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Dry Matter, Nitrogen, Phosphorus, and Potassium Accumulation Rates by Corn on Norfolk Loamy Sand[1]

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ABSTRACT

The maximum amount and rate of nutrient accumulation by irrigated corn (*Zea mays* L.) must be known so that farmers do not waste money or pollute water resources by applying excessive amounts of fertilizer. Aerial whole plant samples were therefore collected from irrigated field experiments conducted on Norfolk (Typic Paleudults) loamy sand in 1980, 1981, and 1982, to determine seasonal dry matter, N, P, and K accumulations for corn yielding 10 Mg ha^{-1} or more in the southeastern Coastal Plain. Rates of accumulation were derived by differentiating compound cubic polynomial equations that described seasonal accumulation patterns. Total dry matter accumulation averaged 23.1 and 24.9 Mg ha^{-1} for two population treatments that averaged 7 × 10^4 or 10 × 10^4 plants ha^{-1}. Aerial N, P, and K accumulation respectively averaged 228, 58, and 258 kg ha^{-1} in 1980; 264, 37, and 372 kg ha^{-1} in 1981; and 225, 37, and 335 kg ha^{-1} in 1982. Grain yields averaged 13.4, 11.7, and 10.9 Mg ha^{-1} in 1980, 1981, and 1982, respectively. Lower P accumulations in 1981 and 1982 were the result of lower grain yields that were apparently caused by excessive K accumulation. Calculated peak dry matter, N, P, and K accumulation rates were 650, 10, 1.6, and 28 kg ha^{-1} day^{-1} in this study, compared to rates of 247, 4.5, 0.6, and 3.2 kg ha^{-1}, respectively, in previous midwestern studies. Peak accumulation rates during both vegetative and reproductive growth stages emphasize that cultural, nutrient, and water management practices must be coordinated to provide a minimum stress production environment for high corn yield.

Additional index words: ***Zea mays*** **L., Maize, Nutrient accumulation, Nutrient ratios, Growing degree units, Dry matter accumulation.**

IRRIGATED corn (*Zea mays* L.) production has been increasing in the southeastern Coastal Plains, especially as more growers invest in irrigation systems to compensate for erratic rainfall patterns on soils with low water retention (Camp et al., 1985). This investment has encouraged the use of improved hybrids, higher fertilization rates, higher plant populations, and narrower row spacing to achieve more stable and profitable production (Karlen and Camp, 1985). These changes in water and cultural management practices have frequently increased grain yields to 10 Mg ha^{-1} or more and dry matter production to 20 Mg ha^{-1} or more (Karlen et al., 1985). Higher yields have also increased daily rates of dry matter and nutrient accumulation, compared to previous midwestern studies (Sayre, 1948; Jordan et al., 1950; Hanway, 1962a,b) that are still used for evaluating accumulation rates by corn because collection of such data is very labor intensive and costly. Those studies, however, were all conducted in the Midwest, without irrigation, and used management practices and hybrids that were customary during the 1940s and 1950s.

Many Coastal Plain soils have dense tillage or genetic horizons, or both, which restrict root growth and further limit plant available water. These soil physical problems, combined with low water and nutrient retention, presumably influence the amount and rate of nutrient and dry matter accumulation by corn. For more profitable production and to prevent pollution of our water resources by excess fertilization, southeastern farmers need to accurately know the amount and rate of nutrient accumulation.

Rhoads and Stanley (1981) reported N, P, K, and dry matter accumulation data for corn grown on Troup (loamy, siliceous, thermic Grossarenic Paleudult) loamy sand in 1978. Although representative for corn production in most of the Southeast, an accurate evaluation of daily dry matter and nutrient accumulation rates requires more than 1 yr of data. The objective of this study was to determine rates of N, P, K, and dry matter accumulation by using aerial accumulation data for corn grown with supplemental irrigation at low and high plant populations on Norfolk (fine-loamy, siliceous, thermic Typic Paleudult) loamy sand during 1980, 1981, and 1982.

MATERIALS AND METHODS

Aerial whole plant samples of Pioneer Brand[3] 3382 hybrid corn (Pioneer Hi-Bred Int., Inc., Johnston, IA) were collected six times in 1980 and 1981, and eight times in 1982, from field experiments (Camp et al., 1985; Karlen and Camp, 1985) in which two irrigation scheduling (tensiometer or water balance), two plant population (10 × 10^4 or 7 × 10^4 plants ha^{-1}), two row spacing (single or twin), and two fertilizer (200-30-167 or 324-34-242 kg N-P-K ha^{-1}) treatments were evaluated. The experimental design consisted of four replications of each treatment arranged in a randomized complete block within a split-split-split-plot configuration. Two plants were randomly selected from each plot (16 plots per replication) at each sampling date to determine dry matter, N, P, and K accumulation.

The experiment was conducted on a Norfolk loamy sand near Florence, SC. Water management treatments were rotated each year, but fertilizer, row spacing, and plant population treatments were returned to the same plot area. The A$_P$ horizon was 230 mm thick with an average pH (1:1, soil/water) of 6.0. Mehlich 1 extractable P, K, Ca, Mg, Mn, and Zn averaged 52, 47, 351, 56, 14, and 2.8 mg kg^{-1}, respectively. The N-P-K fertilizer rates averaged 250-30-167, 268-30-224, and 268-36-224 kg ha^{-1} in 1980, 1981, and 1982, respectively. Granular preplant fertilizer provided 67-30-167 kg ha^{-1} of the total N-P-K applied each year. In 1981, this material also provided 53, 2.8, 6.7, and 3.4 kg ha^{-1} of S, B, Cu, and Zn, respectively, while in 1982, it also provided 22, 53, 2.8, and 3.4 kg ha^{-1} of Mg, S, B, and Zn, respectively. Sidedress N-P-K was applied through a trickle irrigation system four times at 10-day intervals beginning at approximately growth stage V6 (Ritchie and Hanway, 1984). Plant sampling was initiated 47, 27, and 33 days after planting in 1980, 1981, and 1982, respectively. Samples were collected six to eight times during the seasons (Table 1) at growth stages as defined by Ritchie and Hanway (1984).

