# Aerial Accumulation and Partitioning of Nutrients by Corn

D. L. Karlen,* R. L. Flannery, and E. J. Sadler

## ABSTRACT

**Amounts and rates of dry matter and nutrient accumulation for very high-yielding corn (*Zea mays* L.) were unknown, but were needed to develop a base for future research and on-farm maximum economic yield demonstration programs. Aerial whole plant samples, collected from a maximum yield research experiment that resulted in a 19.3 Mg ha$^{-1}$ grain yield on a Typic Hapludult soil (Freehold sandy loam) near Adelphia, NJ, were used to provide that information. Samples were collected at growth stages V4, V8, V12, VT, R1, R2, R5, and R6; separated into lower leaves, upper leaves, stem and tassel, and ear and shank fractions; and analyzed to determine N, P, K, Ca, Mg, S, B, Cu, Fe, Mn, and Zn concentrations. Accumulation curves for each plant fraction were computed using those data and described mathematically using compound cubic polynomial equations. Dry matter and nutrient accumulation rates were computed by differentiating the equations. Total accumulation at physiological maturity was approximately 31 800, 386, 70, 370, 59, 44, 40, 0.13, 0.14, 1.9, 0.9, and 0.8 kg ha$^{-1}$ for dry matter, N, P, K, Ca, Mg, S, B, Cu, Fe, Mn, and Zn, respectively. Distribution among the four plant fractions, as well as rates of accumulation, are discussed. Diagnosis and recommendation integrated system indices were calculated using leaf concentration data. Nutrient balance was very good, although fertilizer recovery was not optimum. Amounts and rates of accumulation measured in this study can provide general guidelines for very high corn yields when more economical practices are used.**

***Additional Index Words:* *Zea mays* L., Maize, Maximum yield research, Nutrient accumulation, Diagnostic and recommended integrated system indices.**

HIGH corn yields can be achieved by planting hybrids with high yield potential early in the season, using narrow rows and high populations, applying adequate fertilization rates, applying supplemental irrigation water as needed, and using pesticides to prevent plant stress caused by limited nutrients, limited water, or excessive pest pressures (Larson and Hanway, 1977). An optimum field environment, where soil type is uniform, drainage and water retention are good, and day/night temperatures approach an optimum for corn (Shaw, 1977), is also required. Recent maximum yield studies emphasize creating a minimum stress environment for crop production. Results of those studies are impressive because, in just 5 yr, corn grain yields ranging from 15.7 to 21.2 Mg ha$^{-1}$ have been achieved at 20 North American locations (Griffith and Dibb, 1985). Those studies demonstrate maximum crop yield potential in field environments and therefore provide an excellent data set for quantifying maximum nutrient uptake rates at high yield levels.

Amounts and rates of dry matter, N, P, and K accumulation for corn grown using current management practices have recently been summarized by Karlen et al. (1987a,b), but accumulation and partitioning patterns for very high-yielding corn needed to be quantified. We hypothesized that providing a minimum-stress crop production environment could significantly change rates of nutrient accumulation when compared to previous corn experiments (Hanway, 1962a,b). This information was needed to develop a base for (i) future research, (ii) maximum economic yield demonstration projects, and (iii) on-farm production.

The objective of this study was to evaluate amounts, rates, and partitioning of aerial dry matter, N, P, K, Ca, Mg, S, B, Cu, Fe, Mn, and Zn accumulated by corn yielding 19.3 Mg ha$^{-1}$ when grown in a minimum-stress field environment.

## METHODS AND MATERIALS

A maximum-yield research study was conducted on a Freehold sandy loam at the Rutgers University Soils and Crops Research Center near Adelphia, NJ. The sand, silt, and clay contents of the soil were approximately 650, 250, and 100 g kg$^{-1}$, respectively, while the organic matter content averaged 15.0 g kg$^{-1}$ and the cation exchange capacity averaged 7.5 cmols kg$^{-1}$. The experimental site had been previously used for maximum-yield research and had produced an average annual corn and soybean [*Glycine max* (L.) Merr.] yield of 19.3 and 6.93 Mg ha$^{-1}$, respectively, during the past 5 yr (1980–1984).

Soil samples collected from the upper 20 cm after soybean harvest in October 1984 showed an initial water pH of 5.7, KCl extractable $NO_3$–N and $NH_4$–N concentrations of 22 and 9 kg ha$^{-1}$, and Mehlich I extractable P, K, Ca, and Mg concentrations of 247, 415, 1614, and 281 kg ha$^{-1}$, respectively. In 1985, Pioneer Brand[1] 3192 corn was grown with two rates of fertilizer with or without supplemental irrigation. Individual plots were 2.4 m wide, 13.4 m long, and replicated four times. Whole plant samples were collected from only the irrigated, high-fertility plots for this study. A total of 44 Mg ha$^{-1}$ of dry matter as cow (*Bos* spp.) manure and 1.1 Mg ha$^{-1}$ of dolomitic limestone (30% CaO + 20% MgO) were broadcast and plowed down within 24 h of application 1 wk prior to planting corn. In addition to manure and lime, ammonium nitrate, normal superphosphate, and potassium sulfate were applied before planting. At the V4 (four-leaf), V8 (eight-leaf), V12 (12-leaf), and R1 (silking) growth stages (Ritchie and Hanway, 1984), the crop was fertigated. These intensive management practices provided a total season fertilizer application of 560, 336, 504, 240, 135, 142, 2.2, 5.6, 28, and 11 kg ha$^{-1}$ N, P, K, Ca, Mg, S, B, Cu, Mn, and Zn, respectively. For weed control, a three-way combination of cyanazine (2-{[4-chloro-6-(ethylamino)-1,3,5-triazin-2-yl]amino}-2-methylpropanenitrile), butylate

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[*S*-ethyl bis (2-methylpropyl) carbamothioate], and atrazine [6-chloro-*N*-ethyl-*N'*-(1-methylethyl)-1,3,5-triazine-2,4-diamine] was applied at rates of 1.1, 3.6, and 0.7 kg a.i. ha$^{-1}$, respectively. For insect and disease control, corn seed was treated with a combination of diazinon [*O,O*-diethyl *O*-(2-isopropyl-4-methyl-6-pyrimidinyl) phosphorothiote], captan {*cis*-N[(trichloromethyl)thio]-4-cyclohexene-1,2-dicarboximide}, and methiocarb [3,5-dimethyl-4-(methylthio)phenyl methylcarbamate] at rates of 1.45, 0.78, and 5.0 g a.i. kg$^{-1}$ seed, respectively. Soil was treated with 4.2 kg a.i. ha$^{-1}$ carbofuran (2,3-dihydro-2,2-dimethyl-7-benzofuranyl methylcarbamate) and 4.2 kg a.i. ha$^{-1}$ fonofos (*O*-ethyl-S-phenylethylphosphonodithioate), and disked before planting. At growth stage V6 (six-leaf), a granular foliar whorl application of 1.6 kg a.i. ha$^{-1}$ carbofuran was made to control European corn borer (*Ostrinia nubilalis*).

