Reprinted from the *Soil Science Society of America Journal*
Volume 43, no. 6, November–December 1979
677 South Segoe Rd., Madison, WI 53711 USA

Influence of Twin-Row Spacing and Nitrogen Rates on High-Frequency Trickle-Irrigated Sweet Corn

C. J. Phene and O. W. Beale

Influence of Twin-Row Spacing and Nitrogen Rates on High-Frequency Trickle-Irrigated Sweet Corn[1]

C. J. Phene and O. W. Beale[2]

ABSTRACT

Sweet corn (*Zea mays* L.) is generally grown in rows spaced about 100 cm apart. Trickle irrigating this type of row configuration is inefficient and costly because one irrigation tube must be installed on each row. The objectives of this research were to determine the influence of trickle irrigation; wide bed, "twin-row" spacing; and trickle N and K fertilization rates on the yield and quality of sweet corn. The twin rows, 35 cm apart, were positioned on wide beds, spaced 165 cm from center to center. A single trickle irrigation tube was placed between the twin rows of corn, providing water and nutrients simultaneously to both rows. Sweet corn was fertilized daily with seasonal applications of 28, 56, 168, and 336 kg/ha of N and K. Plant height, ear yield, and biomass production increased with N and K rates ranging from 0 to 168 kg/ha, but were not affected by the twin-row bed spacing nor by fertilizing with 336 kg/ha each of N and K.

Additional Index Words: **water use efficiency, soil compaction, nitrogen uptake, soil aeration, N-fertilization, crop yield, N-losses, leaching.**

Phene, C. J., and O. W. Beale. 1979. Influence of twin-row spacing and nitrogen rates on high-frequency trickle-irrigated sweet corn. Soil Sci. Soc. Am. J. 43:1216–1221.

In humid regions, high-frequency trickle irrigation (HFTI) with nutrient solutions can be used to stabilize and increase row crop yields by providing adequate water and nutrition by minimizing the soil as a storage reservoir for water and nutrients (Phene and Beale, 1976; Phene et al., 1979). High-frequency trickle irrigation and fertilization consist of irrigating soils frequently at low pressure through a porous tube or system of emitters with a dilute nutrient solution to maintain part of the root zone at optimal soil water and nutrient content for vigorous plant growth, while leaving the unwetted soil volume for partial storage of rainfall, if it occurs.

In humid regions, conventional N fertilization in sandy soils often causes large losses of N by leaching, volatilization, and denitrification. To avoid this, controlled release plant nutrients have been used (Parr, 1967; Nelson and Hauck, 1965; Lunt, 1971). However, to achieve the proper release of N, coated fertilizer must contain 15 to 20% additional material (sulfur) which increases the fertilizer cost 25 to 50% (Prasad et al., 1971) and may only slightly increase farmer profits.

The low organic matter content of shallow sandy soils, like Norfolk sandy loams (Typic Paleudult), often causes a low N-mineralization potential (Stanford and Smith, 1972). Proper timing of N application in these soils is important for increasing fertilizer-N efficiency. Pearson et al. (1961) reported that fall N-fertilization in the Southeastern United States was 50% less effective than spring N-fertilization for growing corn. When prolonged rainfall causes water-saturated soil, the potentials for N losses by leaching and denitrification are greater, particularly if the soil was bare before a crop stand was established.

Phene (1974), Phene and Beale (1976), and Phene and Sanders (1976) demonstrated the feasibility of controlling N-fertilizer applications through a trickle irrigation system at rates adjusted according to plant requirement. With this technique, timely application of fertilizers can be made, regardless of the cropping practices used or of soil trafficability after rainfall. They showed that trickle fertilization of a part of the root zone would alleviate leaching losses by decreasing the use of soil as a storage reservoir for nutrients.

Conventional row crop spacings may not be the most efficient for trickle-irrigation systems. With either a line-source or point-source of water, enough water can be provided for two rows of crops, if these rows are closely spaced (Phene, 1974). Depending upon the soil texture and the type of crop grown, row spacing ranging from 35 to 50 cm may be used to take advantage of a single line water source.

A "twin-row" cropping system for trickle irrigation was described by Phene (1974). Two rows of corn were planted 35 cm apart on wide beds spaced 165 cm from center to center, and a single trickle irrigation tube was installed between the rows to distribute water and nutrients simultaneously to both rows.

Besides the savings in the cost of irrigation tube with this technique, there are several other advantages in using the twin-row design over conventional row spacing, particularly in humid regions where many soils are sandy and shallow and easily compacted. These advantages are:

1) When the wide twin-row system is used with implement wheels spaced at 1.65 m the compacted zone of soil caused by the implement wheel traffic is centered 15 cm further from each side of the crop row than with conventional row spacing, and the reduced soil compaction around the root zone improves soil-root aeration and root growth (Voorhees et al., 1975; Campbell and Phene, 1977).
2) Since the irrigation tube is placed between two narrowly spaced rows, the crop root system should more efficiently intercept the water and nutrients that are supplied between them.
3) The wide-bed twin-row method is easily adaptable to plastic mulching to eliminate water evaporation from the soil surface.
4) In humid areas where rainfall often creates aeration problems (Phene et al., 1976), this method provides a larger portion of soil between the beds for storage water and for possibly draining excess water from the soil surface.

