415	172.2	29.3*	- 3.1	- 3.2	- 2.3	-2.6	0.85
Hybrid & Lines	203.1	30.9*	- 3.2	- 6.4*	- 1.7	-1.7	0.94
Third Harvest (75 days)							
RS 671	1035.0	180.1*	24.5	-27.8*	-26.3	3.9	0.89
Redlan	978.8	138.1*	38.4*	-38.2*	-20.6*	9.5	0.95
Tx 415	892.5	159.1*	6.7	-27.9*	-20.9*	2.8	0.91
Hybrid & Lines	968.8	159.1*	23.2	-31.3*	-22.6*	5.4	0.96

*Indicates a significant difference at the 0.05 probability level.

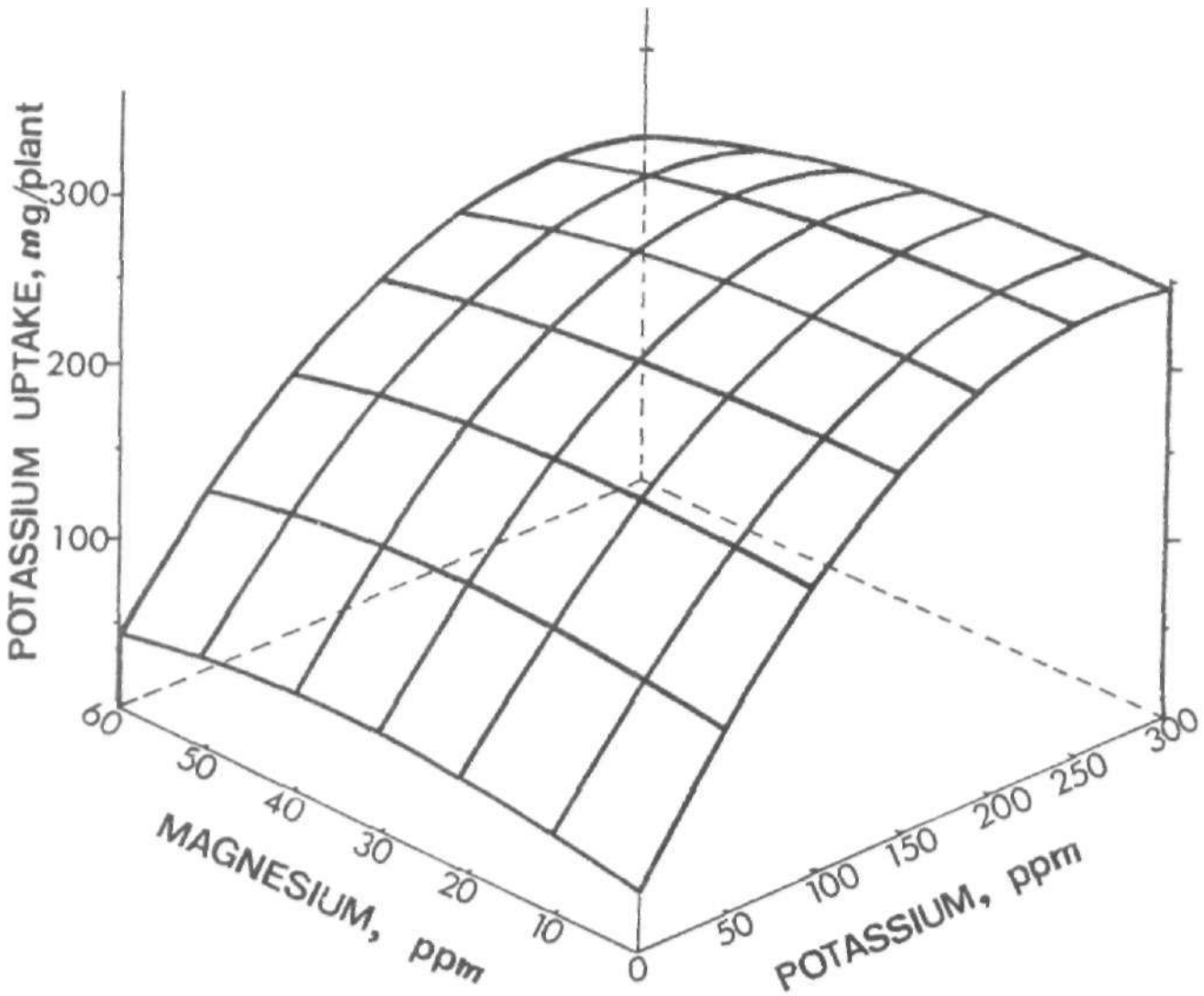


Fig. 26. Predicted response surface of potassium uptake by top tissue of sorghum plants to increasing levels of potassium and magnesium concentrations in nutrient solution at 50 days after seedling emergence (average of 3 lines).

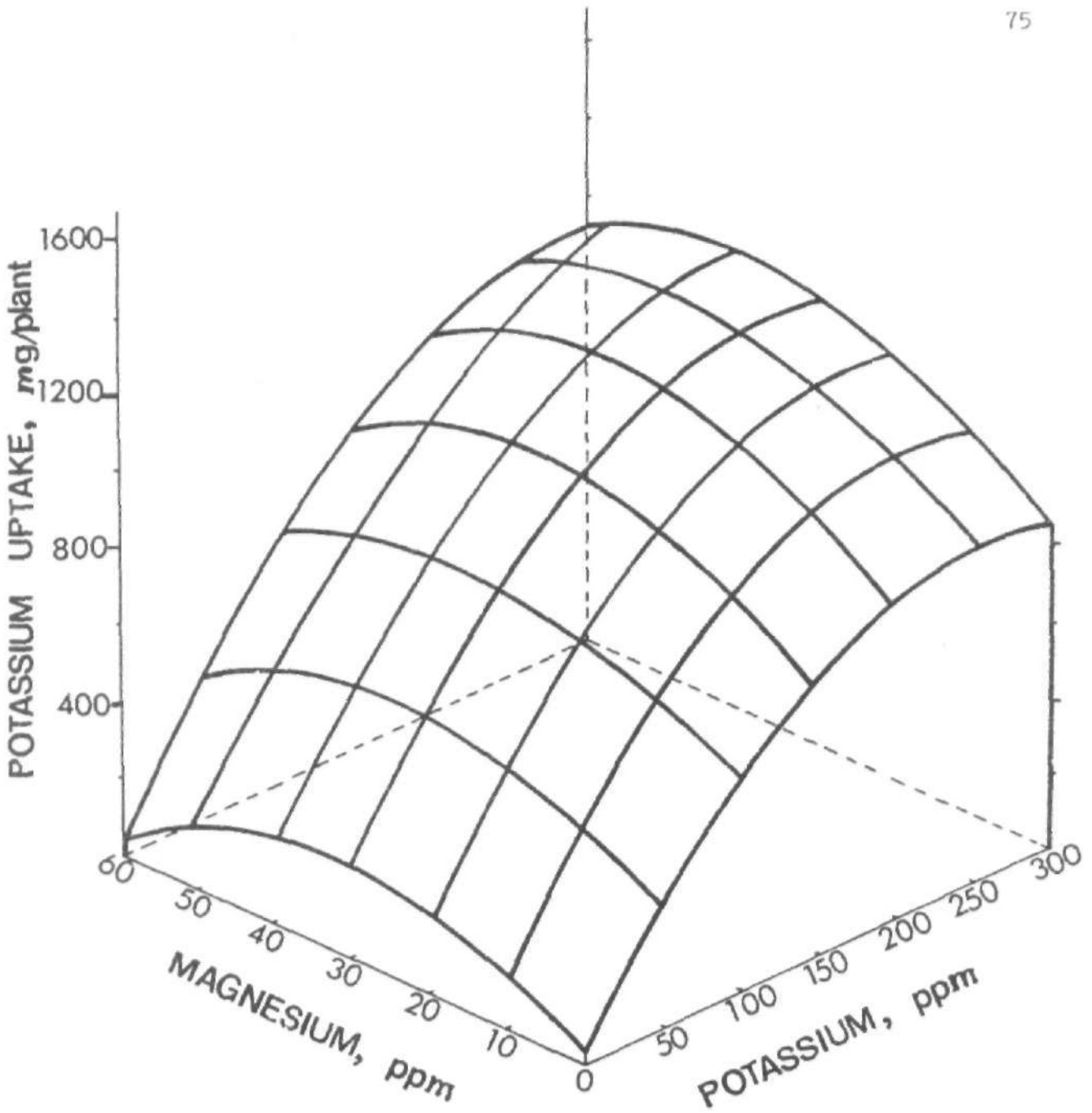


Fig. 27. Predicted response surface of potassium uptake by top tissue of sorghum plants to increasing levels of potassium and magnesium concentrations in nutrient solution at 75 days after seedling emergence (average of 3 lines).

Table 11. Regression coefficients and R^2 values showing the effect of potassium and magnesium concentrations in nutrient solution on magnesium concentration of top tissue of a sorghum hybrid and its parent lines at 50 and 75 days after seedling emergence.

Variable	Intercept	K	Mg	K^2	Mg^2	K x Mg	R^2
Second Harvest (50 days)							
RS 671	0.63	-0.096*	0.069*	0.019*	-0.001	-0.014*	0.96
Redlan	0.60	-0.107*	0.052*	0.026*	-0.010	-0.011	0.91
Tx 415	0.70	-0.052*	0.044*	0.013*	-0.015*	-0.009*	0.90
Hybrid & Lines	0.65	-0.085*	0.055*	0.019*	-0.008	-0.012*	0.96
Third Harvest (75 days)							
RS 671	0.53	-0.096*	0.109*	0.027*	-0.023*	-0.020*	0.96
Redlan	0.38	-0.102*	0.109*	0.024	0.001	-0.032*	0.85
Tx 415	0.56	-0.107*	0.117*	0.031*	-0.014	-0.030*	0.88
Hybrid & Lines	0.47	-0.088*	0.111*	0.018	-0.003	-0.028*	0.89

*Indicates a significant difference at the 0.05 level of probability.

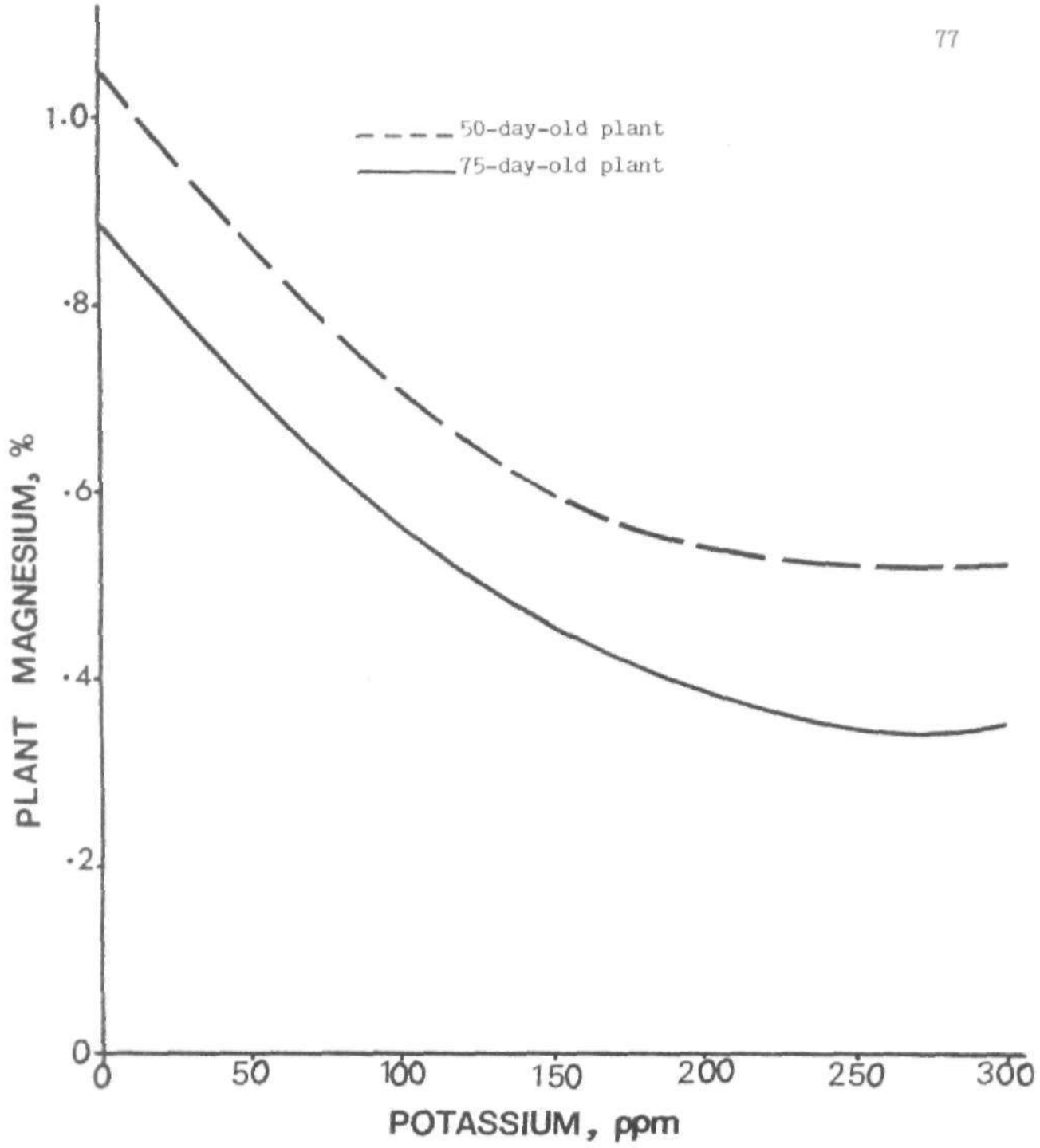


Fig. 28. Magnesium concentration in top tissue of sorghum plants at 50 and 75 days after seedling emergence in response to rates of applied potassium in nutrient solution (average for 3 lines).

application became more pronounced as the concentration of Mg in the growth medium increased. In the absence of Mg in the growth medium, increasing K concentration in the growth medium from 0 to 300 ppm decreased Mg concentration in top tissue by 41%. When the Mg level was increased to 60 ppm, a larger decrease in Mg concentration of 57% resulted in (Fig. 30). This result suggests that high Mg application in the growth medium tends to reduce Mg absorption by sorghum plants. The data in Table 11 bear this out, especially Tx 415 and RS 671 at second and third harvests, respectively.

As expected, Mg absorption increased directly in proportion to the amounts of Mg supplied to the 50-day-old plants. Magnesium absorption in Tx 415, however, showed a curvilinear relationship at this growth stage. At 75 days after seedling emergence, the response of Mg concentration to Mg additions was mainly linear in both lines and the hybrid (Fig. 29). However, the presence of the added nutrients in the growth medium seems to affect the lines and hybrid differently. Magnesium concentration in top tissue of the hybrid decreased and increased curvilinearly with K and Mg additions, respectively (Fig. 32). Magnesium content in Redlan increased directly in proportion to Mg applied but decreased linearly with K application (Fig. 33). In Tx 415, Mg concentration decreased curvilinearly with K addition but increased linearly with Mg application (Fig. 34).

Interactive effect was observed in the hybrid and lines. Figure 31 shows a strong depressive effect of added K on Mg absorption and expecially when both the K and Mg were applied at high concentrations. This trend was noticed also in the 50-day-old plants (Fig. 30). This

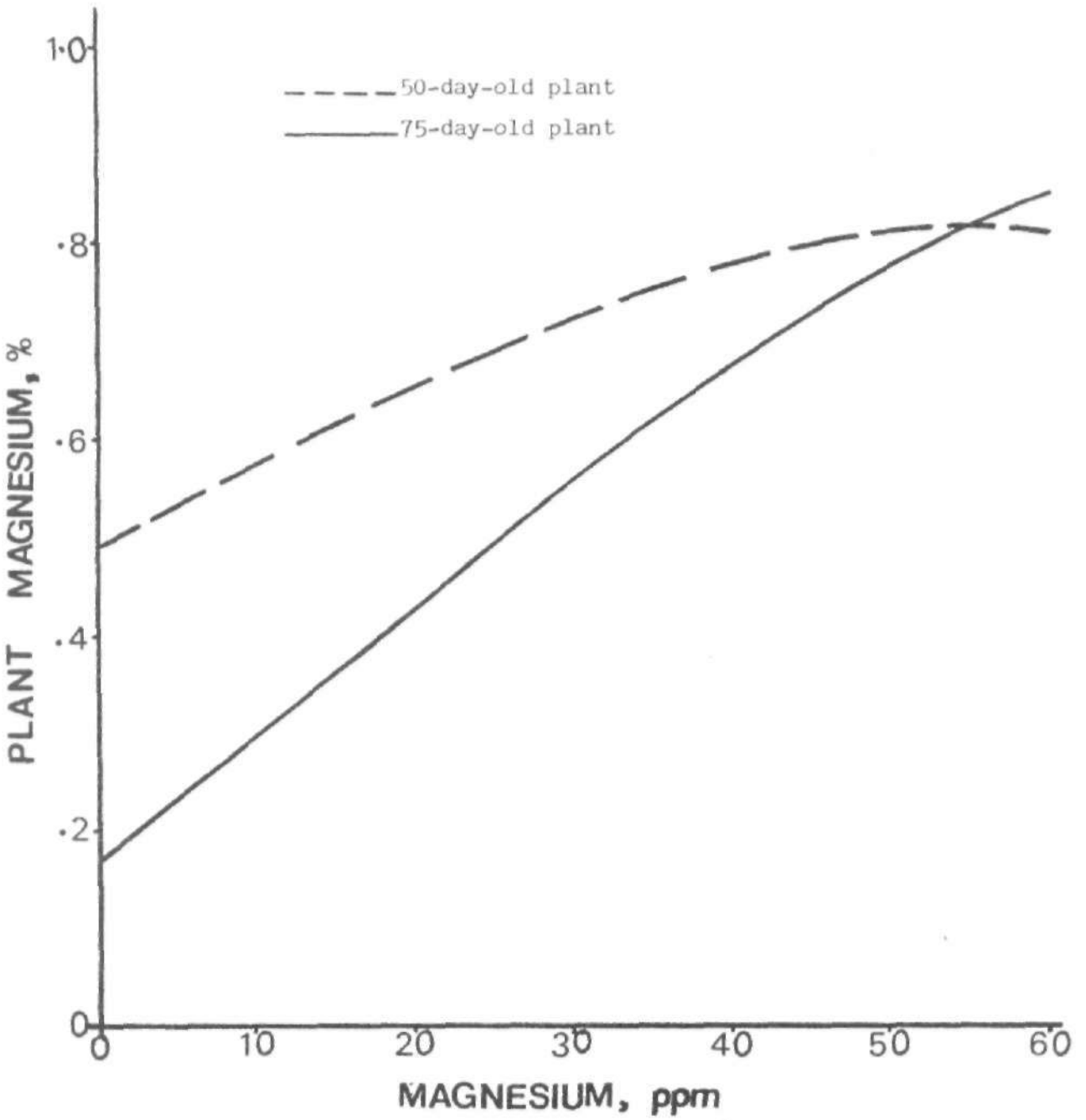


Fig. 29. Magnesium concentration in top tissue of sorghum plants at 50 and 75 days after seedling emergence in response to rates of applied magnesium in nutrient solution (average for 3 lines).