Corn was planted 1 May using an equidistant 0.3- by 0.3-m spacing. Supplemental water was applied through Chapin[1] double-wall trickle irrigation tubing (Chapin Watermatics, Inc., Watertown, NY) to apply fertilizer nutrients and to prevent water stress. In addition to 620 mm of rainfall (Table 1), 152 mm of irrigation water were applied during the growing season. Aerial whole plant samples (12 plants per plot) were collected at growth stages V4, V8, V12, VT, R1, R2, R5, and R6 to measure dry matter and nutrient accumulation. At V4 and V8, plants were not fractionated, but at V12, they were divided into leaves and stalk. At VT,

**Table 1. Cumulative rainfall, irrigation, and growing degree units (GDUs) between planting on 1 May 1985 and each plant sampling date.**

| Sampling date | Rainfall | Irrigation | GDUs | Growth stage and description |
|---|---|---|---|---|
| | —— mm | —— | | |
| 06/06/85 | 141 | 38 | 305 | V4—four leaves fully emerged |
| 06/18/85 | 197 | 51 | 422 | V8—eight leaves fully emerged |
| 07/03/85 | 212 | 64 | 571 | V12—12 leaves fully emerged |
| 07/16/85 | 268 | 76 | 753 | VT—tassel fully emerged |
| 07/28/85 | 311 | 102 | 909 | R1—silks emerging |
| 08/15/85 | 390 | 127 | 1140 | R2—blister stage |
| 09/15/85 | 520 | 152 | 1490 | R5—early dent |
| 09/28/85 | 620 | 152 | 1598 | R6—physiologic maturity |

**Table 2. Aerial dry matter accumulation and nutrient concentrations in corn yielding 19.3 Mg ha$^{-1}$ of grain at 155 g kg$^{-1}$ moisture.**

| | Plant fraction | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Lower leaves | | Upper leaves | | Stalk & tassel | | Ear & shank | |
| Sampling date | Mean | SD | Mean | SD | Mean | SD | Mean | SD |
| | | | | Dry matter, Mg ha$^{-1}$ | | | | |
| 06/06/85 | 0.32 | 0.00 | | | | | | |
| 06/18/85 | 0.95 | 0.01 | | | | | | |
| 07/03/85 | 2.35 | 0.01 | | | 1.01 | 0.01 | | |
| 07/16/85 | 3.80 | 0.03 | 2.62 | 0.01 | 4.02 | 0.01 | | |
| 07/28/85 | 3.32 | 0.02 | 2.76 | 0.02 | 6.32 | 0.02 | 1.79 | 0.03 |
| 08/15/85 | 2.92 | 0.01 | 2.69 | 0.02 | 6.30 | 0.02 | 6.44 | 0.02 |
| 09/15/85 | 2.93 | 0.02 | 2.83 | 0.01 | 6.46 | 0.04 | 18.1 | 0.08 |
| 09/28/85 | 2.80 | 0.01 | 2.80 | 0.01 | 6.42 | 0.02 | 19.8 | 0.02 |
| | | | | N, g kg$^{-1}$ | | | | |
| 06/06/85 | 43.7 | 0.4 | | | | | | |
| 06/18/85 | 37.4 | 1.6 | | | | | | |
| 07/03/85 | 32.6 | 0.5 | | | 16.5 | 0.9 | | |
| 07/16/85 | 32.1 | 0.7 | 29.3 | 1.5 | 13.8 | 0.5 | | |
| 07/28/85 | 25.0 | 2.9 | 29.4 | 1.8 | 7.7 | 0.8 | 12.4 | 0.5 |
| 08/15/85 | 24.4 | 1.0 | 27.3 | 0.8 | 6.3 | 0.6 | 11.0 | 0.3 |
| 09/15/85 | 17.4 | 1.1 | 18.4 | 1.0 | 6.8 | 0.5 | 13.2 | 0.2 |
| 09/28/85 | 16.0 | 0.4 | 17.4 | 0.7 | 5.9 | 0.7 | 12.9 | 0.2 |
| | | | | P, g kg$^{-1}$ | | | | |
| 06/06/85 | 4.2 | 0.2 | | | | | | |
| 06/18/85 | 3.5 | 0.2 | | | | | | |
| 07/03/85 | 3.1 | 0.1 | | | 2.7 | 0.1 | | |
| 07/16/85 | 3.4 | 0.2 | 2.6 | 0.2 | 2.1 | 0.2 | | |
| 07/28/85 | 2.9 | 0.3 | 3.5 | 0.2 | 1.5 | 0.1 | 2.4 | 0.6 |
| 08/15/85 | 3.0 | 0.1 | 3.1 | 0.1 | 1.0 | 0.2 | 2.5 | 0.4 |
| 09/15/85 | 1.5 | 0.2 | 2.0 | 0.3 | 0.4 | 0.05 | 2.6 | 0.5 |
| 09/28/85 | 1.3 | 0.1 | 1.8 | 0.2 | 0.3 | 0.1 | 3.0 | 0.1 |
| | | | | K, g kg$^{-1}$ | | | | |
| 06/06/85 | 54.8 | 1.4 | | | | | | |
| 06/18/85 | 57.8 | 2.1 | | | | | | |
| 07/03/85 | 29.6 | 0.8 | | | 32.4 | 0.6 | | |
| 07/16/85 | 22.0 | 0.5 | 30.0 | 1.1 | 31.3 | 0.8 | | |
| 07/28/85 | 29.0 | 1.7 | 18.2 | 1.6 | 24.6 | 3.0 | 8.6 | 0.3 |
| 08/15/85 | 26.5 | 1.9 | 17.6 | 0.6 | 26.8 | 0.8 | 5.5 | 0.4 |
| 09/15/85 | 20.9 | 2.3 | 18.4 | 0.2 | 29.1 | 1.2 | 3.8 | 0.1 |
| 09/28/85 | 18.9 | 0.4 | 17.4 | 0.5 | 27.5 | 1.0 | 3.6 | 0.1 |
| | | | | Ca, g kg$^{-1}$ | | | | |
| 06/06/85 | 4.4 | 0.3 | | | | | | |
| 06/18/85 | 4.5 | 0.2 | | | | | | |
| 07/03/85 | 5.9 | 0.2 | | | 1.9 | 0.2 | | |
| 07/16/85 | 4.1 | 0.6 | 6.4 | 0.6 | 1.8 | 0.1 | | |
| 07/28/85 | 5.9 | 0.6 | 5.2 | 0.3 | 1.7 | 0.2 | 0.5 | 0.17 |
| 08/15/85 | 6.5 | 0.4 | 6.6 | 0.2 | 2.0 | 0.2 | 0.2 | 0.05 |
| 09/15/85 | 6.4 | 1.0 | 8.6 | 0.4 | 1.8 | 0.1 | 0.1 | 0.05 |
| 09/28/85 | 7.0 | 0.4 | 9.2 | 0.4 | 1.8 | 0.2 | 0.1 | 0.05 |

(continued)

Table 2. Continued.