[1] Contribution from the Coastal Plains Soil and Water Conservation Research Center, USDA-SEA-AR, in cooperation with Clemson Agric. Exp. Stn. Received 1 May 1979. Approved 20 July 1979.

[2] Soil Scientists, formerly USDA-SEA-AR, P. O. Box 3039, Florence, SC 29502; now, respectively, Supervisory Soil Scientist, Water Management Research Laboratory, USDA-SEA, 4816 East Shields Ave., Fresno, CA 93726, and Cooperator.

5) Since no fertilizer would be applied to wide spaces between the bed, fertilizer losses would be minimized.

The objectives of this project were to determine the influence of trickle irrigation; wide-bed, twin-row spacing; and trickle N and K fertilization rates on the yield and quality of sweet corn.

MATERIALS AND METHODS

Experimental Design and Procedures

The experiment to determine the yield response of high-frequency trickle-irrigated corn fertilized with different amounts of N and K, and planted at two different row spacings was conducted in 1973 with a spring and fall planting of sweet corn, respectively (*Zea mays* L., 'Silver Queen' and 'Florida 102'). The experimental design was a completely randomized block with each treatment replicated three times and the fall crop superimposed over the spring crop. All results reported in this manuscript, except for the net seasonal nitrate profile changes (Fig. 4) pertain to the spring sweet corn crop. The various treatments used for fertilization, row spacing, and check are listed in Table 1. Each treatment plot was 7.6 by 6.1 m and rows were oriented in a NW-SE direction. The row spacings were the conventional single (SS) (100 cm apart) and the twin-row (DS) (35 cm apart) positioned on wide beds spaced 165 cm from center to center. Figure 1 is a schematic cross section of the spacing treatments, locations of the irrigation tubing with respect to the row and of the soil matric potential (M.P.) sensor used to control irrigation automatically, and the soil sampling sites for nitrate (NO_3^-) measurements.

The soil, a Varina sandy loam (Typic Paleudult), was adjusted to pH 6 by applying 5 metric tons/ha of dolomitic lime and treated with diazinon AG 500[3] to control soil insects and worms. Sweet corn was planted with a 2-row planter and thinned to a density of about 70,000 plants/ha.

Superphosphate was broadcast uniformly at a rate of 112 kg/ha before planting. Equal amounts of N and K in a nutrient solution, combined with the irrigation water, were applied daily through the porous tubes, according to predetermined corn requirements. The corn growing season, from cotyledon stage (day 149) to the end of plant extension (day 209), was divided into four 15-day periods reflecting the crop growth stages. During the four successive 15-day growth periods, 14, 42, 33, and 11%, respectively, of the total N and K were applied in daily increments, equal to 1/15 of these percentages. Unirrigated plots were fertilized with four applications of N and K (totaling 168 kg/ha each) in the same ratio as that of the irrigated plots but applied at the beginning of each crop-growth stage. The irrigation system was controlled automatically by a calculator-based data acquisition system, using closed loop electronic sensor feedback control (Phene et al., 1973).

Crop response was interpreted based on total and marketable ear yield, mean ear diameter and length, percentage of water content and pericarp, total dry matter production, plant heights, N in the leaf base, and cob and kernel dry matter, total plant N, and soil profile NO_3^- content. The early plant samples were the entire aerial portion of the plant and later samples were the first mature leaf next to the whorl. Total plant N was determined by the Kjeldahl method, and soil NO_3^- content was determined from saturation extracts with the NO_3^- specific ion electrode.

The net seasonal NO_3^- increase was calculated by subtracting the NO_3^- contents of the soil in unfertilized plots from that of fertilized plots (to account for residual and mineralized N) before planting in the spring and in the fall. The resulting spring values were subtracted from fall values to estimate the net NO_3^- gain, and these values were plotted as a function of time and depth.

[3] Trade names are used for identification purposes only and do not imply preference for this item by the USDA.

Table 1—Fertility, row spacing, and irrigation treatments.

N & K rates, kg/ha	Row spacings: Single (SS)	Row spacings: Double (DS)	Irrigation (TI = trickle irrig.) (UI = unirrigated)
0	SS		TI
28	SS		TI
28		DS	TI
56	SS		TI
56		DS	TI
168	SS		TI
168		DS	TI
168	SS		UI
336	SS		TI
336		DS	TI

Irrigation System

Phene (1974) described the water treatment, nutrient and chemical distribution system, and the soil matric potential sensors and control system. Trickle irrigation water was applied through a porous plastic tube (Viaflo, E. I. DuPont de Nemours & Co., Inc.)[3] installed in the upper root zone on the row, 5 cm from the SS plants and midway between the twin-rows of the DS plants and at about the 5-cm depth.