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Table 1. Cumulative days and growing degree units (GDU) between planting, emergence (VE), and collection of aerial whole plant samples at growth stages Vn to R6.

Year	Days after planting	Accumulated GDU†	Growth stage‡
1980	8	42	VE
	43	424	V10
	57	519	V14
	57	626	V18
	64	727	R1
	82	992	R3
	113	1556	R6
1981	6	48	VE
	27	264	V6
	42	406	V10
	50	493	V14
	57	593	V18
	72	874	R2
	113	1561	R6
1982	13	42	VE
	33	174	V5
	45	315	V9
	55	447	V13
	62	554	V17
	76	755	R1
	96	1054	R3
	110	1275	R5
	115	1357	R6

† Growing degree units (GDU) were calculated from planting through physiologic maturity with on-site temperature data.

‡ Corn growth stage as defined by Ritchie and Hanway (1984).

Plant samples were collected, dried at 70°C, weighed, ground to pass a 0.5-mm stainless steel screen, and digested with sulfuric acid (H_2SO_4) and hydrogen peroxide (H_2O_2) in a Technicon[3] block digestor (Technicon Instruments Corp., Tarrytown, NY. Concentrations of N and P were measured colorimetrically with a Technicon[3] Autoanalyzer (Technicon Instruments Corp.), while K was measured by flame emission with a Perkin-Elmer[3] model 5000 spectrophotometer (Perkin-Elmer Corp., Instrument Div., Norwalk, CT). Aerial accumulation was calculated on a per plant basis using dry matter and nutrient concentration data.

On-site weather data were collected, including maximum and minimum temperatures, solar radiation, and rainfall. Accumulated growing degree units (GDU) were calculated and used to normalize seasonal dry matter and nutrient accumulation data. Seasonal weather patterns, including accumulated GDU as a function of days after planting, daily GDU as a function of accumulated GDU, and daily solar radiation as a function of accumulated GDU, are shown in Fig. 1.

Mean dry matter, N, P, and K accumulation values for low and high population treatments at each sampling date in 1980, 1981, and 1982 were mathematically fit 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. Rates of dry matter and nutrient accumulation were computed by differentiating the polynomials. This program forced the fitted curve and its first and second derivatives to be continuous at each subrange junction. Amounts and rates of accumulation for each plant population were plotted as a function of accumulated GDU for comparison among growing seasons and plant population treatments. Seasonal data for each parameter were also composited for the low and high population treatments and analyzed as a function of GDU using least-squares regression analyses (SAS Institute, 1985). The statistical model used for each data set included GDU, GDU^2, and GDU^3 as the independent variables. These were selected to provide a sigmoid curve which described the dry matter and nutrient accumulation data.

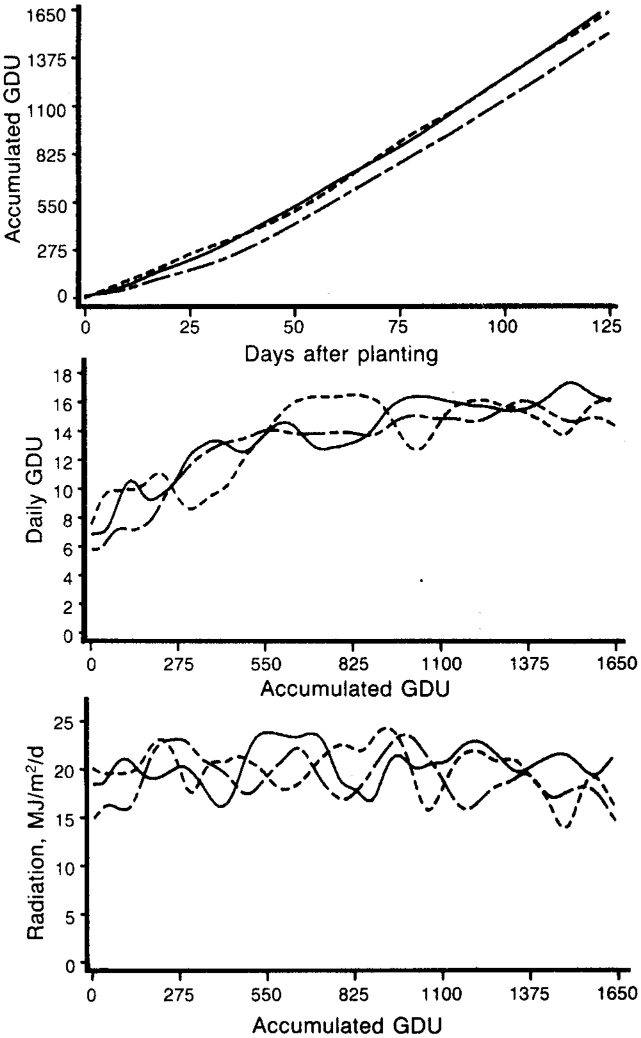


Fig. 1. Seasonal growing degree units (GDU) and solar radiation data collected near Florence, SC, during 1980, 1981, and 1982.