| | Plant fraction | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Lower leaves | | Upper leaves | | Stalk & tassel | | Ear & shank | |
| Sampling date | Mean | SD | Mean | SD | Mean | SD | Mean | SD |
| | | | | Mg, g $kg^{-1}$ | | | | |
| 06/06/85 | 3.0 | 0.2 | | | | | | |
| 06/18/85 | 2.6 | 0.06 | | | | | | |
| 07/03/85 | 2.0 | 0.08 | | | 1.9 | 0.08 | | |
| 07/16/85 | 1.6 | 0.1 | 2.0 | 0.06 | 1.8 | 0.1 | | |
| 07/28/85 | 2.1 | 0.1 | 1.4 | 0.05 | 1.4 | 0.06 | 1.4 | 0.1 |
| 08/15/85 | 2.3 | 0.2 | 1.6 | 0.13 | 1.4 | 0.2 | 1.2 | 0.3 |
| 09/15/85 | 2.2 | 0.2 | 1.3 | 0.22 | 1.2 | 0.1 | 1.3 | 0.3 |
| 09/28/85 | 2.2 | 0.2 | 1.3 | 0.08 | 1.3 | 0.1 | 1.3 | 0.2 |
| | | | | S, g $kg^{-1}$ | | | | |
| 06/06/85 | 2.0 | 0.1 | | | | | | |
| 06/18/85 | 2.0 | 0.05 | | | | | | |
| 07/03/85 | 2.0 | 0.1 | | | 1.0 | 0.1 | | |
| 07/16/85 | 1.6 | 0.1 | 1.8 | 0.1 | 0.9 | 0.0 | | |
| 07/28/85 | 1.7 | 0.2 | 1.7 | 0.1 | 0.8 | 0.1 | 1.0 | 0.1 |
| 08/15/85 | 1.8 | 0.1 | 1.8 | 0.1 | 0.8 | 0.6 | 1.0 | 0.05 |
| 09/15/85 | 1.6 | 0.2 | 1.7 | 0.2 | 0.8 | 0.6 | 1.2 | 0.05 |
| 09/28/85 | 1.6 | 0.2 | 1.7 | 0.1 | 0.8 | 1.0 | 1.3 | 0.2 |
| | | | | B, mg $kg^{-1}$ | | | | |
| 06/06/85 | 9.5 | 1.3 | | | | | | |
| 06/18/85 | 8.8 | 0.5 | | | | | | |
| 07/03/85 | 8.8 | 1.7 | | | 6.8 | 1.0 | | |
| 07/16/85 | 11.2 | 2.2 | 6.2 | 0.5 | 5.8 | 1.0 | | |
| 07/28/85 | 6.0 | 0.8 | 9.2 | 1.7 | 4.8 | 1.0 | 4.8 | 1.0 |
| 08/15/85 | 9.0 | 0.8 | 12.0 | 0.8 | 4.8 | 0.5 | 2.8 | 0.5 |
| 09/15/85 | 9.2 | 1.2 | 12.5 | 1.0 | 4.5 | 0.6 | 2.2 | 0.5 |
| 09/28/85 | 8.0 | 0.8 | 14.0 | 1.9 | 5.0 | 0.8 | 2.0 | 0.8 |
| | | | | Cu, mg $kg^{-1}$ | | | | |
| 06/06/85 | 5.5 | 0.6 | | | | | | |
| 06/18/85 | 4.8 | 1.2 | | | | | | |
| 07/03/85 | 7.8 | 0.5 | | | 4.5 | 1.0 | | |
| 07/16/85 | 7.8 | 0.5 | 7.2 | 0.5 | 3.2 | 0.5 | | |
| 07/28/85 | 6.8 | 1.0 | 9.0 | 0.8 | 3.5 | 1.3 | 4.0 | 0.0 |
| 08/15/85 | 8.5 | 0.6 | 11.5 | 1.3 | 2.8 | 0.5 | 3.0 | 0.0 |
| 09/15/85 | 8.0 | 1.6 | 12.2 | 1.0 | 2.8 | 1.0 | 2.5 | 0.6 |
| 09/28/85 | 8.0 | 1.8 | 12.8 | 1.0 | 3.0 | 0.8 | 3.0 | 0.8 |
| | | | | Fe, mg $kg^{-1}$ | | | | |
| 06/06/85 | 458 | 22 | | | | | | |
| 06/18/85 | 383 | 60 | | | | | | |
| 07/03/85 | 215 | 11 | | | 64 | 4 | | |
| 07/16/85 | 148 | 39 | 285 | 51 | 54 | 27 | | |
| 07/28/85 | 258 | 31 | 110 | 10 | 38 | 7 | 23 | 9 |
| 08/15/85 | 578 | 210 | 162 | 23 | 54 | 13 | 26 | 4 |
| 09/15/85 | 336 | 25 | 149 | 33 | 51 | 16 | 18 | 4 |
| 09/28/85 | 302 | 16 | 142 | 7 | 48 | 2 | 17 | 2 |
| | | | | Mn, mg $kg^{-1}$ | | | | |
| 06/06/85 | 35 | 2 | | | | | | |
| 06/18/85 | 36 | 4 | | | | | | |
| 07/03/85 | 42 | 1 | | | 28 | 1 | | |
| 07/16/85 | 46 | 9 | 40 | 7 | 30 | 3 | | |
| 07/28/85 | 46 | 6 | 67 | 7 | 45 | 11 | 18 | 4 |
| 08/15/85 | 49 | 6 | 75 | 10 | 46 | 11 | 12 | 2 |
| 09/15/85 | 56 | 8 | 129 | 4 | 32 | 7 | 9 | 3 |
| 09/28/85 | 58 | 4 | 142 | 5 | 30 | 4 | 8 | 0.8 |
| | | | | Zn, mg $kg^{-1}$ | | | | |
| 06/06/85 | 56 | 8 | | | | | | |
| 06/18/85 | 54 | 15 | | | | | | |
| 07/03/85 | 45 | 3 | | | 48 | 3 | | |
| 07/16/85 | 36 | 2 | 28 | 4 | 44 | 8 | | |
| 07/28/85 | 29 | 6 | 47 | 2 | 38 | 12 | 32 | 4 |
| 08/15/85 | 31 | 4 | 54 | 6 | 29 | 9 | 26 | 5 |
| 09/15/85 | 25 | 6 | 54 | 6 | 20 | 4 | 24 | 8 |
| 09/28/85 | 23 | 3 | 58 | 7 | 20 | 2 | 23 | 2 |

samples were divided into leaves above the ear (upper leaves), leaves below the ear (lower leaves), and stalk and tassel. Fractionation at R1, R2, R5 and R6 was the same as VT plus the ear and shank. Samples were dried at 65°C, ground, and analyzed using standard procedures at the Pennsylvania State University Plant Analysis Laboratory.

On-site maximum and minimum temperatures, as well as rainfall, were collected. Accumulated growing degree units (GDU), which were calculated using Eq. [1] and used as a time scale for nutrient accumulation and rate plots, are presented in Table 1 for each growth stage at which samples were collected.

$$\mathrm{GDU} = \{[(\mathrm{Tmin}' + \mathrm{Tmax}')/2] - 10^{\circ}\mathrm{C}\}, \quad [1]$$

where Tmin′ is the minimum daily temperature or 10°C, whichever is larger, and Tmax′ is the maximum daily temperature or 30°C, whichever is smaller.

Aerial nutrient accumulation was calculated using dry matter and concentration data (Table 2). Mean data for each plant fraction were fit mathematically using compound cubic polynomials. The equations were generated with a clamped cubic spline interpolant program (Burden et al., 1981) with endpoint (planting and physiologic maturity) derivatives set to zero. This technique was used, rather than a least-squares approach, because previous studies (Karlen et al., 1987a,b) have shown it to be the desired method of analysis when the primary objective is to determine intraseasonal variation in rates of accumulation. This program forced the fitted curve and its first and second derivatives to be continuous at each subrange junction. The interpolant polynomials were differentiated to determine rates of dry matter and nutrient accumulation, which were plotted (SAS Institute, 1985) for each plant fraction, as a function of accumulated GDUs.

## RESULTS AND DISCUSSION

### *Amounts of Accumulation*

Aerial dry matter, N, P, and K accumulations are shown in Fig. 1. Total dry matter at physiological maturity was 31.8 Mg ha$^{-1}$, including 16.3 Mg ha$^{-1}$ of grain dry matter. This resulted in a grain/stover ratio of 0.51, excluding root biomass. Leaves accounted for 18% of the aerial biomass at physiological maturity with 2.8 Mg ha$^{-1}$ of leaves retained both below and above the ear (Fig. 1a). Maximum accumulation in