Irrigation Control and Soil Matric Potential Measurement System

The irrigation control was based on the simultaneous automatic measurements of the crop evapotranspiration, estimated from the screened Class-A evaporation pan, and of a soil matric potential sensor installed in each plot at 15 cm from the soil surface, as described by Phene and Campbell (1975) and Campbell and Phene (1976). Although the time response of the evaporation pan usually lags behind actual evapotranspiration

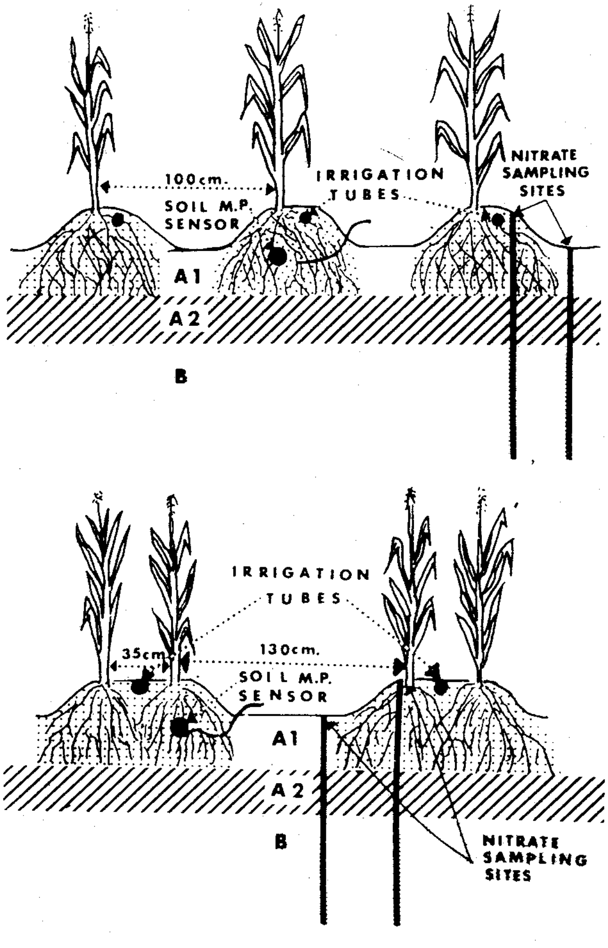


Fig. 1—High-frequency porous tube irrigation system for single row (SS-TI) and twin-row (DS-TI) spacings (not to Scale).

Table 2—Sweet corn stalk measurements as influenced by irrigation, fertilization rates, and row spacings (SS = single row, DS = twin-row, UI = unirrigated).

Treatments	Stalk population	Ear-producing stalks	Ears per stalk	Stalk water content	Stalk fresh weight
	1,000/ha	1,000/ha	No.	%	metric ton/ha
0SS	73.9 cdef†	23.9 e	0.33 e	78.1 bc	13.5 f
28SS	73.2 cdefg	39.8 d	0.55 d	78.9 ab	25.9 c
28DS	68.9 i	44.3 d	0.65 c	76.6 c	19.5 e
56SS	78.2 ab	53.1 c	0.68 c	78.1 b	26.5 c
56DS	70.1 fgh	46.5 cd	0.67 c	76.8 c	25.3 cd
168SS	75.7 abcd	67.3 a	0.90 ab	78.9 ab	36.3 ab
168DS	72.7 defgh	65.1 ab	0.93 ab	78.0 b	30.7 bc
168 SS-UI	75.2 bcde	64.6 b	0.86 b	75.4 e	22.9 de
336SS	76.8 abc	71.4 ab	0.98 a	80.0 a	39.3 a
336DS	79.7 a	75.0 a	0.98 a	80.3 a	39.8 a

† Column means followed by the same letter are not significantly different at the 5% confidence level.

by 4 to 6 hours, the daily proportions agree, and the soil matric potential sensor initiated irrigations, only when soil water was deficient. The amount of irrigation water applied was a function of the ratio of potential evapotranspiration to open pan evaporation and of the physiological age of the crop (Doss et al., 1962). However, when the soil matric potential was higher than the level set for irrigation, no irrigation cycle was initiated, thus optimizing water use. The minimal soil matric potential was maintained between −0.20 and −0.25 bar during the growing period by irrigating as often as 12 times daily, if necessary.

Soil matric potential sensors were installed in each plot, midway between the rows at the 15-, 30-, and 45-cm depths directly below the plant. Electrical wiring schematic for coupling the soil matric potential sensors to the calculator-based data acquisition system are available from the authors. The data from each plot, including Julian date and time, soil matric potentials at three depths, irrigation commands or instructions, and screened pan evaporation over grass were printed and recorded on punched paper tape at 2-hour intervals.