RESULTS AND DISCUSSION

Amounts of Accumulation

Dry matter accumulation patterns (Fig. 2a,b) were similar each year, although there were seasonal differences for the two population treatments. In 1980, total accumulation for the high population (8.9×10^4 plants ha^{-1}) averaged 2.6 Mg ha^{-1} more than at the low population (6.7×10^4 plants ha^{-1}). However, in 1981, when the high population averaged 11.2×10^4 plants ha^{-1}, dry matter accumulation averaged 0.6 Mg ha^{-1} less than at 7.1×10^4 plants ha^{-1}. This indicated that 11.2×10^4 plants ha^{-1} exceeded the optimum density for the hybrid, water, and nutrient management practices used in this experiment. Therefore, the high population treatment was reduced to 10.3×10^4 plants ha^{-1} in 1982. This resulted in an increase in dry matter accumulation of 3.4 Mg ha^{-1} for the high compared to the low (7.1×10^4 plants ha^{-1}), population treatment. The high population treatment was also more sensitive to water stress periods, such as between V10 and V18 in 1980. This stress occurred in spite of irrigation because of drought severity and timing (Camp et al., 1985). It was also the probable cause for the

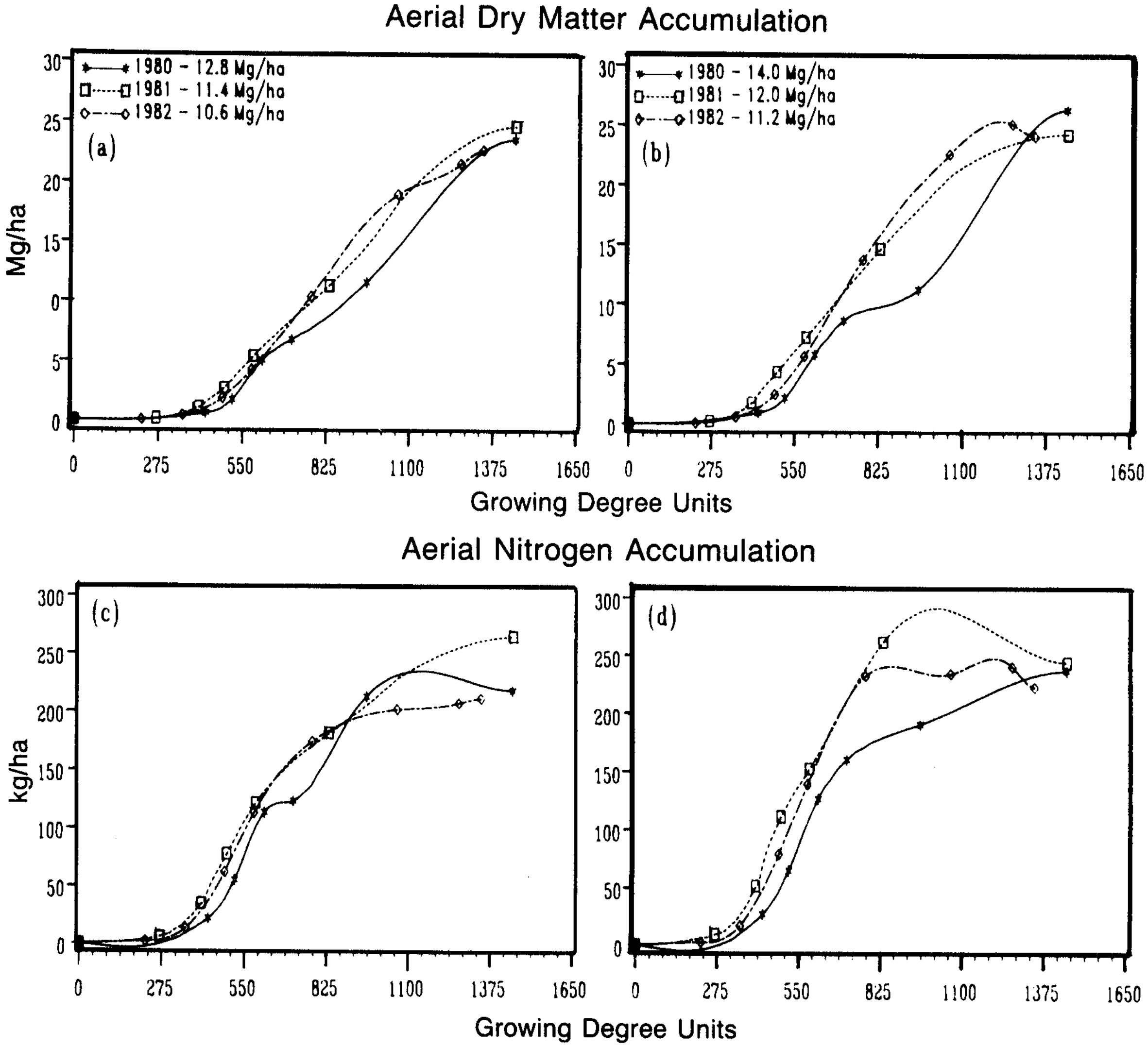


Fig. 2. Aerial dry matter (a,b) and N (c,d) accumulation by corn grown at average populations of 7.0 × 10^4 (a,c) or 10.0 × 10^4 (b,d) plants ha^{-1}. Line captions include year and grain yield.

slight plateau in dry matter accumulation approximately 800 GDU after planting.

Total N accumulation averaged 228, 264, and 225 kg ha^{-1} in 1980, 1981, and 1982, respectively. These values were consistent for both population treatments, but seasonal accumulation patterns were quite different (Fig. 2c,d). In 1980, when grain yields were highest (12.8 and 14.0 Mg ha^{-1} for the low and high populations, respectively), there was steady N accumulation throughout grainfill. However, when grain yields declined to 11.4 and 12.0 Mg ha^{-1} in 1981 or to 10.6 and 11.2 Mg ha^{-1} in 1982, respectively, there was very little late season N accumulation. Decreased N accumulation was probably not the result of N deficiency because the field study included two levels of N fertilization and there was no significant yield increase at either population (Karlen and Camp, 1985). In 1982, leachate was collected periodically at a depth of 2 m from the high population, high fertility plots, but there was no measurable loss of NO_3-N (D.L. Karlen, unpublished data). Soil samples collected before and after the growing season showed an increase of 10 mg kg^{-1} in NO_3-N in the upper 0.46 m. Using this increase in soil nitrate, an average bulk density of 1.55 Mg m^{-3}, and the measured aerial N accumulation (Table 2) to compute a N balance accounts for 312 of the 336 kg ha^{-1} of fertilizer. This confirms that leaching losses were negligible because the remaining 24 kg ha^{-1} can be accounted for by assuming the roots contain approximately 10% as much N as did the aboveground plant parts.