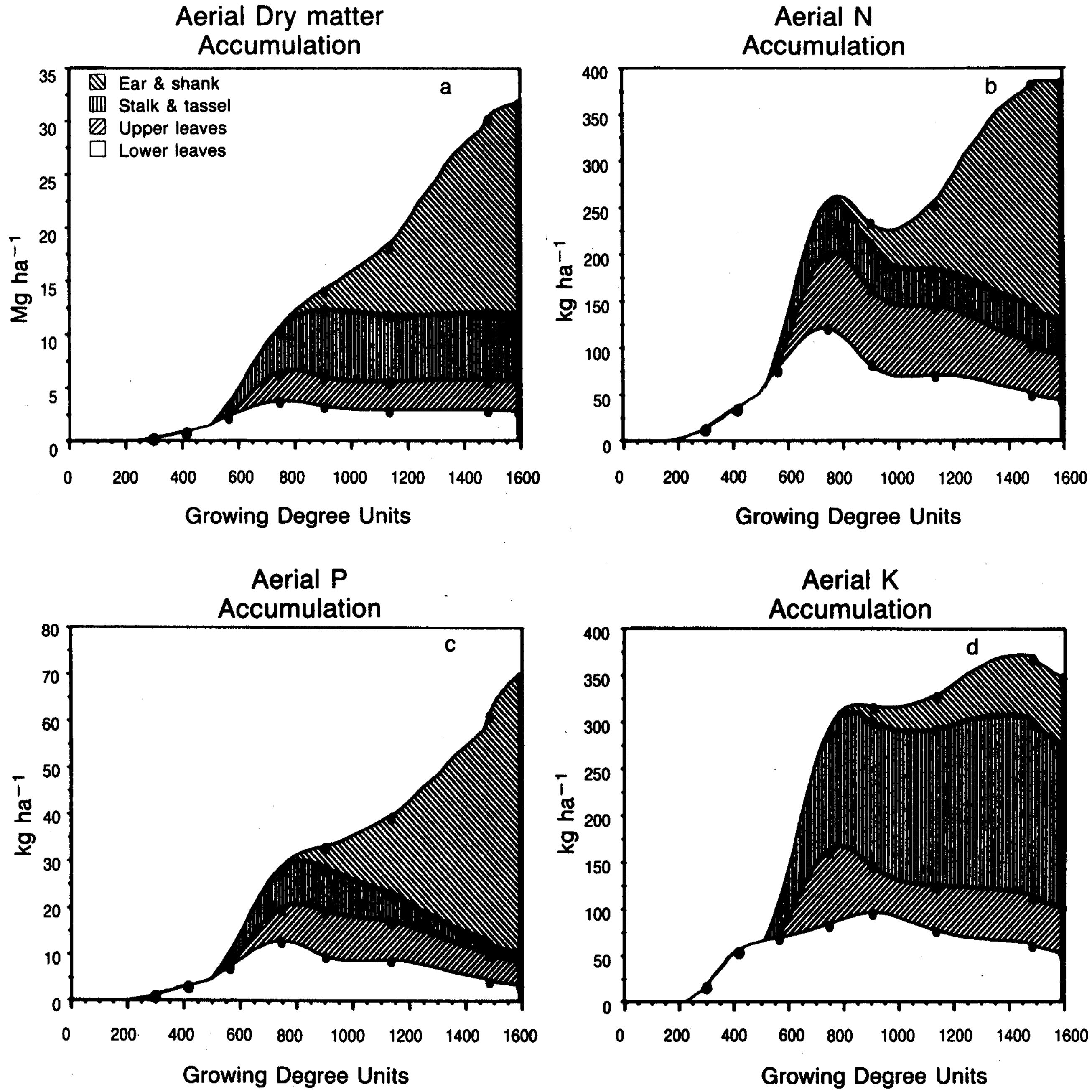


**Fig. 1. Aerial dry matter, N, P, and K accumulation in lower leaves, upper leaves, stalk and tassel, and ear and shank fractions for corn yielding 19.3 Mg ha$^{-1}$ of grain.**

the stalk and tassel was 6.5 Mg ha$^{-1}$ or 20% of the aerial biomass. Nongrain portions of the ear and shank, which were calculated by subtracting grain yield from the ear and shank biomass at physiologic maturity, accounted for 3.4 Mg ha$^{-1}$ or approximately 11% of the aerial dry matter. The dry matter accumulation pattern was similar to those reported in previous accumulation studies (Hanway, 1962a) and did not exhibit any apparent periods of stress.

Total aerial N accumulation was approximately 386 kg ha$^{-1}$ at physiological maturity, with peak accumulations in lower leaves, upper leaves, stem and tassel, and ear and shank of approximately 122, 81, 56, and 255 kg ha$^{-1}$, respectively. Two distinct features of the N curves (Fig. 1b) are the gradual decline in vegetative N during reproductive growth stages and an apparent net loss of aerial N between growth stages VT and R1 (~900 GDU). The former presumably reflects translocation from vegetative plant parts to the developing grain, but the net loss during the transition from vegetative to reproductive growth has not been widely discussed for corn. The apparent net N loss is not unique, however, since similar patterns were evident in previous N accumulation studies conducted in 1940, 1959, 1978, and 1980 (Karlen et al., 1987a). One possible cause for net N loss during this period is volatilization losses because there is no sink. Another mechanism may be feedback inhibition which may actually stop N uptake by the plant. Without actual measurements, this is speculative, but it occurs consistently and thus identifies an area of N uptake research that needs further study.

At physiological maturity total aerial P accumulation was approximately 70 kg ha$^{-1}$ with peak accu-

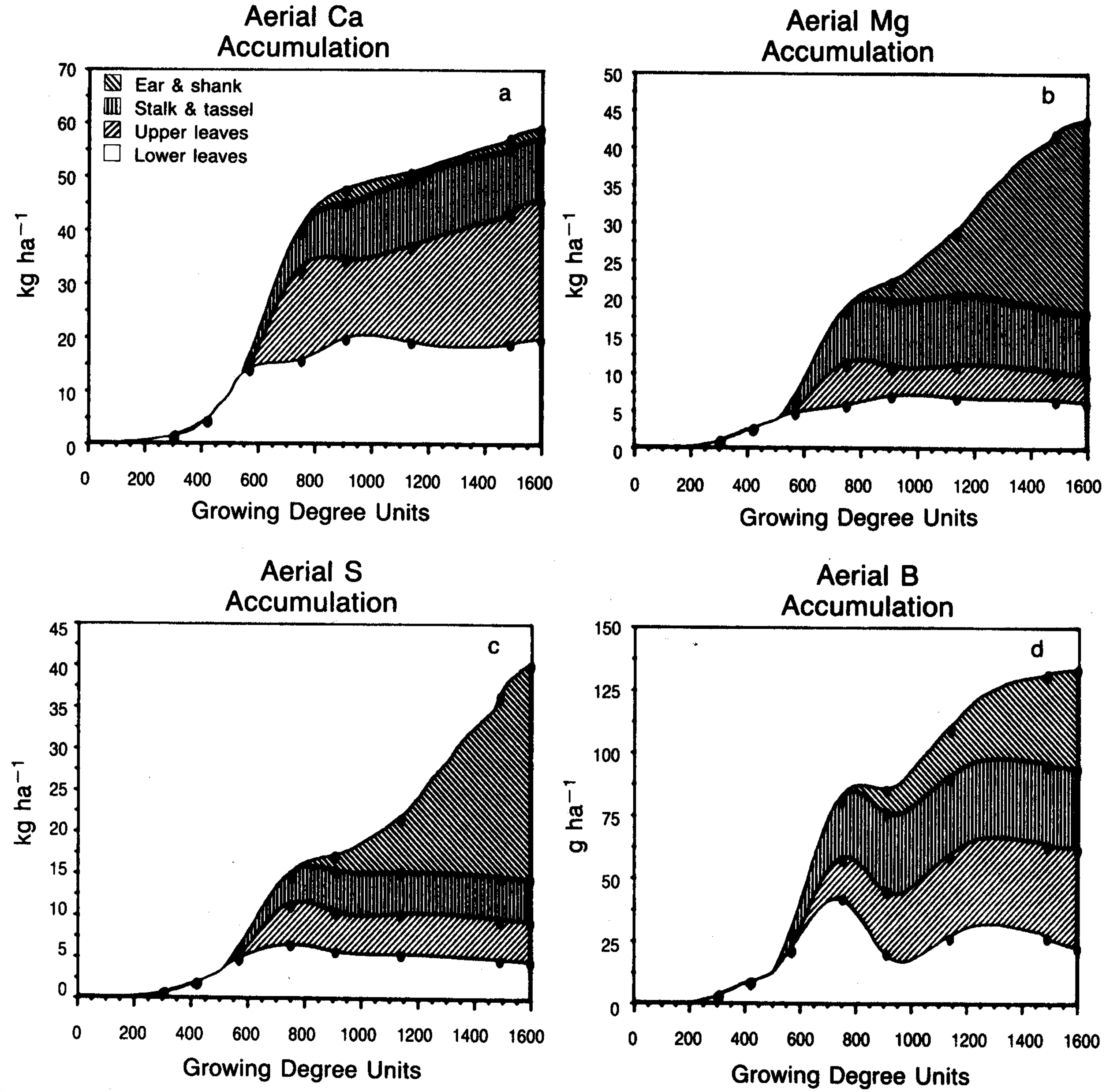


Fig. 2. Aerial Ca, Mg, S, and B accumulation in lower leaves, upper leaves, stalk and tassel, and ear and shank fractions for corn yielding 19.3 Mg ha$^{-1}$ of grain.

mulation in lower leaves, upper leaves, stem and tassel, and ear and shank fractions of approximately 13, 10, 9 and 59 kg ha$^{-1}$, respectively (Fig. 1c). Phosphorus accumulated steadily until maturity without declining as N did between the VT and R1 growth stages. During grainfill, there was considerable translocation of P from vegetative parts to the grain. For example, P in lower leaves decreased 72% between growth stages VT and physiological maturity, while upper leaves and stem and tassel fractions decreased 48 and 80%, respectively, between growth stage R1 and physiological maturity. The P accumulation patterns were very similar to those reported previously (Hanway, 1962b), even though total accumulation was more than doubled.

