ACCUMULATION AND DISTRIBUTION OF ZN, CU, MN, FE, MG, AND CA IN GRAIN SORGHUM, SORGHUM BICOLOR (L.) MOENCH

by

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INTRODUCTION

Grain sorghum, *Sorghum bicolor* (L.) Moench, has become increasingly important as a feed grain in the United States since the development and release of hybrids in the 1950's. Production more than doubled by the second year after their release. The fact that grain sorghum can be adapted to a wide range of cropping systems contributes to its success. It is profitable to grow in hot and relatively dry climatic conditions where other crops may fail without supplementary water and it responds well to irrigation and fertilizers for added profits.

The development of hybrids has given grain sorghum a high genetic potential for yielding ability, but environmental conditions play a significant role in determining what level of yields will be obtained. Management and cultural practices are effective methods of controlling environmental conditions to provide a more favorable environment for growth. To obtain maximum benefits from these practices it will be essential to understand how the plant grows and develops so as to apply appropriate and timely practices.

Nutrient uptake and distribution are important facets of sorghum growth and development. An understanding of these factors is helpful in making decisions about management and cultural practices. Information learned from studying nutrient uptake and distribution which will have an effect on management and cultural practices include 1) the amount of nutrient required to produce the crop, 2) the rate of uptake at various stages of growth, 3) the proportion of nutrients that move into the harvested portion of the crop which must be replaced eventually, and 4) the nutritional quality of the crop for human or livestock consumption.

The investigation of nutrient uptake and distribution may provide information about the internal functioning of the sorghum plant. Also, methods for conducting tissue testing to make valid inferences about the nutrients in relation to deficiency symptoms and fertility status of the soil may be better understood through the study of nutrient uptake and distribution.

Nitrogen, P, and K seasonal uptake and distribution have been reported in some crops, but secondary and micronutrient uptake and distribution have had little reported work. Much of the work involving secondary and micronutrient uptake has been on fertility trials and in determining nutrient sufficiency limits. This work has dealt primarily with certain plant parts and stages of growth, and not on nutrient uptake and distribution throughout the entire growing season.

The lack of work on secondary and micronutrients probably is because they generally have not been found to be deficient in soils for adequate plant growth as long as N, P, and K have been. Development of better adapted hybrids and the increase in irrigated sorghum have resulted in greater nutrient requirements recently. Several areas in the country have encountered secondary and micronutrient deficiency symptoms; thus, interest in these nutrients has increased and they will assume an ever increasing role in management and cultural practices. It will be important to understand the uptake and distribution of the nutrients for application of management and cultural practices accordingly.

This study was conducted to investigate the weekly growth and nutrient uptake and distribution patterns of Zn, Cu, Mn, Fe, Mg, and Ca in whole plants and plant parts of two grain sorghum hybrids throughout the growing season.

REVIEW OF LITERATURE

Vanderlip and Reeves (23) have defined ten growth stages of grain sorghum from emergence to physiological maturity: (1) emergence; (2) collar of third leaf visible; (3) collar of fifth leaf visible; (4) growing point differentiation; (5) final leaf visible in whorl; (6) boot stage; (7) half-bloom; (8) soft dough; (9) hard dough; and (10) physiological maturity. They suggested these stages as standards to describe the timing of sampling or treating sorghum to provide an actual relationship to the morphological or physiological age or status of the plant.

Vanderlip (22) discussed the dry matter production patterns in grain sorghum. In RS610 grown at Manhattan, Kansas, growth was generally slow the first 20 to 25 days after emergence with most of the aboveground portion of the plant consisting of leaves. Starting about half-way through the leaf producing period, the culm started to elongate and grew rapidly in length and weight until flowering occurred. Grain formation and development began then, using materials manufactured by the leaves and moved from the culm into the grain, with a net decrease in the stalk weight. He reported that the general pattern of dry matter accumulation was the same for different sorghum hybrids. Later maturing hybrids tended to be heavier at each stage of development than earlier maturing hybrids. The three hybrids studied had nearly identical rates of dry matter accumulation, but the later maturing one produced longer.

Campbell and Hume (5), and Hanway (9) reported corn to decrease in stalk weight during grain development. Soluble solids in stalks of corn hybrids accumulated and then declined rapidly during the grain filling period. The decline was caused primarily by translocation of metabolites from the stalk to the grain.

Shipley, Unger, and Regier (19) studied the consumptive water use, harvestable dry matter, and nitrogen uptake in irrigated grain sorghum. Dry matter production and nitrogen uptake was slowest from emergence to the 6-8 leaf stage, and from bloom to milk. During early boot to late boot stage, dry matter production and nitrogen uptake occurred most rapidly.

Voss, Hanway, and Dumenil (24) suggested interpretation of the data for tissue analysis of corn leaves should include consideration of soil, management, and climatic factors.

Lockman (13) compared the mineral composition of corn and grain sorghum tissues at several growth stages and under different environments. Values were found to be similar in seedling whole plant samples, but major differences existed in vegetative, bloom, and fruiting stage leaf samples. Seasons affected nutrient levels in grain sorghum, but not always in the same manner and degree as in corn samples. Dry years caused high P, Ca, Mn, Mg, Cu, Fe, and Al levels in grain sorghum third-leaves. He suggested corn criteria should not be used to determine nutrient status for grain sorghum samples.

Bennett (4) reported consistent nutrient composition differences of corn and grain sorghum leaves. He felt the differences were sufficiently great to suggest that critical nutrient levels need to be established for grain sorghum instead of using diagnostic criteria established for corn.

Lockman (14) studied the mineral composition of grain sorghum as affected by soil acidity, soil fertility, stage of growth, variety, and climatic factors. In seedling samples K, Ca, and Zn appeared to be reduced by dry weather, but Ca and Zn accumulated by fruiting stage. Average mineral compositions were not greatly affected by soil acidity, except Mn which increased 2 to 5 times in acid soil. Deviations in varieties were found to be relatively small.

Owen and Furr (18) found contents of N, P, K, S, Ca, Zn, and Mn varied significantly among forage sorghum varieties. The varieties tested were below the postulated optimum beef cattle requirements for P, Ca, S, and Zn.

Lal and Taylor (11) reported improved soil drainage increased the uptake of N, P, K, Zn, Cu, and B, but decreased the uptake of Al, Fe, Mn, and Mo in corn leaves. The concentrations of Ca and Mg were not affected. Mineral uptake under wet soil conditions was associated with reducing conditions, inhibited soil mineralization, and an increase in soil pH.

Doggett (7) reported Ca concentrations in the vegetative parts of Indian sorghum decreased from 1.06% at three weeks to 0.46% at 13 weeks. Average concentrations of nutrients in mature grain of several sorghum varieties were 0.05% Ca, 0.19% Mg, 50 ppm Fe, 16.3 ppm Mn, and 10.8 ppm Cu.

Cherian (6) reported a decrease in the Fe content of grain sorghum leaf samples during growth, but found no change in the contents of Cu, Zn, or Mn in a fertility study.

Matocha et al. (16) studied the influence of Zn, Fe, K, and P on yield and chemical composition of grain sorghum. After 6 to 7 weeks whole plant concentrations, depending on treatment and soil type, ranged from 45 to 210 ppm Fe and 7 to 93 ppm Zn. The harvested mature grain ranged from 10 to 26 ppm Zn and 28 to 49 ppm Fe. The highest concentrations were always associated with added Zn and Fe.

Beason (3) reported the effect of Zn, Mn, and Cu on soil test data, grain sorghum yield, and leaf nutrient content. Nutrient levels of the newest, fully matured leaf at early bloom in N, P, K, Ca, Mg, B, Fe, and Al varied little between treatments. Zinc composition ranged from 18 to 25 ppm, Mn 18 to 28 ppm, and Cu 2 to 3 ppm, but no significant growth or yield response was obtained among treatments.

Whitney and Ellis (25) suggested nutrient sufficiency limits for corn and grain sorghum by sampling at least 12 of the last fully extended leaves during late June and early July across Kansas. Sufficiency limits suggested were 3.0-5.0% N, 0.25-0.40% P, 2.75-4.0% K, 0.15-0.35% Mg, 15-40 ppm Zn, and 5-15 ppm Cu.

Lockman (15) reported on the suggested nutrient sufficiency limits in grain sorghum at various stages of growth. At growth stage two whole plant sufficiency concentration limits suggested were 0.9-1.3% Ca, 0.35-0.50% Mg,8-15 ppm Cu, 160-250 ppm Fe, 40-150 ppm Mn, and 30-60 ppm Zn. At growth stage three the sufficiency limits suggested were 1.0-1.5% Ca, 0.40-0.80% Mg, 3-14 ppm Cu, 90-120 ppm Fe, 40-70 ppm Mn, and 20-50 ppm Zn. Limits on third-leaf samples at stages three, four, and five; third-leaf at bloom (stage six); and third-leaf at fruiting (stages seven and eight) were also suggested. He summarized that whole plant samples taken between 25 and 36 days after planting would be most useful for diagnostic work in grain sorghum. Vegetative third-leaf samples were considered about as good also, but age and tissue definition would be more difficult to define for practical application.

Williams (26) reported that Zn and P were concentrated in the grain and Mn in the straw, while Cu was equally distributed between the grain and straw in mature oat plants. Zinc was translocated to the grain as maturity approached, but Cu was less complete in translocation. Little redistribution of Mn from the leaves occurred, but export from the stems was observed.

Translocation of nutrients from the vegetative plant parts to the developing grain has been well documented by researchers working independently on various crops (2, 9, 10, 12, 22). They found the amount of nutrient redistribution to be different among the nutrients. Some were translocated more readily than others.

Vanderlip (22) reported that nutrient uptake preceded dry matter accumulation in grain sorghum. The nutrients were required for growth and dry matter accumulation. At half-bloom approximately one-half of the total dry weight of the plant was produced, but nutrient uptake had reached nearly 70, 60, and 80% of total for N, P, and K, respectively. A large portion of the N and P but only a small portion of K was removed in the grain at harvest.

Lane and Walker (12) reported nutrient accumulation of N, P, and K in grain sorghum generally followed the sigmoid pattern of the growth curve. The accumulation of the nutrients seemed to fit the general pattern in other plants, however, nutrients were taken up over a longer period of the growth cycle than in some cereals. The distribution of the nutrients within the plant was little affected by supply.

METHODS AND MATERIALS

Two grain sorghum hybrids of different maturity groups, RS610 and RS702[1], were planted in bulk areas at the Kansas State University Agronomy Farm, Manhattan, Kansas in 1969, 1970, and 1971.

Plantings were made in 76 cm rows. Desired population was 123,552 plants per hectare. In 1969 the hybrids were planted on June 30, in 1970 on June 11, and in 1971 on June 4. Weed control was accomplished by herbicide application and sweep cultivation and/or hand weeding when necessary.

The hybrid sorghums were planted on silt loam soils in the same general area at the Agronomy Farm during all three years. In 1969 the two hybrids were planted in bulk areas separated by 100 meters. Approximately half the RS610 grain sorghum bulk area was on a Reading silt loam, 0-1% slope, and half on an Ivan and Kennebec silt loam soil. The RS702 grain sorghum was planted on a Kahola silt loam soil. Nitrogen (112 kg per hectare) was applied preplant on both areas.

In 1970 and 1971 the hybrids were planted on a Reading silt loam, 0-1% slope, soil. In 1970, 90 kg N per hectare was applied and 112 kg N per hectare in 1971.

Aboveground whole plant samples from the bulk areas were taken at weekly intervals, beginning at approximately stage one of growth (collar of third leaf visible), throughout the growth of the sorghum

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[1]Approximate date from emergence to physiological maturity for RS610 and RS702 grown at Manhattan, Kansas, are 95 and 110 days, respectively.

plant in 1969, 1970, and 1971. Two replications consisting of five representative plants each were selected from each hybrid bulk area on every sampling date. The plants were brought into the laboratory and separated into blades, sheaths, culms, and heads in 1969 and 1970. In 1971, in addition to separating the plants into blades, sheaths, and culms, the grain was threshed from the head. Plant parts were dried to a constant weight in a forced-draft oven at 65 C, weighed, and ground to pass a 2 mm stainless steel screen in a Wiley mill having stainless steel internal parts. Ground samples were stored in glass bottles for future analyses.

Ground samples in bottles were dried in an oven at 65 C for 24 hours before weighing out a throughly mixed $\frac{1}{2}$ gram sample for wet ashing with nitric-perchloric acids based on the procedure by Gieseking, Snider, and Getz (8), with modifications. This procedure consisted of adding 25 ml of a ternary digestion mixture (1:1:1 ratio) of 70% $HClO_4$, concentrated HNO_3, and deionized distilled water into a beaker containing a $\frac{1}{2}$ gram plant sample. Material was digested, taken to dryness, 25 ml 0.1N HCl added, and stored in polyethylene bottles. Zinc, Cu, Mn, and Fe concentrations were determined by the Perkin-Elmer Model 303 Atomic Absorption Spectrophotometer (17) on aliquots of the preceding digest. A 1 to 50 dilution using 0.1N HCl was used to get the correct concentration range for analysis of Ca and Mg. For Ca 4 ml of the diluted sample was pipetted into 15 ml glass vials and 1 ml of 5% La_2O_3 (25% HCl v/v) was added to prevent interference from PO_4 and SO_4 ions (1). Calcium and Mg concentrations were then determined by the Perkin-Elmer atomic absorption spectrophotometer.

All glassware and bottles used were washed in EDTA and nitric acid solutions followed by a rinsing in deionized distilled water to minimize contaminations.

Grain yields and plant populations were determined by measuring and harvesting four 4.6-m sections. Grain yield was adjusted to 12.5% moisture.

Percent of total accumulated nutrient uptake and dry matter in each plant part, whole plant nutrient concentrations, and milligrams nutrient uptake per plant part were calculated. Total nutrient uptake and total dry matter accumulated per hectare were also calculated.

Statistical analyses on whole plant nutrient concentration data in 1970 and 1971 were made according to the methods outlined by Snedecor and Cochran (21). No nutrient concentration analyses were conducted in 1969 because of the field layout. The tests for homogeneity of variance to see if whole plant concentration data of each nutrient in 1970 and 1971 could be combined over the two years to perform analysis of variance computations were made according to the procedure outlined by Snedecor (20) for the comparison of two mean squares. In combining hybrids over years for statistical analyses ten representative dates were picked from each year in 1970 and 1971. Dates were chosen on the basis of approximately equal growth stages of the plant between the years.

RESULTS AND DISCUSSION

Plant populations, grain yields, and total dry matter produced during 1969, 1970, and 1971 in the RS610 and RS702 grain sorghum hybrids are shown in Table 1. The desired plant population of 123,552 plants per hectare was not obtained. Actual populations generally ranged from one-half to one-third less, except RS702 in 1970 which was approximately two-thirds less. Plant populations were still adequate to obtain good grain yields. Tillering occurred to compensate for low populations.

Table 1. Plant populations, grain yields, and total above-ground whole plant dry matter accumulated in RS610 and RS702 grain sorghums at Manhattan in 1969, 1970, and 1971.

Year	Population (Plants/ha)	Grain Yield (kg/ha)	Total Dry Matter Accumulation (kg/ha)
1969			
RS610	75,587	6,402	9,048
RS702	83,959	5,084	11,835
1970			
RS610	62,431	6,465	13,835
RS702	41,620	6,591	10,656
1971			
RS610	60,279	7,720	13,673
RS702	63,506	7,658	11,865

Grain yields were near normal for dryland sorghum at Manhattan, Kansas. There was little difference between hybrids within years, except in 1969 when the grain yield of RS702 was 1400 kg below that of RS610. Since only 1.98 cm of rain was received in August and three-fourths of that amount fell on the second day, the difference in yield may have been because RS702 was affected more by the drought than RS610. The RS702 hybrid produced more total dry matter, but if it were under stress during flowering and grain formation, grain yield could have been reduced somewhat.

Plant samples were not washed when brought into the laboratory from the field unless they were muddy or visibly dirty and dusty. Subsequent plant analysis by the author in comparing washed verses nonwashed samples showed that no valid inferences about Fe in the blade and sheath, and possibly the head (grain included) could be made if samples were not washed (Appendix Tables 11-19). No significant differences between washed and nonwashed samples occurred for Mg, Ca, Zn, Cu, or Mn concentrations in any plant part. Because of the highly significant differences in Fe concentration found between washed and nonwashed samples of blade and sheath tissue, there is no discussion of Fe concentration in these tissues, nor are total Fe uptake and distribution in the plant discussed.

Total aboveground whole plant nutrient uptake is shown in Table 2. There were no large differences between hybrids or years within the same nutrient, except in 1969 when the RS610 grain sorghum nutrient uptake was much less in all nutrients studied. Dry matter accumulation was less in RS610 than RS702 during 1969, but not enough less to totally explain the difference observed in nutrient uptake. The fact that the two hybrids were on different soils may have accounted for the difference. The lesser amount of nutrient uptake in the RS610 grain sorghum did not affect grain yield though, since it out yielded RS702 and there was little difference between it and grain yields of RS610 and RS702 in 1970, although nutrient uptake was greater in 1970. The large difference between hybrids in nutrient uptake in 1969 would indicate luxury uptake in RS702 because the lesser amount in RS610 seemed to be adequate.

Table 2. Total aboveground whole plant nutrient uptake during the growing season in RS610 and RS702 grain sorghums at Manhattan in 1969, 1970, and 1971.