Aerial P accumulation patterns were similar for the two population treatments (Fig. 3a,b), but the accumulated amount differed among growing seasons. Yearly total P accumulation averaged 58, 40, and 37 kg ha^{-1}, respectively, and was directly correlated with grain yield. However, lower P accumulation was probably the result rather than the cause of lower grain yields. This is concluded because the soil-test P concentration was high (Karlen and Camp, 1985) and although P fertilizer was not recommended (Clemson University, 1982), a minimum of 30 kg P ha^{-1} was broadcast prior to planting each year.

Aerial K accumulation patterns for the low and high population treatments are also shown in Fig. 3. These data show similar patterns for both treatments, al-

Table 2. Aerial dry matter, N, P, and K accumulation by irrigated corn grown on Norfolk loamy sand in 1980, 1981, and 1982.

		Population															
		Low								High							
		Dry matter		N		P		K		Dry matter		N		P		K	
Year	GDU‡	Mean	Std†	Mean	Std	Mean	Std	Mean	Std	Mean	Std	Mean	Std	Mean	Std	Mean	Std
		g plant^{-1}															
1980	424	9.2	1.1	0.32	0.06	0.04	0.008	0.48	0.08	10.7	2.8	0.30	0.10	0.05	0.01	0.56	0.15
	519	26.0	7.8	0.81	0.24	0.09	0.03	1.17	0.39	24.4	4.2	0.72	0.26	0.08	0.02	0.90	0.21
	626	75.5	19.1	1.67	0.54	0.21	0.09	2.59	0.47	65.6	18.7	1.42	0.42	0.18	0.06	2.54	0.80
	727	101.	15.	1.82	0.36	0.31	0.09	3.05	0.43	97.3	24.0	1.80	0.84	0.26	0.10	2.95	0.48
	992	174.	38.	3.17	0.64	0.47	0.08	3.21	0.60	127.	25.	2.15	0.59	0.34	0.08	2.35	0.47
	1556	354.	29.	3.25	0.34	0.87	0.08	3.63	0.56	296.	30.	2.67	0.36	0.65	0.11	3.08	0.42
1981	264	2.0	0.5	0.08	0.02	0.01	0.002	0.10	0.02	2.1	0.3	0.08	0.02	0.01	0.002	0.11	0.02
	406	15.2	1.2	0.48	0.05	0.05	0.006	0.81	0.07	15.9	3.0	0.45	0.06	0.05	0.008	0.83	0.10
	493	38.8	4.5	1.08	0.15	0.11	0.02	1.80	0.31	39.0	11.9	0.99	0.37	0.10	0.02	1.70	0.27
	593	76.2	14.2	1.70	0.39	0.25	0.06	3.50	0.65	64.6	7.2	1.36	0.17	0.19	0.04	2.71	0.61
	874	160.	12.	2.55	0.40	0.37	0.04	4.35	0.52	131.	10.	2.34	0.74	0.29	0.06	3.76	0.33
	1561	349.	45.	3.72	0.36	0.59	0.06	5.20	0.35	217.	24.	2.18	0.39	0.35	0.06	3.34	0.49
1982	174	0.6	0.08	0.02	0.005	0.002	0.0003	0.03	0.005	0.5	0.06	0.02	0.003	0.002	0.0005	0.03	0.003
	315	5.8	1.1	0.18	0.05	0.02	0.005	0.26	0.07	5.4	0.6	0.16	0.03	0.01	0.002	0.26	0.04
	447	26.1	2.8	0.86	0.14	0.09	0.02	1.69	0.20	24.0	2.4	0.76	0.09	0.08	0.01	1.55	0.20
	554	60.1	4.4	1.57	0.11	0.19	0.03	3.13	0.22	54.9	6.5	1.35	0.10	0.16	0.03	2.92	0.28
	755	146.	17.	2.44	0.28	0.32	0.08	4.25	0.60	134.	10.	2.26	0.29	0.27	0.08	3.86	0.35
	1054	268.	21.	2.83	0.24	0.46	0.05	4.35	0.50	219.	17.	2.28	0.22	0.37	0.06	3.73	0.36
	1275	304.	18.	2.91	0.20	0.49	0.10	3.81	1.05	244.	10.	2.34	0.16	0.36	0.05	3.64	0.36
	1357	321.	27.	2.96	0.25	0.49	0.07	4.18	0.33	234.	19.	2.17	0.16	0.35	0.04	3.12	0.36

† Std = standard deviation from mean. ‡ GDU = growing degree unit.