Total aerial K accumulation at physiological maturity was approximately 370 kg ha$^{-1}$ with peak accumulation in lower leaves, upper leaves, stem and tassel, and ear and shank fractions of approximately 96, 52, 188, and 71 kg ha$^{-1}$, respectively (Fig. 1d). The K curves were also similar to those reported previously (Hanway, 1962b), even though total accumulation was almost four times higher. In this study, 86% of the K was accumulated by growth stage R1 (silking). The K curves also show that only 19% of the K was contained in the ear and shank fraction. Therefore, unless corn is harvested for silage or if the residues are removed for bioenergy production (Karlen et al., 1984), the actual amount of K removed even at high-yield levels will be quite small.

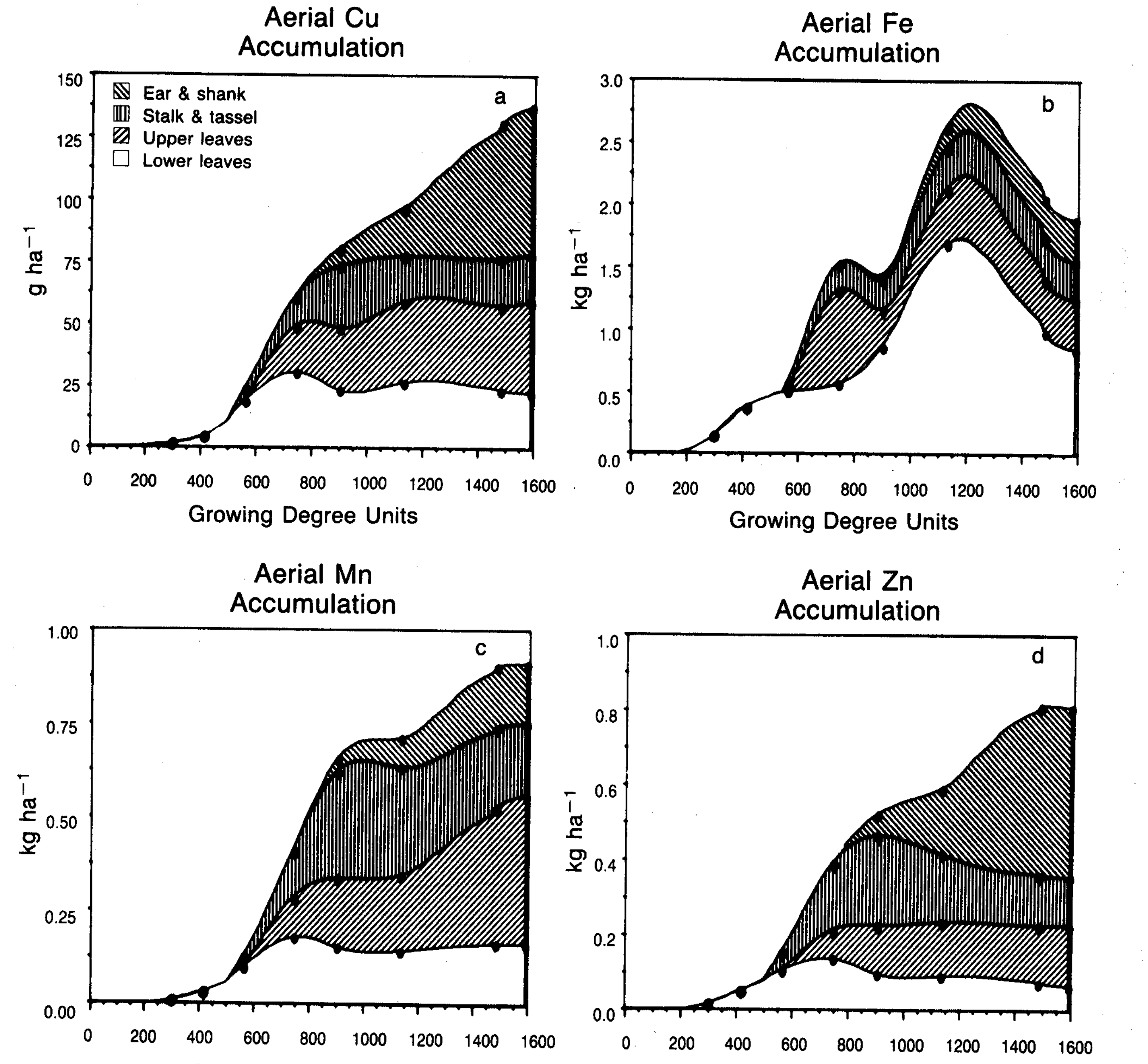


**Fig. 3.** Aerial Cu, Fe, Mn, and Zn accumulation in lower leaves, upper leaves, stalk and tassel, and ear and shank fractions for corn yielding 19.3 Mg ha$^{-1}$ of grain.

Aerial accumulation and distribution of Ca, Mg, S, and B are shown in Fig. 2. Curves such as these have not been presented in previous nutrient accumulation studies (Hanway, 1962a,b) and thus identify several interesting relationships among these essential plant nutrients.

Total aerial Ca accumulation (Fig. 2a) was approximately 59 kg ha$^{-1}$. Accumulation of this nutrient continued throughout the growing season but primarily occurred during vegetative growth with 85% being taken up before stage R2 (blister). Among the various plant fractions at physiological maturity, 33, 44, 20, and 3% of the Ca was located in lower leaves, upper leaves, stalk and tassel, and ear and shank fractions, respectively. There was essentially no translocation to the ear during grainfill.

Aerial Mg accumulation, which totaled approximately 44 kg ha$^{-1}$ (Fig. 2b), occurred throughout the entire growing season. Distribution among plant fractions at physiological maturity was 14, 8, 19, and 59% in lower leaves, upper leaves, stalk and tassel, and ear and shank fractions, respectively. A small amount of Mg translocated from leaf and stalk fractions to the ear and shank during reproductive growth, but this accounted for only 15% or 3.8 of the 26 kg ha$^{-1}$ accumulated during grainfill. This indicates that for high corn yields, a good supply of Mg must be available throughout the growing season.

Aerial S accumulation, which totaled approximately 40 kg ha$^{-1}$ (Fig. 2c), occurred throughout the growing season. At physiological maturity, 11, 12, 13, and 64% was located in lower leaves, upper leaves, stalk and tassel, and ear and shank fractions, respectively. Approximately 2 kg ha$^{-1}$ of S were translocated from the lower leaves during early grain fill, but there was essentially no translocation of S from upper leaves or the stalk and tassel fraction. These results suggest that S accumulated in the ear and shank was taken up by