Year	g/ha			kg/ha	
	Zn	Cu	Mn	Mg	Ca
1969					
RS610	161	40	200	15.22	15.61
RS702	299	94	586	27.01	27.31
1970					
RS610	316	114	269	27.41	24.34
RS702	316	91	314	25.34	26.01
1971					
RS610	264	86	373	23.22	23.14
RS702	257	89	403	23.82	26.86

Total Mn uptake varied the most of the nutrients studied in the hybrids during the three years. The RS702 grain sorghum in 1969 had almost three times more taken up than RS610 and approximately two times more than either hybrid in 1970. Again this difference may have been due to the difference in soil types as discussed previously. Manganese uptake was more in 1971 than 1970, but dry matter accumulation was nearly the same. More Mn was taken up in RS702 than RS610 in each of the three years of study.

Environmental differences among seasons probably played an active role in determining growth and quantity of nutrients taken up. Factors such as temperature, rainfall, and soil conditions varying among the years could have affected growth and nutrient uptake considerably.

Good soil moisture conditions prevailed at planting time during the three years. In 1969, 21.67 cm of rain was received two months prior to planting in May and June. Of that amount, 3.76 cm was received one week prior to planting and 6.76 cm was received by two weeks after planting. In July 19.84 cm of rain was received (Table 3). Only 1.98 cm was received in August and three-fourths of that amount fell on the second day. Although little rain was received in August, the sorghums were never under a severe drought stress since plentiful rainfall was received in July. Above average temperatures did not prevail in August.

Table 3. Precipitation received during the growing season at Manhattan in 1969, 1970, and 1971.

	Month (cm of ppt)				
Year	May	June	July	August	September
1969	10.92	10.74	19.84	1.98	6.22
1970	17.20	21.56	1.78	7.14	22.07
1971	14.12	11.10	20.57	Trace	3.00

In 1970, 30.51 cm of rain was received in May and June prior to planting. Of that amount, 6.88 cm fell one week prior to planting. Within two weeks after planting 8.26 cm had been received. In July and August only 8.92 cm was received with 3.33 cm of it falling on August 22. Above average temperatures were recorded in July and August with 22 and 23 days, respectively, recording 32.2 C or above (Table 4). The accompanying hot, dry winds put the sorghums under drought stress, although it was not severe.

In 1971, 14.43 cm of rain was received in May and June prior to planting. Within two weeks after planting 8.74 cm was received. July received an abundant amount of 20.57 cm. Only a trace of rain was recorded in August, and September received only 3.00 cm. Due to the abundant amount of rain received in July the sorghums were not subjected to a severe drought stress in August though. Above average temperatures did not prevail in August.

Table 4. Average maximum and minimum temperatures recorded during the growing season at Manhattan in 1969, 1970, and 1971.

	Temperature (C)		
Year	Average Maximum	Average Minimum	Days 32.2 or above
1969			
June	28.1	15.3	8
July	32.9	21.1	17
August	31.6	19.1	14
September	28.2	14.9	3
1970			
June	28.4	17.6	9
July	33.5	20.0	22
August	35.0	20.8	23
September	26.6	14.5	8
1971			
June	31.7	20.1	13
July	30.3	18.1	9
August	31.4	18.3	15
September	28.1	15.0	8

The difference in Mn and Mg total uptakes between 1970 and 1971 are good examples of environmental factors affecting nutrient uptake. Since the sorghums were planted in the same general area with the same soil type in 1970 and 1971, and total dry matter accumulation was relatively the same, the difference in total nutrient uptakes may have been due to temperature and rainfall effects on the soil and plant.

In July of 1970, during the sorghum's active growing period, only 1.78 cm of rain was received and 22 days were 32.2 C or above, while during 1971 in July 20.57 cm of rain was received and only 9 days were 32.2 C or above. Only a trace of rain was received in August of 1971 and 7.14 cm was received in August of 1970. Temperatures were hotter in August of 1970 than 1971.

Many significant interactions were indicated in the analysis of variance tests on whole plant nutrient concentrations of RS610 and RS702 (Appendix Tables 5-10). In 1970 the hybrids were significantly different in concentration for all nutrients and date x hybrid interactions were also significant for Cu and Mn. In 1971 the hybrids did not differ significantly in Mn and Mg concentration, but date x hybrid interactions were significant for all nutrients. Analysis of variance of whole plant concentration data combined over 1970 and 1971 showed significant differences between hybrids and years for all nutrients studied, but with significant date x hybrid, date x year, and hybrid x year interactions present also. No date x hybrid interaction existed for Mg and Ca. Because of the many interactions present it was not possible to make consistent conclusions or generalizations about differences in nutrient concentrations between the hybrids or years. Analysis of variance results will not be discussed further, but detailed discussions on various other aspects of whole plant nutrient concentrations will follow.

Dry Matter Production

Dry matter accumulation of the two hybrids in the three years of study are shown in Figure 1. Although total dry matter accumulation was not the same among years or between hybrids, and environmental conditions varied among years, growth curves showed similar trends when shown on a percent of total accumulation basis.

In general, growth was slow the first 20 to 30 days after emergence and then growth and dry matter accumulated at a rapid rate until physiological maturity (maximum dry matter production). During the rapid period of accumulation dry matter production was occurring at almost a linear rate. Average production per day per hectare for the two hybrids was 138 kg in 1969, 164 kg in 1970, and 155 kg in 1971. Average production per day per hectare over three years and both hybrids was 152 kg during the period of rapid dry matter production.

The sorghum plant consisted almost entirely of blades and sheaths until 30 to 40 days after emergence. Maximum dry weight in the blade and sheath was generally reached at an earlier date in RS610 than RS702 grain sorghum. More dry weight was produced in the blade and sheath of RS702 than RS610. Maximum production for RS702 in the blade was 15 to 20% of the total accumulated and for RS610 in the blade it was 10 to 15%. RS702 had 10 to 12% of its total dry matter production in the sheaths of the plant and RS610 had 6 to 10%.

In 1969, 43 days after emergence, there was a peak in dry matter accumulation after which a decline was noted. It is assumed much of the decline was due to sampling error in not obtaining representative plants from the field, although it occurred during August when little rainfall was recorded which could account for a leveling off in dry matter production temporarily. A loss in dry matter produced

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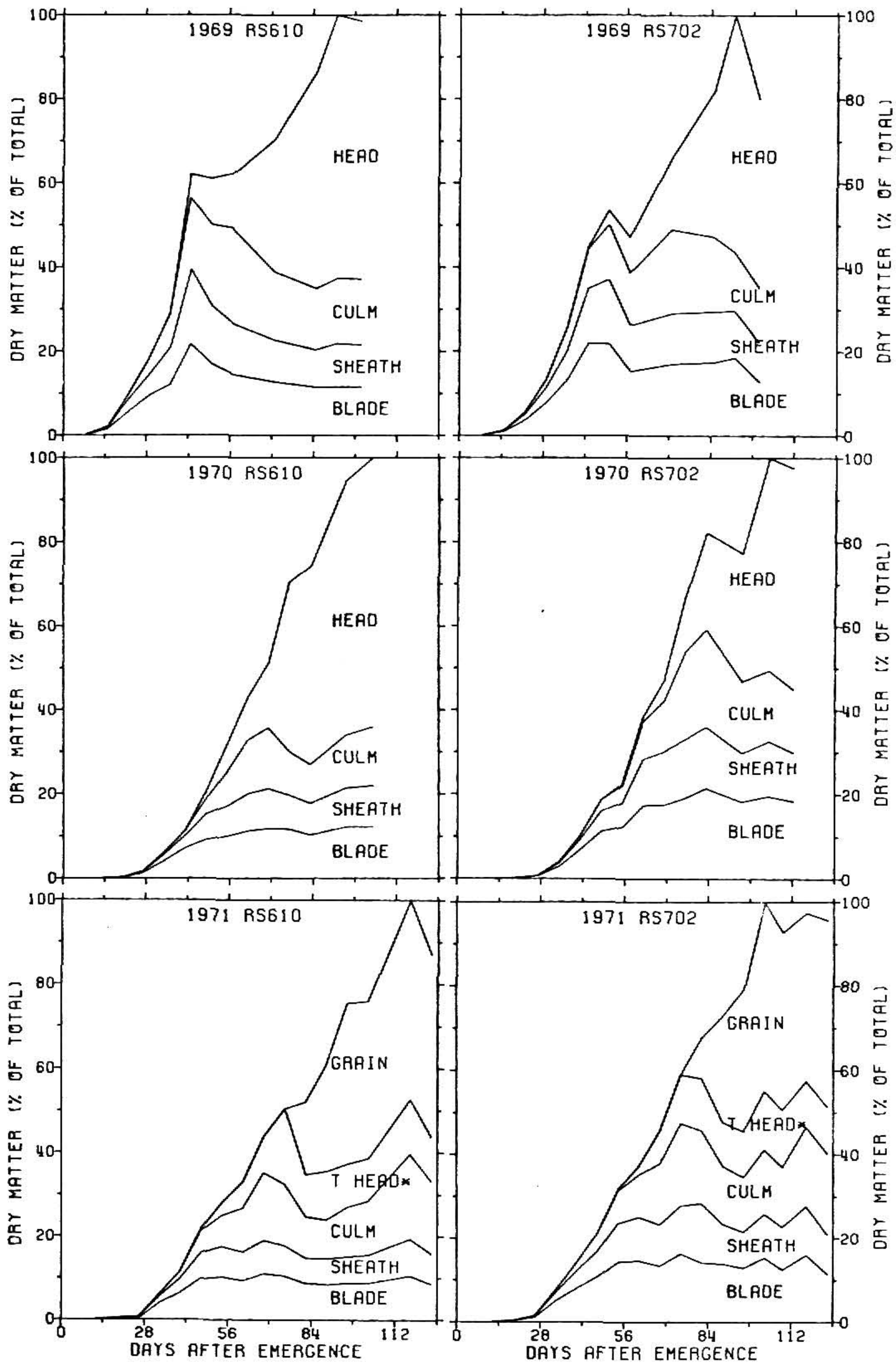

Figure 1. Dry matter production in aboveground plant parts expressed as percent of total produced at physiological maturity in RS610 and RS702 grain sorghum at Manhattan in 1969, 1970, and 1971. (*Threshed head. Grain was separated from the head in 1971.)

previously would not be expected though.

About 30 to 40 days after emergence the culm started to elongate and gain weight rapidly. Maximum weight was reached earlier in RS610 than RS702. Average days after emergence to maximum culm weight was 60 in RS610 and 68 in RS702. Maximum weights were reached earlier in 1969 than in 1970 and 1971. In 1969 the sorghums were planted at a later date and conditions were more favorable for rapid growth. Plentiful rainfall (19.84 cm in July) was received after planting.

The sorghum plant reached its maximum vegetative weight at the time the culm ceased gaining weight. Growth after that was entirely in grain production. The head, prior to grain formation in 1971, reached its maximum weight about the same time as the culm did. The grain was not separated from the head in 1969 and 1970; thus, it was not known when maximum head weight prior to grain formation was reached, but it was assumed it occurred in approximately the same time period as in 1971. Plant weight at maximum vegetative production generally ranged from 40 to 50% of the total weight at physiological maturity.

Grain formation and development continued until physiological maturity was reached in the plant. Little difference was noted in days after emergence to physiological maturity between hybrids, but hybrids differed among years. It ranged from 92 to 115 days during the three years for both hybrids. After physiological maturity was reached there was a decrease in sampling weights. It probably was due to leaf loss occurring and not obtaining all of the leaves when plants were sampled in the field. Difficulty in picking representative plants from the field was also encountered. Translocation of materials out of the aboveground portion of the plant to the roots could account for a small portion of the loss in weight, since under favorable conditions sorghum may act as a perennial.

During grain formation and development there was a loss of dry weight in the culm and an increase again near physiological maturity in some cases. This loss indicated a translocation of material out of the culm into the developing grain, since the grain was still gaining weight rapidly. Materials were being translocated out of the culm faster than they were being manufactured by the leaves and moved to the culm. That may not have been the case as the plant neared physiological maturity and the culm gained weight again. No increase in culm weight was apparent in the RS702 grain sorghum in 1969 and 1970. Renewed growth through tillering could account for the increase in weight of the culm also, since the blades and sheaths increased in weight slightly, indicating new growth.

Iron Accumulation

As discussed previously, no inferences about Fe in the blade and sheath could be made because the samples were not washed. Iron concentration in the culm and head will be discussed only.

Iron concentration in the head was variable in 1969 and 1970 (Figure 2). It generally was around 100 ppm during 1969 in both hybrids, but no apparent pattern was indicated. In 1970 the Fe concentration increased to near 200 ppm prior to grain formation and development, after which it decreased and leveled off near 25 ppm in RS610 and 80 ppm in RS702. In 1971 the threshed head parts maintained a relatively constant

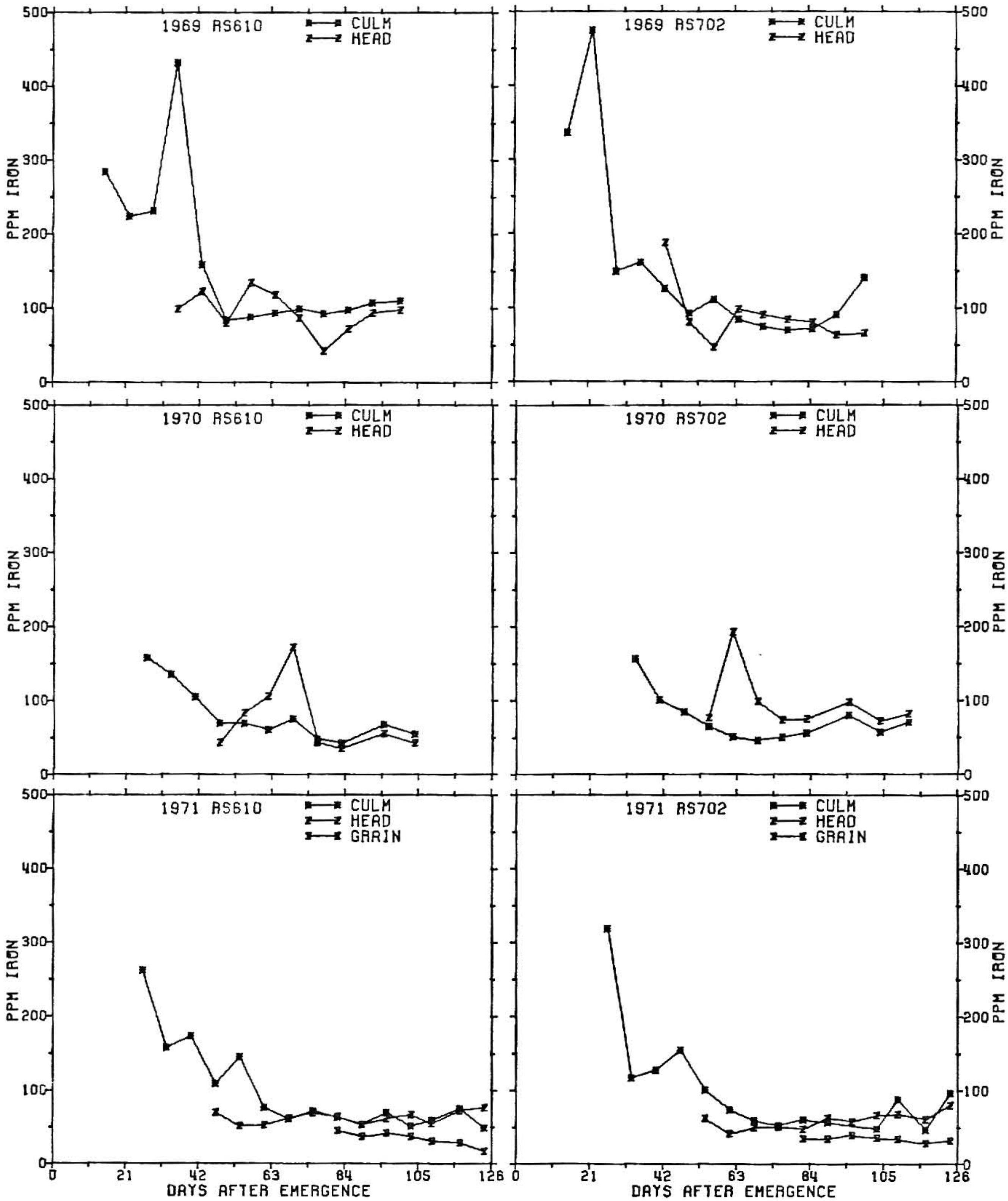

Figure 2. Iron concentration in plant parts of RS610 and RS702 grain sorghum at Manhattan in 1969, 1970, and 1971. (Note: Grain was separated from the head in 1971. 1969 and 1970 head includes the grain.)

concentration ranging from 50 to 75 ppm throughout the growth of the plant in both hybrids.

In 1971 the grain showed a slight decrease in concentration of Fe as the plant reached physiological maturity, especially in the RS610. Concentration steadily declined from 45 to 17 ppm. In RS702 concentration ranged from 28 to 39 ppm, but it remained relatively constant throughout the growing season and showed only a slight trend to decrease as the season progressed.

Zinc Accumulation and Distribution

Figure 3 shows the Zn concentration in plant parts of RS610 and RS702 grain sorghum. Concentrations were high early in the growing season, especially that of the culm. Zinc in the culm was above or near 200 ppm in all but RS610 in 1969. It declined rapidly each week at the rate of 70 to 100 ppm until about the time that vegetative growth ceased in the plant, after which it leveled off and remained relatively constant throughout grain formation and development.

There were little differences among plant parts in Zn concentration after the vegetative growth of the plant had been completed. In 1971 Zn concentration in the threshed head remained above the other plant parts, but there was generally only a few ppm difference.