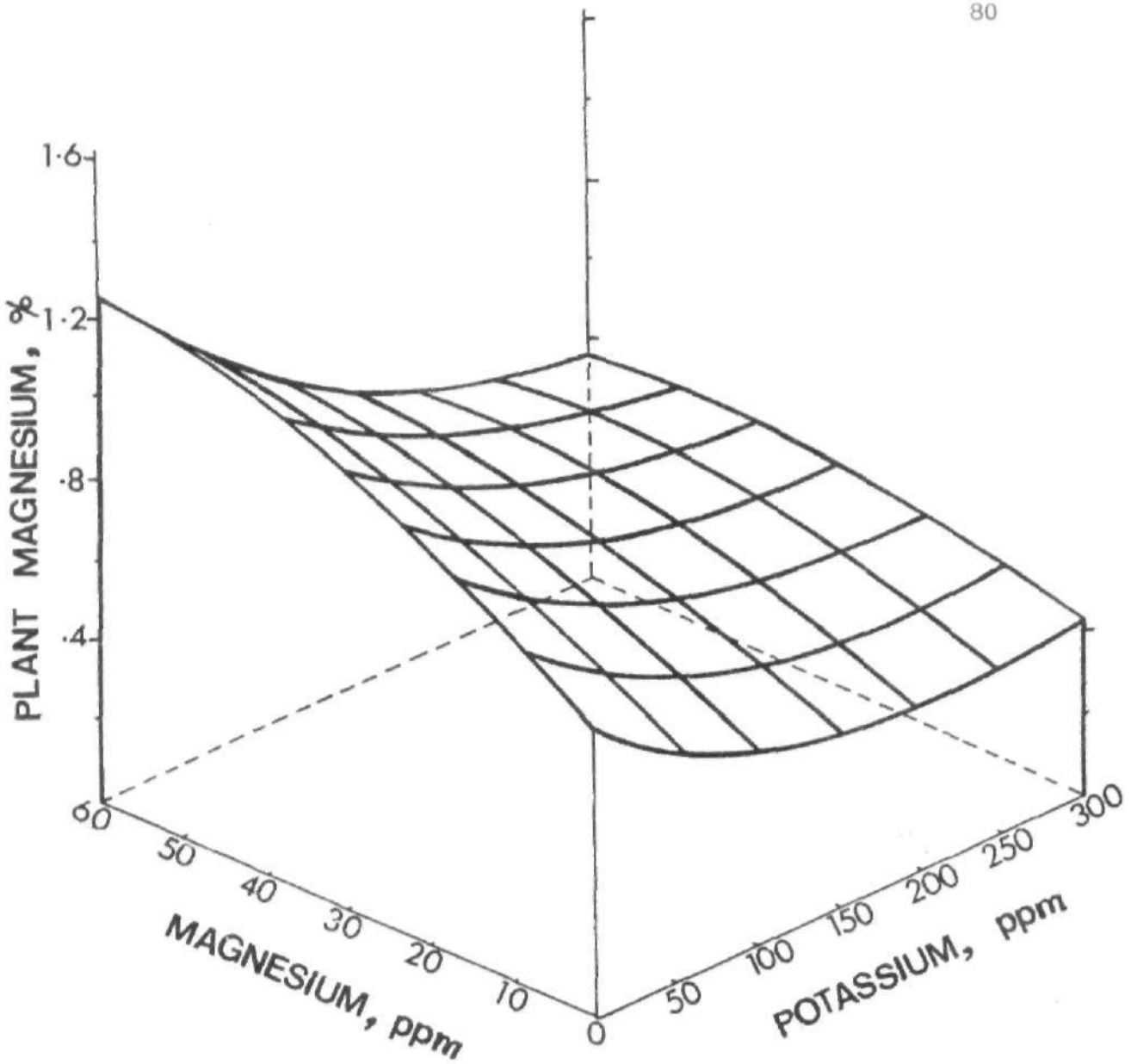


Fig. 30. Predicted response surface of magnesium concentration in top tissue of sorghum plants to increasing levels of potassium and magnesium concentrations in nutrient solution at 50 days after seedling emergence (average for 3 lines).

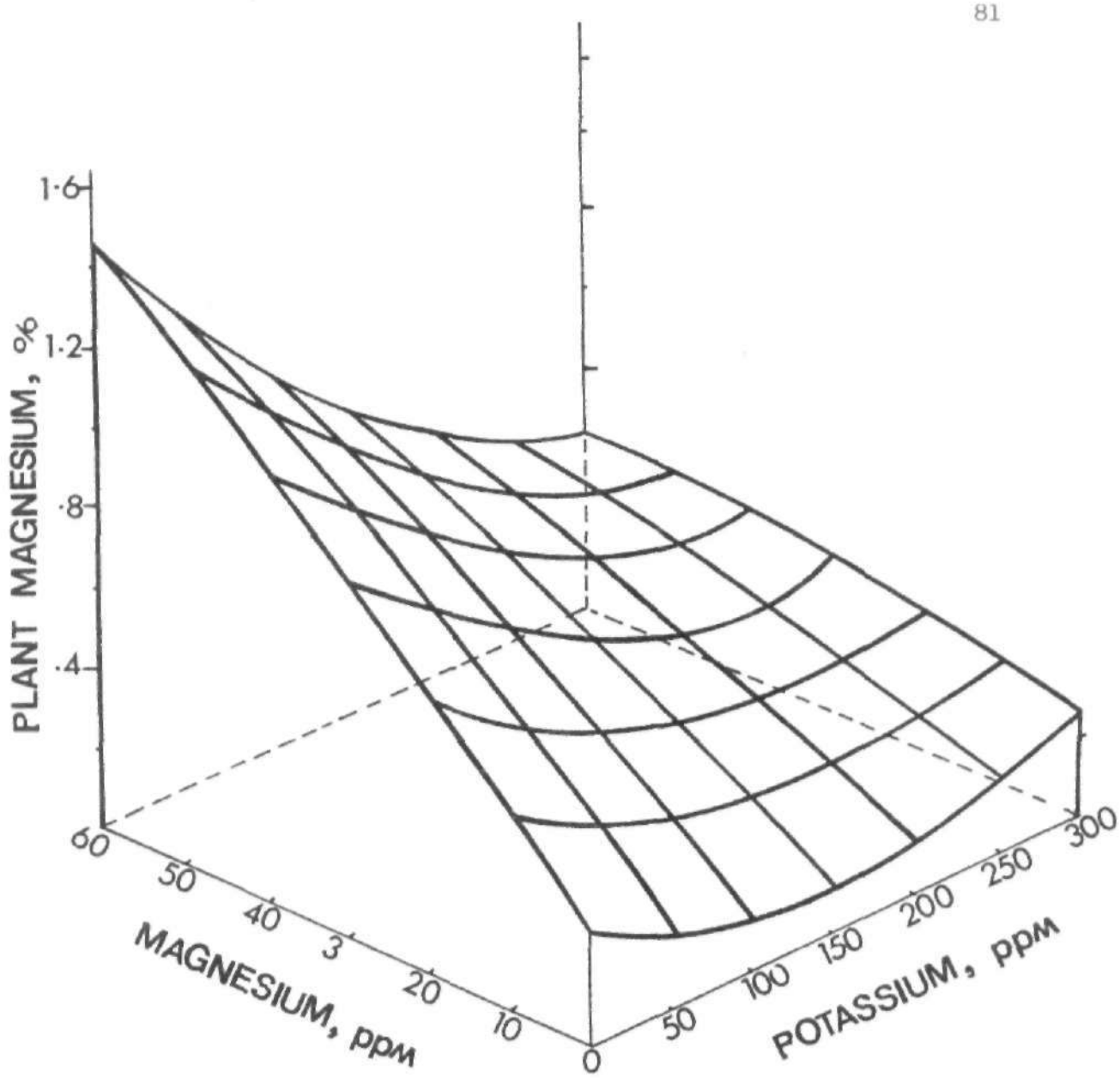


Fig. 31. Predicted response surface of magnesium concentration in top tissue of sorghum plants to increasing levels of potassium and magnesium concentrations in nutrient solution at 75 days after seedling emergence (average for 3 lines).

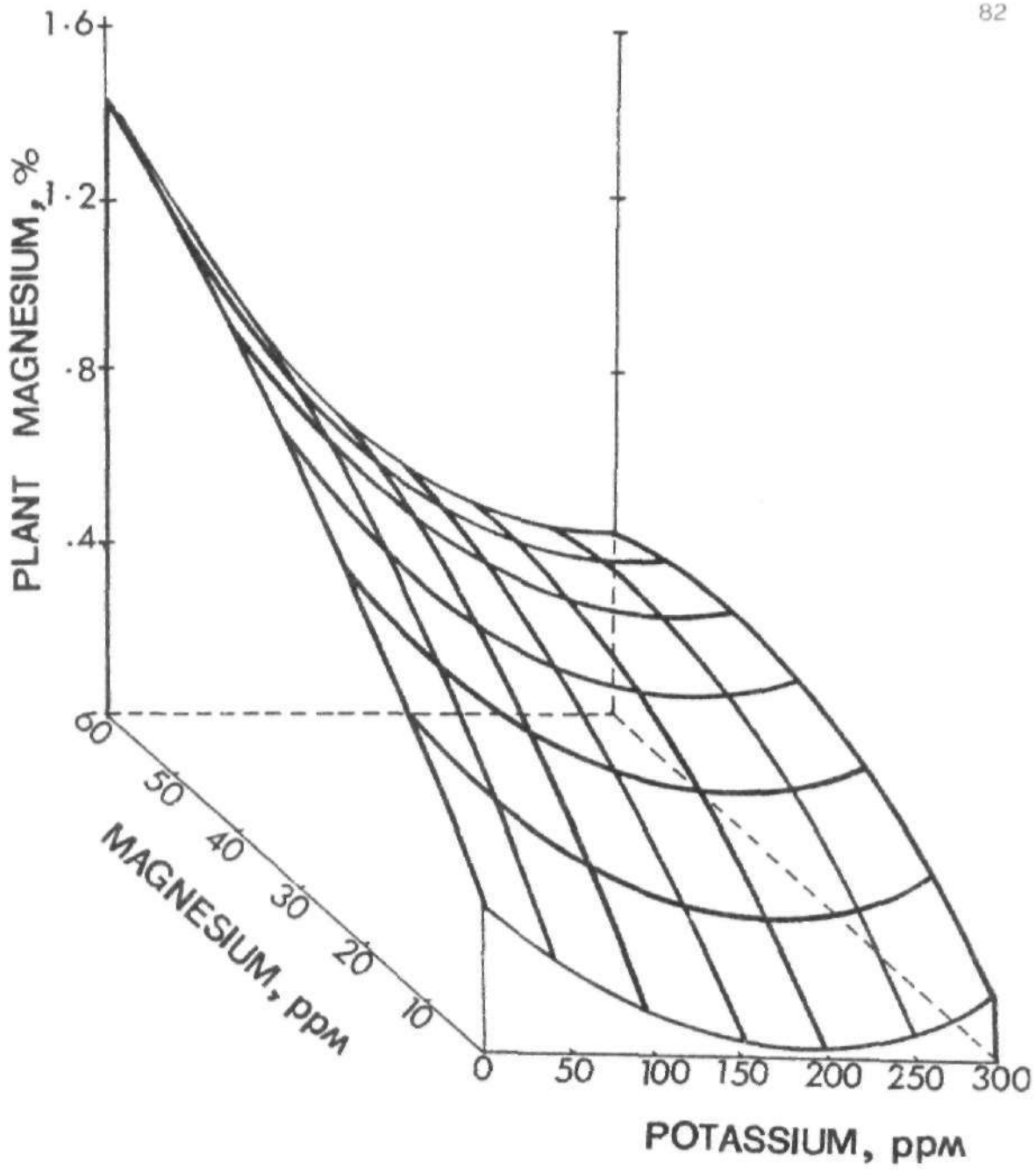


Fig. 32. Predicted response surface of magnesium concentration in top tissue of 'RS 671' to increasing levels of potassium and magnesium concentrations in nutrient solution at 75 days after seedling emergence.

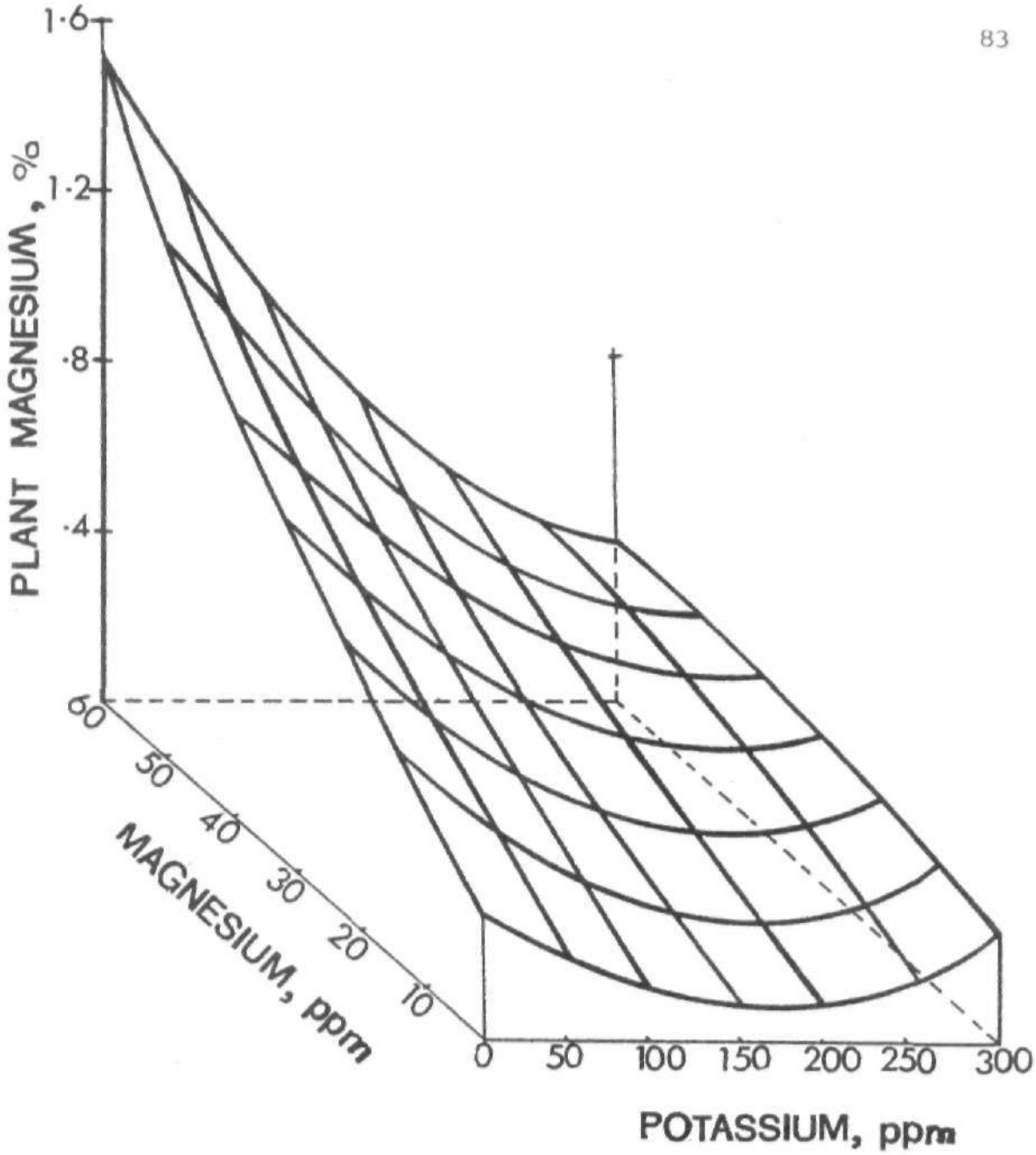


Fig. 3. Predicted response surface of magnesium concentration in top tissue of 'Redlan' to increasing levels of potassium and magnesium concentrations in nutrient solution at 75 days after seedling emergence.

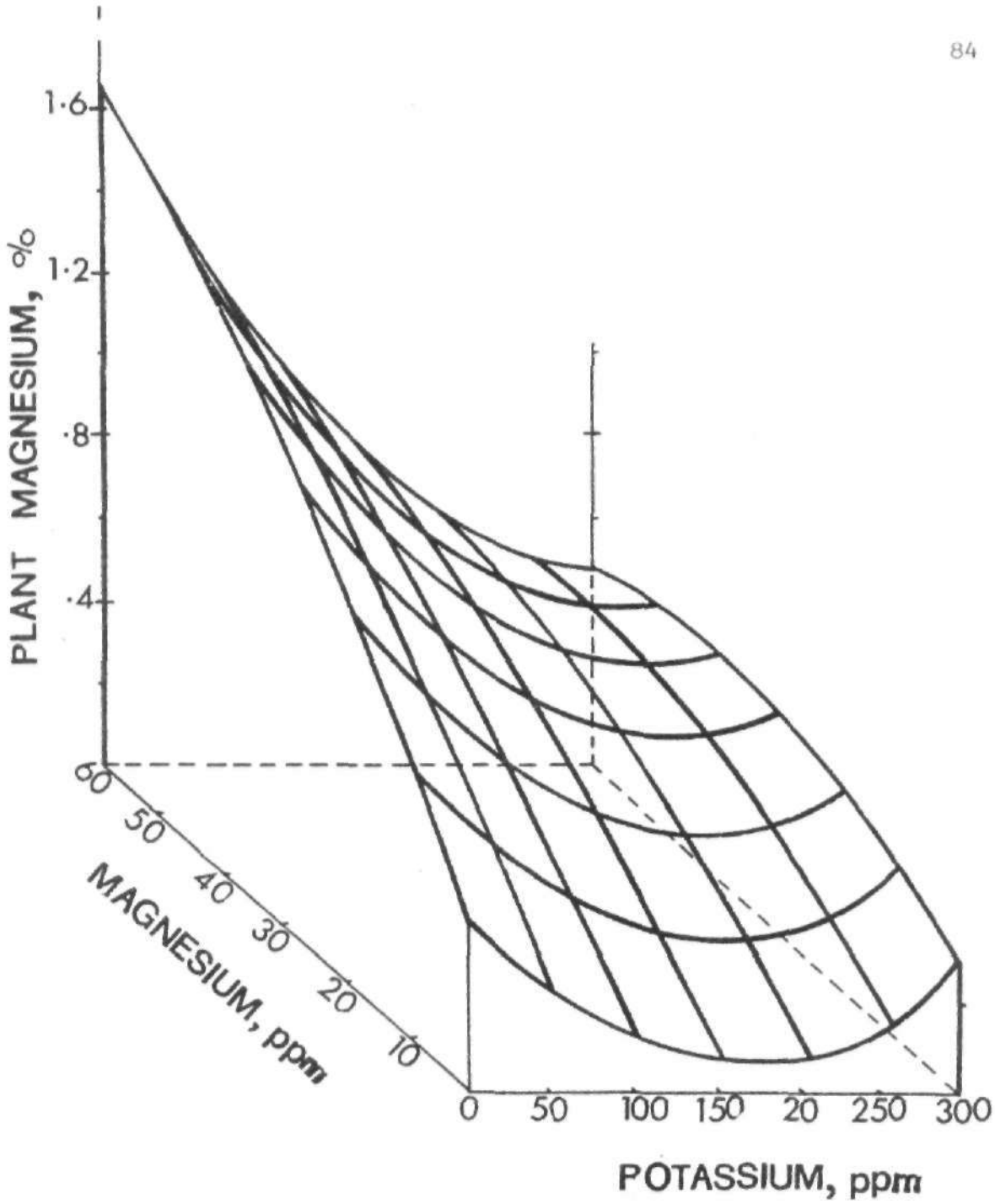


Fig. 34. Predicted response surface of magnesium concentration in top tissue of 'Tx 415' to increasing levels of potassium and magnesium concentrations in nutrient solution at 75 days after seedling emergence.

strong interactive effect indicates that K application in the growth medium antagonized Mg for Mg absorption with the effect becoming more pronounced as more of these nutrients were added to the growth medium. This is the first occasion when a definite interactive effect of the applied nutrients was observed.

These results are in agreement with those reported for many other crops. Heavy K fertilization has often been observed to reduce Mg absorption by plants (Omar and Kobbia, 1966; Terman et al., 1977; Bedi and Sekhon, 1976). Agboola and Corey (1973) reported a negative correlation between exchangeable Mg in soil and K concentration in corn tissue. The low Mg content in maize despite the apparent high level of exchangeable Mg in the soil was attributed to the antagonistic action of K on Mg. Ferrari and Sluijsmans (1955) found that the large amounts of K added to the soil depressed Mg uptake. Prince et al. (1947) had earlier observed an increase in the Mg content of alfalfa grown in soil low in K and Mg.

Table 12 shows the effect of K and Mg applications on Mg uptake. It is observed further in Table 12 and also in Figure 35 that, in spite of the significant increase in dry matter yield as a result of applications of low levels of K, Mg uptake tended to decrease with K applications in the 50-day-old plants. This suggests that K antagonized Mg absorption especially at low rates of K applications on the lines and at any level of K application for the hybrid. This trend was, however, lost in the 75-day-old plants when Mg uptake was not affected by low levels of K application (Fig. 36). An application of over 150 ppm K was required before a substantial reduction in Mg uptake was observed.

Table 12. Regression coefficients and R^2 values showing the effect of potassium and magnesium concentrations in nutrient solution on magnesium uptake by top tissue of a sorghum hybrid and its parent lines at 50 and 75 days after seedling emergence.