RESULTS

Plant population, ear producing stalk, number of ears per stalk, and stalk water content and fresh weight are shown in Table 2. Although plants were thinned to the same population in all treatments, plant populations ranged from 68,900 to 79,700 stalks/ha. Generally, plant populations for the SS treatments were slightly larger than those for the DS, except those for the 336 DS-TI treatment. There was no difference in plant population between the 56, 168, and 336 SS-TI treatments. The ear-producing stalks and the average number of ears per stalk increased gradually with N and K application rates up to 168 kg/ha, but values seldom showed any difference between spacing treatments. The water content of the SS-TI treatment corn stalks at the 28- and 56-kg/ha fertility rates was slightly higher than that of the DS-TI treatment stalks, and the 168 SS-TI (unirrigated) was significantly lower than those of all irrigated treatments. The stalk fresh weight of the irrigated corn increased with N application rates, but values were different between spacings only at the 28-kg/ha fertility treatment. The stalk fresh weights ranged from 13.5 metric tons/ha for the unfertilized treatment (0 SS-TI) to a maximum of 39.8 metric ton/ha for the 336 DS-TI treatment.

The total and marketable number and weight of ears, the ear diameter and length, the pericarp content of the kernel, and the ear water content are shown in Table 3. Standard marketable ears were at least 15 cm long and completely filled with kernels. The total and marketable number and weight of ears increased with increasing fertility rates. Plants from all the irrigated treatments below the 168 SS-TI and 168 DS-TI treatments and those from the unirrigated treatment, 168 SS-UI, produced < 50% marketable ears whereas plants from the 168 and 336 SS-TI treatments produced 75 to 83% marketable ears. The ear diameter was not affected by the N and K or spacing treatments. However, the ear lengths of the 168- and 336-SS-TI and DS-TI treatment corn were greater than those of all other treatments. Generally, the pericarpal content of the corn kernel decreased gradually with increasing N and K, and the kernel water content was only randomly affected. The 168 SS-UI treatment resulted in 49% less marketable ears and 47% less ear weight than the average for the 336 SS-TI and DS-TI treatments. Irrigation did not affect the ear diameter, but the ear length with the 168 SS-UI treatment was 11% shorter

Table 3—Sweet corn ear measurements as influenced by irrigation, fertilization rates, and row spacings (SS = single row, DS = twin-row, UI = unirrigated).

Treatments	Total ears		Marketable ears		Ear diameter	Ear length	Pericarp	Water content
	Number	Weight	Number	Weight				
	1,000/ha	metric ton/ha	1,000/ha	metric ton/ha	cm	cm	%	%
0SS	24.8 f†	3.3 f	3.9 e	0.9 f	4.5 e	12.3 e	0.99 a	77.2 a
28SS	40.2 e	7.1 e	12.2 d	3.3 e	5.1 ab	13.5 d	1.07 a	73.3 d
28DS	44.9 e	7.9 de	11.7 d	3.1 e	5.3 ab	12.3 e	1.03 ab	73.2 e
56SS	53.8 d	9.3 d	17.4 d	4.3 e	5.0 c	13.3 d	0.99 ac	75.1 b
56DS	44.6 d	9.1 d	15.4 d	3.8 e	5.1 a	13.1 d	0.91 c	74.5 b
168SS	67.6 bc	17.7 b	51.1 b	14.8 bc	5.2 a	16.7 ab	1.01 ac	73.6 c
168DS	67.3 bc	16.8 b	50.2 b	13.9 c	5.2 ab	16.1 b	0.86 d	75.2 bc
168SS-UI	64.6 c	14.6 c	31.1 c	8.9 d	5.3 a	14.6 c	0.97 a	74.4 b
336SS	75.3 ab	19.7 a	62.3 a	17.2 a	5.1 a	17.5 a	0.91 c	75.9 ab
336DS	77.9 a	18.9 ab	59.1 ab	16.3 ab	5.0 bc	16.3 ab	0.92 b	74.9 bd

† Column means followed by the same letter are not significantly different at the 5% confidence level.

Table 4—Sweet corn dry matter contents as influenced by irrigation, fertilization rates, and row spacings (SS = single row, DS = twin-row, UI = unirrigated).