There were also only small differences between hybrids or among years in Zn concentration of plant parts after vegetative growth ceased. In 1969 and 1970 concentrations of Zn in the plant parts of RS610 were slightly lower than in RS702. No differences in hybrids were noted in 1971. In general, concentrations ranged from 15 to 30 ppm in

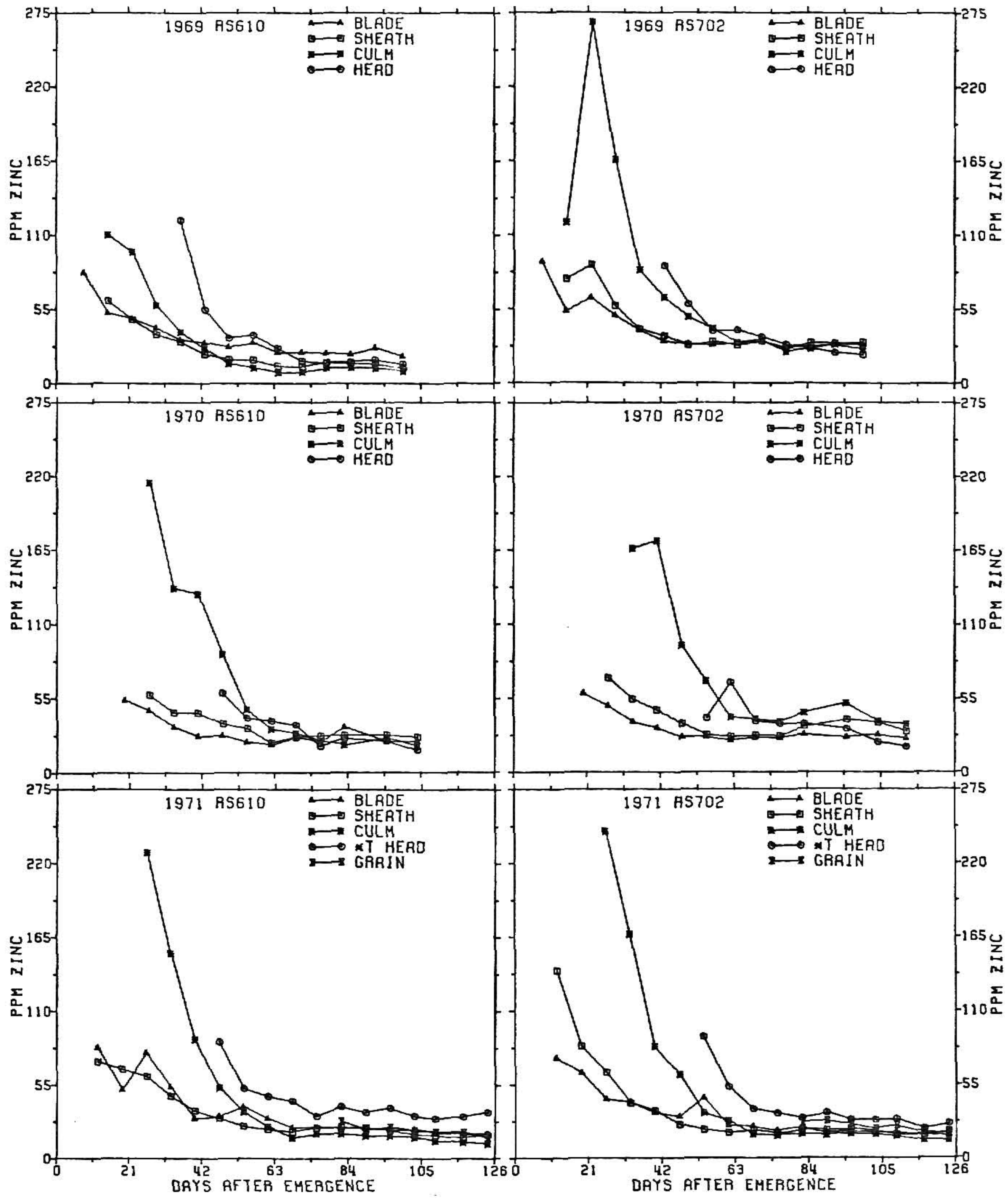

Figure 3. Zinc concentration in plant parts of RS610 and RS702 grain sorghum at Manhattan in 1969, 1970, and 1971. (*Threshed head. Grain was separated from the head in 1971.)

the plant parts after the completion of vegetative growth during the three years.

Zinc concentrations were higher in the head prior to grain formation and development than during. Concentrations decreased only slightly during grain development. Concentrations, prior to grain development, decreased because the head was increasing in weight faster than Zn was being taken up into the head. Concentrations decreased slightly during grain development because the grain was increasing in weight faster than Zn was being taken up into the head and moved to the grain.

Figure 4 shows aboveground whole plant Zn concentrations throughout the growth of the plant. Concentration was high early in the growing season. It decreased nearly linearly as the season progressed until vegetative growth was completed, after which it showed only a small tendency to decrease as the plant reached physiological maturity. Decrease in concentration from the first sampling date to the completion of vegetative growth averaged approximately 1.2 ppm per day combined over hybrids and years.

In 1969 the RS610 grain sorghum was lower in whole plant Zn concentration throughout the growth of the plant than RS702 was in 1969, and RS610 and RS702 in 1970 and 1971. Only a small difference was indicated in concentrations between hybrids and years in 1970 and 1971. It is not known exactly why concentrations in RS610 in 1969 were lower, but it was assumed that soil type was a factor since the hybrids were physically separated in the field and on different soil types. In 1970 RS702 increased in concentration during grain development and then

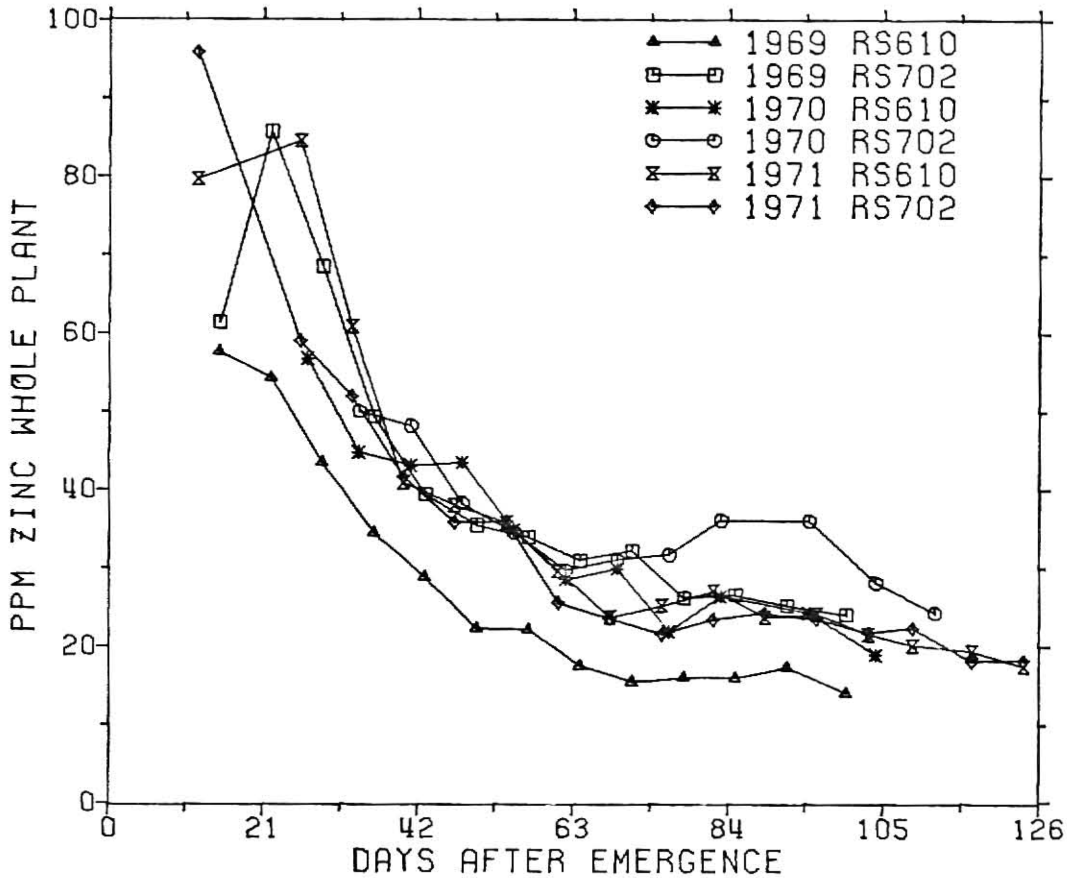

Figure 4. Zinc concentration in aboveground whole plants of RS610 and RS702 grain sorghum at Manhattan in 1969, 1970, and 1971.

decreased again, but remained above the concentration of RS610 in 1970, and RS610 and RS702 in 1969 and 1971. The increase in concentration may have been due to renewed vegetative growth through tillering and/or branching since concentration and weight in the vegetative plant parts also increased slightly. Rather than completely utilizing existing Zn the plant took up more and concentrations increased due to a more rapid rate of uptake than growth dilution. Environmental conditions were favorable at that time for tillering and/or branching. The increase in concentration occurred in the later part of August and most of September and 27.51 cm of rain was received during that period of time.

Zinc uptake (Figure 5) showed the same general pattern as dry matter accumulation. In 1969, 100% of the total uptake in RS610 was reached by 43 days after emergence and then a decline was noted until 70 days after emergence. Zinc uptake then increased again until it was near 100%. No changes in Zn concentration were noted at 43 days, so the peak at 43 days in dry matter production, as discussed previously, would have to be responsible for showing such a large amount of Zn uptake at that time.

The peak in Zn uptake at 54 days in RS610 and RS702 during 1971 was due to an increase in Zn concentration of the blades. In RS702 during 1969 the peak at 43 days followed closely to that of dry matter accumulation. No unusual concentration changes were noted at that time.

A greater percentage of the total Zn uptake ended up in the blade, sheath, and culm of RS702 than in RS610; consequently, a greater percentage was observed in the heads of RS610 than in RS702. At physiological maturity in RS610 average percent Zn in the blade was 12% of

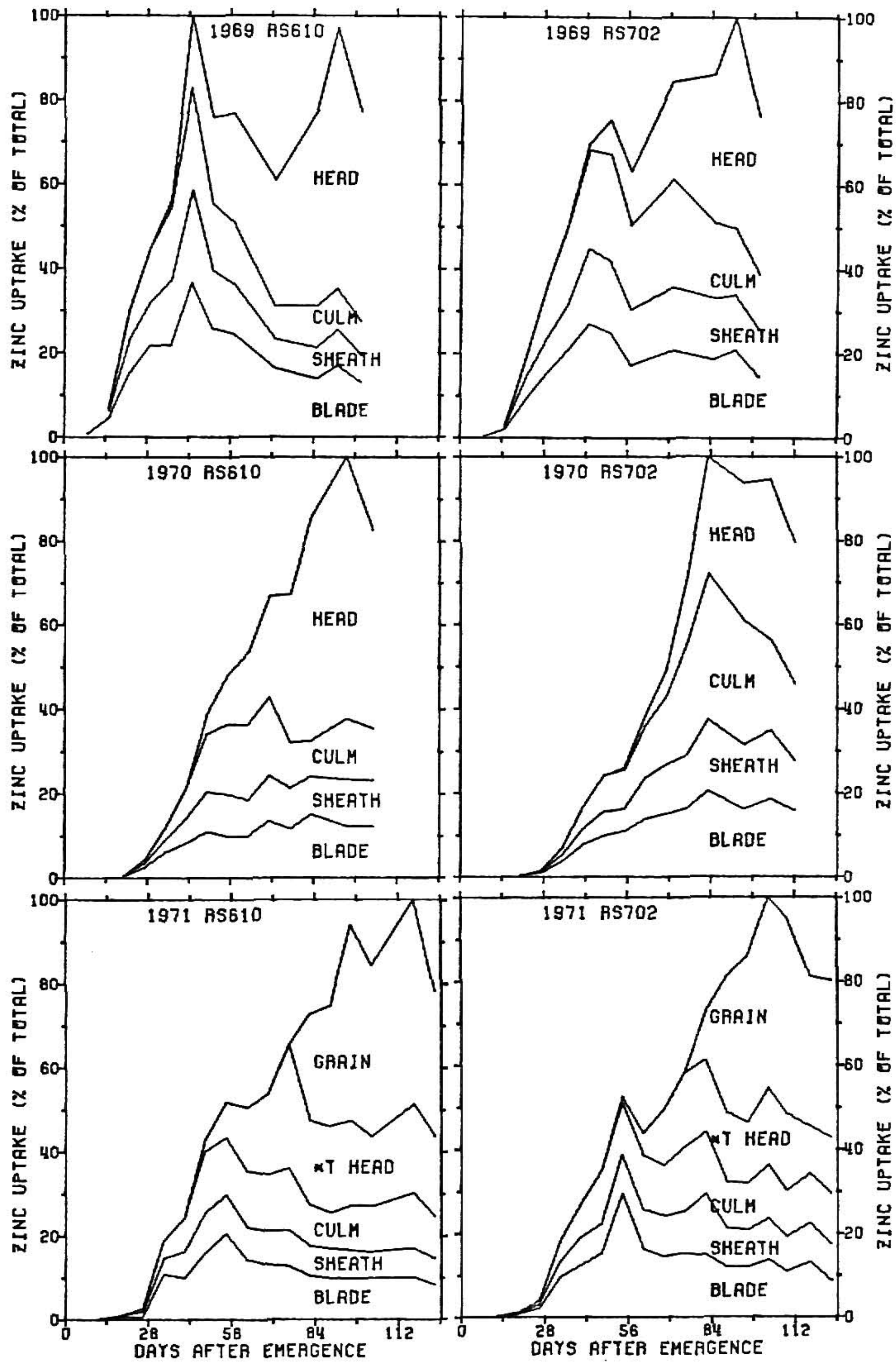

Figure 5. Zinc uptake in aboveground plant parts expressed as percent of total taken up in RS610 and RS702 grain sorghum at Manhattan in 1969, 1970, and 1971. (*Threshed Head. Grain was separated from the head in 1971.)

total uptake, in the sheath it was 7%, the culm contained 13%, and the head 68%. In RS702 average percent of total uptake at physiological maturity was 17% in the blade, 14% in the sheath, 16% in the culm, and 53% in the head. Although a greater percentage of Zn was indicated in the heads of RS610 than in RS702, there seemed to be little difference in percentage contained at physiological maturity in the grain in 1971. The threshed head parts contained a greater Zn percentage in RS610 than RS702. About 50% of the total Zn taken up in the plant was in the grain of both hybrids at physiological maturity.

In general, maximum Zn taken up in the vegetative plant parts was reached by the time dry matter production had ceased in them. Some translocation of Zn out of the plant parts into the developing grain was suggested, but Zn seemed to be relatively immobile in the plant. The amount of Zn in the plant parts did not generally change very much after maximum uptake had been reached.

Copper Accumulation and Distribution

Copper concentrations in plant parts of RS610 during 1969 were very low as shown in Figure 6. Little differences in concentration existed among plant parts and there were no large differences in concentration between the beginning or ending sampling dates. That was not the case in RS702 during 1969, and RS610 and RS702 during 1970 and 1971. Greater differences in concentration among plant parts existed, especially early in the growth of the plant. The culm was highest in concentration and remained higher than the other plant parts throughout the growing season in 1969 and 1970, excluding RS610 in 1969. Concentration in the

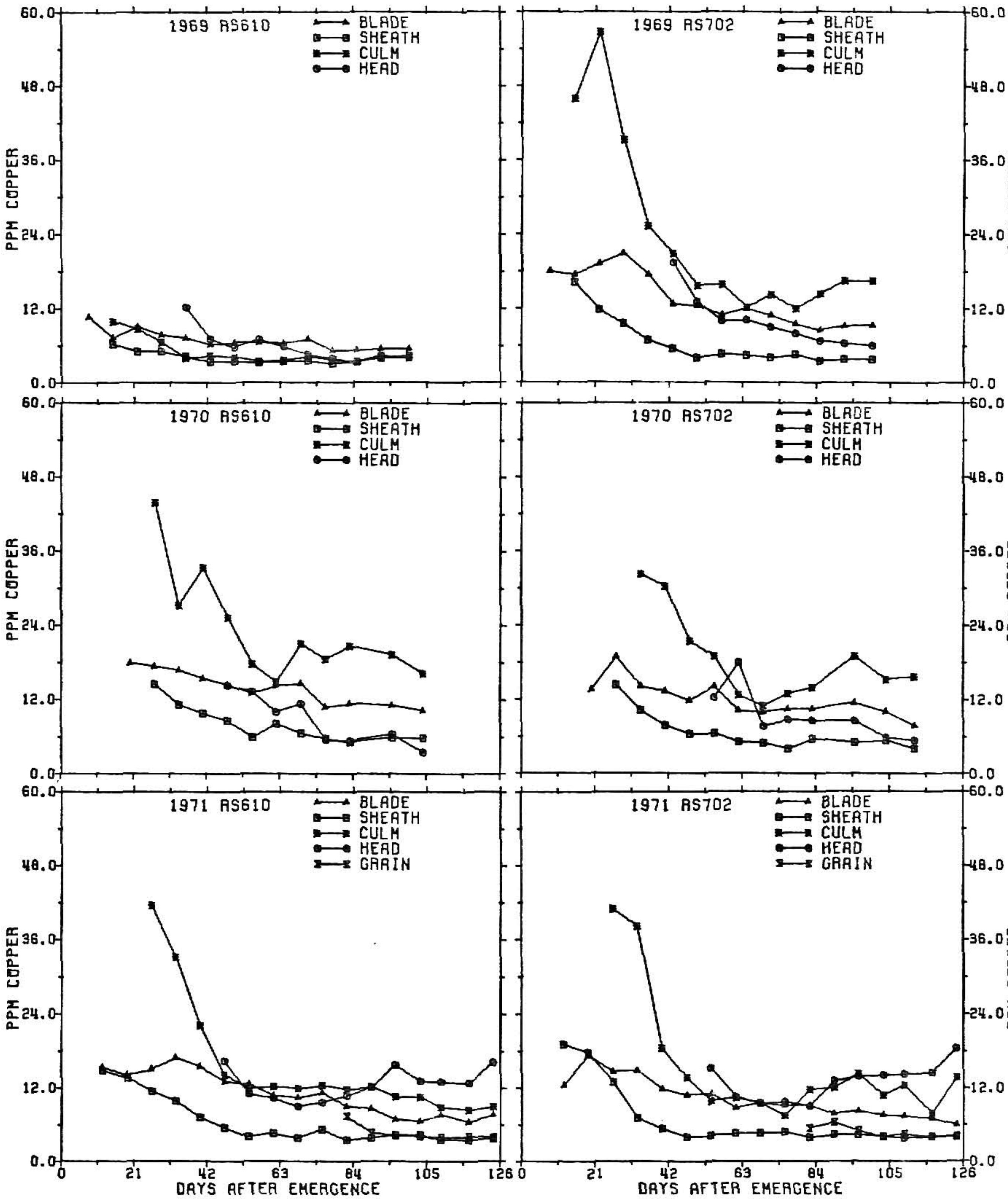

Figure 6. Copper concentration in plant parts of RS610 and RS702 grain sorghum at Manhattan in 1969, 1970, and 1971. (Note: Grain was separated from the head in 1971. 1969 and 1970 head includes the grain.)

culm during 1971 generally remained near or above the other plant parts, except towards the end of the growing season when the threshed head was higher. Culm concentration reached a low point about the time vegetative growth was completed in the hybrids during the three years and then increased again during grain development, except in RS610 during 1969 and 1971. Concentration may have increased because Cu was being accumulated in the culm, and little growth occurred to dilute the concentration, or it was not being translocated to the head as rapidly as it was accumulated in the culm.