Variable	Intercept	K	Mg	K^2	Mg^2	K x Mg	R^2
Second Harvest (50 days)							
RS 671	36.9	-1.34	4.00*	-1.03*	-0.36	-0.56	0.84
Redlan	23.7	-1.54*	1.67*	-0.18	-0.90*	-0.26	0.85
Tx 415	25.5	-1.22	2.04*	-0.13	-0.86*	-0.24	0.65
Hybrid & Lines	28.6	-1.41*	2.50*	-0.43	-0.70*	-0.32	0.88
Third Harvest (75 days)							
RS 671	128.4	1.28	18.59*	-3.88	-1.82	-2.04	0.70
Redlan	101.7	-1.05	14.73*	-2.33	-3.34*	-0.27	0.86
Tx 415	109.9	1.12	13.28*	-3.36*	-3.47*	-0.14	0.89
Hybrid & Lines	113.1	0.38	15.53*	-3.23*	-2.84*	-0.85	0.90

*Indicates a significant difference at the 0.05 probability level.

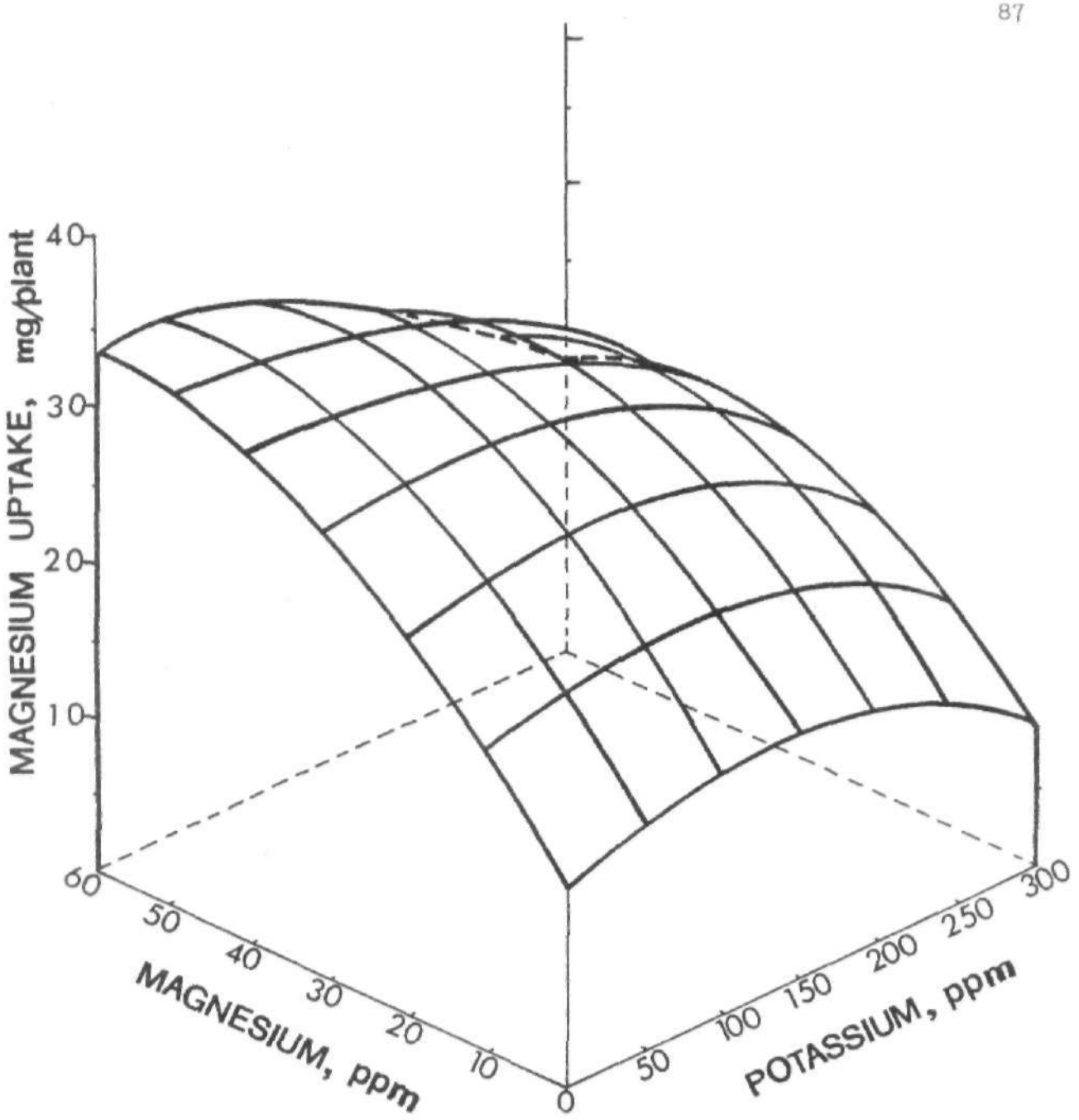


Fig. 35. Predicted response surface of magnesium uptake by top tissue of sorghum plants to increasing levels of potassium and magnesium concentrations in nutrient solution at 50 days after seedling emergence (average of 3 lines).

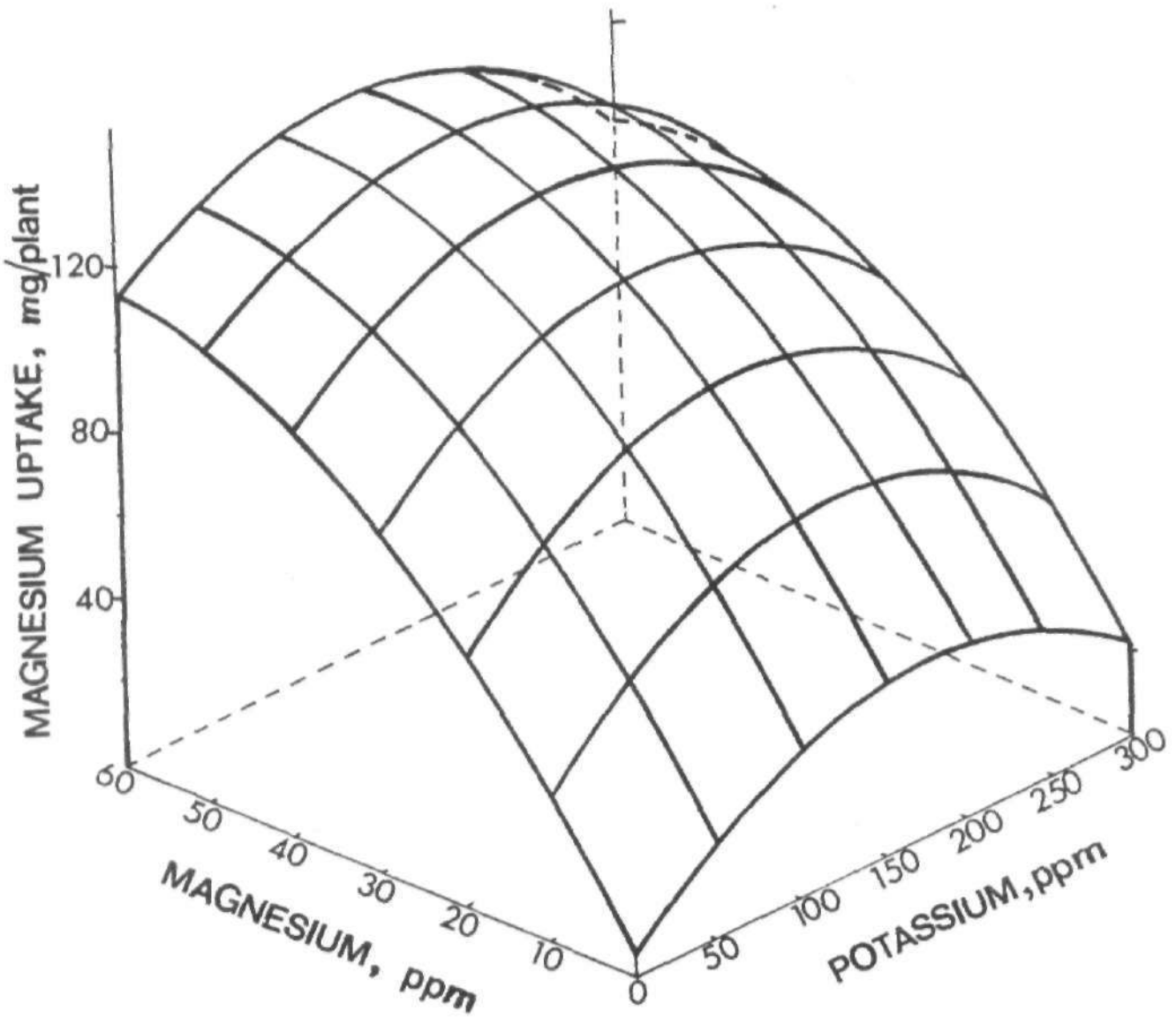


Fig. 36. Predicted response surface of magnesium uptake by top tissue of sorghum plant to increasing levels of potassium and magnesium concentrations in nutrient solution at 75 days after seedling emergence (average of 3 lines).

Differential responses to the addition of both K and Mg were observed among the lines and hybrid and, especially, at the third harvest. Magnesium uptake by RS 671 increased directly in proportion to the amounts of Mg added but was not affected by any levels of K applications (Fig. 37). In Redlan, a curvilinear yield increase to Mg application was observed, while K applications had no effects (Fig. 38). Magnesium uptake by Tx 415 responded curvilinearly to Mg application and slightly decreased by high concentrations of K in the growth medium (Fig. 39). The lack of interactive effect of the nutrients on Mg uptake resulted from the complementary effects of the nutrients on dry matter yield which is the main component of the calculated nutrient uptake.

Calcium. Table 13 shows the regression coefficients for the applied nutrient variables as they influenced plant Ca concentration in the plant. Figure 40 shows the depressing effect of applied K on top tissue Ca concentration at both the 50- and 75-day-sampling periods. The magnitude of the depressing effect of K on Ca concentration was, however, dependent on the concentrations of both K and Mg in the growth medium. Application of one of K and Mg alone tended to decrease Ca concentration in top tissue. However, when the two nutrients were applied together, each tended to decrease the depressive effect of the other on Ca absorption. At 50 days after seedling emergence, increasing K additions from 0 to 200 ppm in the absence of applied Mg resulted in a decrease in Ca concentration of top tissue by 50%. In a nutrient medium containing 60 ppm Mg, a 39% reduction was observed (Fig. 42). This trend was maintained also in the 75-day-old plants (Fig. 43).

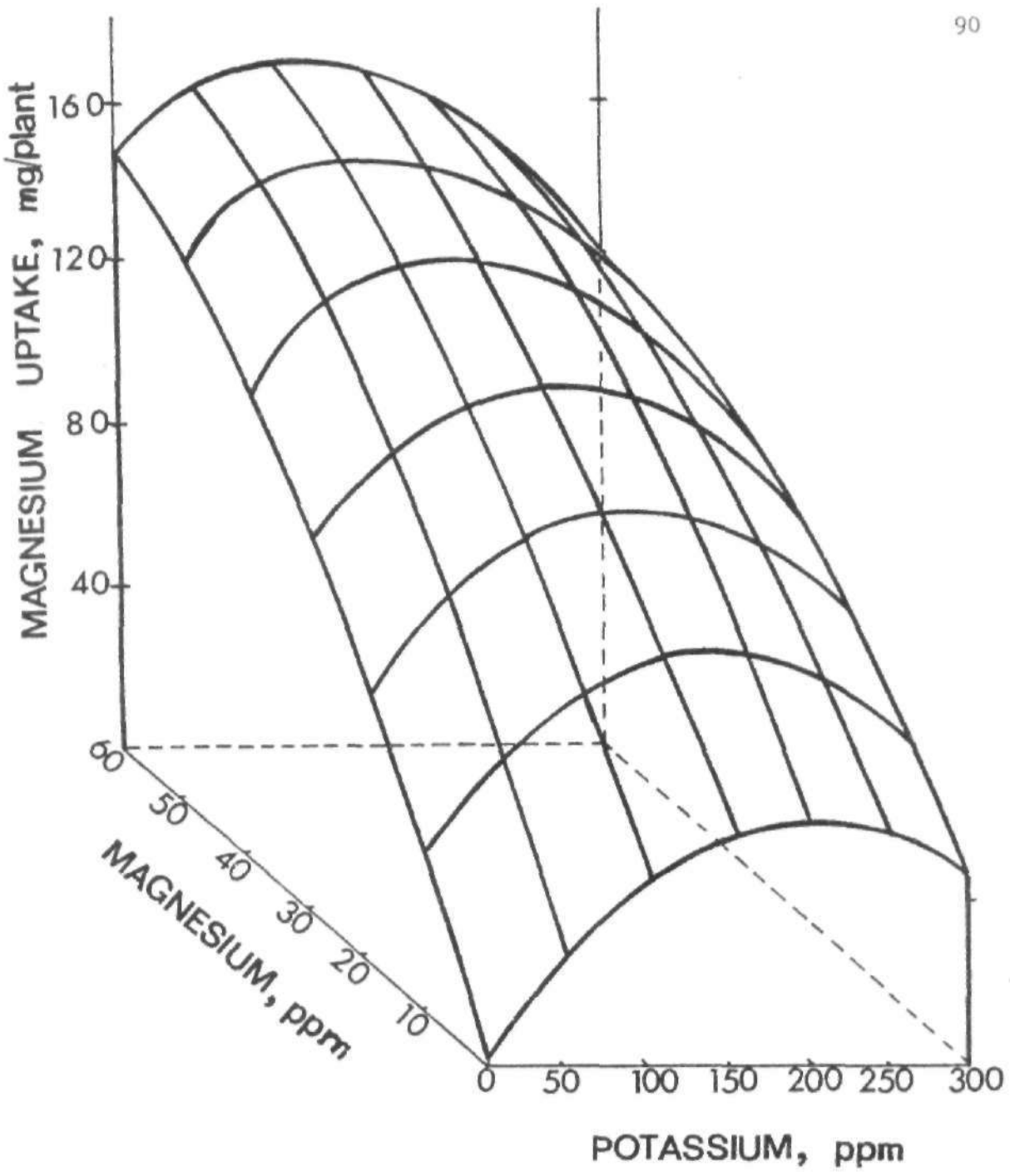


Fig. 37. Predicted response surface of magnesium uptake by top tissue of 'RS 671' to increasing levels of potassium and magnesium concentrations in nutrient solution at 75 days after seedling emergence.

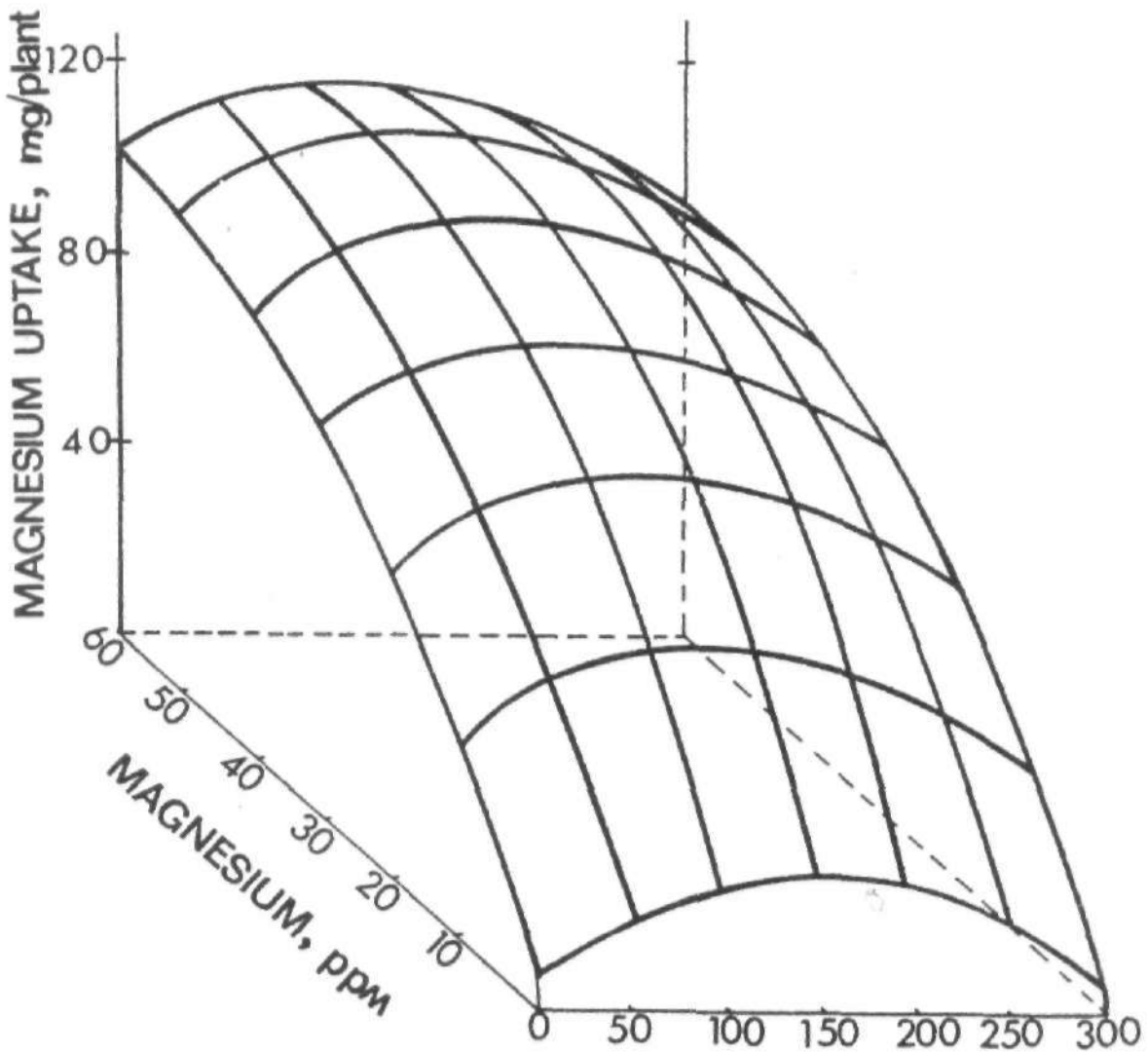


Fig. 38. Predicted response surface of magnesium uptake by top tissue of 'Redlan' to increasing levels of potassium and magnesium concentrations in nutrient solution at 75 days after seedling emergence.