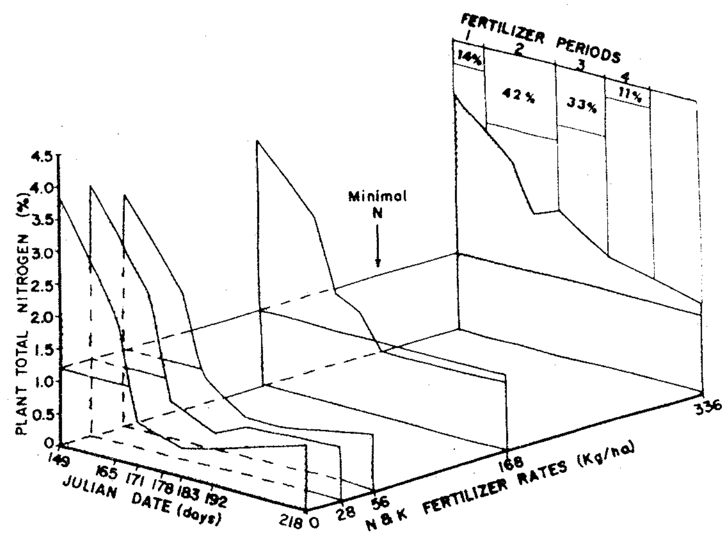
Treatments	Stalk dry matter	Ear dry matter	Total dry matter	Total N‡ in plant
	metric ton/ha			kg/ha
0SS	2.9 e†	0.7 d	3.6 f	35.2 e§
28SS	5.4 cd	1.5 c	6.9 de	55.6 d
28DS	4.6 d	1.9 bc	6.5 e	49.4 de
56SS	5.8 c	2.0 b	7.8 d	65.5 d
56DS	5.9 c	2.1 b	8.0 cd	58.4 d
168SS	7.6 abc	3.7 a	11.3 ab	117.7 c
168DS	6.8 b	3.7 a	10.5 b	119.8 c
168SS-UI	5.6 c	3.8 a	9.4 bc	109.0 c
336SS	7.9 a	4.0 a	11.9 a	161.3 b
336DS	7.8 a	3.7 a	11.5 ab	183.2 a

† Column means followed by the same letter are not significantly different at the 5% confidence level.
‡ Total N in plant measured by Kjeldahl method.
§ Represents plant uptake of soil residual- and mineralized-N.

than the average length of ears with the 168 SS-TI and DS-TI treatments.

The sweet corn dry matter and the total N recovered in plants are shown in Table 4. The stalk dry matter gradually increased with N and K rates from 2.9 to 7.9 metric tons/ha, and the ear dry matter increased from 0.7 to 4.0 metric ton/ha with the 0 to 336 SS-TI treatments, respectively. The total dry matter reflected the same relationship with little difference in values between spacing treatments. The total N content in the plant increased from 35 kg/ha with the unfertilized treatment (representing the plant uptake of soil residual and mineralized N) to 183.2 kg/ha for the 336 DS-TI treatment. Except for the 336 DS-TI treatment corn, which had significantly higher total N than the 336-SS-TI treatment corn, there was no difference due to plant spacing for the other treatments.

The percentage of N in trickle-irrigated sweet corn plants as a function of time, fertilizer rates, fertilization period, and spacing are shown in Fig. 2 for the SS-TI (top) and DS-TI (bottom) treatments, respectively. During the first growth stage (Julian days 142 to 165), different N and K fertilization rates did not cause significant differences in N content of the sweet corn. Therefore, large N applications during the first few days of growth may not be necessary, since the percentage of N in all plant tissues was considerably above the minimal N level line (1.2% plant total N) shown in Fig. 2. As tassels emerged (day 183), the large N demand was reflected by a rapid decrease in the percentage of stored N for all treatments, although the N content of corn in the DS-TI treatments did not seem to decrease as rapidly as did that in the SS-TI treatments. Plants from the 0, 28, and 56-kg/ha fertility levels were deficient in N from ear formation until harvest, regardless of row spacing. From the tasseling stage (day 183) to harvest (day 218), corn plants with the 168-kg/ha fertilizer rate were slightly N deficient for the SS-TI treatment, but not for the DS-TI treatment. The N content of corn with the 336-kg/ha fertilizer rates was above the desired minimum for sweet corn during the entire growing period and significantly higher for the DS-TI treatment than for the SS-TI treatments during the last stage of growth.



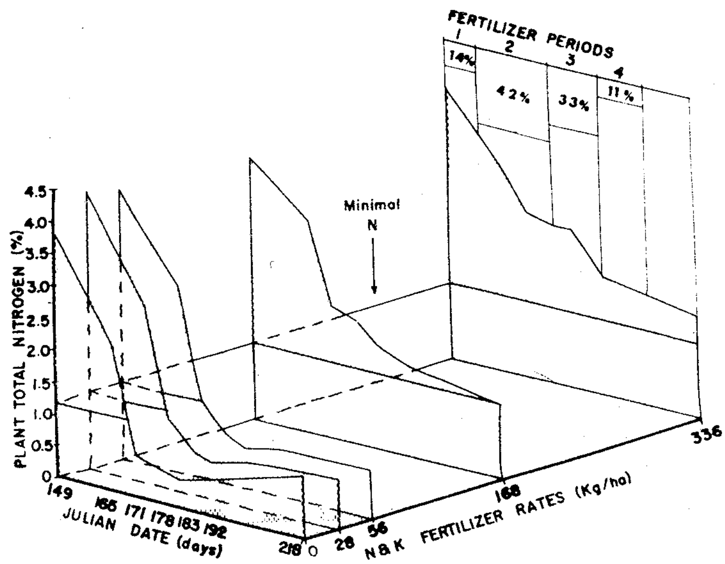


Fig. 2—Nitrogen in corn plant tissue from high-frequency trickle irrigation treatments as a function of time and fertilizer rates for single row (SS-TI) (*top*) and twin-row (DS-TI) (*bottom*).