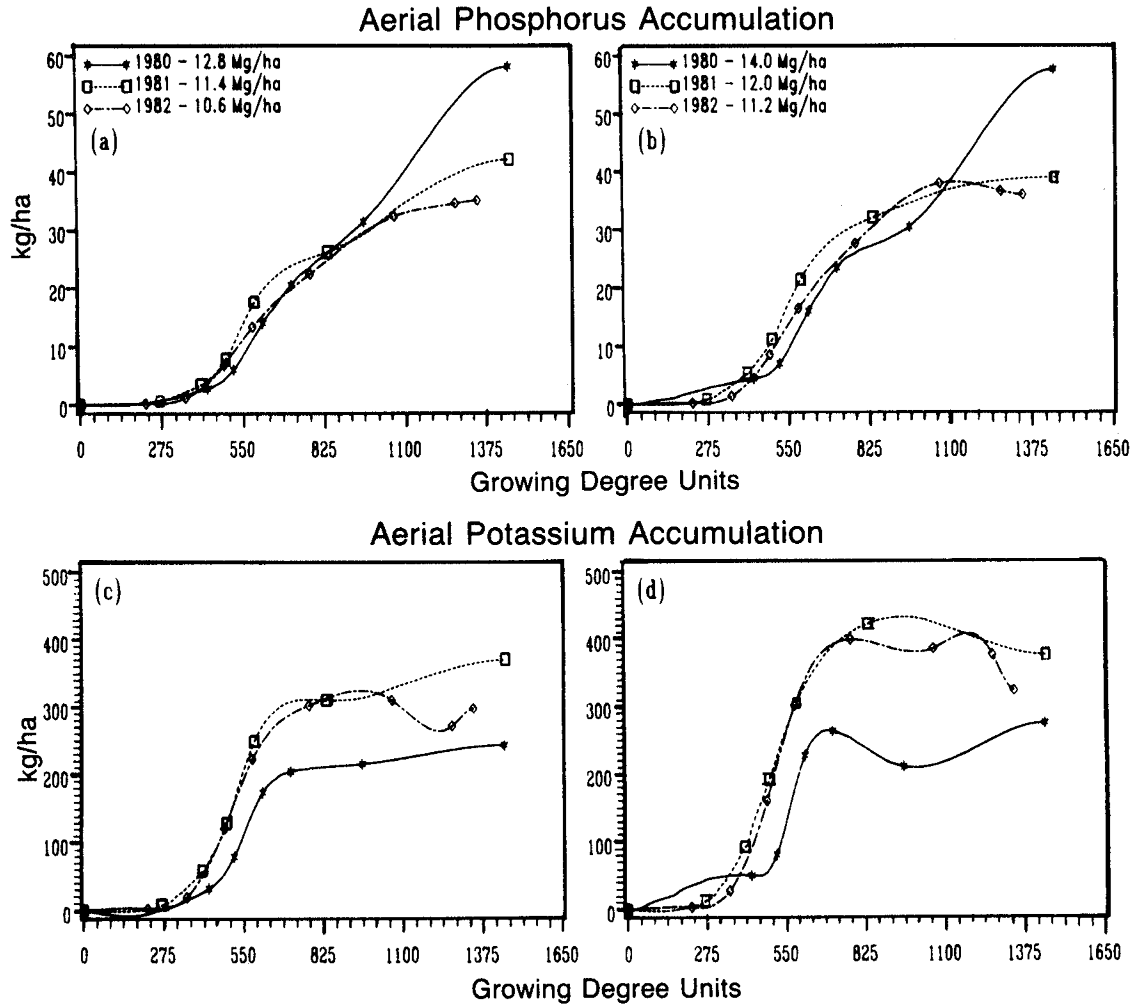


Fig. 3. Aerial P (a,b) and K (c,d) accumulation by corn grown at average populations of 7.0 × 10⁴ (a,c) or 10.0 × 10⁴ (b,d) plants ha^{-1}. Line captions include year and grain yield.

though total accumulation was 30 to 65 kg ha^{-1} yr^{-1} greater for the high population than for the low. Accumulation of K for both population treatments in 1981 and 1982 averaged approximately 138 and 84 kg ha^{-1} more than in 1980. These differences occurred primarily during vegetative growth stages and may offer a possible explanation for lower grain yields. Nelson (1956) reported that high K can depress accumulation of N and corn yield. This may have occurred in this study because K accumulation increased much more than did N accumulation in 1981 and 1982.

The potential for a nutrient imbalance to have caused lower grain yields in 1981 and 1982 was investigated by calculating Diagnosis and Recommendation Integrated System (DRIS) norms (Elwali et al., 1985) by using average ear leaf concentration data (Karlen and Camp, 1985). The N/K ratios averaged 1.010 and 0.936 for 1981 and 1982, while the P/K ratios averaged 0.130 and 0.104, respectively. A comparison of those values to reference N/K and P/K norms of 1.463 and 0.169 (Elwali et al., 1985), or to the 1.60 and 0.163 ratios reported by Escano et al. (1981) indicate that K concentrations in this study were higher than normal. Ear leaf data were not collected in 1980. Therefore, to compare 1980 with 1981 and 1982, N/K and P/K ratios were calculated using whole plant data (Table 2) at growth stages V18, V18, and V17, respectively. Averaging for population shows N/K ratios of 0.636, 0.494, and 0.478 for 1980, 1981, and 1982, respectively, while P/K ratios averaged 0.080, 0.071, and 0.061, respectively. The gradual decline in those ratios also suggests that excessive K accumulation was partially responsible for lower yields in 1981 and 1982. One possible reason for this imbalance was that annual K fertilization rates, selected for maximum yield, were greater than soil test recommendations (Clemson University, 1982). Apparently, excess K gradually accumulated in the upper portion of the Bt horizon (Karlen et al., 1984) and interfered with N uptake.

Another K interaction that may have caused lower grain yields in 1981 and 1982 is with boron (B). This is hypothesized because of recent studies by Woodruff and Moore (1985), which showed that high K depressed N accumulation and corn grain yield on Coastal Plain soils unless supplemental B was applied. This explanation is less plausible, because in 1981 and 1982, the preplant fertilizer contained 2.8 kg B ha^{-1}. Also, at silking (R1), the concentration of B in ear leaf samples was adequate (Karlen and Camp, 1985).