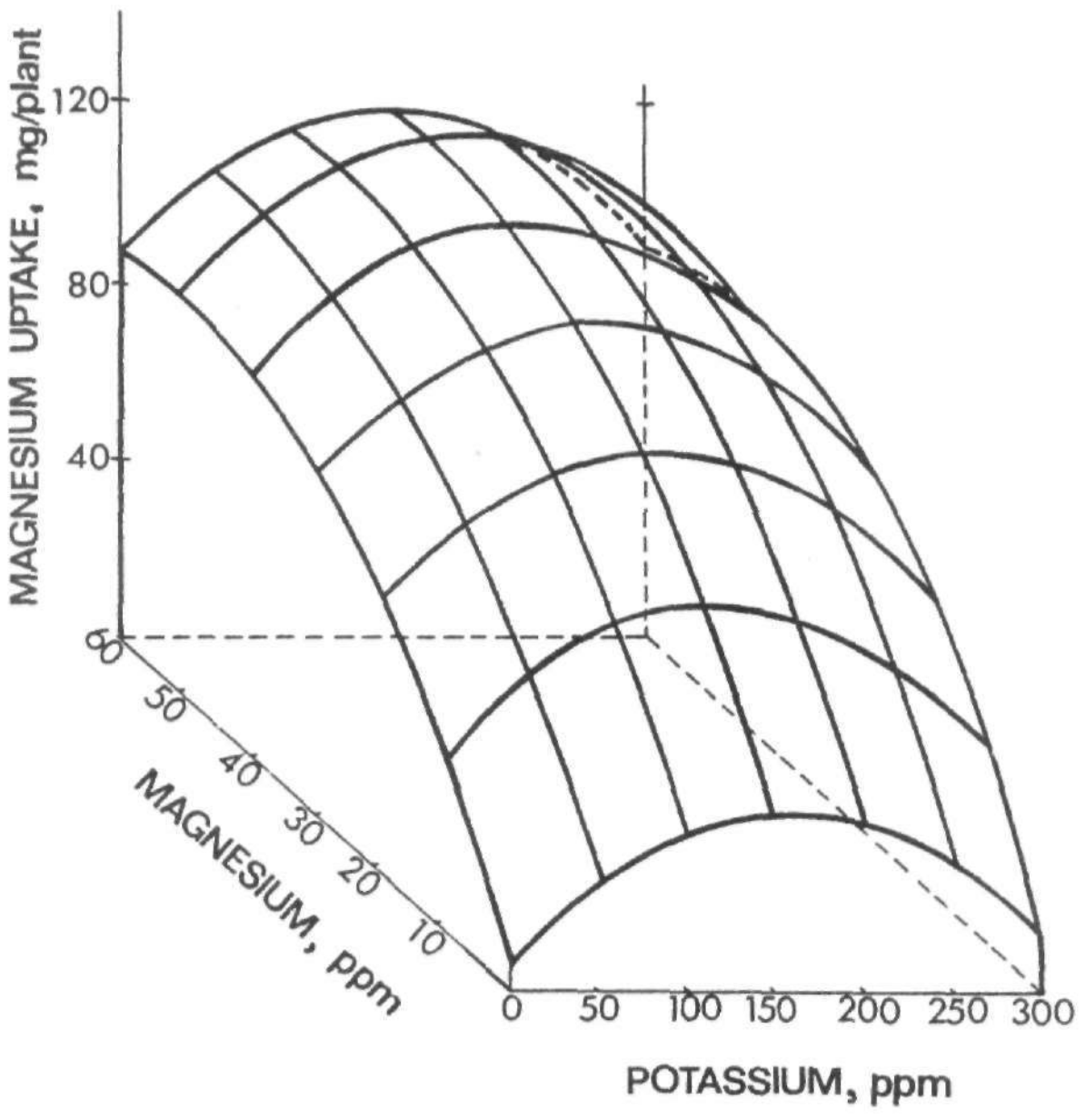


Fig. 39. Predicted response surface of magnesium uptake by top tissue of 'Tx 415' to increasing levels of potassium and magnesium concentrations in nutrient solution at 75 days after seedling emergence.

Table 13. Regression coefficients and R^2 values showing the effect of potassium and magnesium concentrations in nutrient solution on calcium concentration of top tissue of a sorghum hybrid and its parent lines at 50 and 75 days after seedling emergence.

Variable	Intercept	K	Mg	K^2	Mg^2	K x Mg	R^2
Second Harvest (50 days)							
RS 671	0.89	-0.125*	-0.040*	0.022*	0.007	0.009*	0.97
Redlan	0.74	-0.095*	-0.026*	0.024*	0.003	0.014	0.91
Tx 415	0.93	-0.107*	-0.029*	0.019*	0.003	0.009*	0.94
Hybrid & Lines	0.85	-0.108*	-0.036*	0.023*	0.004	0.009*	0.97
Third Harvest (75 days)							
RS 671	0.81	-0.153*	-0.029*	0.032*	-0.009	0.008	0.96
Redlan	0.55	-0.147*	-0.036*	0.046*	0.003	0.009	0.93
Tx 415	0.78	-0.142*	-0.035	0.030*	-0.0005	0.017	0.86
Hybrid & Lines	0.71	-0.148*	-0.033*	0.036*	-0.002	0.011*	0.95

*Indicates a significant difference at the 0.05 probability level.

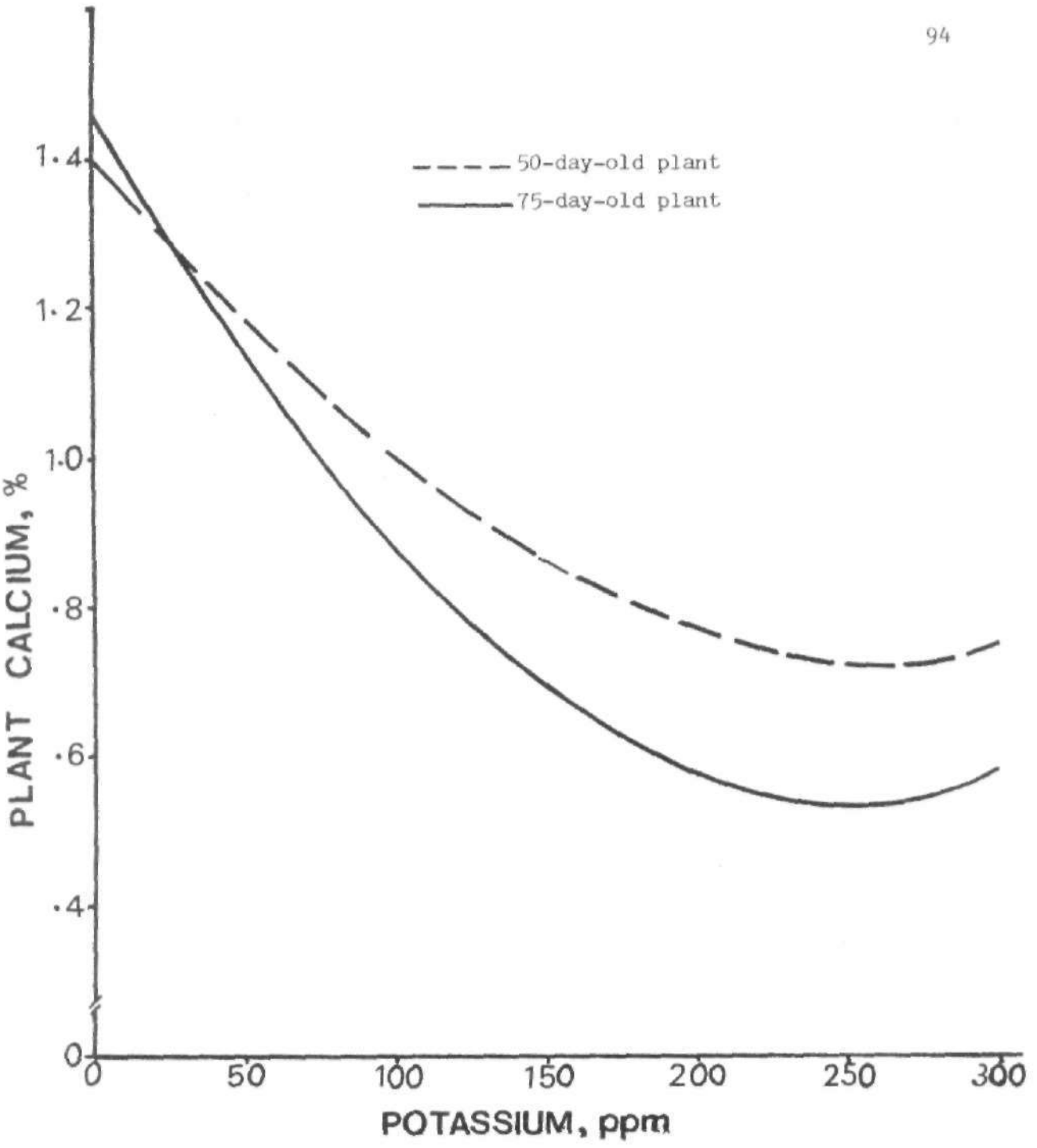


Fig. 40. Calcium concentration in top tissue of sorghum plants at 50 and 75 days after seedling emergence in response to rates of applied potassium in nutrient solution (average for 3 lines).

Figure 41 shows that Mg applications decreased top tissue Ca concentration linearly at both harvests. The depressing effect of Mg on Ca concentration was also more pronounced without, than with, K applications. A 24% reduction in Ca concentration resulted when Mg application increased from 0 to 60 ppm in the absence of K. When K was applied at a rate of 300 ppm, the reduction in Ca concentration was only 6% (Fig. 42). This trend was also shown by the 75-day-old plants (Fig. 43).

The significant interactive effect indicates that the applications of both K and Mg together in the growth medium would reduce the effectiveness of each other in decreasing Ca concentration in top tissue of the plant. Decreased Ca concentration in corn with K application had been reported (Boswell et al., 1957; Gallo et al., 1976; Classen and Wilcox, 1974; Gallaher et al., 1975). Terman et al. (1975, 1977) attributed the reciprocal relationship between K and Ca to both dilution and ion antagonism. Significant decrease in forage Ca content was reported when K was applied to smooth bromegrass (George and Thill, 1979) and coastal bermudagrass (Keisling et al., 1979). The depressive effect of K on groundnuts in East Africa has often been attributed to antagonism with Ca (Herbert, 1970). Information on Ca-Mg interactions on any crop is lacking.

Table 14 shows essentially very little effect of K and Mg applications on Ca uptake. There were no interactions between the effects of these three variables. The complementary main effects of the added nutrients on dry matter yield might explain this lack of interaction. The low R^2 values observed would make any conclusion meaningless.

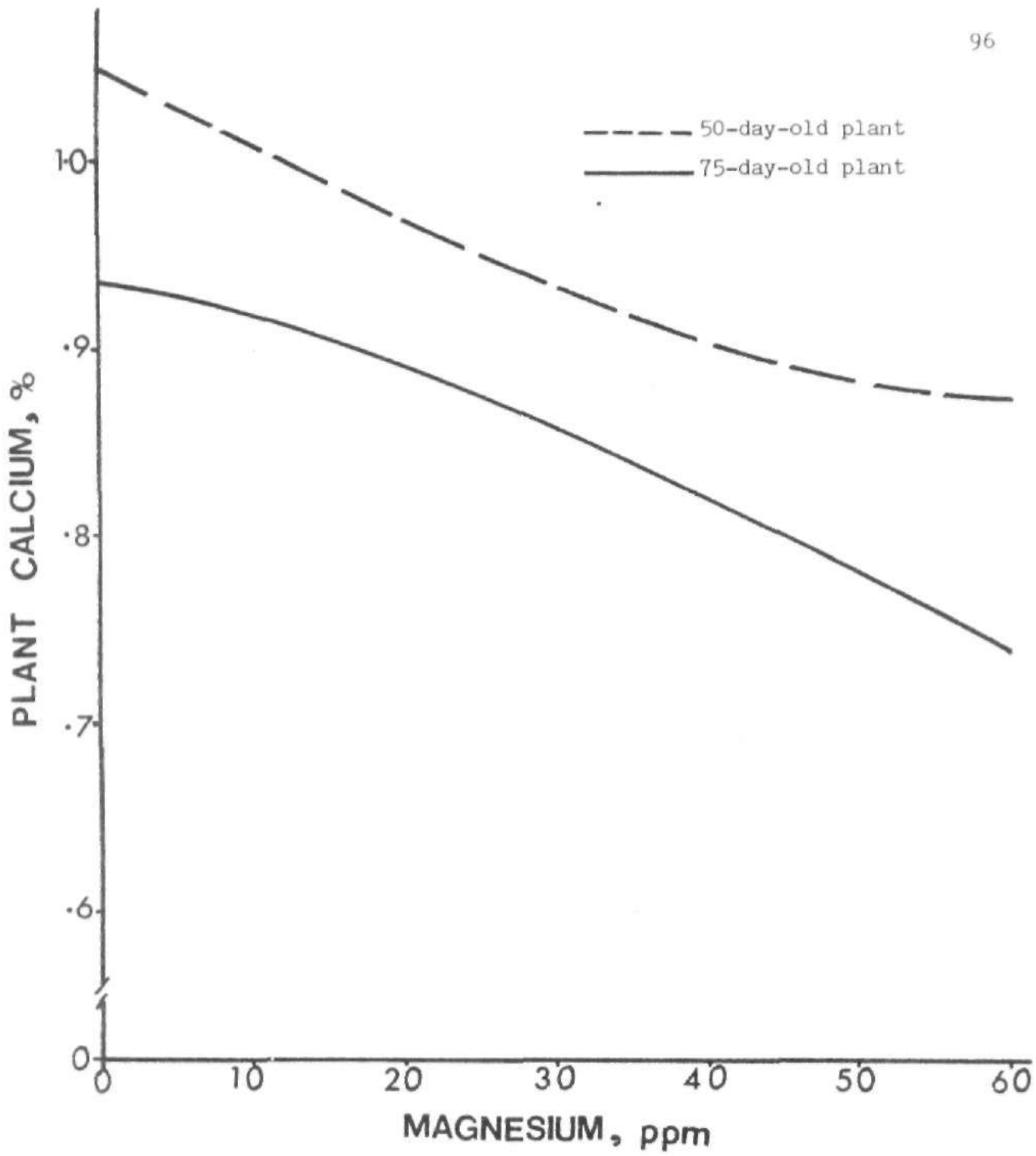


Fig. 41. Calcium concentration in top tissue of sorghum plants at 50 and 75 days after seedling emergence in response to rates of applied magnesium in nutrient solution (average for 3 lines).

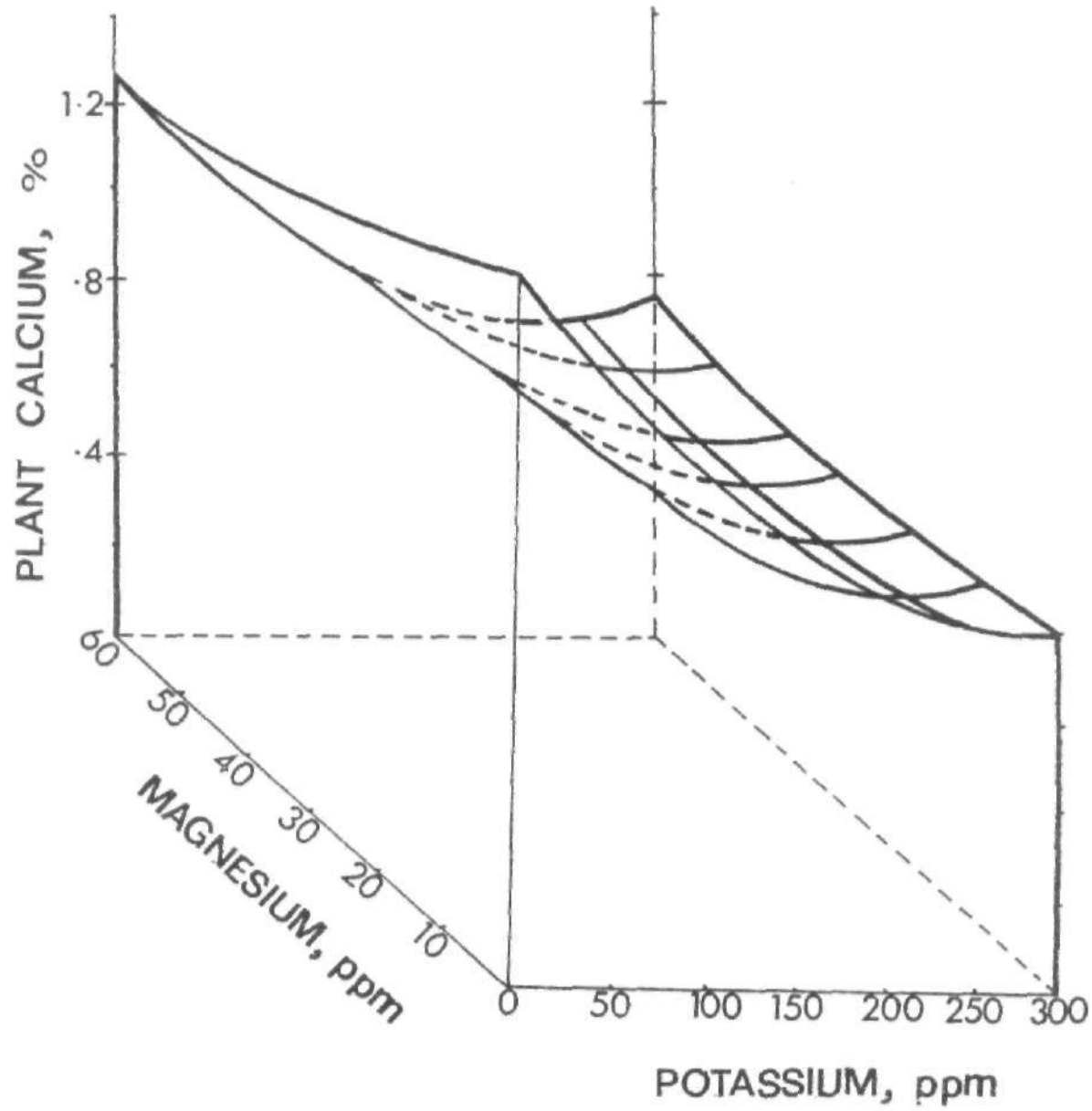


Fig. 42. Predicted response surface of calcium concentration in top tissue of sorghum plants to increasing levels of potassium and magnesium concentrations in nutrient solution at 50 days after seedling emergence (average for 3 lines).

Table 14. Regression coefficients and R^2 values showing the effect of potassium and magnesium concentrations in nutrient solution on calcium uptake by top tissue of a sorghum hybrid and its parent lines at 50 and 75 days after seedling emergence.

Variable	Intercept	K	Mg	K^2	Mg^2	K x Mg	R^2
Second Harvest (50 days)							
RS 671	50.9	-1.82	-1.99	-1.56*	0.11	-0.07	0.59
Redlan	29.2	-1.46*	-1.00	-0.62	-0.51	0.23	0.66
Tx 415	33.5	-1.49	-0.51	-0.30	-0.64	-0.26	0.21
Hybrid & Lines	37.7	-1.57	-1.20	-0.83	-0.33	-0.008	0.51
Third Harvest (75 days)							
RS 671	217.4	-1.61	4.34	-7.24	-5.47	-0.24	0.44
Redlan	152.9	0.43	3.20	-3.70	-5.87*	1.51	0.55
Tx 415	177.9	3.91	3.68	-8.03*	-5.42*	1.67	0.73
Hybrid & Lines	182.3	0.86	3.70	-6.32*	-5.54*	0.97	0.67

*Indicates a significant difference at the 0.05 probability level.

Zinc. Table 15 shows the tendency for Zn concentration to decrease with K application but to increase with Mg application. It is observed in Table 16 that in spite of the increase in dry matter yield with a corresponding increase in nutrients Mg and K, Zn uptake tended to increase. From these results, it appears as if only high levels of K applications depressed Zn absorption, while Mg has a definite synergistic effect on Zn uptake. The low R^2 values obtained, however, make any meaningful conclusion rather difficult.

Information on K-Zn and Mg-Zn relationships is inconsistent. The decrease in Zn concentration in young corn plant resulting from K application was attributed to dilution by Terman and Allen (1974). Gallo et al. (1976) attributed the reduction in Zn concentration with K application to antagonism. Coffman and Gentner (1977) found a negative correlation between soil Mg and plant Zn concentration in Cannabis sativa, indicating an antagonistic effect of Mg on Zn. However, Shukla and Mukhi (1979) reported that increasing K levels in the growth medium decreased Mg concentration in corn, the depressing effect being more pronounced when Zn was not applied, suggesting that Zn had a synergistic relationship with Mg.

Iron. Although application of Mg and K did not affect Fe concentration in the top tissue of sorghum plant (Table 17), the tendency for Fe uptake to increase with low levels and decrease with high levels of K applications (Table 18) suggests a dilution and antagonistic effects of K on Fe uptake. The low R^2 values and inconsistent effects reported in Table 17 make any conclusion difficult.

Table 15. Regression coefficients and R^2 values showing the effect of potassium and magnesium concentrations in nutrient solution on zinc concentration in top tissue of a sorghum hybrid and its parent lines at 50 and 75 days after seedling emergence.

Variable	Intercept	K	Mg	K^2	Mg^2	K x Mg	R^2
Second Harvest (50 days)							
RS 671	36.4	-0.06	1.51*	0.06	-0.38	0.40	0.40
Redlan	35.6	-0.64	1.06	0.35	-0.22	0.08	0.30
Tx 415	35.7	-2.60*	0.35	0.89*	-0.50	0.22	0.58
Hybrid & Lines	35.9	-1.05*	0.97*	0.44*	-0.37	0.23	0.67
Third Harvest (75 days)							
RS 671	22.1	0.11	1.15*	1.54*	-0.24	0.11	0.65
Redlan	24.7	-1.36*	1.58*	1.78*	-0.24	0.43	0.71
Tx 415	29.6	-1.88*	0.71	1.43*	-0.34	0.07	0.52
Hybrid & Lines	25.1	-1.53*	1.00	1.27*	-0.03	0.12	0.67

*Indicates a significant difference at the 0.05 probability level.

