Soil & Tillage Research, 4 (1984) 511—529
Elsevier Science Publishers B.V., Amsterdam — Printed in The Netherlands

CONSERVATION TILLAGE FOR MAIZE PRODUCTION IN THE U.S. SOUTHEASTERN COASTAL PLAIN*

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(Accepted 19 April 1984)

ABSTRACT

Campbell, R.B., Karlen, D.L. and Sojka, R.E., 1984. Conservation tillage for maize production in the U.S. southeastern coastal plain. *Soil Tillage Res.*, 4: 511—529.

Eight conservation tillage methods were evaluated for maize (*Zea mays* L.) production and were related to water conserved, soil strength, plant stand, plant nutrient status, and methods of managing crop residues on Norfolk loamy sands (Typic Paleudults) in the U.S. southeastern coastal plain. This study summarizes 10 site-years of data collected from 1978 through 1982.

Seasonal soil-water balance and crop residue management largely determined the success of maize production under conservation tillage. Autumn subsoiling increased winter forage and maize production under both conventional and conservation tillage. When early-season rainfall was limited, water extraction by a winter cover crop or winter weeds often reduced early-season growth and yield of maize under conservation tillage. For adequate stands, increased seeding rates and effective weed-, rodent-, bird- and insect-control were all necessary.

Under adequate water regimes, conventional tillage resulted in greater yields at low levels of nitrogen, but maximum yields occurred regardless of tillage system, when 200 kg ha^{-1} were applied. Conventionally-tilled maize generally resulted in higher yields than conservation tillage production. The only significant increase for conservation tillage occurred under non-irrigated conditions in 1981 during severe drought. The interactive soil and climatic factors which have impact on conservation tillage in this physiographic region were identified.

INTRODUCTION

Reduction of soil erosion and petroleum consumption are 2 factors which have stimulated development of conservation tillage practices throughout the U.S. (Larson, 1981; Campbell et al., 1984). In the U.S. southeastern

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coastal plain (US-SCP), production of maize using conservation tillage is being slowly accepted, but generally it has been less successful than in the Piedmont or other physiographic areas which have more rolling topography (Jones et al., 1968; Shear and Moschler, 1969; Reicosky et al., 1977; Phillips et al., 1980; Campbell et al., 1983, 1984). Regional differences in soil physical and chemical properties apparently reduce potential benefits of conservation tillage for maize production in the US-SCP.

On sloping fields, conservation tillage reduces runoff, nutrient and pesticide movement, and loss of soil (Phillips et al., 1980). However, on poorly-drained soils or where fragipans restrict root development, maize yields with conservation tillage are often lower (Triplett and van Doren, 1977; Blevins and Thomas, 1981). In the humid US-SCP, flatter topography, low water and nutrient retention, and higher disease, weed, and insect pressures also reduce the competitive advantage of conservation tillage systems for maize. In addition, Kronstad et al. (1978) listed: (a) physical problems in seed placement; (b) unfavorable changes in microclimate; (c) phytotoxic decomposition products as factors associated with crop residues that reduce germination, emergence and seedling establishment in conservation tillage systems.

In the US-SCP, the amount and frequency of rainfall is erratic, soils are coarse textured, and plant rooting is shallow due to physical impedence. These problems can be alleviated during conventional tillage by subsoiling to disrupt the dense genetic E horizon or tillage pan (Campbell et al., 1974; Doty et al., 1975; Peele and Suman, 1973; Reicosky et al., 1977). Fortunately, commercial equipment is now available so that this can also be accomplished as part of a conservation tillage program.

In the US-SCP, a winter cover crop or periodic surface tillage is also necessary to prevent proliferation of weeds. This winter vegetation further complicates conservation tillage because any plant growth can deplete soil water if early-season rainfall is low. When this occurs, soil strength increases, maize germination and seedling growth is slowed, and root proliferation is restricted (Campbell et al., 1984).

These physical and environmental factors have presumably contributed to the slow acceptance of conservation tillage in the U.S. southeastern coastal plain. Therefore, the objectives of this research were: (1) to compare maize production under various methods of crop residue management; (2) to investigate the seasonal water balance/tillage relationships; (3) to determine the effects of subsoiling in autumn prior to growing a maize crop; (4) to evaluate N rates and sources for maize grown with or without supplemental irrigation using conventional or conservation tillage practices.