Plant heights (Fig. 3) were not affected by fertilizer rates or spacing during the seedling stage (day 142 to 165). As the corn matured, heights of unfertilized corn were significantly lower than those fertilized at 168- and 336-kg/ha fertilizer rates. Heights of plants from the 168- and 336-SS-TI and DS-TI treatments were not affected by fertilizer or spacing treatments.

Figures 4A and 4B show the net seasonal soil NO_3^- increases for spring and fall sweet corn as influenced by N- and K-fertilizer treatments, spacing treatments, and soil depth. The amount of total applied N will double the values shown in Fig. 4, because each fertilizer treatment rate was applied twice, once to each spring and fall crop. Figures 4C and 4D show that soil NO_3^- midway between the rows were similar. Since the residual and mineralized N were accounted for by subtracting the N measured in nonfertilized plots from that measured in the fertilized plots, the net increase in soil NO_3^- with depth and fertilizer rates was probably caused by excessive N fertilization. The NO_3^- content profiles for the 28 SS-TI and DS-TI treatments did not differ significantly but the 168 and 336 treatments resulted in greater NO_3^- contents between the 0- and 60-cm soil depth for the DS-TI treatments than for the SS-TI treatments. The soil NO_3^- content for the 336 SS-TI and DS-TI treatments were significantly greater than those for the 168 and 28 SS-TI and DS-TI treatments.

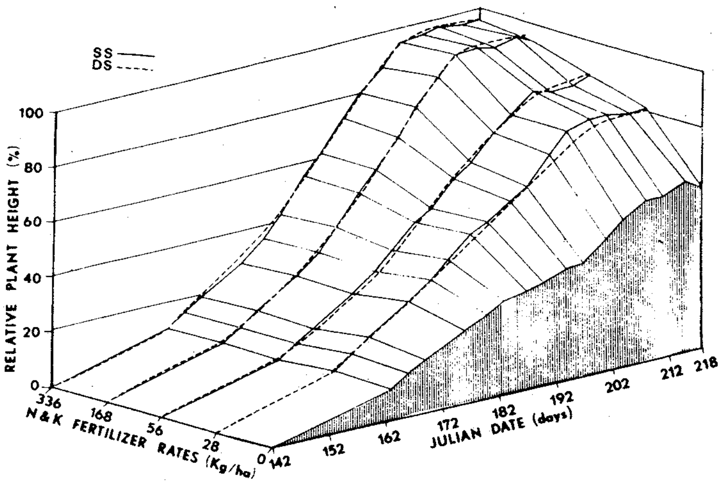


Fig. 3—Relative corn plant heights as influenced by N and K fertilization row spacing, and time.

The mean net seasonal soil NO_3^- increase for fertilizer rates and soil depth, measured midway between the rows, showed no significant differences for the various depths, fertilizer treatments, and row spacing, except for the 336 DS-TI treatment which had significantly higher soil NO_3^- values in the top 60 cm of soil.

Figures 2 and 4 and Table 4 (col. 5) indicated that the DS-TI treatment may be a better N management technique with HFTI because the 168 DS-TI and SS-TI treatments had the same plant N content, with a higher soil NO_3^- increase measured in the 168 DS-TI than in the 168 SS-TI treatment, indicating the possibility of smaller N losses from the soil profile. Furthermore, the plant N content for the 336 DS-TI treatment was significantly higher than that for the 336 SS-TI treatment, and the net seasonal soil NO_3^- increase was greater for the DS-TI treatment than that for the SS-