Table 16. Regression coefficients and R^2 values showing the effect of potassium and magnesium concentrations in nutrient solution on zinc uptake in top tissue of a sorghum hybrid and its parent lines at 50 and 75 days after seedling emergence.

Variable	Intercept	K	Mg	K^2	Mg^2	K x Mg	R^2
Second Harvest (50 days)							
RS 671	0.181	0.012*	0.009*	-0.004*	-0.003	0.001	0.75
Redlan	0.132	0.005*	0.002	-0.003*	-0.003*	0.002	0.64
Tx 415	0.119	-0.002	-0.006	0.004	-0.002	-0.000	0.14
Hybrid & Lines	0.144	0.005*	0.004	-0.002	-0.003*	-0.000	0.62
Third Harvest (75 days)							
RS 671	0.582	0.066*	0.038*	-0.014*	-0.010	0.004	0.81
Redlan	0.552	0.055*	0.054*	-0.007	-0.012	0.016*	0.80
Tx 415	0.557	0.049*	0.030*	-0.017*	-0.012*	0.006	0.84
Hybrid & Lines	0.563	0.056*	0.041*	-0.013*	-0.011*	0.009*	0.94

*Indicates a significant difference at the 0.05 probability level.

Table 17. Regression coefficients and R^2 values showing the effect of potassium and magnesium concentrations in nutrient solution on iron concentration in top tissue of a sorghum hybrid and its parent lines at 50 and 75 days after seedling emergence.

Variable	Intercept	K	Mg	K^2	Mg^2	K x Mg	R^2
Second Harvest (50 days)							
RS 671	73.2	-0.10	-0.89	-0.11	-0.60	0.59	0.35
Redlan	66.1	-0.88	-0.42	0.24	-0.15	-0.17	0.30
Tx 415	65.6	-4.13*	-1.06	0.75	0.70	0.10	0.77
Hybrid & Lines	68.3	-1.70*	-0.79*	0.29	-0.02	0.18	0.69
Third Harvest (75 days)							
RS 671	68.8	-0.88	-0.49	-0.09	-0.04	-0.54	0.23
Redlan	49.4	-0.96	-1.47	1.91*	0.33	0.09	0.49
Tx 415	76.6	-1.77	-1.92	-0.10	-0.38	0.31	0.25
Hybrid & Lines	64.9	-1.20	-1.30	0.57	-0.03	-0.14	0.42

*Indicates a significant difference at the 0.05 probability level.

Table 18. Regression coefficients and R^2 values showing the effect of potassium and magnesium concentrations in nutrient solution on iron uptake by top tissue of a sorghum hybrid and its parent lines at 50 and 75 days after seedling emergence.

Variable	Intercept	K	Mg	K^2	Mg^2	K x Mg	R^2
Second Harvest (50 days)							
RS 671	0.406	0.027*	-0.004	-0.012*	-0.004	0.000	0.84
Redlan	0.290	0.010*	-0.003	-0.010*	-0.005	0.000	0.75
Tx 415	0.233	0.009	-0.005	-0.002	-0.000	-0.002	0.31
Hybrid & Lines	0.310	0.015*	-0.004	-0.008*	-0.003	-0.000	0.78
Third Harvest (75 days)							
RS 671	1.761	0.138*	0.057	-0.067*	-0.034	0.004	0.75
Redlan	1.301	0.142*	0.071*	-0.025*	-0.045*	0.014	0.91
Tx 415	1.489	0.108*	0.032	-0.062*	-0.049*	0.006	0.88
Hybrid & Lines	1.517	0.129*	0.054*	-0.051*	-0.043*	0.008	0.90

*Indicates a significant difference at the 0.05 level of probability.

Manganese. Table 19 shows the effect of K and Mg applications on the concentration of Mn in top tissue of sorghum plants. Depressive effects of both K and Mg applications were observed on both the 50- and 75-day-old plants. However, differences were noted among hybrid and lines. While Mn accumulation in RS 671 was not affected by low levels of K applications on the 50-day-old plants, high K rates increased it. The Mn content of Redlan and Tx 415 decreased directly in proportion to the amounts of K supplied in the growth medium. In the 75-day-old plants, Mn concentration decreased curvilinearly with K application on the hybrid and lines.

Application of Mg resulted in a direct reduction in Mn concentration in both RS 671 and Redlan during the second harvest and in RS 671 and Tx 415 at the third harvest. Table 20 shows the effect of K and Mg on Mn uptake. The tendency for Mn uptake to increase with low levels of K applications and decrease with high rates suggests a dilution effect at low and antagonism at high rates of K applications. The decrease in Mn uptake in spite of the increase in dry matter yield with increasing levels of Mg applications is a clear demonstration of antagonistic effect of Mg on Mn absorption (Tables 24 and 25 also show that sorghum top Mn was negatively correlated with applied K and Mg.). Coffman and Gentner (1977) reported that corn leaf Mn was negatively correlated with soil Mg.

The significant K-Mg interactive effect indicates that the applications of both K and Mg together would reduce the effectiveness of each other in decreasing Mn concentration in top tissue of the plant.

Table 19. Regression coefficients and R^2 values showing the effect of potassium and magnesium concentrations in nutrient solution on manganese concentration in the top tissue of a sorghum hybrid and its parent lines at 50 and 75 days after seedling emergence.

Variable	Intercept	K	Mg	K^2	Mg^2	K x Mg	R^2
Second Harvest (50 days)							
RS 671	98.7	- 4.58	- 7.36*	3.88*	1.06	1.15	0.62
Redlan	107.3	-11.32*	- 9.61*	2.02	2.72	2.62*	0.80
Tx 415	105.3	- 6.94*	- 5.74	3.41	0.91	1.41	0.54
Hybrid & Lines	102.8	- 6.06*	- 6.93*	3.92*	1.48	2.06*	0.77
Third Harvest (75 days)							
RS 671	88.2	- 8.42*	-11.74*	5.14*	1.79	4.21*	0.71
Redlan	83.7	- 9.05*	- 6.06*	4.54*	1.94	1.21	0.62
Tx 415	105.1	-12.45*	-10.54*	4.32*	2.09	2.70*	0.79
Hybrid & Lines	92.3	- 9.97*	- 9.35*	4.67*	1.94	2.71*	0.74

*Indicates a significant difference at the 0.05 probability level.

Table 20. Regression coefficients and R^2 values showing the effect of potassium and magnesium concentrations in nutrient solution on manganese uptake by top tissue of a sorghum hybrid and its parent lines at 50 and 75 days after seedling emergence.

Variable	Intercept	K	Mg	K^2	Mg^2	K x Mg	R^2
Second Harvest (50 days)							
RS 671	0.565	0.046*	-0.035*	-0.001	0.000	-0.000	0.72
Redlan	0.512	0.008	-0.037*	-0.012	-0.004	0.005	0.59
Tx 415	0.324	0.010	-0.028*	0.011*	0.000	-0.002	0.59
Hybrid & Lines	0.467	0.021*	-0.033*	-0.000	-0.001	0.000	0.73
Third Harvest (75 days)							
RS 671	2.427	0.233*	-0.009	-0.067*	-0.036	0.017	0.78
Redlan	2.003	0.183*	0.073*	-0.054*	-0.041*	0.015*	0.95
Tx 415	1.992	0.122*	-0.038	-0.077*	-0.035*	0.009	0.81
Hybrid & Lines	2.140	0.180*	0.008	-0.067*	-0.037*	0.014*	0.95

*Indicates significant difference at the 0.05 probability level.

Forage cation ratio. Since sorghum can be used as a fodder for livestock (Rachie, 1970), its ability to supply the necessary nutrients at a balanced condition becomes of utmost importance especially to diversified farmers. The role of Mg in grass tetany has been given the proper recognition since it is the most important problem associated with Mg nutrition. One of the mechanisms responsible for grass tetany in animals is the ratio of Mg to other mineral elements in the feed they consume (Fontenot, 1972). Forages which are associated with high incidence of grass tetany are frequently high in K. This suggests that recommendation involving the applications of K and Mg to a forage crop must take into consideration the necessity to keep the K/Mg ratio in the plant at the minimum.

The cation data in this report are expressed in milliequivalents (Munson, 1968), the quantitative expression used to calculate cation ratios. Forage cation ratios have been used as an index for predicting the incidence of tetany in animals (Rahman et al., 1960; Butler, 1963). Most often a K/(Ca + Mg) milliequivalent ratio of 2.2 is used. When values above 2.2 are observed, a greater risk of tetany is assumed.

The regression coefficients for the effect of K and Mg applications on K/(Ca + Mg) ratio in top tissue of sorghum plants are shown in Table 21. As expected, the effect of K on the ratio was mainly linear, although the two lines showed a small but significant quadratic response to this nutrient element, indicating a leveling up of the ratio at high levels of K applications.

The effect of Mg applications was dependent on the age and type of lines or hybrid. The ratio in the top tissue of the 50-day-old RS 671

Table 21. Regression coefficients and R^2 showing the effect of potassium and magnesium concentrations in nutrient solution on the K/(Ca + Mg) cation ratio in top tissue of a sorghum hybrid and its parent lines at 50 and 75 days after seedling emergence.

Variable	Intercept	K	Mg	K^2	Mg^2	K x Mg	R^2
Second Harvest (50 days)							
RS 671	1.131	0.29*	-0.05*	-0.01	0.00	-0.01	0.95
Redlan	1.50	0.30*	-0.07*	-0.04*	0.03	-0.03*	0.90
Tx 415	1.47	0.25*	-0.03	-0.03*	0.00	-0.02*	0.93
Hybrid & Lines	1.43	0.28*	-0.05*	-0.03*	0.00	-0.02*	0.96
Third Harvest (75 days)							
RS 671	1.28	0.42*	-0.19*	-0.02	0.07*	-0.05*	0.93
Redlan	1.92	0.46*	-0.23*	-0.09*	0.09*	-0.06*	0.89
Tx 415	1.48	0.50*	-0.18*	-0.01	0.07*	-0.05*	0.93
Hybrid & Lines	1.56	0.46*	-0.20*	-0.04	0.07	-0.06*	0.93

*Indicates a significant difference at the 0.05 probability level.

and Redlan was directly proportional to the amounts of Mg added to the growth medium (Fig. 44). The male line, Tx 415, showed no response to Mg application. At 75 days after seedling emergence, the effect of K was still linear (Fig. 45). Although application of low amounts of Mg substantially reduced the ratio, increase in the ratio was observed at high Mg concentrations. The reason for this is apparent. At low rates of K and Mg applications, the absorption of K and Mg increased but that of Ca decreased. As the concentrations of K and Mg in the growth medium increased, the luxury consumption of K resulted, while Mg and to some extent Ca absorption decreased. Figure 45 shows further that ratios of over 2.2 were not observed unless K rates of over 200 ppm were applied in the presence of any rate of Mg application. When K rate was increased above 200 ppm, a Mg rate of 20 ppm was required to reduce the ratio from 2.5 to 2.2. Successive additions of Mg resulted in further reductions of the ratio. This is in contrast with the ratio in the 75-day-old plants (Fig. 45), where the highest ratio of 4.4 resulted when K and Mg were applied at rates of 300 and 60 ppm, respectively. During this growth stage, the ratio increased more rapidly with K applications than during the second harvest. About 150 ppm K was required to raise the ratio over 2.2 when 10 ppm Mg was applied. As K applications increased, more Mg was needed to lower the ratio to an acceptable value. At 300 ppm K, a Mg application of 50 ppm was needed to lower the ratio from 4.3 to 2.1. The significant interactive effect at both harvests shows that the effect of K is modified by the presence of Mg in the growth medium and vice versa.

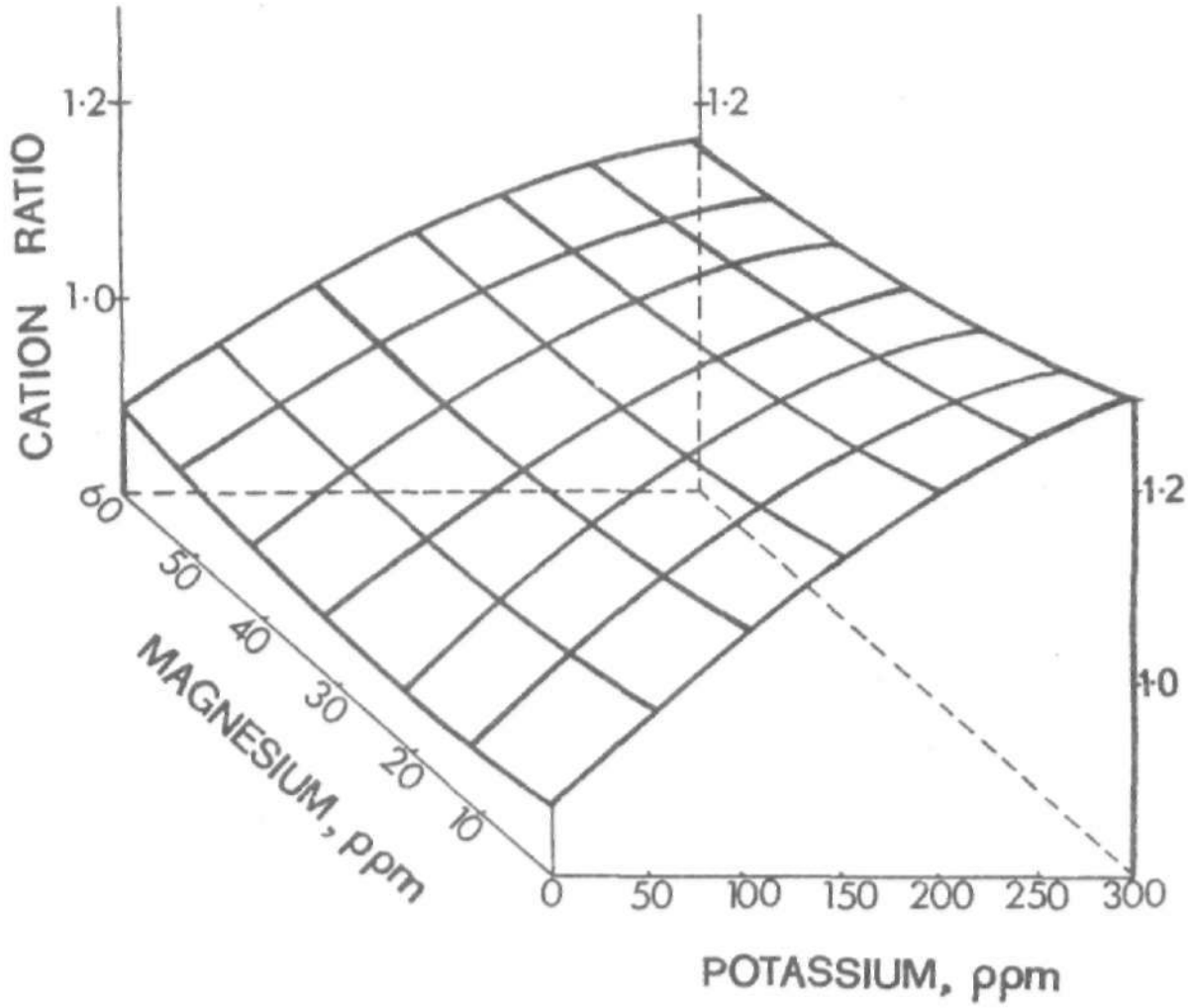


Fig. 44. Predicted response surface of K/(Ca + Mg) cation ratio in top tissue of sorghum plants to increasing levels of potassium and magnesium concentrations in nutrient solution at 50 days after seedling emergence (average for 3 lines).

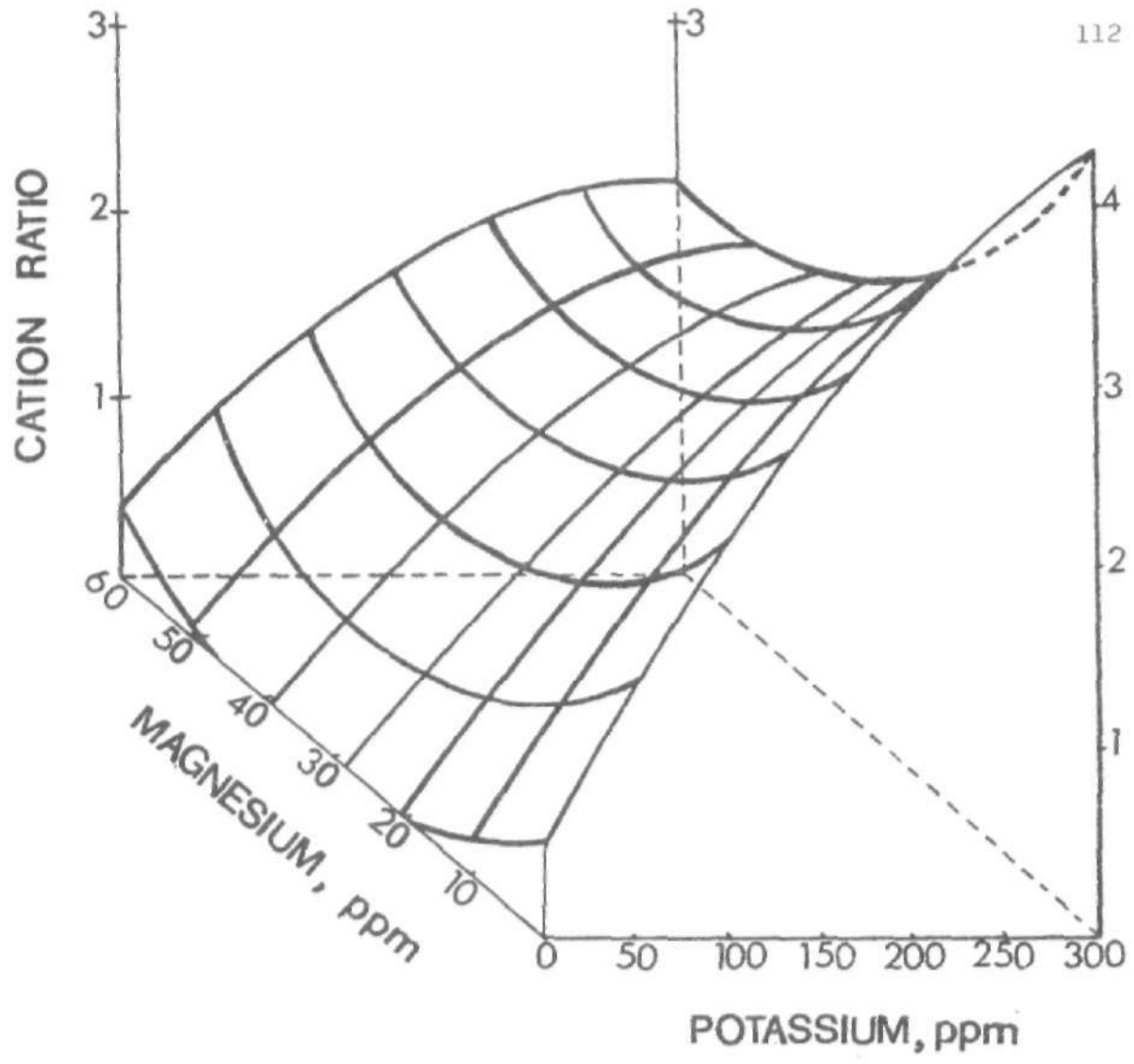


Fig. 45. Predicted response surface of K/(Ca + Mg) cation ratio in top tissue of sorghum plants to increasing levels of potassium and magnesium concentrations in nutrient solution at 75 days after seedling emergence (average for 3 lines).

The results show that increased K/(Ca + Mg) cation ratios suggest a greater grass tetany risk when K supply is higher than normal in the growth medium. Applications of higher rates of Mg to a medium already high in K may not necessarily lead to a reduction in the ratio. The severity of the effect of K depends on the age of the plant. These results are in agreement with those reported by George and Thill (1979) on smooth bromegrass, that high fertilization with K produced a relatively large increase in cation ratios especially when N supply was equally high. The values obtained were also reported to be dependent on the season, with values near 2.2 during late April and exceeding 2.2 during early to mid-May.

Correlation and Multiple Regression Analyses

Chemical elements in plants or parts of plant have been known to be related to dependent variables such as dry matter yield in plants. Shear, Crane and Myers (1948) indicated that plant growth was a function of intensity and balance, as they are reflected in the composition of leaves when plants are in the same stages of development. Correlation analysis has thus been long in use to study the relationships between nutrient elements in plants.