The data in Table 2 can also be used to compute N, P, and K accumulations as a percentage of maximum accumulation for comparison with previous studies. Sayre (1948) and Chandler (1960) reported that when dry matter accumulation was 50%, N, P, and K accumulations averaged 66, 58, and 96%, respectively. Hanway (1962a,b) reported that at silking, dry matter, N, P, and K accumulations averaged 44, 65, 50, and 75%, respectively. In this experiment, dry matter accumulation averaged only 30% when N, P, and K accumulations averaged 60, 46, and 80% of maximum, respectively. This lower dry matter accumulation at similar N, P, and K percentages suggests that early season nutrient accumulation occurred more rapidly than in previous experiments. This presumably reflects improvements in early season hybrid vigor, but may also reflect the effects of much higher plant populations. The more rapid N accumulation pattern suggests that all N fertilizer should be applied within approximately 50 days after planting and may explain why Gascho et al. (1984) found no difference between conventional sidedressing and scheduled sprinkler application of N for corn on a Bonifay (loamy, siliceous, thermic grossarenic, Plinthic Paleudult) sand.

Rates of Accumulation

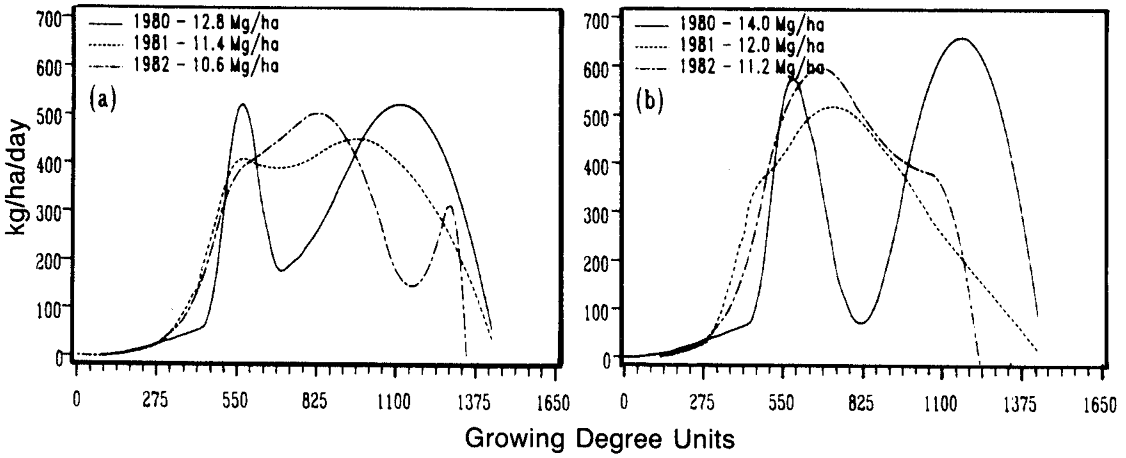
Rates of dry matter, N, P, and K accumulation were evaluated for the high and low population treatments by describing the accumulation data with compound cubic polynomials (Burden et al., 1981) and by using regression analyses (SAS Institue, 1985). Both methods were used because they differ in their basic assumptions about the data and are, therefore, suitable for different applications. Regression analyses used a fixed model with GDU, GDU^2, and GDU^3 as the independent variables. This type of model has a sigmoidal shape, provides a parabolic rate of accumulation curve when differentiated, and assumes that variation in the data can be attributed primarily to sampling error. Assumptions for the cubic spline interpolant are that the data points are real and related to data points on either side, and that the derivative at the beginning and end of the growing season is zero.

The intended result of these processes, the rate of uptake, also differs. For regression analyses, the rate curve is a single parabola, while for the cubic spline interpolant, the rate curve consists of a series of parabolas. The advantage of splining is that it can describe intraseasonal variation such as short-term drought stress. The disadvantage is that a spuriously low level of accumulation in the data will appear as a pause in the rate curve and thus be overemphasized. Our objective was to compare rates. Therefore, since most pauses in the data could be explained by various environmental factors, we chose to primarily use the interpolant method to describe the accumulation patterns (Fig. 2 and 3) and to retain information regarding potential variations in uptake rates.

Seasonal rates of dry matter, N, P, and K accumulation for the low and high population treatments are shown in Fig. 4 and Fig. 5. In 1980, when grain yields for two population treatments averaged 12.8 and 14.0 Mg ha^{-1}, respectively, calculated peak rates of dry matter accumulation were approximately 500 and 650 kg ha^{-1} day^{-1}, respectively (Fig. 4a,b). These rates are greater than suggested by Tollenaar (1983), but are within the range found by Monteith (1978). The more important observation, however, is that there were distinct peaks during both vegetative and reproductive growth stages. This is important because the first peak occurred during stages V12 to V18, when potential kernel number (yield) was being established, and the second, during grainfill when potential yield was being achieved.

In 1981 and 1982, when grain yields were lower than in 1980, dry matter accumulation rates were also much lower, especially during reproductive growth stages (>800 GDU). This suggests that some factor or factors limited the plant's reproductive growth. Water was