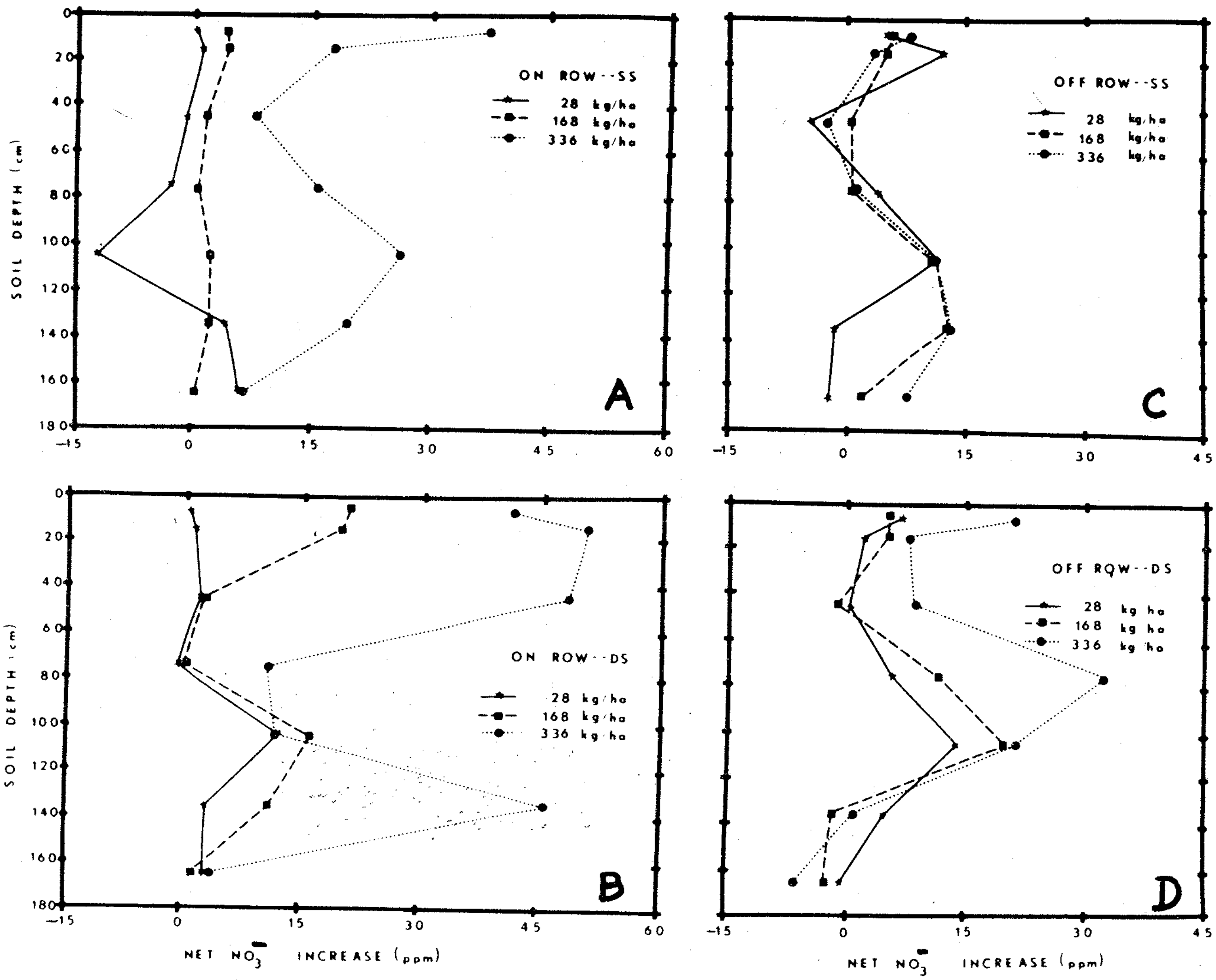


Fig. 4—The net seasonal NO_3-N increase with soil depth for "on row" (*A*) single row (SS-TI) and (*B*) twin-row (DS-TI) treatments, and for "off row" (between beds) (*C*) SS-TI and(*D*) DS-TI, respectively.

TI treatment. These results substantiate a need for soil water-nutrient management methods for the humid region and clearly demonstrate the effectiveness of the twin-row, high-frequency, water-nutrient/trickle irrigation method for water and nutrient distribution.

Figure 5 shows the mean soil matric potential measurement at the 15-cm depth and rainfall for the corn growing season (day 179 to 221) for the 168 SS-UI unirrigated and HFTI SS-TI and DS-TI treatments. The rainfall during the growing season totaled 44 cm. The lower soil matric potential for the HFTI treatments was maintained at −0.25 bar by irrigating as often as 12 times daily. The highest range of soil matric potential during that period was −0.78 bars for the 168 SS-UI, −0.30 for the DS-TI treatment, and −0.27 bar for the SS-TI treatment. Tensiometer measurements in each plot, reflecting soil matric potentials, were not significantly different among spacing and fertility treatments.

Irrigation water applied to control the soil matric potential at −0.25 bar in each irrigated treatment were: 8 cm for the 0 and 28 SS-TI and DS-TI treatments, 10 cm for the 56 SS-TI and DS-TI treatments, 12 cm for the 168 SS-TI and DS-TI treatments, and 15 cm for the 336 SS-TI and DS-TI treatments. This significant difference in applied irrigation water resulted from lower evapotranspiration by the smaller plants rather than from an imposed irrigation treatment. This controlled irrigation method prevented extended water logging conditions in the soil root zone even after a rainfall event of 15.2 cm (Fig. 5).

CONCLUSIONS

Distribution of water and nutrient solution over the crop cycle with trickle irrigation is adaptable for high-frequency irrigation in sandy soils of the Southeastern Coastal Plains. The application is not affected by the wide bed, twin-row planting (DS) which requires 40% less trickle irrigation tubing than conventional spacing. The wide bed twin-row planting (DS) did not detrimentally affect yield, biomass production, N and water-use efficiency of sweet corn, and the automatic control of the irrigation system by the soil matric potential sensors.