It has been suggested by Goodall and Gregory (1947) that yield response could be related to the concentrations of various elements in the plant using multiple regression technique. They postulated that a quadratic function could be of use in characterizing yield as a function of plant nutrient composition. Voss, Hanway and Dumenil (1970) reported multiple regression equations for yield as a function of linear and

quadratic leaf concentrations of N and P. Peck and co-workers (1969) in a similar experiment determined the concentration of 10 elements in leaf tissue of maize and used a quadratic polynomial to measure the relationship between levels of N, P and K in leaf tissue and grain yield.

Simple correlation analysis. Tables 22 and 23 present the simple correlation for the relationship between nutrient K and Mg in the growth medium and each of the plant variables measured at 50 and 75 days after seedling emergence, respectively. Table 22 shows that nutrient K was correlated more closely with dry matter accumulation in lower leaves ($r = 0.240$) than in the upper leaves ($r = 0.167$). However, in the 75-day-old plant (Table 23), dry matter production in the upper leaves was more closely correlated ($r = 0.424$) with nutrient K than in the lower leaves ($r = 0.269$). The mobility of K in the plant would probably account for this apparent difference. In young plants, K accumulation occurred in the more mature and actively photosynthesizing lower leaves. Seventy-five days after seedling emergence, the photosynthetic activity in the lower senile leaves was much less than that in the upper leaves, resulting in the movement of K from the lower to the upper leaves. Stem diameter was more positively correlated with applied K than any of the other measured plant variables.

As expected, application of Mg had no effect on any of the plant variables measured at 50 days after seedling emergence. The fact that applied Mg was positively correlated with dry weight of upper and not with that of the lower leaves of the 75-day-old plants suggests a ready movement of Mg from the lower to the upper leaves. Applied Mg was

Table 22. Simple correlation coefficients for the relationships between the growth medium variables and various measured plant variables of a sorghum hybrid and its parent lines at 50 days after seedling emergence (average of 3 lines).

	Growth Medium			Dry Weight of Leaves			Leaf Area		
	K	Mg	K/Mg	Lower	Upper	Total	Dry matter	Lower	Total
K	1.000	---	---	0.240**	0.167*	0.384***	0.198**	0.153*	0.238**
Mg		1.000	---	0.027	-0.028	-0.025	-0.021	0.044	-0.011
K/Mg			1.000	0.002	0.035	0.065	0.029	-0.005	0.018
Lower				1.000	0.668***	0.634***	0.769***	0.616***	0.791***
Upper					1.000	0.913***	0.960***	0.397***	0.939***
Total						1.000	0.973***	0.323**	0.936***
Dry matter							1.000	0.447***	0.964***
Lower								1.000	0.510***
Total									1.000

*, **, *** Significant at .05, .01 and .001 levels of probability, respectively.

Table 23. Simple correlation coefficients for the relationships between the growth medium variables and various measured plant variables of a sorghum hybrid and its parent lines at 75 days after seedling emergence (average of 3 lines).

	Growth Medium			Leaf Dry Weight			Leaf Area		Stem			
	K	Mg	K/Mg	Lower	Upper	Total	Lower	Total	Weight	Diam-eter	Length	Dry Matter
K	1.000	---	---	0.269***	0.424***	0.433***	0.151*	0.430***	0.369***	0.490***	0.399***	0.448***
Mg		1.000	---	-0.002	0.203**	0.196**	0.136	0.193**	0.252***	0.148*	0.229***	0.222**
K/Mg			1.000	0.010	0.087	0.083	-0.049	0.103	0.025	0.097	0.011	0.078
Lower				1.000	0.476***	0.553***	0.649***	0.447***	0.280***	0.414***	0.151*	0.486***
Upper					1.000	0.993***	0.392***	0.867***	0.700***	0.769***	0.566***	0.953***
Total						1.000	0.443***	0.869***	0.688***	0.774***	0.558***	0.954***
Lower							1.000	0.500***	0.127	0.446***	0.064	0.346***
Total								1.000	0.429***	0.870***	0.383***	0.752***
Weight									1.000	0.284***	0.800***	0.869***
Diameter										1.000	0.207**	0.631***
Length											1.000	0.762***
Dry matter												1.000

*, **, *** Significant at the .05, .01 and .001 probability levels, respectively.

correlated more closely with stem dry weight than with any of the other plant variables.

There was no relationship between K/Mg ratio in the growth medium and any of the measured plant variables, either at the 50- or the 75-day-sampling period.

Dry weight of the lower leaves was closely more correlated with top dry matter yield in the 50-day-old plants ($r = 0.769$) than that in the 75-day-old plants ($r = 0.486$), indicating less contribution of the lower leaves to total top dry matter yield as the plant matured. Correlation between the dry weight of the upper leaves and total top dry weight remained approximately the same at both the 50- ($r = 0.960$) and the 75- ($r = 0.953$) day-sampling periods.

Tables 24 and 25 show the simple correlation for the relationship between growth medium variables, top tissue nutrient concentrations and the total top dry matter yields of the 50- and 75-day-old plants, respectively. As earlier observed, applied K was negatively correlated with N, P, Mg, Ca, Zn and Mn but positively correlated with K in the top tissue. Both dilution and ion antagonism have been given as reasons for the inverse relationships.

Percent K in top tissue was negatively correlated with N, Mg, Ca, Zn and Fe in the tissue but had no relationship with Mn (Table 25). These results indicate that the antagonism between K and each of N, Mg and Ca observed earlier was the result of a non-selective absorption which might have occurred at high concentrations of K in the growth medium in addition to the ions competitive effect in the long-distance translocation within the plant. Coffman and Gentner (1977), in contrast

Table 24. Simple correlation coefficients for the relationships between growth medium variables, dry matter yield and each of eight elements in top tissue of a sorghum hybrid and its parent lines at 50 days after seedling emergence (average of 3 lines).

	Growth Medium			Nutrient Concentration in Top Tissue								Dry Matter
	K	Mg	K/Mg	N	P	K	Mg	Ca	Zn	Fe	Mn	
K	1.000	---	---	-0.136	-0.324***	0.629***	-0.609***	-0.651***	-0.169*	-0.259**	-0.220**	0.198**
Mg		1.000	---	-0.088	0.094	-0.030	0.399***	-0.168*	0.155*	-0.120	-0.252**	-0.021
K/Mg			1.000	0.029	-0.123	0.160	-0.482***	-0.133	-0.189*	-0.090	0.182*	0.029
N				1.000	0.303***	0.240**	0.144*	0.279***	0.306***	0.015	0.092	-0.697***
P					1.000	-0.066	0.292***	0.275***	0.182**	-0.080	0.104	-0.409***
K						1.000	-0.443***	-0.437***	0.129	-0.212**	-0.233**	-0.174*
Mg							1.000	0.506***	0.174*	0.001	0.061	-0.222**
Ca								1.000	0.136	0.097	0.310***	-0.318***
Zn									1.000	0.169*	0.124	-0.342***
Fe										1.000	0.249**	-0.000
Mn											1.000	-0.092
Dry matter												1.000

*, **, *** Significant at .05, .01 and .001 probability levels, respectively.

Table 25. Simple correlation coefficients for the relationships between growth medium variables, dry matter yield and each of eight elements in top tissue of a sorghum hybrid and its parent lines at 75 days after seedling emergence.

	Growth Medium			Nutrient concentration in Top Tissue								Dry Matter
	K	Mg	K/Mg	N	P	K	Mg	Ca	Zn	Fe	Mn	
K	1.000	---	---	-0.559***	-0.363***	0.693***	-0.510***	-0.730***	-0.246**	-0.110	-0.338***	0.447***
Mg		1.000	---	-0.110	0.326***	-0.097	0.563***	-0.157*	0.161*	-0.118	-0.317***	0.222***
K/Mg			1.000	-0.069	-0.250**	0.247**	-0.554***	-0.182*	-0.068	-0.134	0.113	0.078
N				1.000	0.430***	-0.294***	0.419***	0.613***	0.541***	0.239**	0.781***	-0.690***
P					1.000	-0.098	0.663***	0.127	0.305***	-0.107	0.108	-0.254**
K						1.000	-0.428***	-0.709***	-0.139**	-0.255***	-0.137	0.100
Mg							1.000	0.382***	0.415***	0.036	0.063	-0.206**
Ca								1.000	0.364***	0.311***	0.465***	0.359***
Zn									1.000	0.248**	0.532***	-0.463***
Fe										1.000	0.244**	-0.123
Mn											1.000	-0.628***
Dry matter												1.000

*, **, *** Significant at the 0.05, .01 and .001 probability levels, respectively.

with this observation, observed a positive correlation between plant K and tissue Ca, Mn and N in Cannabis sativa. However, Agboola and Corey (1973) reported a negative correlation between K and Ca in maize leaves.

The effect of applied Mg was not apparent on tissue P concentration until the third harvest (Table 25), when Mg was positively correlated with tissue P. This is expected, since Mg has a key role in phosphorus and carbohydrate metabolism and is a cofactor of nearly all enzymes which act on phosphorylated substances (Gauch and Krauss, 1959). At both harvests, applied Mg was positively correlated with tissue Mg and Zn but negatively correlated with tissue Ca and Mn. Applied Mg had no effect on tissue N, K and Fe. Coffman and Gentner (1977) reported negative correlation between soil Mg and plant N, Mg, Zn and Mn. Ahmad and Tulloch-Reid (1968) reported reduced N accumulation by okra fruit with soil Mg application greater than 56 kg/ha. Embleton (1966) indicated that Mg-deficiency symptoms may be reduced with increased levels of soil or plant N.

Although applied Mg decreased the absorption of Ca and N, a positive correlation was observed between plant Mg and each of top tissue N and Ca. This result indicates that the decreased N or Ca concentration in top tissue of the plant in response to Mg application was as a result of lack of uptake of the nutrients from the medium and not due to competition between Mg and each of the ions during translocation within the plant. In the 75-day-old plants, tissue Mg was positively correlated with N, P, Ca and Zn but negatively correlated with tissue K. No relationship was detected between plant Mg and tissue Fe and Mn. Agboola and Corey (1973) reported a positive relationship between soil Mg and N

in maize plants but found no relationship between the two elements in plant tissue. Coffman and Gentner (1975) also found no relationship between Mg and N in leaf tissue of C. sativa.

Top tissue Mg concentration was correlated more closely with K/Mg ratio than with applied Mg during the second harvest (Fig. 24). However, in the 75-day-old plants, top tissue Mg was correlated about equally with applied Mg ($r = 0.563$) and K/Mg ratio ($r = -0.554$) in the growth medium. Other researchers (Walsh and O'Donohoe, 1945; McColloch et al., 1957) have observed that K/Mg ratio was a better estimate of Mg availability than the exchangeable Mg. And, Lombin and Fayemi (1976) reported a closer correlation between Mg uptake by maize plant and K/Mg ratio than between any of the other soil variables studied.

Table 25 shows that plant N was positively correlated with tissue P, Mg, Ca, Zn, Fe and Mn but negatively correlated with tissue K. Coffman and Gentner (1977) reported a positive correlation between plant N and tissue K, P, Mg, Ca, Zn and Fe but detected no relationship between soil K and plant N. Agboola and Corey (1973) reported positive correlation between plant N and tissue P, B and Cu.

Plant P was positively correlated with tissue Mg, Zn and Ca at the second harvest, but there was no effect of P on Ca during the third harvest. There was no relationship between tissue P and plant K, Fe and Mn at both harvests. Coffman and Gentner (1977) reported positive correlation between plant P and Ca but negative correlation with Mn.

Plant Ca was positively correlated with plant Zn, Fe and Mn, indicating that high accumulation of Ca can accentuate high accumulation

of Mn, Fe and Zn in plant tissue which might eventually result in the toxicities of these elements.

The negative correlation between each plant N, P, Mg and Ca with top dry matter yield was probably due to plant growth response to the application of K and Mg, resulting in the carbohydrate dilution of the nutrient elements in the plant.

Plant Fe, Mn and Zn were each negatively correlated with top dry matter yield. The relatively high negative correlation between top tissue Mn and top dry matter yield ($r = -0.628$) indicated a high Mn concentration as a result of low dry matter yield, or the low dry matter yield was a direct result of Mn toxicity. Sorghum plants grown in medium without either K, Mg or both accumulated relatively more Mn, Fe and Zn than plants grown in medium with relatively higher amounts of these nutrients. However, the higher concentration of Mn, Fe or Zn might have resulted from the reduced growth due to the deficiency of either K, Mg or both. Continued ion uptake without growth dilution would result in high metal concentration in top tissue possibly resulting in toxicities and stunted growth. White (1970) reported that peas grown in acid soils showed Mn toxicity with 500 ppm Mn in tissue. Jones (1967) reported that Mn greater than 250 ppm in upper matured trifoliate leaves of soybean and Zn greater than 100 ppm in top 15-cm of alfalfa before bloom were excessive.

Multiple regression analysis. The partial regression coefficients and T values for the relationship between dry matter yield and top tissue concentration of 5 macroelements are contained in Table 26. The

Table 26. Multiple regression coefficients and T values for the relationships between N, P, K, Mg, Ca concentrations and their interactions in top tissue with dry matter yield of a sorghum hybrid and its parent lines at 50 and 75 days after seedling emergence.

Independent Variables	Days After Seedling Emergence			
	50		75	
	Coefficient	T-Value	Coefficient	T-value
Intercept	34.26	9.30	89.52	6.26
Nitrogen (N)	-12.75***	9.12	-20.39	1.92
Phosphorus (P)	- 4.58	0.88	33.01	1.46
Potassium (K)	0.16	0.30	- 9.12**	3.61
Magnesium (mg)	- 2.37	0.67	-21.86	1.59
Calcium (Ca)	2.34	0.74	-45.43*	3.34
N^2	0.68***	4.16	0.48	0.19
P^2	0.14	0.72	-39.13*	2.68
K^2	0.00	0.02	0.21	1.41
Mg^2	1.01	0.85	- 7.19	1.89
N x P	2.78*	2.33	2.46	0.31
N x K	0.09	0.41	0.49	0.51
N x Mg	0.68	0.49	3.23	0.60
N x Ca	0.54	0.46	3.92	0.69
P x K	- 0.04	0.12	0.91	0.41
P x Mg	- 1.83	0.75	11.58	1.04
P x Ca	- 5.55**	2.65	- 2.95	0.23
K x Mg	0.01	0.03	2.75	1.79
K x Ca	- 0.41*	2.73	4.89**	3.06
Mg x Ca	0.32	0.20	11.53	1.48
No. of observations	240		240	
Residual mean squares	1.23		32.12	
Dry weight mean	3.73		16.88	
R^2	0.84		0.66	

*, **, *** Significant at .05, .01 and .001 probability levels, respectively.

regression equation used contained linear, quadratic and interaction terms for the top tissue concentration of N, P, K, Mg and Ca. Although simple correlation analysis indicates significant negative correlation between top dry matter yield and each of N, P, Ca and Mg, the partial regression coefficients indicate the effect of top tissue N to be relatively more important for dry matter yield than the other nutrients in the 50-day-old plant. Linear and quadratic effects of N were observed. The N x P, P x Ca and K x Ca interactions explained substantial variations in top dry matter yield of the plant. The R^2 value of 0.84 suggests that this equation would have some value in predicting the top dry matter yield of sorghum when the concentrations of the 5 macronutrients in top tissue of the 50-day-old plants are known. In the 75-day-old plants, the presence of both K and Ca in top tissue affected top dry matter yield more than N, P and Mg. The same equation resulted in an R^2 value of only 0.66. The explanation for the lower R^2 value could be the production of more dry matter as time progressed. As the plants matured, the dry matter produced contained higher proportions of cellulose, lignin and other carbohydrates than protein compounds formed in the younger plants. Level of management and climatic factors are also known to play important roles in increasing R^2 value (Voss et al., 1970). Peck et al. (1969) obtained R^2 value of 0.45 when concentrations of N, P and K in leaf tissue of maize were used to estimate grain yield. However, when concentrations of 10 elements (N, P, K, Ca, Mg, B, Cu, Fe, Mn and Zn) were used in the equation, the resultant R^2 was 0.81. The inclusion of top tissue content of the measured micronutrients would have resulted in a higher R^2 value.

Effect of K/Mg Ratio in Growth Medium on Dry Matter Yield and Nutrient Contents

Nutrient contents. Table 27 shows that the increase in K/Mg ratio in the growth medium from 1.0 to 25.0 had no effect on top tissue N concentration of the 50-day-old plant. The increase in medium ratio resulted in marked increase in K and decrease in Mg, Ca and P concentrations. The decrease in Ca and Mg with a corresponding increase in K content as K/Mg ratio increased resulted in the observed increase in tissue K/(Ca + Mg) ratio. This trend was also observed in the 75-day-old plant (Table 28).

Data further indicate a near constancy of the sum equivalents of the 3 cations (K, Ca and Mg) within the crop in spite of the marked changes in the composition of the growth medium. This result suggests that the 3 cations are able to substitute for each other to some extent to maintain the dry matter yield.

Dry matter yield. Table 29 suggests that in spite of the reductions in top tissue P, Mg and Ca concentrations, dry matter yield was not affected by the increase in K/Mg ratio in growth medium. This result is not in agreement with the view expressed by Doll and Lucas (1973) that K/Mg ratio in the rooting medium is an important factor to be considered in interpreting the effect of Mg on yield. They reported that Mg deficiency could be induced by a wide K to Mg ratio in soil even when the absolute quantity of Mg in soil was far in excess of that required by the crop. They suggested that on an equivalent basis, the K/Mg ratio in the growth medium should be 1.5 and 5.0 on weight basis

Table 27. Effect of K to Mg ratio in the growth medium on the nutrient concentrations in top tissue of a sorghum hybrid and its parent lines at 50 days after seedling emergence.

K/Mg	N	P	K	Mg	Ca	K+Mg+Ca	K/(Mg+Ca)
Ratio	-------%--------		----------meq/100 g----------				Ratio
1.0	3.39 a*	1.01 a	105.2 b	74.8 a	50.2 a	230.2 a	0.84 d
2.5	3.32 a	0.84 ab	125.5 ab	61.3 ab	41.6 bc	228.5 a	1.22 cd
5.0	3.36 a	0.83 ab	137.2 a	52.6 ab	44.0 b	233.8 a	1.42 bc
10.0	3.36 a	0.76 b	146.4 a	43.1 b	37.0 cd	226.5 a	1.84 ab
25.0	3.48 a	0.72 b	149.8 a	37.0 b	35.0 d	220.9 a	2.08 a

* Within columns, means followed by a common letter are not different at 5% level according to Duncan's New Multiple Range test.

Table 28. Effect of K to Mg ratio in the growth medium on nutrient concentrations in top tissue of a sorghum hybrid and its parent lines at 75 days after seedling emergence.

K/Mg	N	P	K	Mg	Ca	K+Mg+Ca	K/(Mg+Ca)
Ratio	-------%--------		----------meq/100 g----------				Ratio
1.0	2.48 a*	0.67 a	75.2 b	65.2 a	47.1 a	187.6 a	0.67 c
2.5	2.41 a	0.65 a	107.6 ab	53.2 ab	35.5 c	196.3 a	1.21 bc
5.0	2.46 a	0.65 a	120.0 a	39.7 bc	38.9 b	198.6 a	1.53 b
10.0	2.45 a	0.61 b	139.9 a	32.1 bc	30.4 d	202.5 a	2.24 a
25.0	2.35 a	0.53 c	139.2 a	23.1 c	29.2 d	191.5 a	4.73 a

* Within columns, means followed by a common letter are not different at 5% level according to Duncan's New Multiple Range test.

Table 29. Effect of K to Mg ratio in nutrient medium on top dry matter yield of a sorghum hybrid and its parent lines at 3 harvest periods.

K/Mg	Top Tissue			Root Tissue		
	Days After Emergence			Days After Emergence		
	25	50	75	25	50	75
Ratio	g/plant			g/plant		
1.0	0.25 a*	3.37 b	17.32 a	0.06 a	0.88 b	4.90 a
2.5	0.29 a	4.42 a	20.99 a	0.08 a	1.03 a	5.05 a
5.0	0.27 a	4.04 ab	20.73 a	0.07 a	0.94 b	5.56 a
10.0	0.29 a	4.52 a	21.90 a	0.08 a	1.04 a	5.59 a
25.0	0.28 a	4.00 ab	20.75 a	0.07 a	0.95 ab	6.13 a

* Within columns, means followed by a common letter are not different at 5% level according to Duncan's New Multiple Range test.

for field crops. Martin and Pages (1969) indicated that plant growth was reduced when Mg in the soil exceeded 50% saturation. The reduction in yield probably resulted from low uptake of Ca.