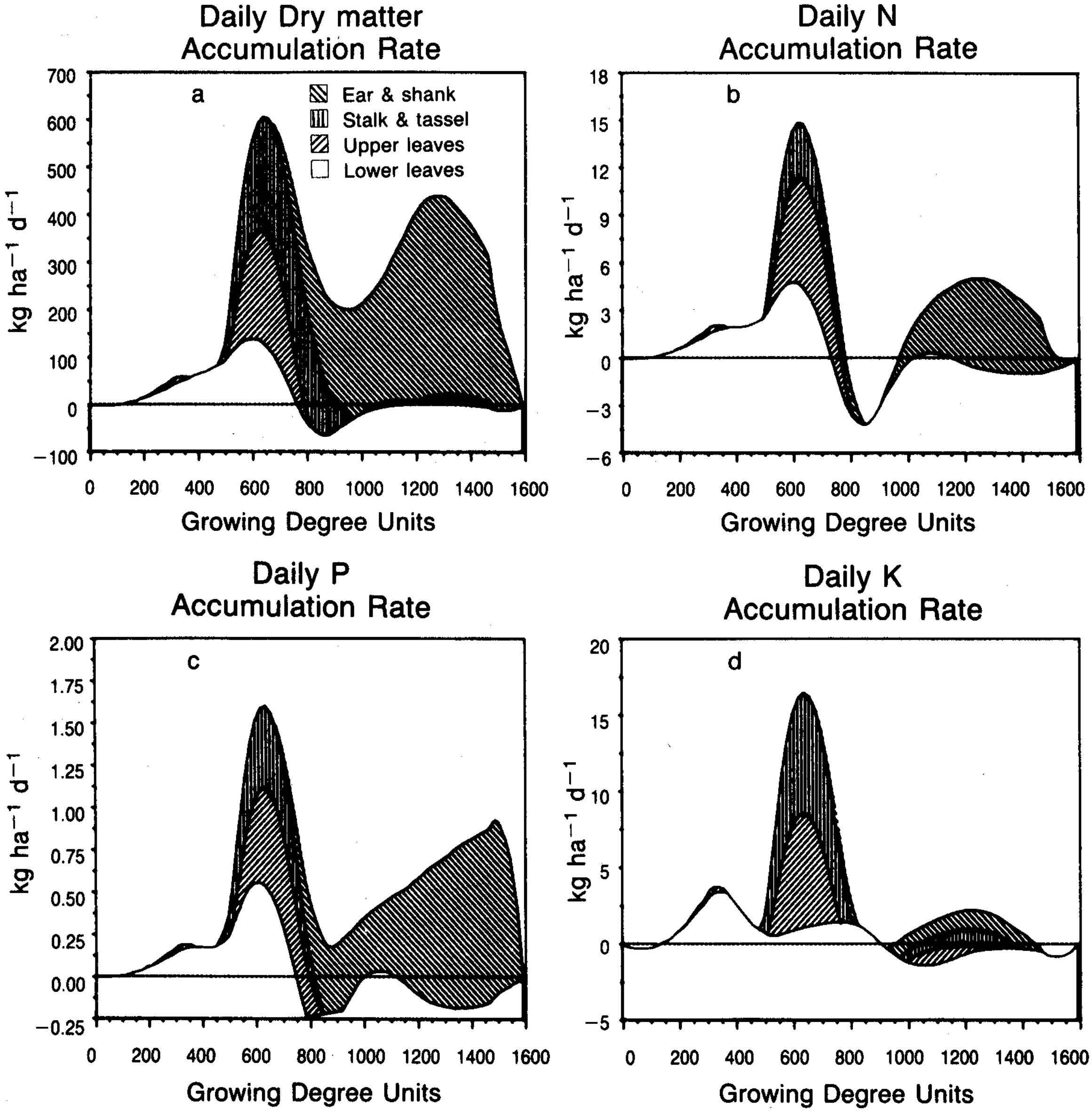


**Fig. 4. Rates of aerial dry matter, N, P, and K accumulation in lower leaves, upper leaves, stem and tassel, and ear and shank fractions for corn yielding 19.3 Mg ha$^{-1}$ of grain.**

the plant during reproductive growth stages, and that if mineralization or other sources of S are not adequate to provide late-season S requirements, sidedress fertilization programs may be needed.

Aerial B accumulation, which totaled approximately 0.13 kg ha$^{-1}$ (Fig. 2d), showed a pattern similar to N, with a slight decline between growth stages VT and R1. Distribution among plant fractions at physiological maturity showed approximately 17, 29, 24, and 30% in the lower leaves, upper leaves, stem and tassel, and ear and shank fractions, respectively. The decline in B during early grain fill occurred in all plant fractions, which suggests that uptake slowed since B does not readily translocate from older tissues to meristematic regions. This decline in accumulation as the plant changes from vegetative to reproductive growth may reflect changes in flux rates into roots as shown by Scott et al. (1975) for soybean. Increased accumulation during the latter stages of grain fill and nearly uniform distribution at physiological maturity suggest that fertilization programs must provide adequate amounts of B throughout the season.

Aerial accumulation and distribution of Cu, Fe, Mn, and Zn are shown in Fig. 3. Curves such as these have not been presented in previous nutrient accumulation studies (Hanway, 1962a,b) and thus identify several interesting relationships among these essential micronutrients.

Aerial Cu accumulation (Fig. 3a) increased steadily throughout the growing season and totaled approximately 0.14 kg ha$^{-1}$ at maturity. There appeared to be very little translocation of Cu among the plant fractions, and at physiological maturity, distribution was 16, 26, 14, and 43% in the lower leaves, upper leaves, stem and tassel, and ear and shank, respectively. The nearly equal distribution between vegetative and re-