Copper concentration in the blade declined nearly linearly as the plant progressed towards physiological maturity. Average change in concentration, excluding RS610 in 1969, from the first sampling date to the last was 10 ppm.

Concentration in the sheath was generally lower than in the other plant parts throughout the entire growing season. It declined at a linear rate until about the time that maximum dry matter production was reached in the sheath, and then concentration leveled off during the rest of the season.

Head Cu concentration decreased during grain development in 1969 and 1970, but in 1971, when the head was separated from the grain, concentration increased in the head and only changed slightly in the grain. Since most of the head weight consisted of grain and the grain concentration decreased as the plant reached maturity, the head with grain would also decrease in concentration as in 1969 and 1970. Concentration may have increased in the threshed head because Cu was being translocated to the head and it was not all going into the grain for some reason.

In general, there was little difference between hybrids in Cu concentration, except in 1969. There were some differences among years, but generalized patterns in plant parts were still evident.

Lower Cu concentration in RS610 during 1969 is readily detected when looking at whole plant concentrations in Figure 7. There were only small differences between RS702 in 1969, and RS610 and RS702 in 1970 and 1971. In general, concentrations were higher early in the growing season and decreased at a linear rate until maximum vegetative production, after which concentrations again decreased in a linear manner, but not as rapidly.

In 1970 and 1971 RS610 was higher in Cu concentration until maximum vegetative production, but during grain development RS702 increased in concentration while RS610 continued decreasing. Whether or not it was due to environmental and/or genetic factors affecting the hybrids differently is not known. In 1969 RS702 did not increase in concentration during grain development. As discussed previously environmental conditions during 1970 seemed to be favorable for tillering and/or branching late in the growing season, but not particularly favorable in 1971. In 1970 RS702 showed a greater increase in concentration than did RS702 in 1971. That was also the case in Zn concentration as discussed earlier, so environmental conditions may very well have been involved.

Copper uptake (Figure 8) followed the same general pattern as dry matter accumulation. There were differences between hybrids and years in uptake, but generalized curves were evident.

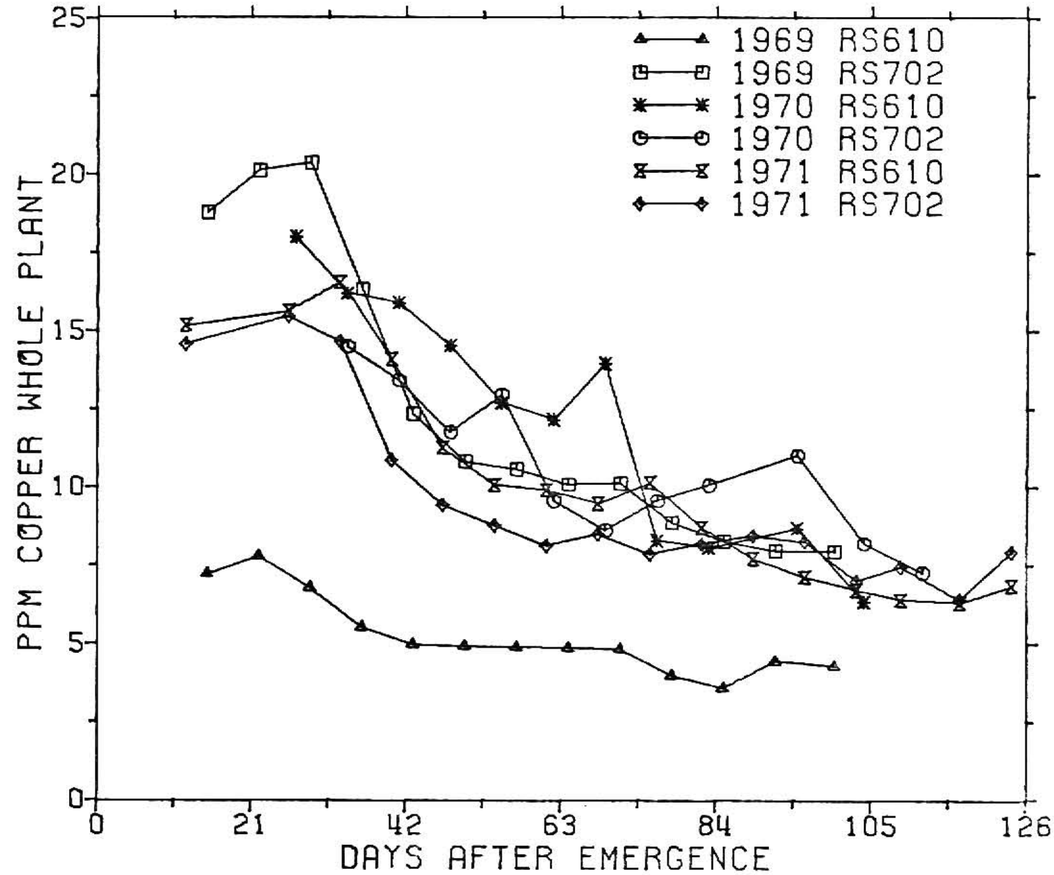

Figure 7. Copper concentration in aboveground whole plants of RS610 and RS702 grain sorghum at Manhattan in 1969, 1970, and 1971.

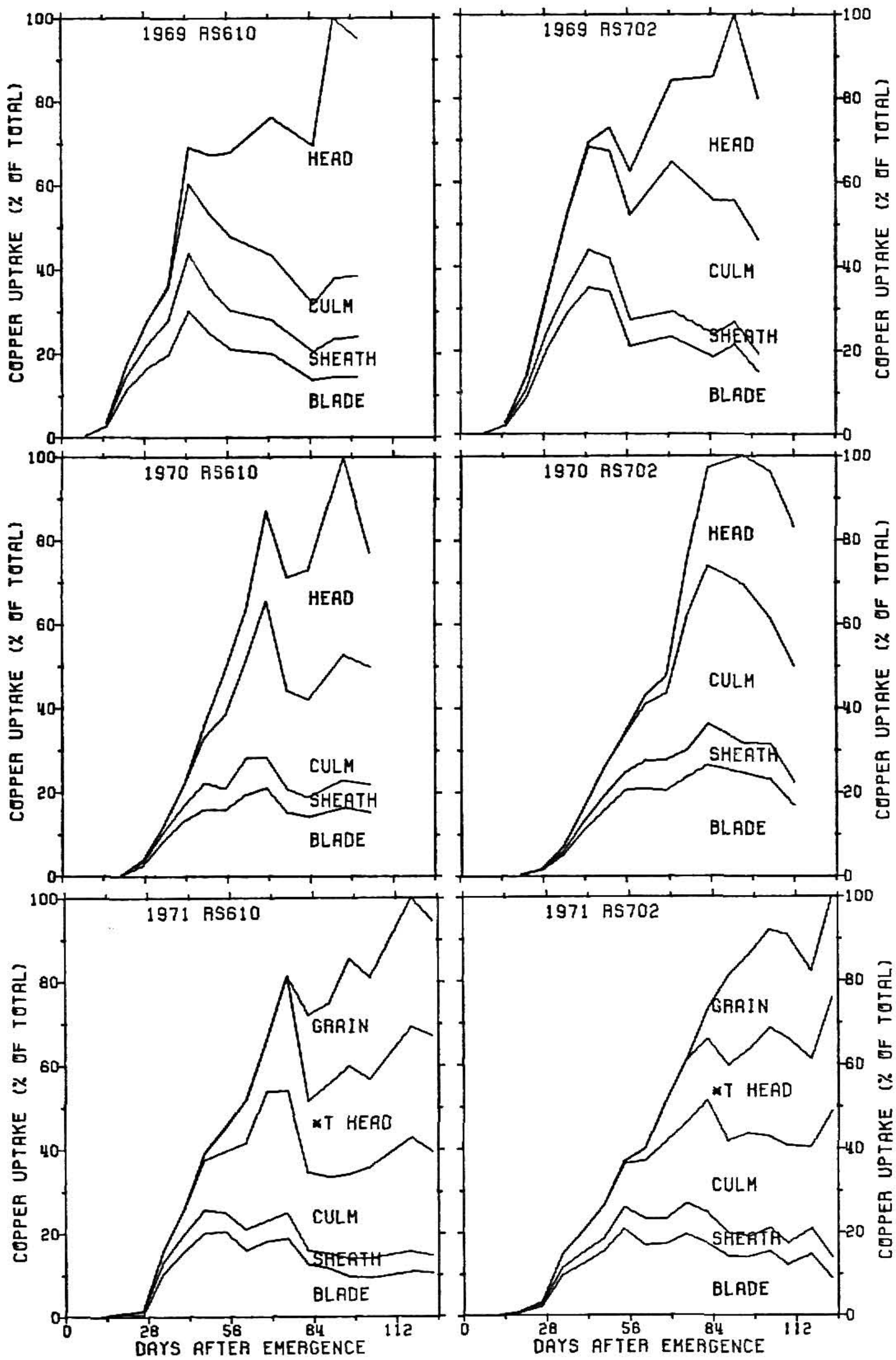

Figure 8. Copper uptake in aboveground plant parts expressed as percent of total taken up in RS610 and RS702 grain sorghum at Manhattan in 1969, 1970, and 1971. (*Threshed Head. Grain was separated from the head in 1971.)

A greater percentage of the total amount of Cu taken up was in the blades of RS702 than RS610, but little difference was noted in the sheath and culm between hybrids, except in 1969 when the culm of RS610 contained a lower percentage of the total than RS702. Only 5 to 7% of the total amount taken up was contained in the sheaths and 25 to 30% was in the culm of the plant at maturity, except RS610 in 1969 which had 15% in the culm at maturity.

Percent of total Cu uptake was less in the heads of RS702 than in RS610 at physiological maturity. Little difference was observed in 1970, but in 1969 percent of total uptake was 20% less and in 1971 5% less in the heads (grain included). In 1971 Cu in the head was equally divided between the grain and threshed head parts.

Translocation of Cu in the plant from the blade was indicated since the percentage of total uptake decreased as the season progressed. Copper was probably translocated to the developing grain, or at least to the head where it could be readily available. Such was indicated in 1971 since the threshed head increased in percent of total uptake as the season progressed and no increase in dry matter production occurred.

Copper seemed to be taken up more rapidly during vegetative accumulation than during grain development. About the time that vegetative growth was completed a leveling off in the uptake curve occurred and weekly gains in uptake were not as great. It was not readily apparent in RS702 during 1970 though.

Manganese Accumulation and Distribution

Manganese concentration differences among plant parts were considerable (Figure 9). The blade and sheath were higher in concentration than the culm and head. Differences in concentration were more pronounced during 1969 in RS702 and 1971 in both RS610 and RS702 than RS610 and RS702 during 1970 and RS610 during 1969.

Differences in concentrations between the culm and head in 1969 and 1970 and the culm, grain, and threshed head in 1971 were small, except in the culm during vegetative growth. Manganese concentration in the culm was high then, especially RS702 in 1969 and RS610 and RS702 in 1971 when blade and sheath concentrations were also high. After maximum dry matter was produced in the culm concentration changed only slightly. During that time concentrations were generally between 10 and 20 ppm in the culm and head during 1969 and 1970, and the culm, threshed head, and grain during 1971.

The sheath was highest in Mn concentration throughout the entire growing season, except RS610 during 1969 when the blade was higher. Sheath concentration of RS702 was higher in 1969 than either RS610 or RS702 in 1970 and 1971. Concentration increased during early grain development and then decreased near physiological maturity, except in RS610 during 1969 and 1970. No decrease was noted near physiological maturity in RS702 during 1969 other than on one sampling date.

Manganese concentration in the blade also increased during grain development. Concentration decreased until maximum blade weight was reached then increased throughout the remaining growing period. A decrease in concentration was observed in some instances as the plant

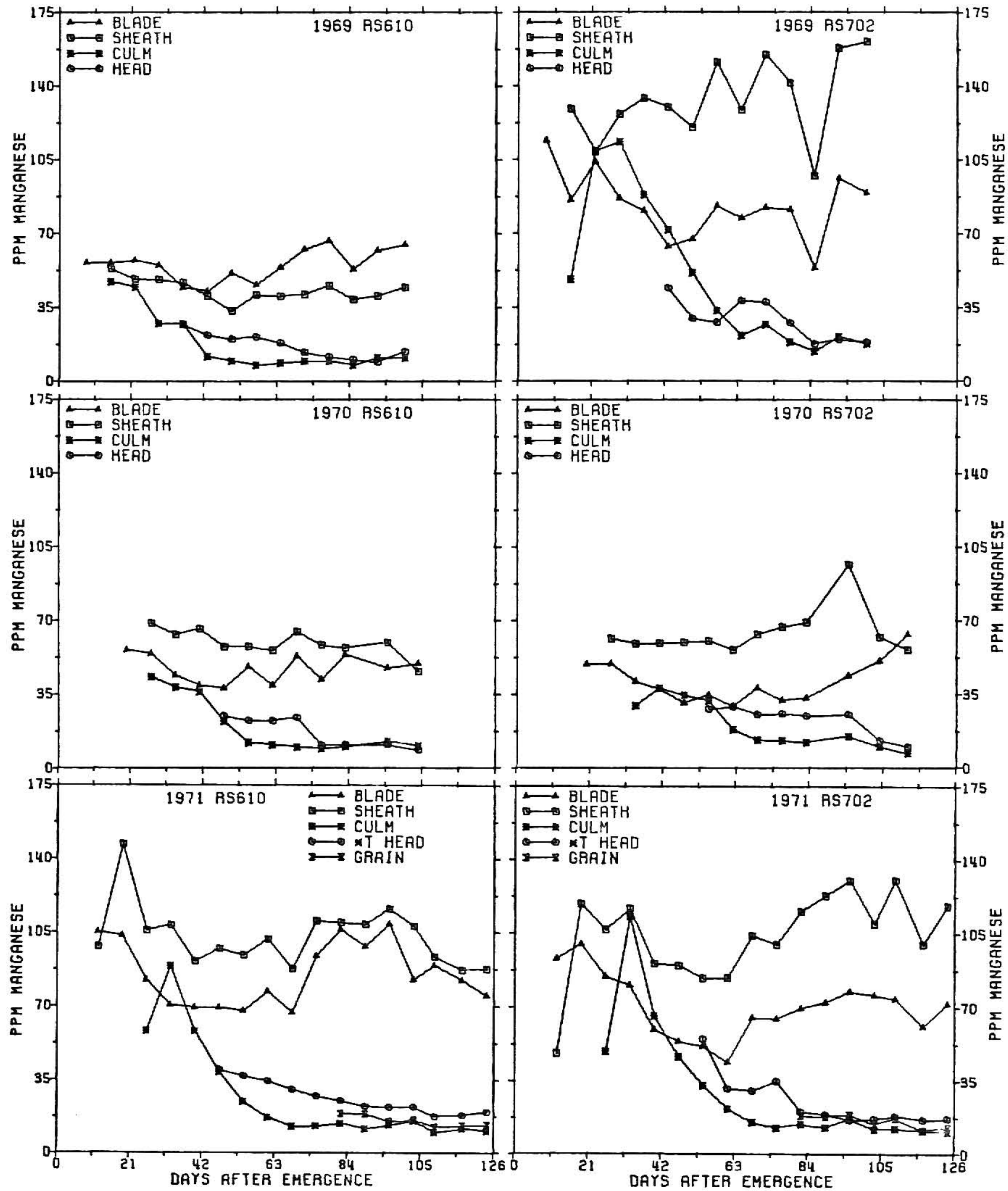

Figure 9. Manganese concentration in plant parts of RS610 and RS702 grain sorghum at Manhattan in 1969, 1970, and 1971. (*Threshed Head. Grain was separated from the head in 1971.)

neared physiological maturity. It is not known exactly why concentrations in the sheath and blade increased as the season progressed. Since Mn is an activator of enzymes perhaps more was needed to activate enzymes to form products for translocation to the head for grain development.