Figure 46 shows that the top dry matter yield of sorghum was maintained even when the K/Mg ratio in the growth medium varied from 1.0 to 25.0. Variations in yield were, however, observed with changing K-Mg treatments. The result suggests that as long as the total amounts of Mg and K in the growth medium were not too low, the K/Mg ratio in the growth medium could vary widely without affecting top dry matter yield.

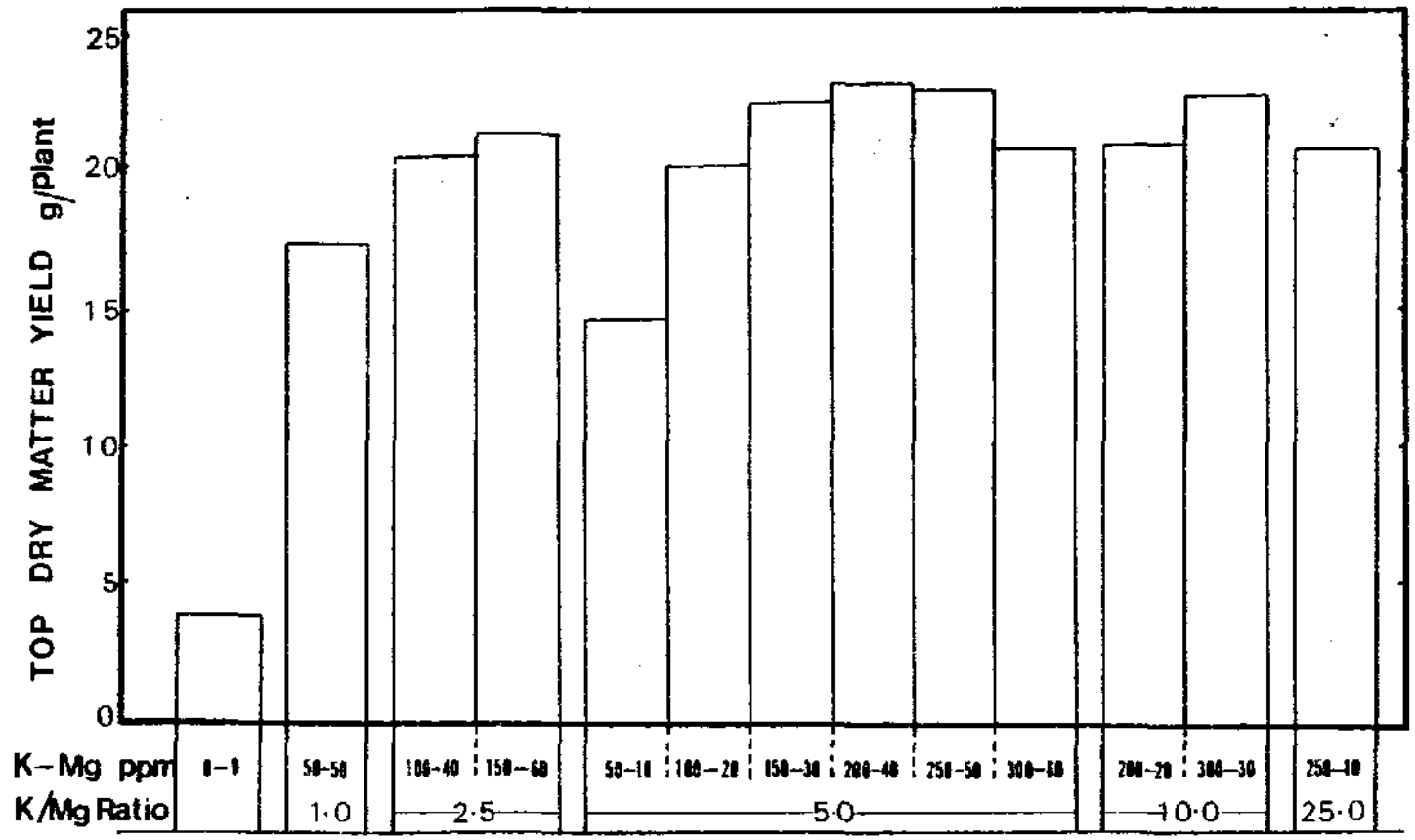


Fig. 46. The effect of applied potassium and magnesium and the K/Mg ratio in the nutrient solution on dry matter yield of a sorghum hybrid and its parent lines at 75 days after seedling emergence.

SUMMARY AND CONCLUSION

Plants were grown in free-draining plastic pots containing washed river sand. Nutrient treatments consisted of 7 levels each of potassium as KCl from 0-300 ppm at 50 ppm increments and magnesium applied as $MgCl_2$ from 0-60 ppm at 10 ppm increments. Seventeen of the possible treatment combinations were used. All other essential elements were applied as required.

Four seeds each of a sorghum hybrid 'RS 671' and its parent lines, 'Redlan' and 'Tx 415' were shown per pot and watered with distilled water until germination. Seedlings were thinned to 2 plants per pot 5 days after emergence. Each pot was watered with nutrient solution as required beginning 8 days after seedling emergence and continued on alternate days until final harvest. Whole plants were harvested at 25, 50 and 75 days after seedling emergence and dried samples of the top and root tissues were subjected to chemical analysis.

Variables measured included top and root dry weights and leaf area of the lower and upper leaves at each harvest. Top and root tissue concentrations of nitrogen, phosphorus, potassium, magnesium, calcium, zinc, iron and manganese were determined for the 50- and 75-day-old plants. Stem length and diameter of the 75-day-old plants were also measured.

Top dry matter yield was not affected by K application until 50 days after seedling emergence. At both the 50- and 75-day-sampling periods, top dry matter yield reached a peak at a K concentration of about 200 ppm in the growth medium. Magnesium application had no effect

until 75 days after seedling emergence. These results suggest that sorghum plant would respond to both K and Mg applications, especially when the levels of these elements were low in the growth medium. Even then the age or the growth stage of the plant becomes an important factor to be considered if response is to be demonstrated.

The effect of K application on yield was not dependent on the rate of Mg in the growth medium and vice versa. The optimum levels of the nutrients required for maximum yield were 195 and 38 ppm for K and Mg, respectively.

The response of root dry weight to the nutrients followed essentially the same trend as top dry weight. Again, the effects of Mg and K on root dry weight were independent.

The responses of stem diameter and stem length were similar to that of top dry matter yield. However, differences among lines and hybrid were noted for stem length. These differences are attributable to the inherent size differences among the lines and hybrid. Redlan is a relatively taller plant than Tx 415, and the resulting hybrid has a size between the two parent lines.

The response of nutrient accumulations in the plant to the nutrient variables varied, depending on the element, with the age of the plant and to some extent the line. Generally, however, reciprocal relationships between each of the applied nutrients and top tissue concentration of each of the measured nutrients may be explained largely by dilution, with yield response to low application rates of K and Mg. Antagonism, where demonstrated, was found mostly at high rates of K or Mg application.

The depressing effect of K on N absorption was due mostly to dilution. Magnesium application appeared to decrease N concentration only at the early growth stage of the plant. As the plant became more mature, Mg application had no effect on N absorption in both lines but reduced N concentration in the hybrid. The response to Mg may have been due to lack of N uptake at zero level of Mg applications and/or to dilution effect resulting from dry matter response to low rates of Mg application. The positive K-Mg interactive effect on the hybrid indicates that the effect of K on N absorption increased as the rate of Mg in the growth medium increased and vice versa.

Top tissue N uptake increased with K additions up to 200 ppm at both harvests. Magnesium application did not have any effect until 75 days after seedling emergence when maximum uptake occurred at about 40 ppm.

Potassium application decreased top tissue P concentration at both harvests, but P uptake was increased to a maximum, and then fell when nutrient K was increased above 200 ppm. This suggests that the depressive effect of K on P absorption was due mainly to dilution at low rates and antagonism occurring at high rates of K application. Magnesium application did not affect P concentration in the 50-day-old plants. However, both the P concentration and uptake in the 75-day-old plants increased with Mg addition. This indicated a synergistic effect of Mg on P absorption. The positive K-Mg interactive effect on P absorption in Redlan is indicative of increased P absorption as rates of K and Mg in the growth medium increased.

Potassium application increased both K concentration and uptake at both harvests. Magnesium application decreased K concentration only in the 75-day-old plants. Potassium uptake was decreased only at high rates of Mg application. The observed negative K-Mg interactive effect on RS 671 and Redlan indicates that the effect of K on K absorption decreased as the rate of Mg in the nutrient medium increased. This suggests that Mg had a slight antagonistic effect on K absorption.

Within any Mg rate and at any sampling period, application of any rate of K reduced top Mg concentration and uptake. Magnesium uptake was reduced in spite of the increase in dry matter yield, particularly in the 75-day-old plants. The decrease in Mg absorption was more pronounced as the concentration of K in the nutrient solution increased, suggesting a strong antagonistic effect of K on Mg absorption. Magnesium absorption increased directly in proportion to the amounts of Mg applied in the growth medium. However, due to the strong K-Mg interactive effect, the stimulating effect of Mg decreased as K rates in the nutrient solution increased.

Strong antagonistic effects of K on Ca and Mg on Ca were demonstrated. Although each applied nutrient had a strong depressing effect on Ca absorption, the addition of both nutrients in the growth medium reduced the effectiveness of each other in decreasing Ca concentration. This positive interactive effect was observed, particularly on the 50-day-old plants. Essentially, application of either K or Mg had no effect on top tissue Ca uptake.

High rates of K depressed Zn absorption, but the effect of Mg on Zn uptake was apparently synergistic.

Application of K and/or Mg had no effect on Fe concentration or uptake in the plant.

Each of the applied nutrients depressed Mn uptake. The decrease in Mn uptake in spite of the increase in dry matter yield indicates an antagonistic effect of Mg on Mn absorption. However, the depressing effect of Mg decreased as the rate of K in the nutrient solution increased.

Forage cation ratio, a measure of the plants' possibility of causing grass tetany in animals, was observed to increase directly in proportion to the amounts of K in the nutrient solution. Although application of low rates of Mg decreased the ratio, a substantial increase in the ratio resulted when high rates of Mg was applied along with high K rates. The likelihood of grass tetany in animals fed with more mature plants is higher than those fed on relatively younger plants, particularly if the plants are grown in high K and Mg medium.

Simple correlation analysis showed that nutrient K was correlated more closely with total dry weight of lower leaves than with any of the other variables measured at second harvest. In the 75-day-old plants, however, nutrient K was correlated more closely with stem diameter.

There was no relationship between applied Mg and any of the measured variables at the second harvest. At 75 days, Mg content was, however, positively correlated with dry weight of upper and lower leaves, stem dry weight, stem diameter and length.

Percent K in top tissue was negatively correlated with tissue N, Ca, Mg, Zn and Fe. This suggests that the presence of K in the plant

tissue antagonized the translocation of these ions in the plant, apart from interfering with their absorption.

Applied Mg was positively correlated with tissue P and Zn but negatively correlated with tissue Ca and Mn. However, a positive correlation was noted between plant tissue Mg and tissue N, P, Ca and Zn. This indicates that applied Mg enhanced absorption and translocation of both P and Zn, but the antagonistic effect of Mg on Ca reported earlier was probably confined to lack of Ca uptake. In the plant tissue, translocation of Ca was enhanced by the presence of Mg in the tissue.

Plant N was positively correlated with tissue P, Mg, Ca, Fe and Mn but negatively correlated with tissue K.

Plant P was positively correlated with tissue Mg, Zn and Ca but had no relationship with plant K, Fe and Mn. Plant Ca was positively correlated with plant Zn, Fe and Mn.

Simple correlation analysis showed a negative correlation between top dry matter yield and each of tissue N, P, Mg and Ca contents. However, the partial regression coefficients indicated that tissue N in the 50-day-old plants affected dry matter yield relatively more than did tissue P, Mg, Ca and K. At 75 days, tissue K and Ca affected yield more than N, Mg, Ca and K.

Although the increase in the K to Mg ratio in the nutrient solution markedly decreased plant tissue P, Mg and Ca, dry matter yield was not adversely affected. However, dry matter yield changed with changes in concentrations of K and Mg in the nutrient solution. This indicates that as long as the absolute amounts of Mg and K in the growth medium

are adequate to satisfy the demand of the plant, the K/Mg ratio in the growth medium could vary widely without affecting the yield of the plant.

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APPENDIX

Table A1. Mean squares from the analysis of variance of dry matter yield per plant at 25, 50 and 75 days after seedling emergence.

	Time Df=1	Treatment Df=16	Lines Df=2	T x L Df=32
Dry Matter-Top				
First harvest (25)	4.315*	0.012	0.528	0.010
Second harvest (50)	857.823*	8.998	61.501	1.200
Third harvest (75)	1145.667*	522.027	561.230	16.222
Dry Matter-Root				
First harvest (25)	0.054*	0.002	0.049*	0.003
Second harvest (50)	47.253*	0.685*	9.049*	0.182
Third harvest (75)	401.006*	50.222*	112.267*	3.893*

*Indicates a significant difference at the 0.05 probability level.

Table A2. Mean squares from the analysis of variance of the leaf area per plant, stem diameter and length of stem.

	Time Df=1	Treatment Df=16	Lines Df=2	T x L Df=32
Leaf Area				
First harvest (25)	257058.3*	288.14	34543.12	230.21
Second harvest (50)	16033474.4*	266090.25	1649405.96	34267.61
Third harvest (75)	5773180.5*	4414178.78	5005618.74	226219.72
Stem Diameter				
Third harvest (75)	0.45*	0.61*	1.34*	0.03
Length of Stem				
Third harvest (75)	1.70	2366.60*	19120.19*	468.30*

*Indicates a significant difference at the 0.05 probability level.

Table A3. Mean squares from the analysis of variance for top tissue contents of nitrogen, phosphorus, potassium, magnesium and calcium at 50 and 75 days after seedling emergence.

	Time Df=1	Treatment Df=16	Lines Df=2	T x L Df=32
Nitrogen				
Second harvest (50)	28.515*	0.390	0.655	0.143
Third harvest (75)	3.898*	2.383*	3.260*	0.121*
Phosphorus				
Second harvest (50)	4.690*	0.523*	0.361	0.216
Third harvest (75)	1.997*	0.192*	0.395	0.014
Potassium				
Second harvest (50)	127.538*	26.137*	2.387	1.424
Third harvest (75)	186.493*	35.903*	9.162*	1.501
Magnesium				
Second harvest (50)	0.062*	0.703*	0.039	0.037
Third harvest (75)	0.140*	1.681*	0.325*	0.057*
Calcium				
Second harvest (50)	0.655*	0.758*	0.524*	0.035
Third harvest (75)	3.641*	1.605*	0.547	0.033

*Indicates a significant difference at the 0.05 probability level.

Table A4. Mean squares from the analysis of variance for root tissue contents of nitrogen, phosphorus, potassium, magnesium and calcium at 50 and 75 days after seedling emergence.

	Time Df=1	Treatment Df=16	Lines Df=2	T x L Df=32
Nitrogen				
Second harvest (50)	---	0.906*	0.871*	0.078*
Third harvest (75)	2.684*	0.584*	0.443*	0.095
Phosphorus				
Second harvest (50)	---	0.010	0.094*	0.006
Third harvest (75)	0.145*	0.011*	0.070*	0.005
Potassium				
Second harvest (50)	---	5.453*	0.517	0.666
Third harvest (75)	4.205*	12.764*	0.284	0.667
Magnesium				
Second harvest (50)	---	0.115*	0.072*	0.006
Third harvest (75)	0.002	0.153*	0.003	0.014*
Calcium				
Second harvest (50)	---	0.045*	0.112*	0.016
Third harvest (75)	0.548*	0.112*	0.423*	0.034

*Indicates a significant difference at the 0.05 probability level.

Table A5. Mean squares from the analysis of variance for efficiency of nutrients' uptake by a sorghum hybrid and its parent lines at 25 and 50 days after seedling emergence.

	Time Df=1	Treatment Df=16	Lines Df=2	T x L Df=32
Nitrogen				
Second harvest (50)	2851.5*	38.9	65.5	14.3
Third harvest (75)	389.8*	238.3*	326.0*	12.0*
Phosphorus				
Second harvest (50)	469.0*	52.3	36.1	21.6
Third harvest (75)	199.7*	23.2*	39.5	1.4
Potassium				
Second harvest (50)	12753.8*	2613.7*	238.7	142.4
Third harvest (75)	18649.3*	3590.3*	916.0*	150.1
Magnesium				
Second harvest (50)	6.2*	70.3*	3.9	3.7
Third harvest (75)	14.0*	168.1*	32.1*	5.7*
Calcium				
Second harvest (50)	65.5*	75.8*	52.4*	4.1
Third harvest (75)	364.1*	160.5*	54.7	3.3

*Indicates a significant difference at the 0.05 probability level.

Table A6. Concentrations and uptake of nitrogen, phosphorus, potassium, calcium and magnesium in top tissues of 'RS 671,' 'Redlan' and 'Tx 415' at 50 and 75 days after seedling emergence (average for all treatments and two experiments).

Variables	Days After Seedling Emergence					
	50			75		
	RS 671	Redlan	Tx 415	RS 671	Redlan	Tx 415
Concentration (%)						
Nitrogen	3.41	3.40	3.57	2.53	2.48	2.88
Phosphorus	0.83	0.96	0.95	0.63	0.58	0.73
Potassium	4.67	4.60	4.96	3.94	4.10	4.64
Magnesium	0.71	0.66	0.68	0.56	0.49	0.63
Calcium	1.01	0.85	1.00	0.90	0.75	0.91
Uptake (mg/plant)						
Nitrogen	148.3	101.9	104.3	466.0	393.5	366.1
Phosphorus	34.3	26.0	26.2	116.3	99.2	96.4
Potassium	208.4	147.1	148.3	800.0	722.9	679.8
Magnesium	31.2	19.1	21.2	103.5	77.0	80.1
Calcium	44.6	24.3	29.4	161.9	111.3	119.3

Table A7. Dry matter yields and other yield variables of a sorghum hybrid and its parent lines at 25, 50 and 75 days after seedling emergence (average for all treatments and 2 experiments).

Variable	Days After Seedling Emergence								
	25			50			75		
	RS 671	Redlan	Tx 415	RS 671	Redlan	Tx 415	RS 671	Redlan	Tx 415
Dry Matter (g/plant)									
Top Total	0.38	0.24	0.22	4.83	3.25	3.12	19.5	17.4	13.9
Leaves	0.38	0.24	0.22	3.48	2.31	2.36	14.9	12.1	12.0
Stem	--	--	--	1.35	0.94	0.76	4.6	5.3	1.8
Roots	0.08	0.05	0.07	1.12	0.50	0.71	4.64	2.56	3.08
Leaf Area (cm^2)	99.0	64.0	56.7	877.4	584.2	639.8	2166.3	1631.2	1976.3
Top/Root Ratio	4.6	4.5	3.1	4.3	6.6	4.4	4.2	6.8	4.5
Stem Length (cm)	--	--	--	--	--	--	36.0	46.5	13.7
Stem Diameter (cm)	--	--	--	--	--	--	1.1	0.9	1.2

Table A8. Efficiency of nutrients' use by a sorghum hybrid and its parent lines at 50 and 75 days after seedling emergence (average for treatments and 2 experiments).

Line	Days	N	P	K	Mg	Ca
		---Efficiency of use (mg/g top dry matter)----				
RS 671	50	34.1	8.3	46.7	7.1	10.1
	75	25.8	6.3	39.4	5.6	9.0
Redlan	50	34.0	9.6	46.0	6.6	8.5
	75	24.8	5.8	41.0	4.9	7.5
Tx 415	50	35.7	9.5	49.5	6.8	10.9
	75	28.8	7.3	46.4	6.3	9.1

Table A9. Regression coefficients and R^2 values showing the effect of potassium and magnesium concentrations in nutrient solution on nitrogen concentration in root tissue of a sorghum hybrid and its parent lines at 50 and 75 days after seedling emergence.