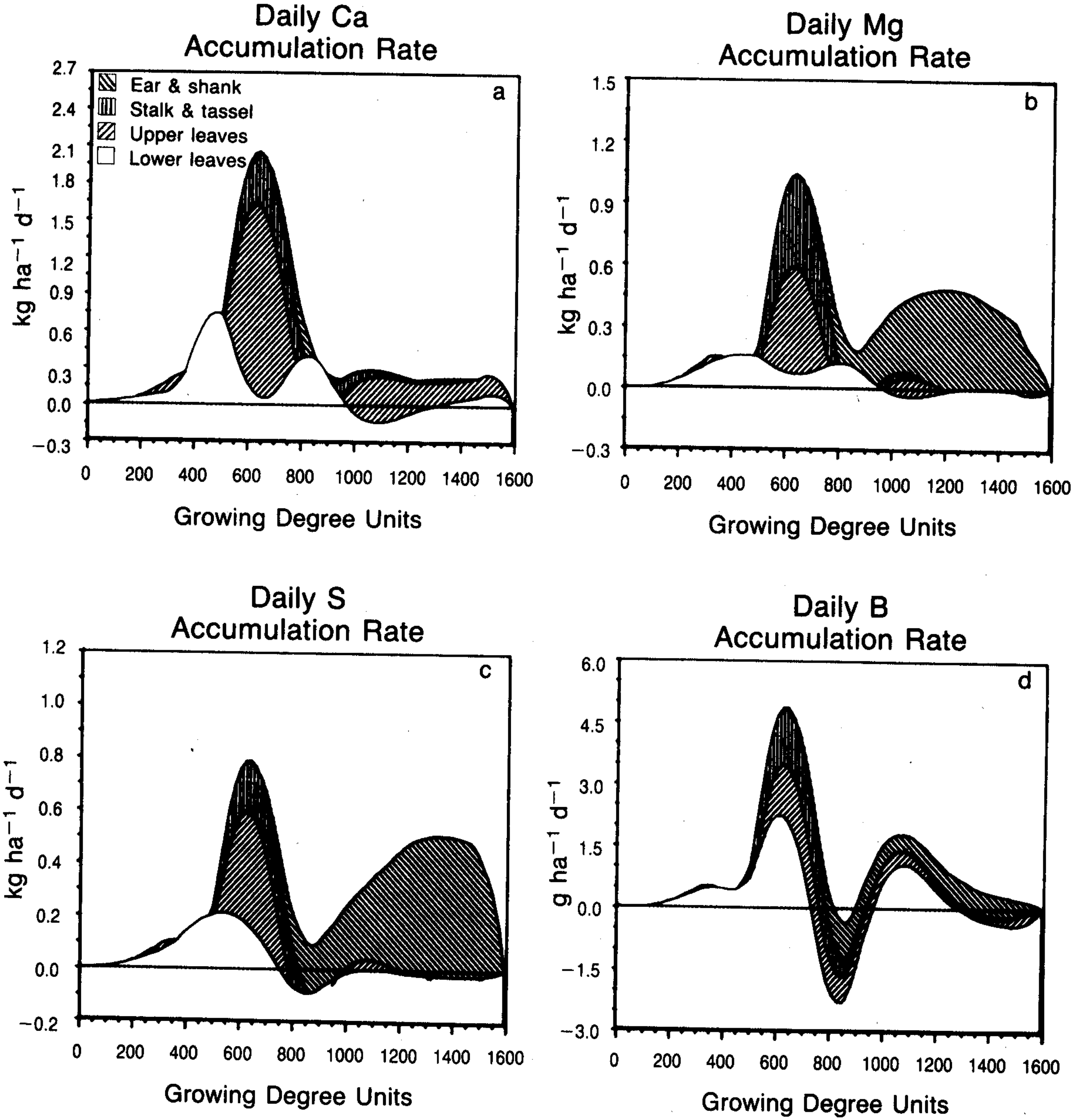


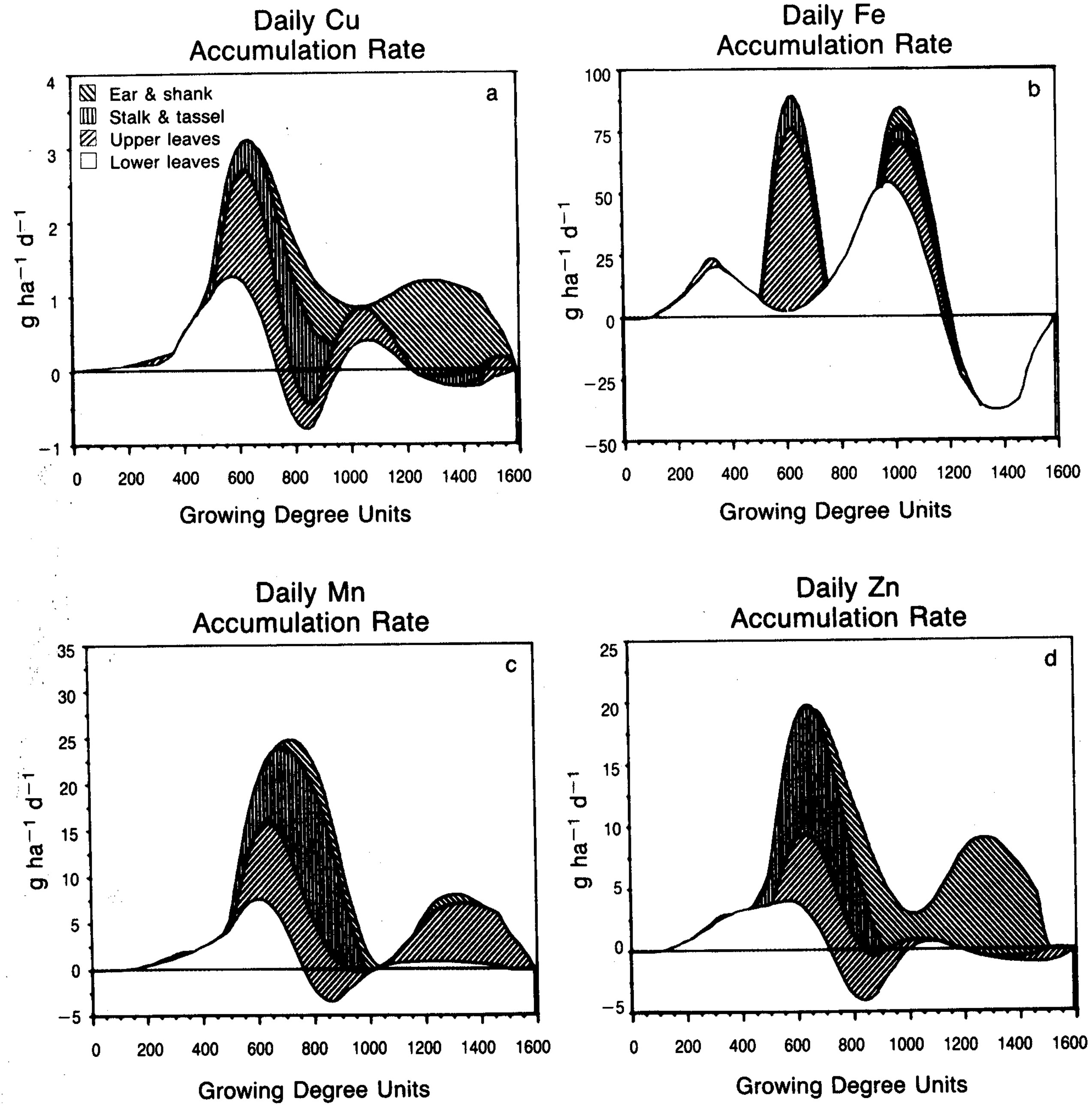
Fig. 5. Rates of aerial Ca, Mg, S, and B accumulation in lower leaves, upper leaves, stem and tassel, and ear and shank fractions for corn yielding 19.3 Mg ha$^{-1}$ of grain.

productive plant parts suggest that, for very high corn yields, Cu must be available for the entire growing season.

Aerial Fe accumulation showed two distinct accumulation periods, one near silking and the other approximately halfway through the grain-fill period (Fig. 3b). The reason for these peaks is not known, but the major change occurred in the upper and lower leaf fractions. At physiological maturity, total Fe accumulation was approximately 1.9 kg ha$^{-1}$, with 45, 21, 16, and 18% found in lower leaves, upper leaves, stem and tassel, and ear and shank fractions, respectively.

Aerial Mn accumulation, which totaled approximately 0.9 kg ha$^{-1}$ (Fig. 2c), increased throughout the growing season, although more than 70% was accumulated by growth stage R1. There was a small amount of translocation from lower leaves and the stalk and tassel fractions to the ear and shank during grain fill, but there was no net loss from the upper leaves. Approximately 18, 44, 21, and 17% was located in the lower leaves, upper leaves, stem and tassel, and ear and shank fractions, respectively, at physiological maturity.

Aerial Zn accumulation (Fig. 3d) totaled approximately 0.8 kg ha$^{-1}$ at physiological maturity, with approximately 8, 20, 16, and 56% distributed in lower leaves, upper leaves, stem and tassel, and ear and shank fractions, respectively. More Zn accumulated during grain fill than was lost from vegetative fractions, which indicates that for very high corn yields, adequate Zn must be available to the plant throughout the growing season.


Daily Cu Accumulation Rate

Daily Fe Accumulation Rate

Daily Mn Accumulation Rate

Daily Zn Accumulation Rate

**Fig. 6. Rates of aerial Cu, Fe, Mn, and Zn accumulation in lower leaves, upper leaves, stem and tassel, and ear and shank fractions for corn yielding 19.3 Mg ha$^{-1}$ of grain.**

### *Rates of Accumulation*

Daily rates of aerial dry matter and nutrient accumulation (Fig. 4, 5, and 6) were derived by differentiating the interpolant equations that described accumulation patterns shown in Fig. 1, 2, and 3. The interpolant method was used because it retains information regarding intraseasonal variation in uptake rates (Karlen et al., 1987b). This technique was used to compare total dry matter, N, P, and K accumulation rates for 19.3 Mg ha$^{-1}$ corn with those measured by Hanway (1962a,b) and Karlen et al. (1987a), but the authors are unaware of any previous attempt to evaluate primary, secondary, and micronutrient accumulation rates by plant fraction.

Daily dry matter accumulation rates (Fig. 4a) show two distinct peak periods of aerial accumulation. The first, during vegetative growth when the potential ovule number is being established, shows maximum rates of dry matter accumulation for lower leaves, upper leaves, and stalk and tassel fractions of approximately 100, 200, and 300 kg ha$^{-1}$ d$^{-1}$, respectively. The second peak, which occurs during grain fill when final yield is being determined, shows a peak rate of approximately 450 kg ha$^{-1}$ d$^{-1}$ going directly into the ear and shank fraction.

The N accumulation rates (Fig. 4b) show two peak accumulation periods and an apparent net loss of N from the aerial plant fractions immediately after pollination. Peak rates for lower leaves, upper leaves, and stalk and tassel fractions during vegetative growth were approximately 4, 7, and 4 kg ha$^{-1}$ d$^{-1}$, respectively. During grain fill, a rate of approximately 6 kg ha$^{-1}$ d$^{-1}$ was maintained for about 14 d or 200 GDUs. The negative accumulation rate following tasseling (VT) reflects decreased accumulation, possibly because there is no strong sink until the kernels begin to develop rapidly. There presumably is also some loss of N associated with pollen shed during this growth stage, because this type of pattern for N accumulation rate is consistent for several corn studies (Karlen et al., 1987a).