Manganese concentrations in the blade and sheath somewhat paralleled each other throughout the growing season. There was a larger difference in concentrations between the blade and sheath in RS702 than in RS610. The difference in concentration in RS610 was from 20 to 30 ppm and in RS702 it ranged from around 70 ppm during 1969 to 35 to 50 ppm during 1970 and 1971.

Figure 10 shows Mn concentrations in the whole plant throughout the growing season. There were no large differences between hybrids in 1970 and 1971, but in 1969 concentration in RS702 was from two to two and one-half times greater than in RS610. Since soil types differed it would be logical to assume the soil was a major factor contributing to the differences observed in concentrations. Of course complex climatic and soil interactions could have also been involved. RS610 in 1971 was generally slightly greater in concentration than RS702 in 1971 until initiation of grain development when RS702 was higher throughout the remaining growing season. RS702 in 1970 was also higher in concentration at that time than RS610 in 1970. As suggested before in the discussion on Zn and Cu, the differences observed in concentration between the hybrids may have been due to environmental factors affecting growth more so in RS702 than RS610 late in the growing season. Of course genetic factors must not be excluded as a possibility either.

Differences in Mn concentration among years were also noted.

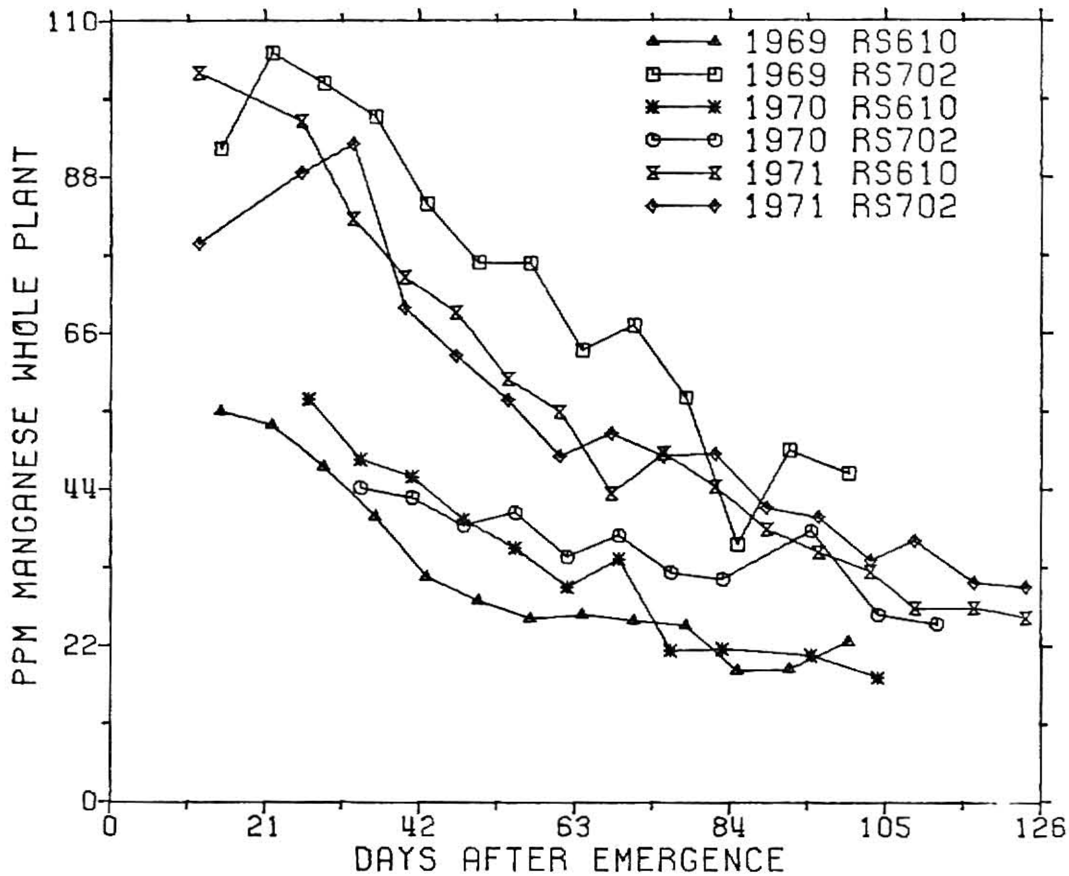

Figure 10. Manganese concentration in aboveground whole plants of RS610 and RS702 grain sorghum at Manhattan in 1969, 1970, and 1971.

Both hybrids in 1971 were higher in concentration throughout the growing season than in 1970. In 1969 RS702 was higher than anything else, but RS610 in 1969 was lowest in concentration. It is assumed environmental factors were largely responsible for the differences observed among years.

Manganese uptake curves (Figure 11) show that much of the Mn was in the blade and sheath. At physiological maturity in the plant 50 to 60% of the total Mn taken up was in the blade and sheath. The blade contained a greater percentage of the total uptake in RS610 than RS702 throughout most of the growing season, although by physiological maturity there was little difference between the hybrids. Since percentage of total uptake was not appreciably different between hybrids in the blade and sheath, and the blade contained a greater percentage of total uptake than the sheath in RS610, percentage of total uptake must be less in the sheath of RS610 than RS702 which was the case. As in the blade, little difference was noted by physiological maturity though.

Only about 5% of the total Mn taken up in the hybrids was located in the culm. Percentage of total uptake changed only slightly throughout the growing season.

The head at physiological maturity contained 30 to 35% of the total Mn taken up in the plant. Most of that seemed to be concentrated in the grain since in 1971 only about 5% was located in the threshed head parts.

There was little evidence indicated for translocation of Mn in the plant. In 1970 it was taken up in the blade throughout the

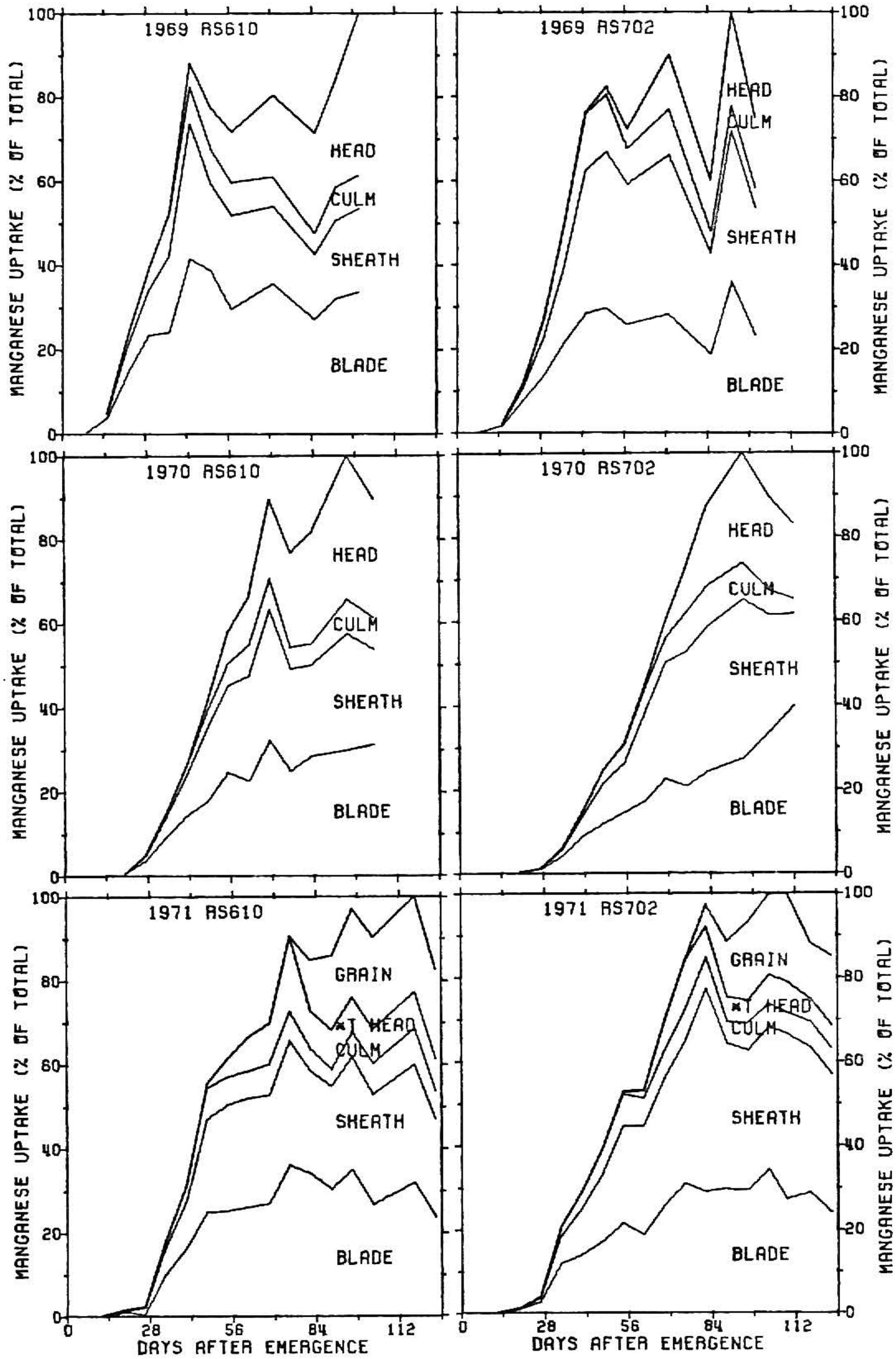

Figure 11. Manganese uptake in aboveground plant parts expressed as percent of total taken up in RS610 and RS702 grain sorghum at Manhattan in 1969, 1970, and 1971. (*Threshed Head. Grain was separated from the head in 1971.)

entire season, and no indication of it being translocated from other plant parts. The percentage of Mn contained in the blade increased as the season progressed even after the blade had reached its maximum dry weight.

Manganese was taken up more rapidly during vegetative growth than during grain development. A leveling off of the curves was noted during grain development, except in RS702 during 1970.

Magnesium Accumulation and Distribution

Magnesium concentrations in plant parts are shown in Figure 12. Differences were encountered among years, especially in 1970 when concentrations were higher. They were particularly higher in the sheath and culm. The sheath remained higher throughout the growing season, but the culm decreased rapidly in concentration as the season progressed. Concentration during 1970 in the hybrids decreased from 0.90% in the culm early in the season to 0.20% on the last sampling date.

In general, the sheath remained highest in Mg concentration of the plant parts throughout the growing season. It was little separated from the blade during 1971 in the hybrids and during 1969 in RS610 the blade was higher in concentration through much of the growing season. The sheath decreased in concentration until about the time it reached its maximum weight in the plant. During grain development concentration increased again. No initial decrease of concentration was noted in RS702 during 1969, but concentration increased late in the growing season.

The blade changed little in Mg concentration while it was still gaining weight from dry matter production. Concentration increased

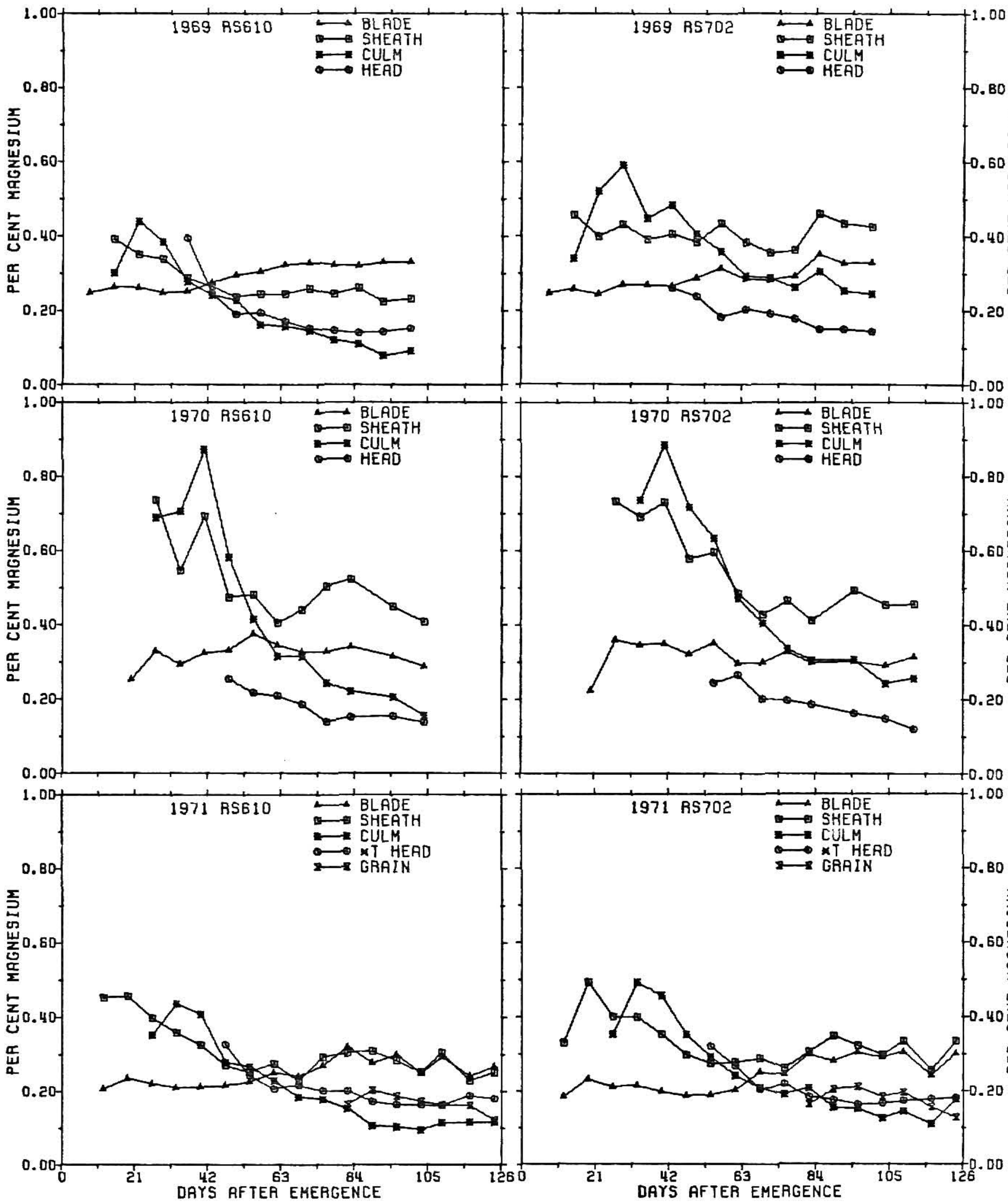

Figure 12. Magnesium concentration in plant parts of RS610 and RS702 grain sorghum at Manhattan in 1969, 1970, and 1971. (*Threshed Head. Grain was separated from the head in 1971.)

after that then leveled off somewhat during grain development. A decrease was observed in RS610 in 1970 during grain development, but RS702 in 1970 showed no change. In general, Mg concentration in the blade was fairly constant even though it increased and decreased during the growing season, but changes observed were not usually more than 0.1%.

The head was generally lowest in Mg concentration of all the plant parts in 1969 and 1970. It averaged about 0.20% during the two years. Concentration decreased as the plant reached physiological maturity. In 1971 when the head was separated from the grain, the grain decreased in concentration as development progressed, but the threshed head parts remained constant near 0.20%.

The higher Mg concentrations in 1970 were also evident in the whole plant (Figure 13), although RS610 in 1970 was not higher than RS702 in 1969 and 1971 after midway through the growing season.

RS702 in 1969 and 1970 was higher than RS610 in Mg concentration throughout the growing season. In 1971 RS702 was higher than RS610 during the latter half of the growing season, but no one hybrid was consistently higher or lower in concentration than the other during the first half.