Aerial Dry Matter Accumulation Rate



Aerial Nitrogen Accumulation Rate

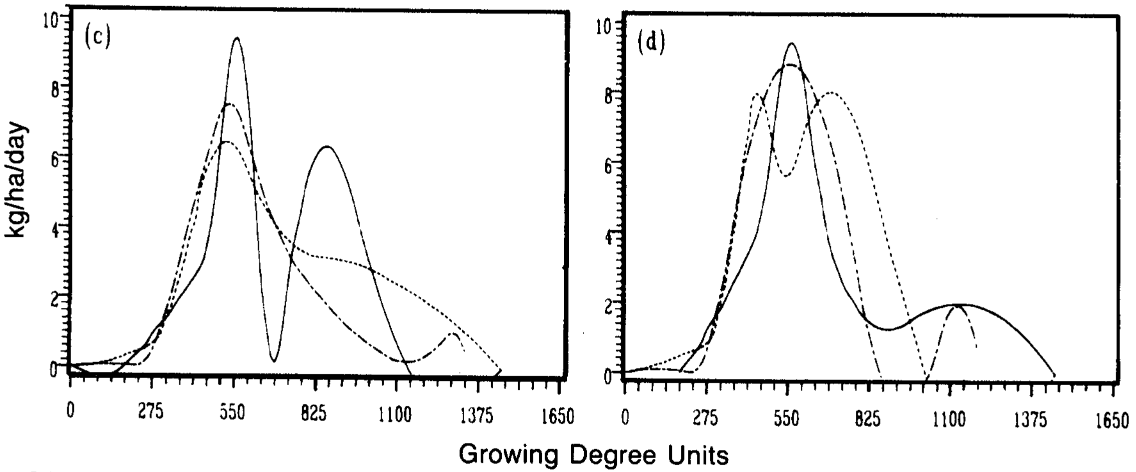


Fig. 4. Rates of dry matter (a,b) and N (c,d) accumulation by corn grown at average populations of 7.0 × 10^4 (a,c) or 10.0 × 10^4 (b,d) plants ha^{-1}. Line captions include year and grain yield.

probably not the limiting factor because these studies were irrigated and tensiometer measurements showed that root zone water content was adequate (Camp et al., 1985). There were no significant differences in grain yield for the high and low fertilizer treatments (Karlen and Camp, 1985), indicating that lower yields were not caused by simple nutrient deficiencies. However, as shown previously, a nutrient imbalance between N and K may have caused lower grain yields.

A difference in seasonal weather patterns (Fig. 1) is another factor that may have increased grain yields in 1980 compared to 1981 and 1982. In 1980, during late-vegetative and early reproductive growth (589–797 GDU) and during mid-grainfill (1100–1300 GDU), daily solar radiation was slightly greater and temperatures slightly cooler (Fig. 1) than in 1981 or 1982. These are conditions that contribute to higher corn yields (Shaw, 1977) and may have done so at this location in 1980.

Nitrogen accumulation rates for the two population treatments are shown in Fig. 4c and Fig. 4d. Peak N accumulation rates during vegetative growth stages (< 800 GDU) in 1980 averaged approximately 9.5 kg ha^{-1} day^{-1} for both treatments. During reproductive growth stages, peak rates were approximately 6 and 2 kg ha^{-1} day^{-1} for the low and high population treatments, respectively. In 1981 and 1982, when grain yields declined, peak N accumulation rates during vegetative growth stages were slightly lower (7–9 kg ha^{-1} day^{-1}), but more importantly, there was essentially no second peak N accumulation period during the reproductive growth stages.

Seasonal rates of P accumulation are shown in Fig. 5a and Fig. 5b. These data are similar to the N data because they show two distinct peaks for 1980, but only one in 1981 and 1982. Maximum P accumulation rates during the vegetative growth stages (<800 GDU) for the low population treatment were approximately 1.2, 1.5, and 1.0 kg ha^{-1} day^{-1} in 1980, 1981, and 1982, respectively. The high population treatment had peak P accumulation rates of 1.4, 1.6, and 1.2 kg ha^{-1} day^{-1} in 1980, 1981, and 1982, respectively. During the reproductive (>800 GDU) growth stages, P accumulation occurred at a much greater rate in 1980 (>1.0 kg ha^{-1} day^{-1}) than when yields were lower in 1981 and 1982 (<0.5 kg ha^{-1} day^{-1}). This suggests that the lower total P accumulation (Fig. 3) in 1981 and 1982 occurred because of a very limited accumulation during