Aerial P accumulation rates (Fig. 4c) peaked during latter vegetative growth and after dropping at pollination, increased linearly throughout most of the grain-fill period. Peak accumulation rates in the lower leaves, upper leaves, and stalk and tassel fractions were about 0.5, 0.6, and 0.5 kg ha$^{-1}$ d$^{-1}$, respectively. In the ear and shank fraction, the P accumulation rate increased linearly from approximately 0.25 to 1.0 kg ha$^{-1}$ d$^{-1}$ between silking and physiological maturity. The negative rates shown for leaf and stalk fractions after approximately 750 GDUs reflect translocation of P from vegetative plant parts to the developing grain.

The K accumulation rate curve (Fig. 4d) is dominated by a single peak during vegetative growth because 86% of the K was accumulated before silking. During early growth stages (V4), the peak K accumulation rate in the lower leaves was between 3 and 4 kg ha$^{-1}$ d$^{-1}$, but during the rapid growth phase, K accumulation in the upper leaves and stalk and tassel fraction peaked at approximately 7 and 10 kg ha$^{-1}$ d$^{-1}$, respectively. During grain fill, K accumulated at a rate of less than 2 kg ha$^{-1}$ d$^{-1}$.

Daily accumulation rates for Ca (Fig. 5a) show peaks for lower leaves, upper leaves, and stalk and tassel fractions of approximately 0.8, 1.7, and 0.4 kg ha$^{-1}$ d$^{-1}$, respectively. There was essentially no Ca accumulation in the ear and shank fraction, but during reproductive growth, upper leaves accumulated Ca at a rate of approximately 0.3 kg ha$^{-1}$ d$^{-1}$.

Daily Mg accumulation rates (Fig. 5b) in lower leaves, upper leaves, stalk and tassel, and ear and shank fractions peaked during vegetative growth stages at approximately 0.2, 0.5, and 0.5 kg ha$^{-1}$ d$^{-1}$, respectively. Aerial Mg accumulation during reproductive growth stages occurred at a nearly constant rate of 0.5 kg ha$^{-1}$ d$^{-1}$.

Aerial S accumulation rates (Fig. 5c) showed peaks of approximately 0.2, 0.4, and 0.2 kg ha$^{-1}$ d$^{-1}$ in lower leaves, upper leaves, and stalk and tassel fractions, respectively, during vegetative growth stages. During grain fill, daily S accumulation rates increased from 0.1 kg ha$^{-1}$ to almost 0.6 kg ha$^{-1}$. The high rate of S accumulation during grain fill emphasizes that adequate S must be available to the plant during reproductive growth as well as during vegetative growth.

Daily rates of B accumulation (Fig. 5d) show a pattern similar to that for N because of an apparent net loss from aerial fractions between growth stages VT and R1. Peak accumulation rates for lower leaves, upper leaves, stalk and tassel, and ear and shank fractions were approximately 2.5, 1.0, 1.5, and 1.0 g ha$^{-1}$ d$^{-1}$, respectively. The decline during the transition from vegetative to reproductive growth presumably reflects translocation and lack of a strong sink prior to rapid kernel development.

Curves showing daily Cu accumulation rates (Fig. 6a) show a rather complex mixture of accumulation and apparent translocation (loss) from the various plant parts. Peak accumulation rates for lower leaves, upper leaves, stalk and ear, and ear and shank fractions were approximately 1.2, 1.6, 0.5, and 1.2 g ha$^{-1}$ d$^{-1}$, respectively. During latter vegetative growth stages, Cu was apparently translocated from upper leaves and the stalk and tassel fractions to the developing ear and shank, but by growth stage R2 (blister), Cu once again accumulated in both upper and lower leaves. Accumulation of Cu occurred at a steady rate throughout latter stages of grain fill.

Daily Fe accumulation rates (Fig. 6b) show peak rates in lower leaves, upper leaves, stalk and tassel, and ear and shank fractions of approximately 55, 70, 15 and 10 g ha$^{-1}$ d$^{-1}$, respectively. The reason that peak Fe accumulation in lower leaves occurred during reproductive growth stages is unknown, but high variability in the data (Table 2) may have been the predominant cause.

The Mn rate curves (Fig. 6c) show peak accumulation rates for lower leaves, upper leaves, stem and tassel, and ear and shank fractions of about 7, 8, 10, and 2 g ha$^{-1}$ d$^{-1}$, respectively. An interesting feature of these curves is that most Mn accumulation during reproductive growth stages was into the upper leaves rather than into the ear and shank fraction.

Daily rates of Zn accumulation (Fig. 6d) show peak rates for the lower leaves, upper leaves, stem and tassel, and ear and shank fractions of approximately 4, 6, 10, and 10 g ha$^{-1}$ d$^{-1}$, respectively. The high rate

**Table 3. Soil pH and extractalbe $NO_3$-N, $NH_4$-N, P, K, Ca, and Mg following 5 yr of maximum yield research and harvest of 19.3 Mg ha$^{-1}$ corn grain.**

| Sampling depth | pH | $NO_3$-N | $NH_4$-N | P | K | Ca | Mg |
|---|---|---|---|---|---|---|---|
| mm | | kg ha$^{-1}$ | | | | | |
| 0-200 | 6.1 | 34 | 7 | 281 | 478 | 2050 | 406 |
| 200-400 | 6.1 | 45 | 8 | 106 | 390 | 1789 | 423 |
| 400-610 | 5.4 | 29 | 6 | <15 | 272 | 1458 | 406 |
| 610-810 | 4.9 | 28 | 8 | <15 | 172 | 1154 | 337 |

of Zn accumulation in stalk and tassel as well as ear and shank fractions, relative to the leaves, emphasizes that adequate Zn must be available to the plants throughout the entire corn growing season.

### *Nutrient Balance and Recovery*

Achieving high corn yields requires good nutrient balance in addition to an adequate supply and rate of accumulation. To evaluate nutrient balance for this study, concentration data for the upper leaves at each sampling date were used to calculate diagnosis and recommendation integrated system (DRIS) indices (Elwali et al., 1985). The calculations showed that for N, P, K, Ca, Mg, S, B, Cu, Fe, Mn, and Zn, all but four indices were within ± 18. The four indices outside that range were for Fe (+22 or +23) at the V4 and V8 samplings, and N (+19 or +23) at the R5 and R6 samplings. These analyses, as well as the 19.3 Mg ha$^{-1}$ grain yield, confirmed that in this study, nutrient balance was very good.

Nutrient recovery was not as high as would be desired for corn production, but this study was designed to determine maximum research yields. Soil test data (Table 3) show that after 5 yr of intensive management, there was a substantial amount of residual N, P, K, Ca, and Mg. However, amounts and rates of accumulation, as well as the dry matter and nutrient distribution among the four plant fractions, were similar to those reported for much lower corn yields. These results can therefore be used as a reference for corn production using an appropriate balance of the most economical and environmentally acceptable nutrient management practices.

## SUMMARY AND CONCLUSIONS

Amounts and rates of dry matter and nutrient accumulation for corn yielding 19.3 Mg ha$^{-1}$ of grain, as well as the distribution among four plant fractions, provided a unique data set, not only because of the very high yield level, but also because information on secondary and micronutrients was obtained. Dry matter and accumulation of various nutrients showed peaks during vegetative and reproductive growth stages. The magnitude of those peaks, plant fractions associated with them, and importance to plant nutrition, yield, and fertilizer management are discussed. The interpolant equations that described accumulation patterns were differentiated to compute rates of accumulation. Nutrient balance was evaluated by using leaf nutrient concentrations to calculate DRIS indices. This technique showed very good nutrient balance in this maximum research yield study. Nutrient recovery was not optimum, but the amounts and rates of accumulation provide general guidelines for achieving high corn yields when an appropriate balance of the most economical and environmentally acceptable nutrient management practices are used.

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