Differences between years in Mg concentration were more evident early in the growing season. In 1970 concentrations were about three-fourths greater than during the same period in 1971, but towards the end of the growing season there were no large differences between the two years in concentration. As in the other nutrients discussed, environmental conditions probably contributed much to the Mg concentration

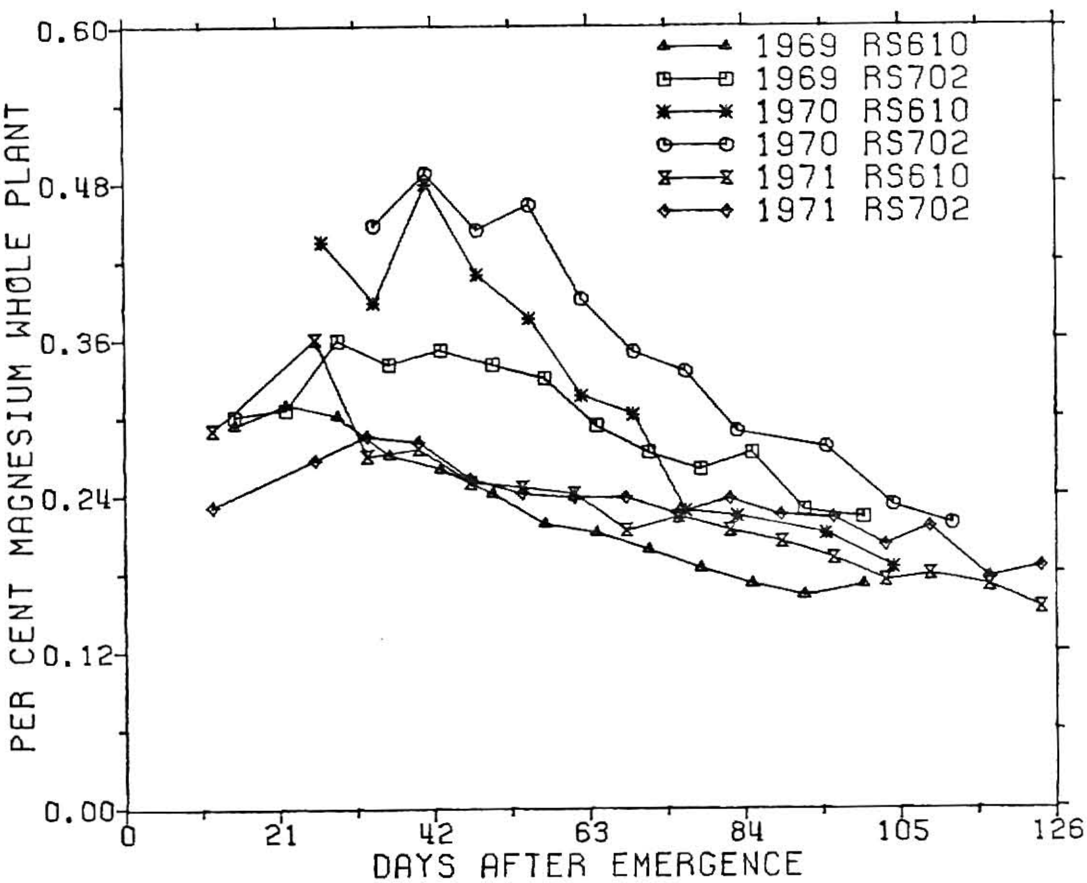

Figure 13. Magnesium concentration in aboveground whole plants of RS610 and RS702 grain sorghum at Manhattan in 1969, 1970, and 1971.

gradients observed among years.

Magnesium was fairly evenly distributed in the blade, sheath, and culm (Figure 14). Larger percentages of the total amount taken up were located in the vegetative plant parts of RS702 than RS610; consequently, a lower percentage of the total amount taken up was in the head of RS702. At physiological maturity average percent of the total Mg taken up in the plant and located in the head (grain included) of RS702 was about 37% and in RS610 it was approximately 52%. A larger percentage was in the head (grain included) during 1971 than 1969 or 1970. At physiological maturity in 1971 the grain of RS702 contained 40% of the total amount taken up in the plant and the grain of RS610 in 1971 contained 45%.

Magnesium was taken up for a longer period of time in the blade, sheath, and culm of RS702 than RS610. This followed dry matter accumulation as it continued over a longer period of time in the blade, sheath, and culm of RS702 than RS610.

Evidence of Mg being translocated out of the culm into the head was indicated. During grain development the percentage of Mg decreased in the culm. An increase following the decrease was noted in some instances.

Calcium Accumulation and Distribution

Calcium concentration in the head was very low as compared to the other plant parts (Figure 15). In 1971, when the grain was separated from the head, concentration was lower in the grain than the threshed head parts. Grain Ca concentration was from 0.01 to 0.02%

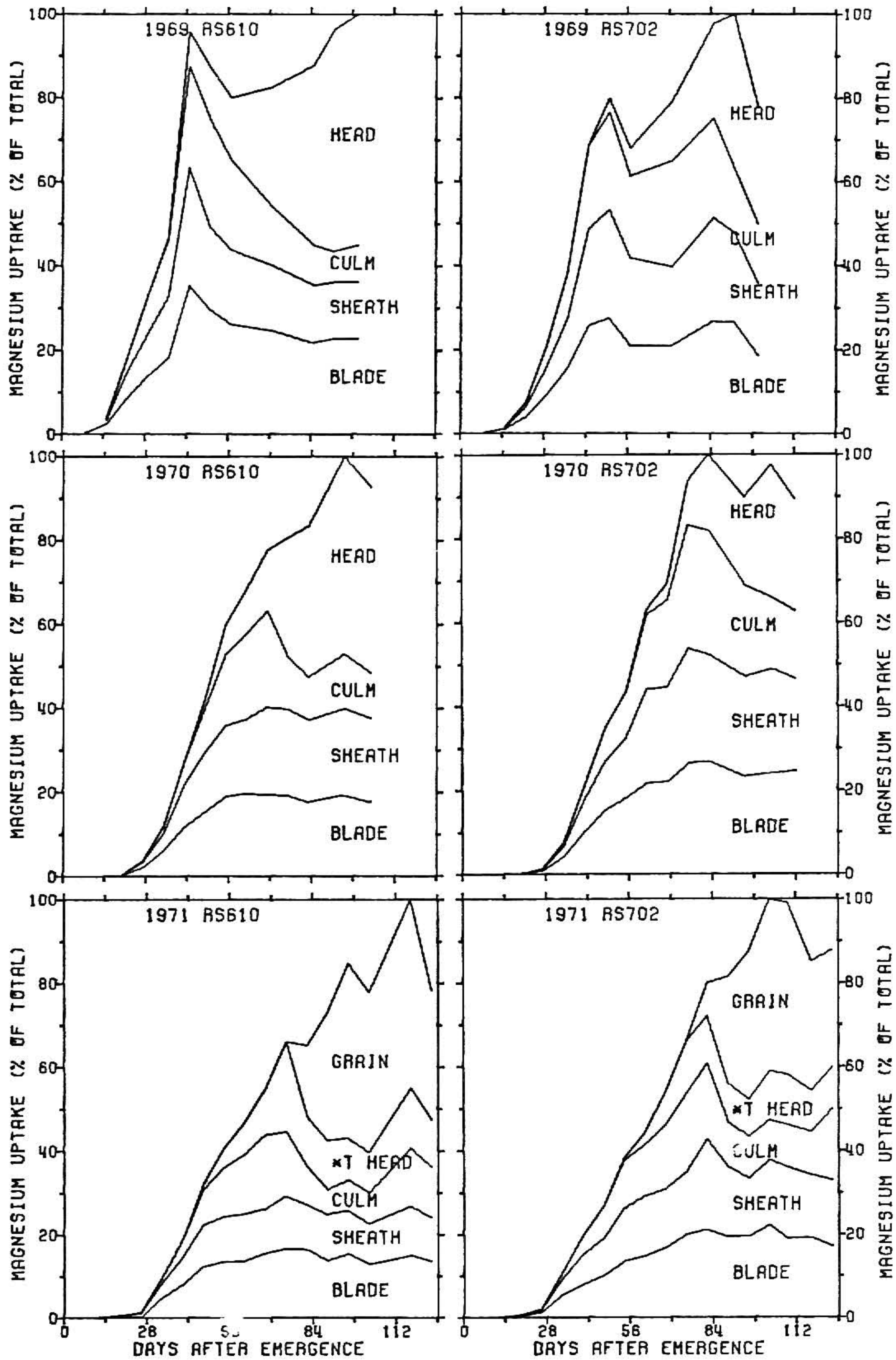

Figure 14. Magnesium uptake in aboveground plant parts expressed as percent of total taken up in RS610 and RS702 grain sorghum at Manhattan in 1969, 1970, and 1971. (*Threshed Head. Grain was separated from the head in 1971.)

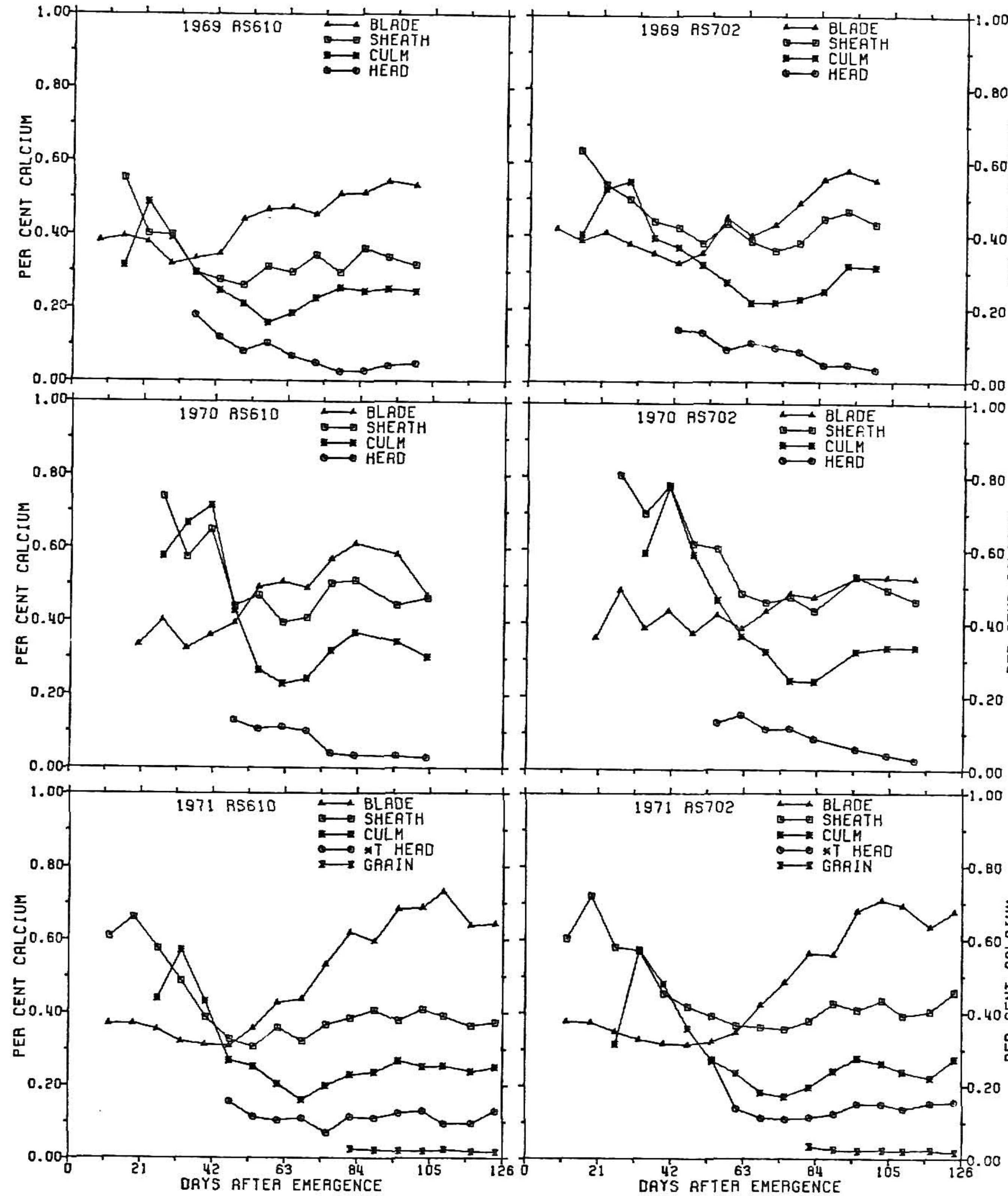

Figure 15. Calcium concentration in plant parts of RS610 and RS702 grain sorghum at Manhattan in 1969, 1970, and 1971. (*Threshed Head. Grain was separated from the head in 1971.)

or 100 to 200 ppm. Concentration in the threshed head parts generally remained constant during the growing season at 0.1 to 0.15%. In 1969 and 1970 the head decreased in concentration as grain development progressed. At physiological maturity there was no more than 0.05% (500 ppm) in the head.

Calcium concentrations in the blade increased as the growing season progressed, especially in 1971. The increase from the first sampling date to the last was about 0.20% in 1969 and 1970, and 0.35% in 1971. Concentrations in the blade were higher during the last half of the growing season than in the other plant parts at the same time. The increase in concentration probably occurred because large amounts of Ca were needed for Ca-pectate formation to cement cell walls together for rigid binding of mature cells.

Calcium concentration in the sheath decreased until about the time the sheath showed no more increase in weight from dry matter accumulation, after which concentration remained relatively constant throughout the rest of the growing season. It showed only a slight tendency to increase.

The culm decreased in Ca concentration rapidly until maximum dry matter was produced in it. Concentration increased during grain development, but decreased slightly again towards the end of the growing season. It probably increased for the same reason as mentioned in the discussion on blade concentration previously.

There were differences, although small, between hybrids in Ca concentrations of the plant parts and differences were observed among years, especially in 1971 when the blade tissue was higher in concentration during the second half of the growing season.

Although differences between hybrids in Ca concentration were not readily evident when looking at plant part concentrations, differences can be seen in whole plant concentrations (Figure 16). RS702 was higher in concentration than RS610 throughout the growing seasons in 1969, 1970, and 1971. Since this phenomenon occurred in all three years the differences observed in Ca concentration between the hybrids may be genetically controlled.

More Ca was taken up in the blade than in the other plant parts as seen in Figure 17. At physiological maturity about 40% of the Ca taken up in the plant was in the blade. It was accumulated in the blade throughout much of the season, except in RS610 during 1969.

Total Ca uptake was reached in RS610 during 1969 early in the season when compared to RS702 in 1969, and RS610 and RS702 in 1970 and 1971. It is doubtful that total uptake was actually reached so early in the field, but Ca did seem to be taken up faster then. A decrease of only 15% from total uptake to physiological maturity was noted. As mentioned in the discussion on dry matter production, difficulty in retrieving representative plants from the field was encountered. Larger and heavier samples obtained from the field on a particular sampling date(s) than the average plant in the field would conceivably give erroneous results in nutrient uptake also.

Calcium was fairly evenly distributed between the sheath and culm. No differences between hybrids were indicated. Twenty to 30% of the Ca taken up in the plant was located in the sheath and culm each.

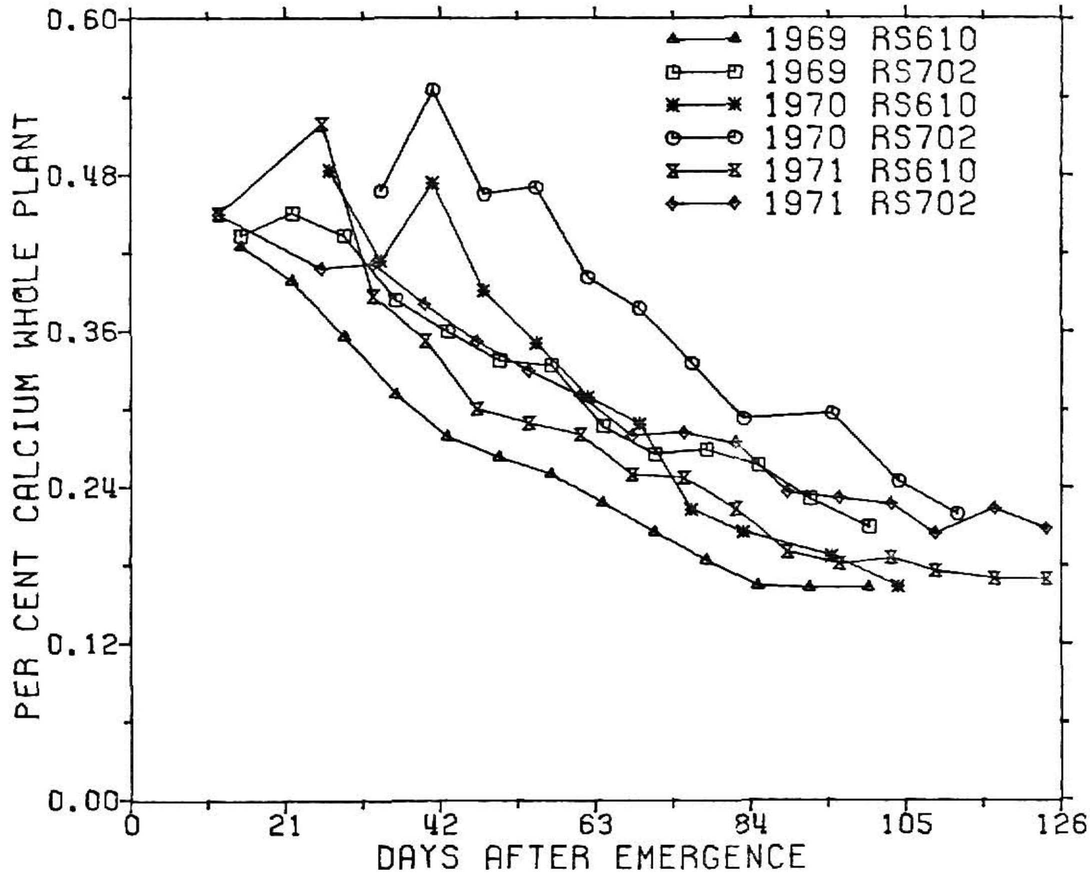

Figure 16. Calcium concentration in aboveground whole plants of RS610 and RS702 grain sorghum at Manhattan in 1969, 1970, and 1971.