The ear yield and biomass production increased significantly and consistently with increasing N and K fertilizer rates ranging from 0 to 168 kg/ha, but were not highly or consistently affected by increasing the fertilizer rate above 168 kg/ha.

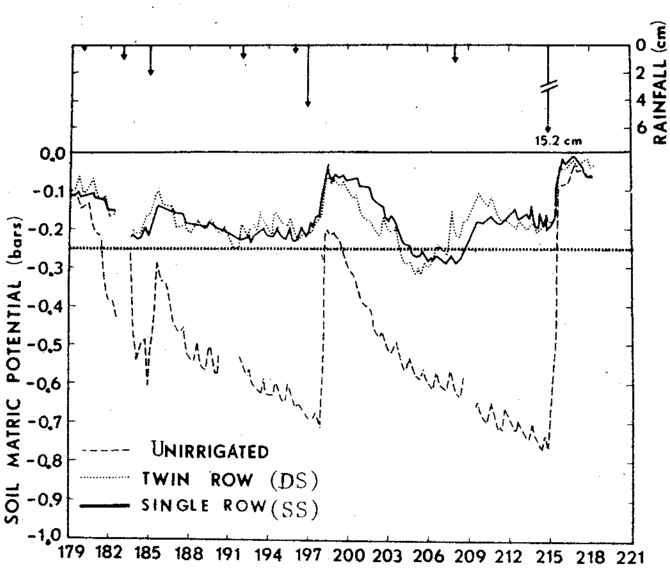


Fig. 5—The mean soil matric potential at the 15-cm depth as influenced by high-frequency trickle irrigation (HFTI), row spacings, and rainfall.

ACKNOWLEDGMENT

The authors express their gratitude to the support staff at the Coastal Plains Soil and Water Conservation Research Center for their participation in this research project.

LITERATURE CITED

1. Campbell, R. B., and C. J. Phene. 1976. Estimating potential evapotranspiration from screened pan evaporation. Agric. Meteorol. 16:343–352.
2. Campbell, R. B., and C. J. Phene. 1977. Tillage, matric potential, oxygen and millet yield relations in a layered soil. Trans. Am. Soc. Agric. Eng. 20:271–275.
3. Doss, B. D., O. L. Bennett, and D. A. Ashley. 1962. Evapotranspiration by irrigated corn. Agron. J. 54:497–498.
4. Lunt, O. R. 1971. Controlled-release fertilizers: Achievements and potential. J. Agric. Food Chem. 19:797–800.
5. Nelson, L. B., and R. D. Hauck. 1965. Nitrogen fertilizers: Progress and problems. Agric. Sci. Rev. 3:38–47.
6. Parr, J. F. 1967. Biochemical considerations for increasing the efficiency of nitrogen fertilizers. Soils Fert. 30:207–213.
7. Pearson, R. W., H. V. Jordan, O. L. Bennett, C. E. Scarsbrook, W. E. Adams, and A. W. Shite. 1961. Residual effects of fall- and spring-applied nitrogen fertilizers on crop yields in the southeastern United States. USDA-ARS, Tech. Bull. 1254.
8. Phene, C. J. 1974. Subsurface irrigation in the humid Southeastern Coastal Plains. p. 267–303. *In* M. C. Blount (ed.) Proc. Symposium on Water Resources: Utilization and conservation in the southeastern environment, Ft. Valley, Ga.
9. Phene, C. J., and O. W. Beale. 1976. High-frequency irrigation for water nutrient management in humid regions. Soil Sci. Soc. Am. J. 40:430–436.
10. Phene, C. J., and R. B. Campbell. 1975. Automating pan evaporation measurements for irrigation control. Agric. Meteorol. 15:181–191.
11. Phene, C. J., R. B. Campbell, and C. W. Doty. 1976. Characterization of soil aeration *in situ* with automated oxygen diffusion measurements. Soil Sci. 122:271–281.
12. Phene, C. J., J. L. Fouss, and D. C. Sanders. 1979. Water-nutrient management of potatoes with trickle irrigation. Am. Potato J. 56:51–59.
13. Phene, C. J., G. J. Hoffman, and R. S. Austin. 1973. Controlling automated irrigation with soil matric potential sensor. Trans. Am. Soc. Agric. Eng. 16:773–776.
14. Phene, C. J., and D. C. Sanders. 1976. High-frequency trickle irrigation and row spacing effects on yield and quality of potatoes. Agron. J. 68:602–607.
15. Prasad, R., G. B. Rajale, and B. A. Lakhdive. 1971. Nitrification retarders and slow-release nitrogen fertilizers. Adv. Agron. 23:337–383.
16. Stanford, G., and S. J. Smith. 1972. Nitrogen mineralization potentials of soils. Soil Sci. Soc. Am. Proc. 36:465–472.
17. Voorhees, W. B., D. A. Farrell, and W. E. Larson. 1975. Soil strength and aeration effects on root elongation. Soil Sci. Soc. Am. J. 39:948–953.