Variable	Intercept	K	Mg	K^2	Mg^2	K x Mg	R^2
Second Harvest (50 days)							
RS 671	1.40	-0.060*	0.016	0.036*	0.000	0.000	0.65
Redlan	1.60	-0.070*	-0.013	0.015	0.007	0.000	0.38
Tx 415	1.73	-0.034	0.001	0.014	-0.001	-0.004	0.36
Hybrid & Lines	1.57	-0.054*	0.009	0.022*	0.002	-0.001	0.63
Third Harvest (75 days)							
RS 671	1.47	-0.093*	-0.022	0.020*	0.022*	0.008	0.84
Redlan	1.48	0.056*	-0.023	0.035*	0.018	0.003	0.65
Tx 415	1.70	0.009	0.029	0.014	-0.015	-0.008	0.53
Hybrid & Lines	1.54	-0.047*	-0.002	0.024*	0.009	0.000	0.82

*Indicates a significant difference at the 0.05 probability level.

Table A10. Regression coefficients and R^2 values showing the effect of potassium and magnesium concentrations in nutrient solution on nitrogen uptake by root tissue of a sorghum hybrid and its parent lines at 50 and 75 days after seedling emergence.

Variable	Intercept	K	Mg	K^2	Mg^2	K x Mg	R^2
Second Harvest (50 days)							
RS 671	35.8	1.54*	-0.66	-1.45*	-0.51	-0.19	0.69
Redlan	18.9	0.38	-0.28	-0.57*	-0.62*	-0.08	0.80
Tx 415	28.6	0.34	0.51	-0.60	-0.55	-0.26	0.34
Hybrid & Lines	27.5	0.72	-0.08	-0.89*	-0.50*	-0.15	0.77
Third Harvest (75 days)							
RS 671	120.5	8.8*	4.1	-4.8*	-2.9	0.22	0.74
Redlan	70.3	4.1*	4.1*	-2.0	-2.6*	0.55	0.74
Tx 415	103.2	8.2*	3.6	-4.2*	-3.6*	0.78	0.81
Hybrid & Lines	98.3	7.1*	3.9	-3.7*	-3.1*	0.53	0.80

*Indicates a significant difference at the 0.05 probability level.

Table A11. Regression coefficients and R^2 values showing the effect of potassium and magnesium concentrations in nutrient solution on phosphorus concentration in root tissue of a sorghum hybrid and its parent lines at 50 and 75 days after seedling emergence.

Variable	Intercept	K	Mg	K^2	Mg^2	K x Mg	R^2
Second Harvest (50 days)							
RS 671	0.28	0.003	0.006	0.007	-0.0007	0.002	0.28
Redlan	0.37	-0.006	0.0007	0.002	0.004	-0.001	0.10
Tx 415	0.37	0.004	-0.009	0.005	-0.003	0.000	0.24
Hybrid & Lines	0.33	-0.001	-0.002	0.005	0.000	0.000	0.24
Third Harvest (75 days)							
RS 671	0.28	-0.009*	0.0007	0.002	0.003	0.0006	0.42
Redlan	0.32	-0.003	0.0007	0.003	0.001	0.004	0.29
Tx 415	0.35	0.005	0.002	-0.001	0.004	-0.002	0.28
Hybrid & Lines	0.33	0.002	0.005	0.001	0.002	0.003	0.19

*Indicates a significant difference at the 0.05 probability level.

Table A12. Regression coefficients and R^2 values showing the effect of potassium and magnesium concentrations in nutrient solution on phosphorus uptake by root tissue of a sorghum hybrid and its parent lines and 50 and 75 days after seedling emergence.

Variable	Intercept	K	Mg	K^2	Mg^2	K x Mg	R^2
Second Harvest (50 days)							
RS 671	6.7	0.49*	-0.04	-0.26*	-0.09	-0.02	0.72
Redlan	4.4	0.14	0.03	-0.15*	-0.15*	-0.02	0.75
Tx 415	6.0	0.28*	-0.07	-0.07	-0.19*	-0.06	0.59
Hybrid & Lines	5.6	0.24*	-0.04	-0.17*	-0.11*	-0.00	0.82
Third Harvest (75 days)							
RS 671	22.0	1.94*	0.88	-0.83*	-0.56	0.03	0.76
Redlan	15.4	1.10*	1.05*	-0.50*	-0.56*	0.22	0.82
Tx 415	20.0	1.74*	0.72	-0.86*	-0.64*	0.25	0.87
Hybrid & Lines	19.2	1.62*	0.89*	-0.69*	-0.58*	0.17	0.83

*Indicates a significant difference at the 0.05 probability level.

Table A13. Regression coefficients and R^2 values showing the effect of potassium and magnesium concentrations in nutrient solution on potassium concentration in root tissue of a sorghum hybrid and its parent lines at 50 and 75 days after seedling emergence.

Variable	Intercept	K	Mg	K^2	Mg^2	K x Mg	R^2
Second Harvest (50 days)							
RS 671	1.77	0.355*	-0.051	-0.019	0.017	-0.053*	0.94
Redlan	1.81	0.389*	0.020	0.020	0.055	-0.024	0.67
Tx 415	2.11	0.414*	-0.126	-0.028	0.001	-0.070*	0.80
Hybrid & Lines	1.90	0.386*	-0.053	-0.009	0.024	-0.049*	0.89
Third Harvest (75 days)							
RS 671	2.77	0.416*	-0.023	-0.065	0.016	0.025	0.65
Redlan	2.54	0.465*	0.014	-0.086*	0.079*	0.031	0.88
Tx 415	2.44	0.507*	-0.033	-0.016	0.038	-0.034	0.91
Hybrid & Lines	2.59	0.454*	-0.007	-0.055*	0.045	0.003	0.92

*Indicates a significant difference at the 0.05 probability level.

Table A14. Regression coefficients and R^2 values showing the effect of potassium and magnesium concentrations in nutrient solution on potassium uptake by root tissue of a sorghum hybrid and its parent lines at 50 and 75 days after seedling emergence.

Variable	Intercept	K	Mg	K^2	Mg^2	K x Mg	R^2
Second Harvest (50 days)							
RS 671	41.8	7.60*	-1.18	-1.78*	0.16	-0.54	0.94
Redlan	21.9	3.61*	0.18	-0.31	-0.65	-0.23	0.62
Tx 415	34.0	5.89*	-1.11	-0.56	-0.78	-1.12	0.71
Hybrid & Lines	32.6	5.69*	-0.70	-0.89*	-0.39	-0.66*	0.90
Third Harvest (75 days)							
RS 671	176.8	35.2*	6.0	-4.6	-4.1	0.7	0.87
Redlan	105.3	18.8*	9.7	-2.4	-2.6	2.9	0.91
Tx 415	137.2	24.6*	6.5	-3.9	-4.2*	2.2	0.89
Hybrid & Lines	140.0	26.2*	7.4*	-3.6*	-3.7*	1.9	0.93

*Indicates a significant difference at the 0.05 probability level.

Table A15. Regression coefficients and R^2 values showing the effect of potassium and magnesium concentrations in nutrient solution on magnesium concentration in root tissue of a sorghum hybrid and its parent lines at 50 and 75 days after seedling emergence.

Variable	Intercept	K	Mg	K^2	Mg^2	K x Mg	R^2
Second Harvest (50 days)							
RS 671	0.30	-0.025*	0.051*	-0.003	-0.003	-0.003	0.95
Redlan	0.39	-0.028*	0.050*	-0.011*	-0.007	-0.004	0.86
Tx 415	0.31	-0.006	0.041*	-0.008	-0.006	0.006	0.78
Hybrid & Lines	0.32	-0.021*	0.046*	-0.006	-0.004	-0.0009	0.89
Third Harvest (75 days)							
RS 671	0.31	-0.009	0.050*	-0.010	-0.002	-0.0004	0.75
Redlan	0.29	-0.021*	0.051*	-0.004	-0.002	-0.005	0.87
Tx 415	0.32	-0.012	0.035*	-0.007	-0.006	0.004	0.82
Hybrid & Lines	0.31	-0.014*	0.045*	-0.007*	-0.004	-0.002	0.89

*Indicates a significant difference at the 0.05 probability level.

Table A16. Regression coefficients and R^2 values showing the effect of potassium and magnesium concentrations in nutrient solution on magnesium uptake by root tissue of a sorghum hybrid and its parent lines at 50 and 75 days after seedling emergence.

Variable	Intercept	K	Mg	K^2	Mg^2	K x Mg	R^2
Second Harvest (50 days)							
RS 671	6.9	-0.05	0.72*	-0.38*	-0.11	0.01	0.80
Redlan	4.1	-0.18	0.28*	-0.09	-0.20*	-0.06	0.73
Tx 415	6.7	-0.31	0.58*	-0.20	-0.20	-0.05	0.53
Hybrid & Lines	5.9	-0.22	0.53*	=0.23*	-0.17*	0.01	0.78
Third Harvest (75 days)							
RS 671	23.9	1.08	3.28*	-1.26*	-0.53	0.08	0.68
Redlan	14.6	0.13	1.89*	-0.74*	-0.41	0.05	0.73
Tx 415	18.6	0.95	1.87*	-1.10*	-0.54	0.34	0.77
Hybrid & Lines	18.7	0.74	2.42*	-1.03*	-0.47	0.15	0.83

*Indicates a significant difference at the 0.05 probability level.

Table A17. Regression coefficients and R^2 values showing the effect of potassium and magnesium concentrations in nutrient solution on calcium concentration on root tissue of a sorghum hybrid and its parent lines at 50 and 75 days after seedling emergence.

Variable	Intercept	K	Mg	K^2	Mg^2	K x Mg	R^2
Second Harvest (50 days)							
RS 671	0.49	-0.034*	-0.022	-0.015*	0.009	0.001	0.62
Redlan	0.42	-0.031*	-0.008	0.0004	-0.002	-0.004	0.39
Tx 415	0.56	-0.033*	-0.023	-0.0004	-0.007	-0.006	0.58
Hybrid & Lines	0.47	-0.026*	-0.011	-0.004	-0.000	-0.005	0.49
Third Harvest (75 days)							
RS 671	0.70	-0.032*	0.001	-0.023*	0.0002	0.003	0.62
Redlan	0.47	-0.024*	-0.018	-0.0003	-0.008	0.005	0.57
Tx 415	0.66	-0.006	-0.021	-0.027*	0.001	0.003	0.69
Hybrid & Lines	0.61	-0.020*	-0.013	-0.017*	-0.002	0.003	0.74

*Indicates a significant difference at the 0.05 probability level.

Table A18. Regression coefficients and R^2 values showing the effect of potassium and magnesium concentrations in nutrient solution on calcium uptake by root tissue of a sorghum hybrid and its parent lines at 50 and 75 days after seedling emergence.

Variable	Intercept	K	Mg	K^2	Mg^2	K x Mg	R^2
Second Harvest (50 days)							
RS 671	11.1	0.04	-0.35	-0.65*	-0.15	-0.08	0.66
Redlan	5.2	-0.01	-0.15	-0.19	-0.19	-0.29	0.57
Tx 415	9.6	-0.30	-0.26	-0.23	-0.29	-0.10	0.24
Hybrid & Lines	8.8	-0.04	-0.22	-0.37*	-0.20	-0.07	0.70
Third Harvest (75 days)							
RS 671	52.7	1.96	1.43	-3.03*	-1.19	-0.29	0.65
Redlan	22.5	0.49	0.45	-0.84	-1.01*	0.13	0.57
Tx 415	40.5	1.88	0.59	-2.54*	-1.26	0.30	0.73
Hybrid & Lines	38.5	1.49	0.85	-2.10*	-1.16*	0.05	0.80

*Indicates a significant difference at the 0.05 probability level.

Table A19. Regression coefficients and R^2 values showing the effect of potassium and magnesium concentrations in nutrient solution on the efficiency of nitrogen use by a sorghum hybrid and its parent lines at 50 and 75 days after seedling emergence.

Variable	Intercept	K	Mg	K^2	Mg^2	K x Mg	R^2
Second Harvest (50 days)							
RS 671	32.8	-0.42	-0.33	0.11	-0.05	0.14	0.17
Redlan	32.7	-0.39*	-0.06	0.24*	0.05	-0.01	0.74
Tx 415	35.5	-0.37*	-0.37*	0.08	-0.02	0.12	0.59
Hybrid & Lines	34.0	-0.39	-0.25	0.14	-0.01	0.09	0.45
Third Harvest (75 days)							
RS 671	23.4	-1.10*	-0.50*	0.48*	-0.02	0.28*	0.84
Redlan	23.0	-1.77*	-0.06	0.61*	0.04	-0.00	0.84
Tx 415	25.7	-1.67*	-0.33	0.71*	0.01	0.19	0.79
Hybrid & Lines	23.7	-1.52*	-0.30	0.60*	0.01	0.16	0.85

*Indicates a significant difference at the 0.05 probability level.

Table A20. Regression coefficients and R^2 values showing the effect of potassium and magnesium concentrations in nutrient solution on the efficiency of phosphorus use by a sorghum and its parent lines at 50 and 75 days after seedling emergence.

Variable	Intercept	K	Mg	K^2	Mg^2	K x Mg	R^2
Second Harvest (50 days)							
RS 671	7.3	-0.65*	-0.00	0.21*	0.01	0.08*	0.90
Redlan	8.4	-0.73*	0.12	0.05	0.02	-0.02	0.83
Tx 415	8.8	-0.51*	0.05	0.10	0.02	0.10*	0.76
Hybrid & Lines	8.2	-0.62*	0.05	0.12*	0.01	0.05	0.88
Third Harvest (75 days)							
RS 671	5.9	-0.37*	0.33*	0.16	-0.07	-0.04	0.67
Redlan	6.0	-0.35*	0.36*	0.02	-0.05	-0.02	0.89
Tx 415	7.4	-0.45*	0.38*	0.09	-0.11	-0.02	0.64
Hybrid & Lines	6.4	-0.39*	0.35*	0.09	-0.08	-0.03	0.76

*Indicates a significant difference at the 0.05 probability level.

Table A21. Regression coefficients and R^2 values showing the effect of potassium and magnesium concentrations in nutrient solution in the efficiency of potassium use by a sorghum hybrid and its parent lines at 50 and 75 days after seedling emergence.

Variable	Intercept	K	Mg	K^2	Mg^2	K x Mg	R^2
Second Harvest (50 days)							
RS 671	52.0	6.30*	-0.44	-1.26*	0.06	0.06	0.90
Redlan	52.8	5.19*	-0.54	-1.67*	0.12	-0.10	0.81
Tx 415	58.3	6.75*	0.10	-1.31*	-0.69	-0.61	0.90
Hybrid & Lines	54.3	6.09*	-0.29	-1.41*	-0.17	-0.22	0.94
Third Harvest (75 days)							
RS 671	42.9	6.77*	-0.56	-0.93*	0.14	-0.10	0.93
Redlan	47.8	6.03*	-1.66*	-2.08*	0.51	-0.41	0.91
Tx 415	51.7	9.47*	-0.87	-1.32*	0.10	-0.23	0.96
Hybrid & Lines	47.4	7.43*	-1.04*	-1.44*	0.25	-0.24	0.97

*Indicates a significant difference at the 0.05 probability level.

Table A22. Regression coefficients and R^2 values showing the effect of potassium and magnesium concentrations in nutrient solution on the efficiency of magnesium use by a sorghum hybrid and its parent lines at 50 and 75 days after seedling emergence.

Variable	Intercept	K	Mg	K^2	Mg^2	K x Mg	R^2
Second Harvest (50 days)							
RS 671	6.3	-0.96*	0.69*	0.19*	-0.01	-0.13*	0.96
Redlan	5.9	-1.04*	0.51*	0.26*	-0.09	-0.11	0.89
Tx 415	7.0	-0.57*	0.48*	0.12*	-0.16*	-0.07	0.90
Hybrid & Lines	6.4	-0.86*	0.56*	0.19*	-0.09	-0.10*	0.96
Third Harvest (75 days)							
RS 671	5.1	-0.87*	1.02*	0.27*	-0.15*	-0.26*	0.95
Redlan	3.8	-1.01*	1.07*	0.23	0.03	-0.32*	0.84
Tx 415	5.3	-1.09*	1.18*	0.32*	-0.15	-0.30*	0.88
Hybrid & Lines	4.8	-0.98*	1.09*	0.27*	-0.09	-0.29*	0.94

*Indicates a significant difference at the 0.05 probability level.

Table A23. Regression coefficients and R^2 values showing the effect of potassium and magnesium concentrations in nutrient solution on the efficiency of calcium use by a sorghum hybrid and its parent lines at 50 and 75 days after seedling emergence.

Variable	Intercept	K	Mg	K^2	Mg^2	K x Mg	R^2
Second Harvest (50 days)							
RS 671	8.8	-1.25*	-0.39*	0.21*	0.08	0.09*	0.97
Redlan	7.4	-1.00*	-0.33*	0.23*	0.03	0.12*	0.89
Tx 415	9.6	-0.86*	-0.09	0.12	-0.04	-0.03	0.81
Hybrid & Lines	8.6	-1.04*	-0.24*	0.20*	0.00	0.06	0.95
Third Harvest (75 days)							
RS 671	9.0	-1.53*	-0.28*	0.31*	-0.08	0.09	0.96
Redlan	5.4	-1.47*	-0.36*	0.45*	0.03	0.09	0.93
Tx 415	7.9	-1.45*	-0.31	0.30*	-0.01	0.16*	0.90
Hybrid & Lines	7.1	-1.48*	-0.32*	0.36*	-0.03	0.11*	0.96

*Indicates a significant difference at the 0.05 probability level.

Table A24. Simple correlation coefficients for the relationships between growth medium variables, nutrient uptake, ratio of nutrients and total cations in top tissue and top dry matter yield of a sorghum hybrid and its two parent lines at 50 days after seedling emergence.

	Growth Medium			Nutrient Uptake/Plant					Ratio in Plant		Total Cations	Dry Matter
	K	Mg	K/Mg	N	P	K	Mg	Ca	K/Mg	K/(Ca+Mg)		
K	1.000	---	---	0.186	-0.031	0.498***	-0.160*	-0.142*	0.589***	0.608***	0.152*	0.198**
Mg		1.000	---	-0.033	0.083	-0.052	0.286***	-0.103	-0.306***	-0.157*	0.114	-0.021
K/Mg			1.000	0.027	-0.067	0.143	-0.203*	-0.058	0.447***	0.325***	-0.031	0.029
N				1.000	0.853***	0.805***	0.747***	0.829***	0.128	0.103	-0.359***	0.965***
P					1.000	0.569***	0.792***	0.788***	-0.167*	-0.133	-0.364***	0.833***
K						1.000	0.428***	0.485***	0.490***	0.463***	-0.018	0.891***
Mg							1.000	0.759***	-0.345***	-0.294***	-0.251**	0.750***
Ca								1.000	-0.143*	-0.248**	-0.352***	0.825***
K/Mg									1.000	0.873***	0.179*	0.120
K/(Ca+Mg)										1.000	0.208**	0.090
Total cations											1.000	-0.429***
Dry matter												1.000

*, **, *** Significant at the .05, .01 and .001 levels of probability, respectively.

Table A.5. Simple correlation coefficients for the relationships between growth medium variables, nutrient uptake, ratio of nutrients and total cations in top tissue and top dry matter yield of a sorghum hybrid and its parent lines at 75 days after seedling emergence.

	Growth Medium			Nutrient Uptake/Plant					Ratio in Plant		Total Cations	Dry Matter
	K	Mg	K/Mg	N	P	K	Mg	Ca	K/Mg	K/(Ca+Mg)		
K	1.000	---	---	0.414***	0.327***	0.619***	0.015	0.020	0.392***	0.707***	0.160*	0.447***
Mg		1.000	---	0.213**	0.320***	0.101	0.556***	0.088	-0.440***	-0.286***	0.241**	0.222***
K/Mg			1.000	0.053	-0.101	0.296**	-0.386***	-0.072	0.645***	0.414***	0.018	0.078
N				1.000	0.932***	0.743***	0.729***	0.779***	-0.288***	-0.054	-0.061	0.964***
P					1.000	0.680***	0.753***	0.711***	-0.364***	-0.116	0.013	0.881***
K						1.000	0.352***	0.332***	-0.005	0.425***	0.352***	0.707***
Mg							1.000	0.710***	-0.438***	-0.391***	0.073	0.689***
Ca								1.000	0.312***	-0.365***	-0.201**	0.779***
K/Mg									1.000	0.757***	0.070	-0.236**
K/(ca+Mg)										1.000	0.350***	-0.051
Total cations											1.000	-0.194*
Dry matter												1.000

*, **, *** Significant at the .05, .01 and .001 levels of probability, respectively.