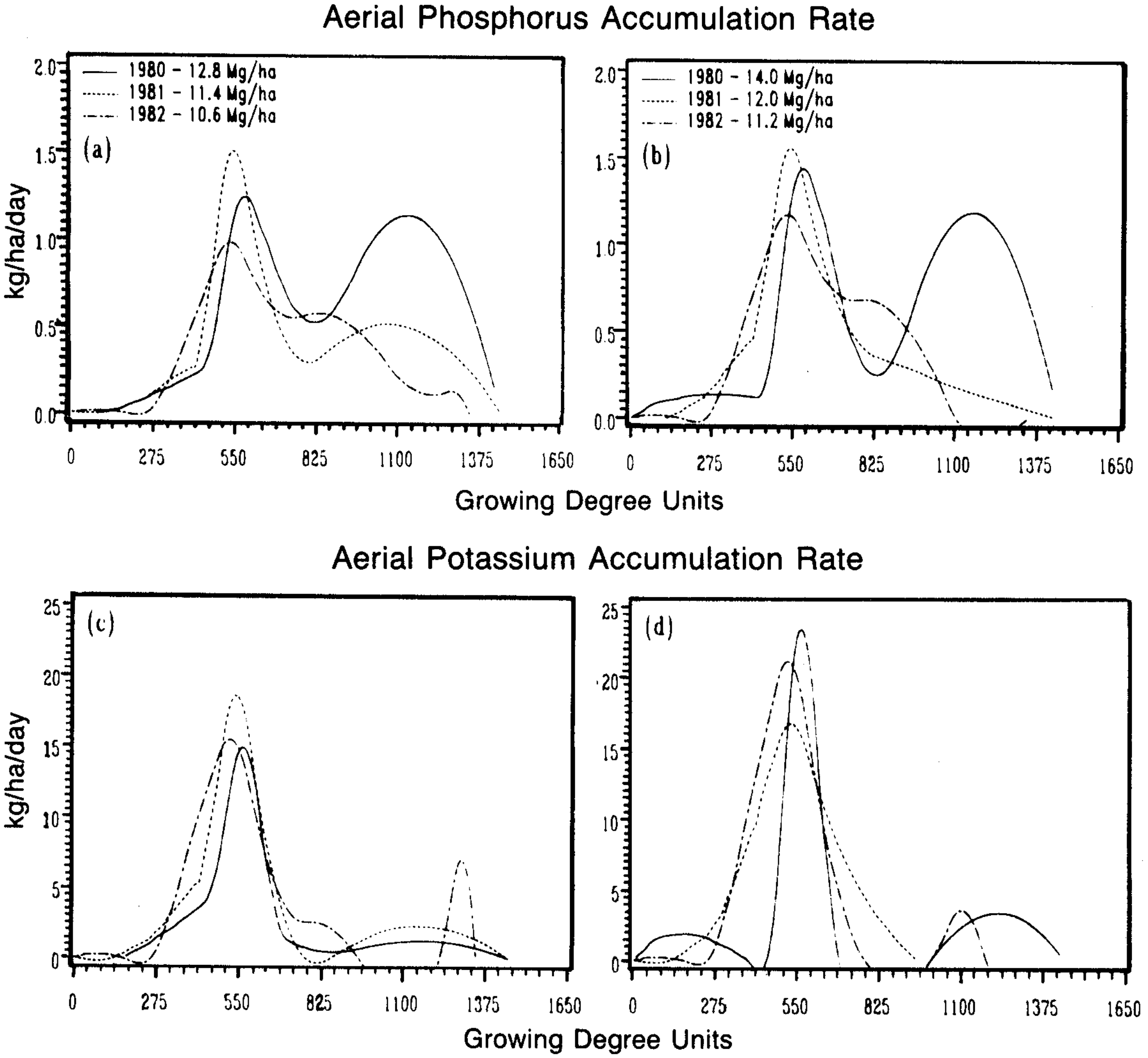


Fig. 5. Rates of P (a,b) and K (c,d) accumulation by corn grown at average populations of 7.0 × 10^4 (a,c) or 10.0 × 10^4 (b,d) plants ha^{-1}. Line captions include year and grain yield.

grainfill rather than because of differences during vegetative growth.

Accumulation rates for K are shown in Fig. 5c and Fig. 5d. Data for both population treatments show peak accumulation rates during vegetative growth ($<$ 800 GDU) with very little accumulation during grainfill. Peak K accumulation rates ranged from 15 to 18 kg ha^{-1} day^{-1} for the low population treatment and from 17 to 23 kg ha^{-1} day^{-1} for the high population treatment. They were similar to rates calculated by Welch and Flannery (1985). The absence of K accumulation during reproductive growth agrees with previous studies that showed K accumulation to be essentially completed by silking (Sayre, 1948; Hanway, 1962a,b).

Least-squares regression analysis (SAS Institute, 1985) of dry matter and nutrient accumulation data for individual years using GDU, GDU^2, and GDU^3 as independent variables did not fit the data well enough to determine peak accumulation rates and was too restrictive to identify short-term fluctuations caused by various environmental factors. Use of higher order polynomials was not desirable because there were only six to eight sampling dates that were not distributed evenly throughout the growing season. Therefore, the data were pooled for the low and high population treatments and analyzed using the same independent variables. Equations and R^2 values for each data set are presented in Table 3.

The least-squares dry matter curves fit reasonably well and predicted peak accumulation rates of 411 or 457 kg ha^{-1} day^{-1} (not shown) for the low and high population treatments, respectively. These values were lower than those predicted by splining because regression analyses integrated the rate for the entire growing season, whereas splining identified periods of short-term fluctuation in the accumulation rates. The least-squares approach using GDU, GDU^2, and GDU^3 as independent variables for the pooled N, P, and K accumulation curves was too restrictive to fit the data and when differentiated did not show any intraseasonal peak rates of accumulation. Determining rates of accumulation was the objective of this study, thus splining was the desired method of analysis.

The most important finding of this research was the occurrence of two distinct peak dry matter and nu-

Table 3. Least-squares regression equations describing seasonal dry matter, N, P, and K accumulation in grams per plant for corn grown at low (7.0×10^4 plants ha^{-1}) and high (10.0×10^4 plants ha^{-1}) populations.

	Low population	
Dry matter	$= 24.1 - 2.7E-1(GDU) + 7.3E-4(GDU^2) - 2.8E-07(GDU^3)$	$R^2 = 0.98$
Nitrogen	$= -1.2 + 4.8E-3(GDU) - 2.5E-7(GDU^2) - 6.3E-10(GDU^3)$	$R^2 = 0.95$
Phosphorus	$= -0.2 + 7.3E-4(GDU) - 1.5E-7(GDU^2) + 2.9E-11(GDU^3)$	$R^2 = 0.92$
Potassium	$= -2.8 + 1.3E-2(GDU) - 7.4E-6(GDU^2) + 1.3E-09(GDU^3)$	$R^2 = 0.84$
	High population	
Dry matter	$= 11.6 - 1.8E-1(GDU) + 5.7E-4(GDU^2) - 2.3E-07(GDU^3)$	$R^2 = 0.95$
Nitrogen	$= -1.1 + 4.7E-3(GDU) - 8.4E-7(GDU^2) - 5.0E-10(GDU^3)$	$R^2 = 0.92$
Phosphorus	$= -0.1 + 5.9E-4(GDU) - 1.2E-7(GDU^2) + 4.0E-12(GDU^3)$	$R^2 = 0.87$
Potassium	$= -2.2 + 9.9E-3(GDU) - 4.4E-6(GDU^2) + 9.9E-11(GDU^3)$	$R^2 = 0.83$

trient accumulation periods. The first occurs during vegetative growth when the potential kernel number (yield) is being established (V12–V18), and the second, during reproductive growth when the potential yield is being achieved. This emphasizes that for high corn yield, a minimum stress production environment must be provided during all growth stages. Peak dry matter, N, P, and K accumulation rates were 650, 10, 1.6, and 28 kg ha^{-1} day^{-1} in this study. These rates reflect the effects of improved hybrids and management practices when compared to previous studies that showed peak accumulation rates of 247, 4.5, 0.6, and 3.2 kg ha^{-1} day^{-1}, respectively. An apparent interaction between N and K accumulation also emphasizes the importance of a balanced fertilization program when striving for higher grain yields.

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