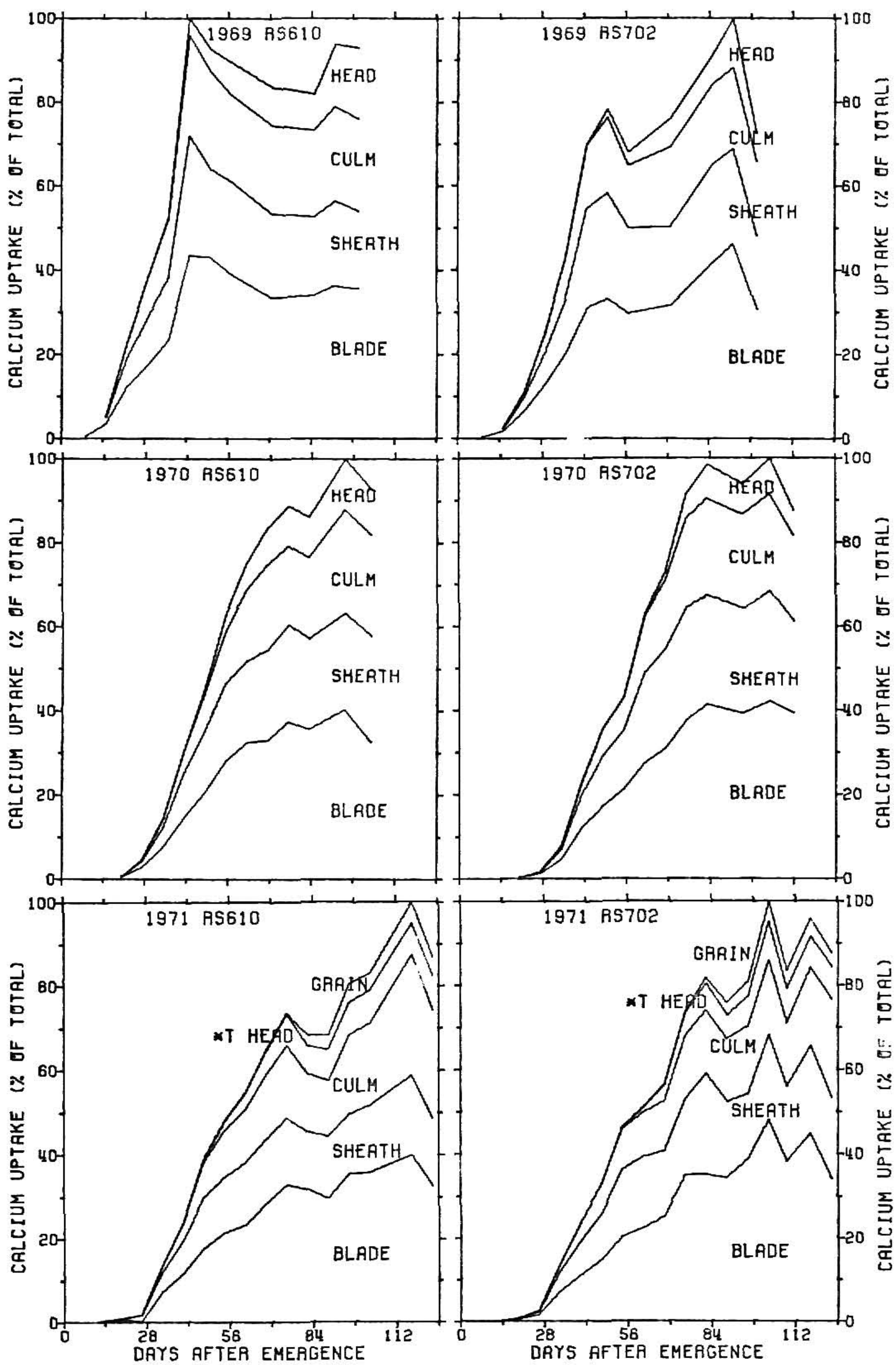

Figure 17. Calcium uptake in aboveground plant parts expressed as percent of total taken up in RS610 and RS702 grain sorghum at Manhattan in 1969, 1970, and 1971. (*Threshed Head. Grain was separated from the head in 1971.)

The head contained less than 10% of the total Ca taken up in the plant. In 1971 when the grain was separated from the head only about 2 to 3% of the total taken up was in the grain. The threshed head parts contained more Ca than the grain.

No evidence of translocation of Ca from the vegetative parts to the developing grain was indicated. Calcium seemed to be very immobile in the plant.

Nutrient Uptake in Relation to Growth

Figures 18 and 19 show the relationship between nutrient uptake and dry matter accumulation in the sorghum plant. It was evident that nutrient uptake preceded dry matter accumulation. For example, in Figure 18 the RS610 grain sorghum during 1970 by 60 days after emergence[2] had accumulated about 40% of the total dry matter produced at physiological maturity while Zn taken up in the plant had reached 52% of the total amount eventually taken up, Cu 60%, Mn 65%, Mg 67%, and Ca 72%. It would probably be safe to make the assumption that nutrient uptake preceded dry matter accumulation because the nutrients were required before growth and dry matter accumulation could occur.

Nutrients were taken up more rapidly in RS610 than RS702. For example, percent of total nutrient uptake of RS702 in 1970 by 60 days after emergence was 37% for Zn, 42% for Cu, 43% for Mn, and 62%

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[2]Average time for RS610 grain sorghum grown at Manhattan, Kansas, to reach half bloom. RS702 normally reaches half bloom 72 days after emergence. Days to half bloom varies depending on environmental conditions.

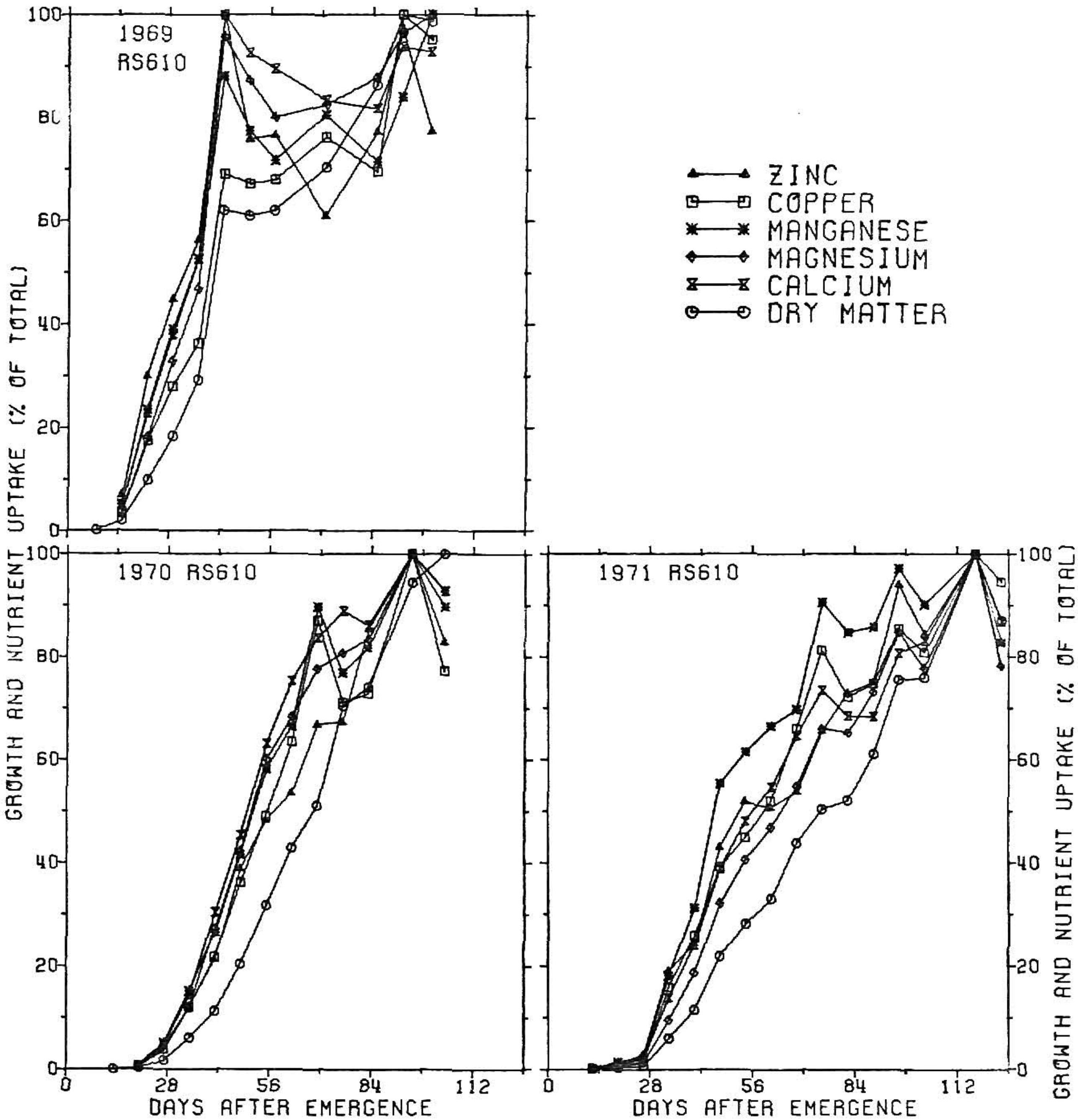

Figure 18. Aboveground whole plant dry matter production and nutrient uptake expressed as percent of total in RS610 grain sorghum at Manhattan in 1969, 1970, and 1971.

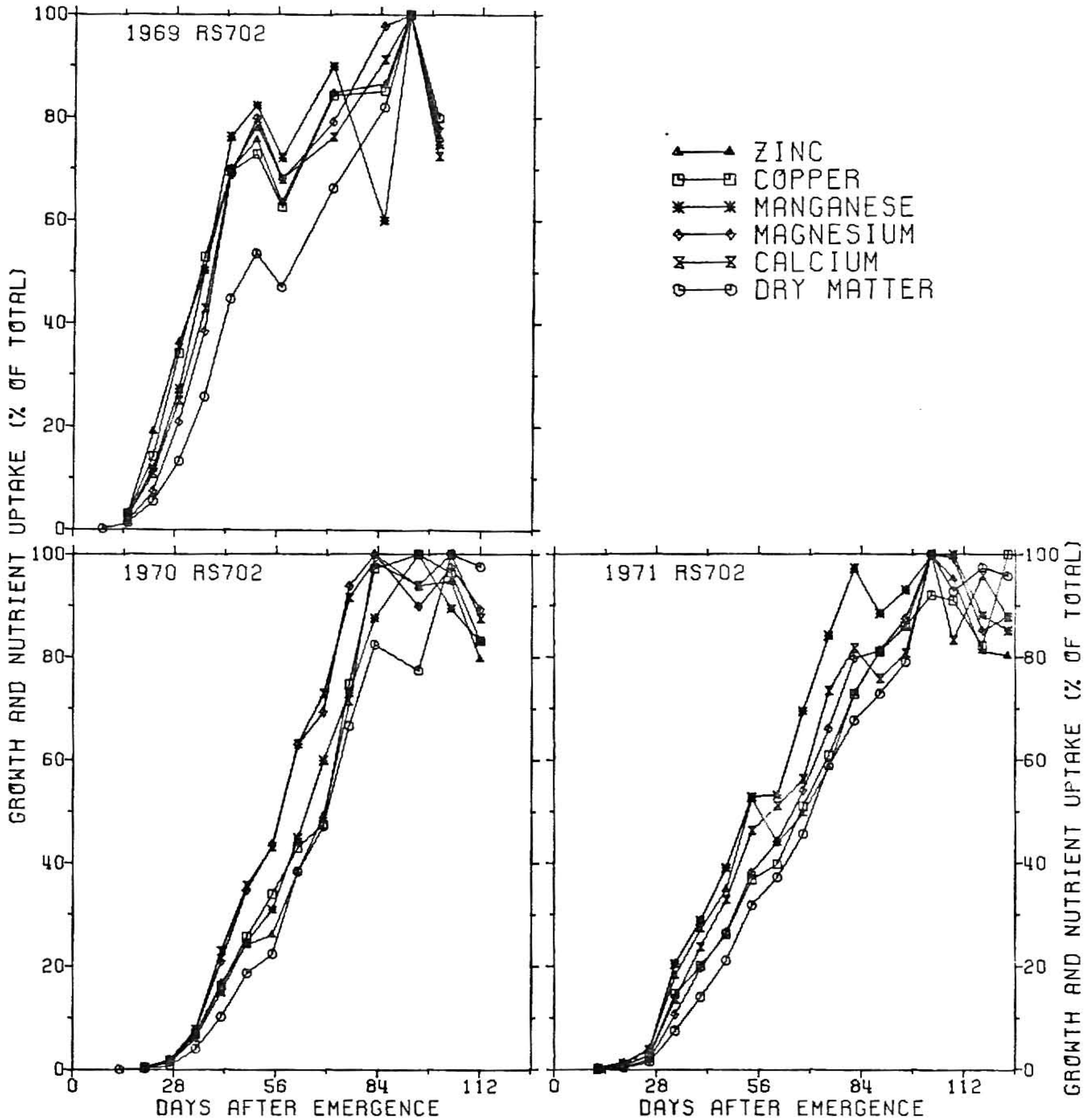

Figure 19. Aboveground whole plant dry matter production and nutrient uptake expressed as percent of total in RS702 grain sorghum at Manhattan in 1969, 1970, and 1971.

for Mg and Ca. When comparing this to RS610 in 1970, as described previously, percent of total nutrient uptake was less in RS702. This is logical because RS702 is normally later maturing than RS610 and dry matter accumulation occurs over a longer period of time, thus, nutrient uptake likewise would be expected to occur over a longer period of time. Although maximum nutrient uptake was reached at about the same time in the hybrids each year as was physiological maturity, rate of nutrient uptake was more rapid during the vegetative growth of RS610 than RS702.

There was no indication that any one nutrient was continually being taken up at a faster rate than another. In 1971 Mn was accumulated at a faster rate than the other nutrients, but in 1970 Ca and Mg accumulated more rapidly. In 1969 no one nutrient accumulated more rapidly than another throughout the growing season.

Nutrient concentrations in the plant may affect the rate of nutrient uptake in some manner. Manganese concentrations were higher in the plant during 1971 than 1970 and uptake was more rapid in 1971. In 1970 Ca and Mg concentrations were higher in the plant than in 1971 and uptake was more rapid in 1970. Such was not the case in 1969 though. In RS702 during 1969 Mn concentration was higher than RS610 in 1969, and RS610 and RS702 in 1970 and 1971, but uptake was not at a more rapid rate.

SUMMARY AND CONCLUSIONS

Growth of the sorghum plant was slow the first 20 to 30 days after emergence. The rate of growth increased as more blade and sheath area was produced and culm elongation began. The plant consisted almost entirely of blades and sheaths until 30 to 40 days after emergence when culm elongation began. Subsequent growth and dry matter accumulation was rapid to physiological maturity. Vegetative growth of the plant was completed by the time flowering was initiated which occurred about two-thirds of the way from emergence to physiological maturity. The culm had ceased to elongate and gain weight and maximum weight in the blades and sheaths was reached earlier. Grain formation and development comprised about one-third of the time from emergence to physiological maturity. During grain development material manufactured by the leaves was moved from the culm into the grain.

The general pattern of dry matter accumulation was the same for both hybrids. RS702 accumulated a greater portion of its dry matter in the vegetative plant parts, consequently, less weight proportionly was located in the head of RS702 than RS610.

When making inferences about nutrient uptake and distribution in the plant it is important to know existing environmental factors at the time of uptake. Environmental factors affected growth and nutrient uptake as was evidenced by variations in dry matter accumulation and nutrient uptake among the years. Although this was the case growth and nutrient uptake curves were similar among years and general patterns were indicated.

Nutrient concentrations in the plant parts were generally high, more so in the culm, early in the growing season and decreased as the season progressed. Concentrations stabilized after maximum weight was reached in each plant part and did not change appreciably throughout the remaining growing period. A notable exception to this was the blade tissue in Ca and Mn concentrations which increased throughout the growth of the plant.

Nutrient concentrations varied among plant parts. The culm was usually highest in concentration during the early growth of the plant, but blade and sheath tissue were normally highest in concentration thereafter. An exception was Cu in which the culm remained highest in concentration throughout the growth of the plant and the sheath lowest in concentration. The head was usually lowest of all the plant parts in nutrient concentration, especially after grain development began. In 1971 nutrient concentrations were lower in the grain than the threshed head parts, except Mg which was more concentrated in the grain. Little difference among plant parts in Zn concentration was observed, except early in the growth of the plant.

Whole plant nutrient concentrations decreased throughout the growth of the plant. Decrease was generally linear in nature. Zinc and Cu concentrations stabilized somewhat after vegetative growth of the plant was completed. Nutrient concentrations were high early in the growth of the plant because nutrients were being accumulated while growth was occurring at a slow rate. The nutrients were available in the soil and taken up in the plant before rapid growth began. Concentrations were diluted as the season progressed because dry matter accumulation was proceeding at a more rapid rate than nutrient uptake could maintain the high level of concentrations in the plant that existed early in growth. Consequently, nutrient concentrations decreased through most of the plant growth.

Since nutrients changed in concentration throughout the growth of the plant and plant parts were not equal in concentration, it would be important to establish tissue and age of the sorghum plant sample if tissue analyses diagnostic work were to be performed. Inferences about nutrient concentrations could not accurately be made if these were not known.

Nutrient uptake curves were similar to dry matter accumulation curves, but nutrient uptake preceded dry matter accumulation because the nutrients were required for growth and dry matter production. No one nutrient seemed to be taken up more rapidly in the plant than another. There were differences among years and between hybrids in total nutrient uptake, but uptake curves were still similar and definite general patterns were indicated.

Differences in nutrient distribution between hybrids and plant parts within a hybrid were observed. In general, the RS702 grain sorghum had a larger proportion of its nutrients in the vegetative portion of the plant than RS610 did. Consequently, nutrients were proportionly less in the head of RS702 than RS610. Extreme differences were noted among the plant parts in nutrient distribution, and accumulations were not necessarily proportional to dry matter accumulations. For example, of the total amount of Ca taken up in the plant about 40% of it was in the blade at physiological maturity, but less than 10% in the head (grain included), even though the head comprised 50 to 60% of the total weight of the plant at physiological maturity and the blade only 10 to 20%. Nutrients also differed in proportion of their respective uptake within plant parts. As an example, Cu accumulation in the sheath at physiological maturity was generally less than 10% of the total amount taken up, but Mn accumulation in the sheath at the same time averaged about 25% of the total Mn taken up in the plant.

Some of the nutrients were translocated to the head from the vegetative plant parts during grain development. No translocation of Ca and Mn appeared to occur, but there was at least slight evidence of translocation of Mg, Cu, and Zn in the plant.

By the completion of the vegetative growth of the plant nutrient accumulation had generally reached at least 50% and usually more of total uptake in the plant for all nutrients studied. Dry matter accumulation at that time was from 40 to 50% of total production depending on hybrid and year.

In studying nutrient distribution in the plant it was possible to tell what proportion of the total uptake was removed at harvest. Since total uptake was known the amount of nutrients removed at harvest could be determined. This varied among nutrients in the case of grain sorghum. Large amounts of Zn and Mg in proportion to the other plant parts were removed in the grain at harvest, but only a small proportion of Ca and intermediate portions of Cu and Mn were removed. Since the amount of nutrients removed at harvest must eventually be replaced, knowledge of nutrient distribution in the grain sorghum plant gives one an idea of what magnitudes of nutrients must be replaced in relation to the total amounts taken up.

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LITERATURE CITED

1. Analytical Methods for Atomic Absorption Spectrophotometry. Perkin-Elmer Corporation, Norwalk, Connecticut. 1966.

2. Bassett, D. M., W. D. Anderson, and C. H. E. Werkhoven. 1970. Dry matter production and nutrient uptake in irrigated cotton. Agron. J. 62:299-303.

3. Beason, E. F. 1971. Effect of zinc, manganese, and copper on soil test data, grain sorghum yield, and leaf nutrient content, p. 52-53. In Southeast Kansas Branch Exp. Sta. Plant and Soil Sci. Res. Rep. No. 179. Kansas State University, Manhattan, Kansas.

4. Bennett, W. F. 1971. A comparison of the chemical composition of the corn leaf and the grain sorghum leaf. Commun. Soil Sci. Plant Anal. 2:399-405.

5. Campbell, D. K. and D. J. Hume. 1972. Accumulation and translocation of soluble solids in corn stalks. Can. J. of Plant Sci. 52:363-367.

6. Cherian, E. C. 1969. Microelement nutrition of grain sorghum. Ph. D. Thesis. Kansas State University, Manhattan, Kansas.

7. Doggett, H. 1970. The chemistry of the sorghum plant, p. 212-222. In H. Doggett, Sorghum. Longmans, Green and Co. Ltd.

8. Gieseking, J. E., H. J. Snider, and C. A. Getz. 1935. Destruction of organic matter in plant material by the use of nitric and perchloric acids. Ind. and Eng. Chem. (Anal. Ed.) 7:185-186.

9. Hanway, J. J. 1971. How a corn plant develops. Coop. Ext. Services Spec. Rep. No. 48. Iowa State University, Ames, Iowa.

10. Hanway, J. J. and H. E. Thompson. 1967. How a soybean plant develops. Coop. Ext. Services Spec. Rep. No. 53. Iowa State University, Ames, Iowa.

11. Lal, R. and G. S. Taylor. 1970. Drainage and nutrient effects in a field lysimeter study. II: Mineral uptake by corn. Soil Sci. Soc. Amer. Proc. 34:245-248.

12. Lane, H. C. and H. J. Walker. 1961. Mineral accumulation and distribution in grain sorghum. Texas Agric. Exp. Sta. Bull. No. MP-533. The Agricultural and Mechanical College of Texas, College Station, Texas.

13. Lockman, R. B. 1972. Mineral composition of grain sorghum plant samples. Part I: Comparative analysis with corn at various stages of growth and under different environments. Commun. Soil Sci. Plant Anal. 3:271-281.

14. Lockman, R. B. 1972. Mineral composition of grain sorghum plant samples. Part II: As affected by soil acidity, soil fertility, stage of growth, variety, and climatic factors. Commun. Soil Sci. Plant Anal. 3:283-293.

15. Lockman, R. B. 1972. Mineral composition of grain sorghum plant samples. Part III: Suggested nutrient sufficiency limits at various stages of growth. Commun. Soil Sci. Plant Anal. 3:295-303.

16. Matocha, J. E., B. E. Conrad, L. Reyes, and G. W. Thomas. 1970. Influence of zinc, iron, potassium, and phosphorus on yield and chemical composition of grain sorghum. Texas Agric. Exp. Sta. Prog. Rep. No. 2839. Texas A & M University, College Station, Texas.

17. Model 303 Atomic Absorption Spectrophotometer. Perkin-Elmer Corporation, Norwalk, Connecticut. 1966.

18. Owen, D. F. and R. D. Furr. 1967. Effect of sulfur and trace minerals on forage sorghum yield and mineral composition. Agron. J. 59:611-612.

19. Shipley, J., P. Unger, and C. Regier. 1971. Consumptive water use, harvestable dry matter production, and nitrogen uptake by irrigated grain sorghum. Texas Agric. Exp. Sta. Prog. Rep. No. 2951. Texas A & M University, College Station, Texas.

20. Snedecor, G. W. 1956. Statistical Methods. The Iowa State College Press, Ames, Iowa.

21. Snedecor, G. W. and W. G. Cochran. 1967. Statistical Methods. The Iowa State University Press, Ames, Iowa.

22. Vanderlip, R. L. 1972. How a sorghum plant develops. Coop. Ext. Services Circ. No. 447. Kansas State University, Manhattan, Kansas.

23. Vanderlip, R. L. and H. E. Reeves. 1972. Growth stages of sorghum. Agron. J. 64:13-16.

24. Voss, R. E., J. J. Hanway, and L. C. Dumenil. 1970. Relationship between grain yield and leaf N, P, and K concentrations for corn (Zea mays L.) and the factors that influence this relationship. Agron. J. 62:726-728.

25. Whitney, D. A., and R. Ellis. 1970. Soil and plant analyses from corn and sorghum survey. Department of Agronomy Pamphlet. Kansas State University, Manhattan, Kansas.

26. Williams, R. F. 1955. Redistribution of mineral elements during development. Ann. Rev. Plant Physiol. 6:25-42.

Table 5. Analysis of variance for aboveground whole plant nutrient concentrations of RS610 and RS702 grain sorghum at Manhattan in 1970.

Source	d.f.	Mean Squares				
		Zn	Cu	Mn	Mg	Ca
Replicates	1	0.06	0.37	5.12	88096	17601
Dates	9	257.21**[1]	28.03**	263.60**	3509876**	4095610**
Hybrids	1	230.83**	5.01**	268.17**	3727678**	8036296**
Dates x Hybrids	9	30.41	6.68**	44.04*	70196	41345
Error	19	13.59	0.50	13.86	49451	37850

Table 6. Analysis of variance for aboveground whole plant nutrient concentrations of RS610 and RS702 grain sorghum at Manhattan in 1971.

Source	d.f.	Mean Squares				
		Zn	Cu	Mn	Mg	Ca
Replicates	1	110.36	0.21	139.71	12420	10348
Dates	15	1665.00**	39.03**	1914.50**	637299**	3387786**
Hybrids	1	52.06*	6.59**	0.04	32295	1195863**
Dates x Hybrids	15	68.12**	1.78**	73.68**	119090**	152424**
Error	31	9.88	0.53	20.55	20413	22488

[1]One asterisk (*) designates significance at the 5% level and two asterisks (**) designate significance at the 1% level.

Table 7. Mean aboveground whole plant nutrient concentrations of RS610 and RS702 grain sorghum at Manhattan in 1969, 1970, and 1971.

Year	PPM Zn	PPM Cu	PPM Mn	Percent Mg	Percent Ca
1969					
RS610	27.6	5.2	32.0	0.230	0.260
RS702	41.4	12.5	73.0	0.298	0.327
1970					
RS610	31.5	11.7	31.4	0.312	0.300
RS702	36.3	11.0	36.6	0.373	0.390
1971					
RS610	35.6	10.1	53.7	0.228	0.272
RS702	33.8	9.5	53.7	0.233	0.300

Table 8. Analysis of variance for aboveground whole plant nutrient concentrations of RS610 and RS702 grain sorghum at Manhattan combined over years (1970 and 1971).[1]

Source	d.f.	Mean Squares Zn	Cu	Mn	Mg[2]	Ca
Replicates	1	5.96	0.12	61.71	40964	1655
Dates	9	452.74**	34.74**	863.44**	2749636**	4852028**
Hybrids	1	73.73**	14.37**	179.64**	2796021**	8144145**
Years	1	707.10**	114.43**	4800.35**	25854180**	11848998**
Dates x Hybrids	9	20.75*	6.94**	58.65**	58140	27962
Dates x Years	9	11.81	4.06**	75.96**	1045755**	543569**
Hybrids x Years	1	166.41**	0.39	95.18**	1120039**	1334646**
Dates x Hybrids x Years	9	14.18	1.62*	16.79	32076	22250
Error	39	8.31	0.59	16.70	38057	31136

[1]Ten representative dates were chosen from each year that approximated equal growth periods of the plant between years.

[2]The test for homogeneity of variance between 1970 and 1971 error mean squares was significant at the 5% level, but not at the 1% level.

Table 9. Mean aboveground whole plant nutrient concentrations of RS610 and RS702 grain sorghum at Manhattan combined over years (1970 and 1971)[1].

Hybrid	PPM Zn	PPM Cu	PPM Mn	Percent Mg	Percent Ca
RS610	34.0	10.7	45.1	0.260	0.283
RS702	34.8	10.1	47.1	0.286	0.335

[1]Includes all sampling dates from each year.

Table 10. Mean aboveground whole plant nutrient concentrations in grain sorghum at Manhattan in 1970 and 1971 combined over hybrids (RS610 and RS702).

Year	PPM Zn	PPM Cu	PPM Mn	Percent Mg	Percent Ca
1970	33.9	11.4	34.0	0.342	0.345
1971	34.7	9.8	53.7	0.230	0.287

Table 11. Analysis of variance for head nutrient concentrations of RS610 grain sorghum at Manhattan in 1972.

Source	d.f.	Mean Squares Zn	Mean Squares Cu	Mean Squares Fe
Replicates	1	66.13	0.05	78.3
Dates	7	1748.86**	21.97**	1483.93**
Methods	1	50.00	2.53	684.50*
Dates x Methods	7	26.21	0.51	148.57
Error	15	62.53	1.30	130.13

Table 12. Analysis of variance for head nutrient concentrations of RS610 grain sorghum at Manhattan in 1972.

Source	d.f.	Mean Squares		
		Mn	Mg	Ca
Replicates	1	42.78	3720	17020
Dates	7	192.60**	895958**	194828**
Methods	1	11.28	5025	14878
Dates x Methods	7	1.71	35289	16979
Error	15	16.18	35611	30573

Table 13. Analysis of variance for culm nutrient concentrations of RS610 grain sorghum at Manhattan in 1972.

Source	d.f.	Mean Squares		
		Zn	Cu	Fe
Replicates	1	1163.77	102.48	6.94
Dates	12	48008.56**	588.70**	7543.46**
Methods	1	27.77	5.30	159.25
Dates x Methods	12	142.06	20.17*	142.96
Error	25	138.69	8.62	178.94

Table 14. Analysis of variance for culm nutrient concentrations of RS610 grain sorghum at Manhattan in 1972.

Source	d.f.	Mean Squares		
		Mn	Mg	Ca
Replicates	1	848.08	122414	557451
Dates	12	1801.63**	16420931**	7908341**
Methods	1	0.31	13666	130400
Dates x Methods	12	13.60	147123	185240*
Error	25	46.80	109469	68765

Table 15. Analysis of variance for sheath nutrient concentrations of RS610 grain sorghum at Manhattan in 1972.

Source	d.f.	Mean Squares		
		Zn	Cu	Fe
Replicates	1	24.45	1.93	90.0
Dates	13	789.90**	87.99**	16312.3**
Methods	1	0.16	2.75	25330.0**
Dates x Methods	13	24.05	3.21**	2759.7**
Error	27	11.89	0.91	559.0

Table 16. Analysis of variance for sheath nutrient concentrations of RS610 grain sorghum at Manhattan in 1972.

Source	d.f.	Mean Squares		
		Mn	Mg	Ca
Replicates	1	5245.79	245258	858578
Dates	13	336.80	2442136**	5846786**
Methods	1	48.29	149765	22883
Dates x Methods	13	75.94	93438	115379
Error	27	167.30	173735	120415

Table 17. Analysis of variance for blade nutrient concentrations of RS610 grain sorghum at Manhattan in 1972.

Source	d.f.	Mean Squares		
		Zn	Cu	Fe
Replicates	1	1.79	9.36	11343
Dates	13	327.90	22.72**	10753**
Methods	1	28.57	0.00	99710**
Dates x Methods	13	35.73	1.74	4423
Error	27	29.19	1.78	3953

Table 18. Analysis of variance for blade nutrient concentrations of RS610 grain sorghum at Manhattan in 1972.

Source	d.f.	Mean Squares		
		Mn	Mg	Ca
Replicates	1	2064.29	1607	94958
Dates	13	297.71*	1206749**	4726879**
Methods	1	0.00	375233	21765
Dates x Methods	13	25.77	230933	43912
Error	27	112.47	237917	94196

Table 19. Mean nutrient concentrations in plant parts of RS610 grain sorghum at Manhattan in 1972.

Plant Part	PPM				Percent	
	Zn	Cu	Fe	Mn	Mg	Ca
Blade						
Washed	31.6a[1]	13.3a	185.4a	63.2a	.316a	.409a
Unwashed	30.2a	13.3a	269.8 b	63.2a	.332a	.413a
Sheath						
Washed	41.8a	8.4a	79.4a	87.4a	.452a	.453a
Unwashed	41.7a	8.8a	122.0b	89.3a	.462a	.457a
Culm						
Washed	100.0a	24.4a	84.8a	32.2a	.429a	.358a
Unwashed	98.5a	23.8a	88.3a	32.4a	.432a	.348a
Head						
Washed	45.4a	11.0a	55.6a	27.6a	.227a	.089a
Unwashed	42.9a	10.4a	64.9 b	26.4a	.225a	.093a

[1]Numbers within a column and from each plant part followed by the same letter do not differ at the 5% level using the LSD test.

ACCUMULATION AND DISTRIBUTION OF ZN, CU, MN, FE, MG, AND CA IN GRAIN SORGHUM, *SORGHUM BICOLOR* (L.) MOENCH

by

GARY LYNN JACQUES

B. S., Kansas State University, 1968

AN ABSTRACT OF A MASTER'S THESIS

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ABSTRACT

Grain sorghum, Sorghum bicolor (L.) Moench, has become increasingly important as a feed grain in the United States since the development and release of hybrids. To reach the genetic yielding potential and understanding of the growth and development of the sorghum plant is essential to use appropriate and timely management and cultural practices. Nutrient accumulation and distribution are an integral part of sorghum growth and development, hence, will have a bearing on management and cultural practices, particularly those dealing with soil fertility and fertilizers.

This study was conducted to investigate the accumulation and distribution of Zn, Cu, Mn, Fe, Mg, and Ca in grain sorghum.

RS610 and RS702 grain sorghum hybrids were planted in bulk areas on the Kansas State University Agronomy Farm in 1969, 1970, and 1971. Samples were taken weekly and analyzed for their nutrient constituents in the plant parts.

Environmental factors affected growth and nutrient uptake among years, but dry matter accumulation and nutrient uptake curves were similar. Generalized patterns were indicated.

Nutrients were taken up from the soil and accumulated in the plant before rapid growth and dry matter production ensued. Nutrient concentrations were generally high in the plant parts, particularly in the culm, early during plant growth and decreased until maximum dry matter production was reached in each plant part, after which

concentrations stabilized and changed little thereafter, although in some cases an increase occurred during grain development. Whole plant concentrations decreased nearly linearly throughout plant growth.

Concentrations varied among plant parts within a nutrient. The culm was usually highest in concentration early in growth, but decreased rapidly during vegetative growth and the blade and sheath were generally highest through grain development. Copper was an exception in which the culm and threshed head remained highest in concentration and the sheath lowest. The head and culm, after vegetative growth and during grain development, were generally lowest in nutrient concentrations of all the plant parts. The grain was usually lower than the threshed head parts.

Tissue and age of the sorghum plant must be established to make inferences about nutrient concentrations since nutrients changed in concentration throughout plant growth and plant parts were not equal in concentration. An idea of the nutrient concentrations in plant parts and the changes with time will give more needed information concerning tissue testing procedures and inferences made.

Hybrids differed in nutrient uptake and distribution. No consistent whole plant concentration differences in Zn, Cu, Mn, or Mg existed, but Ca concentrations were higher in RS702 than RS610 throughout the entire season during each of the 3 years. RS702 generally had a larger proportion of its dry matter and nutrients distributed in the vegetative portion of the plant and less in the head than RS610 did.

Because nutrient concentration and/or dry matter production differed among plant parts, differences in nutrient distribution occurred also. Nutrient distribution was not necessarily proportional to dry matter distribution. The nutrients were evidently more concentrated in the plant parts where they were most needed. This varied among the nutrients studied.

There was evidence of translocation of Mg, Cu, and Zn from the vegetative plant parts to the developing grain, but Ca and Mn seemed to be immobile. Only a small portion of the total Ca taken up was in the grain while large portions of the Zn and Mg total uptake were in the grain.

Nutrient uptake preceded dry matter accumulation. The nutrients were required for growth and dry matter production. No one nutrient studied seemed to be consistently taken up more rapidly in the plant than another. Generally more than half of total uptake for each nutrient had occurred by the completion of the vegetative phase of growth.