METHODS AND MATERIALS

Conservation tillage practices for maize were evaluated from 1978 through 1982 in the coastal plain of South Carolina, U.S.A. Ten field experiments were conducted at 4 locations within a 15 km radius of the USDA-ARS, Coastal Plains Soil and Water Conservation Research Center at Florence, SC. The four locations were: Site A, the Frank Williamson farm; Site B, Clemson University's Pee Dee Research and Education Center; Site C, the Ned Dargan farm; Site D, the Coastal Plain Soil and Water Conservation Research Center. The predominant soil type at each site was a Norfolk loamy sand (fine-loamy, silicious, thermic, Typic Paleudults).

Production-scale and plot-scale approaches were used to evaluate maize response to 8 tillage systems. The production-scale approach utilized large (>1 ha) blocks for each treatment. These blocks were repeated 3 or 4 times in alternate strips across 7- to 10-ha fields at Sites A and C. Plot-scale evaluations were made at Sites B and D on plots that were approximately 0.01 ha in size. Treatments at Site B were evaluated with and without supplemental irrigation water in a stripped-split-plot experimental design which was replicated 5 times. Crop residue management treatments at Site D were evaluated using a randomized block design that was replicated 4 times.

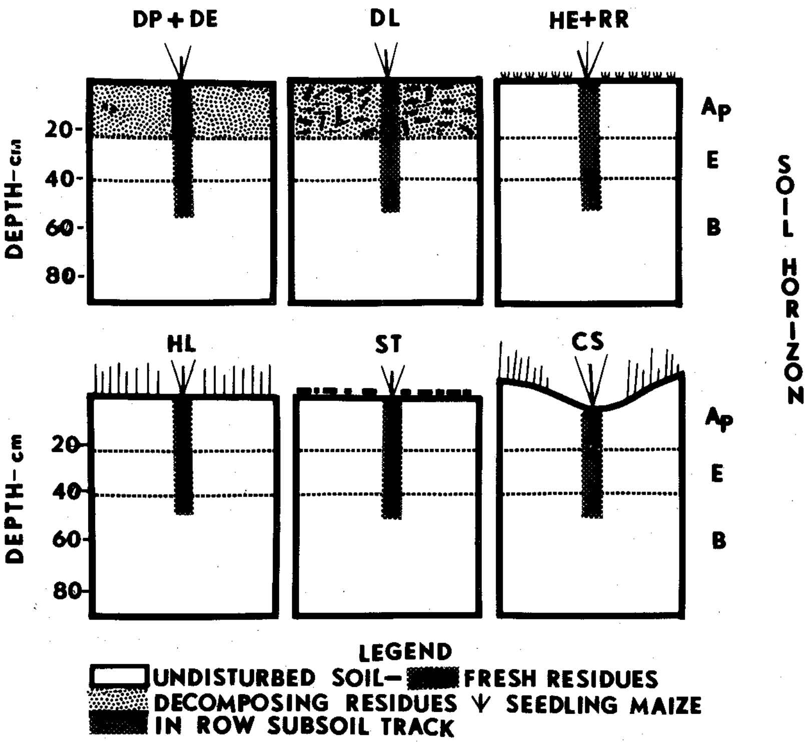

Fig. 1. Surface soil conditions evaluated for maize production in the U.S. Southeastern Coastal Plain (US-SCP).

Surface soil conditions, which are referred to as treatments, are illustrated in Fig. 1, symbolized and described as follows: (1) DP, disked periodically to maintain a residue- and weed-free surface; (2) DE, cover crops or winter weeds disked 20 to 30 days before planting; (3) DL, cover crop disked 1 day before planting; (4) HE, non-selective herbicide applied to cover crops 20 to 30 days before planting; (5) RR, crop residue harvested mechanically prior to planting; (6) HL, non-selective herbicide applied to cover crop after planting; (7) ST, stover and weeds, but no cover crop with a non-selective herbicide applied after planting; (8) CS, "Cole System", partial mechanical displacement of cover crop with formation of a shallow furrow in which maize was planted. Variants of CS included evaluation with application of non-selective herbicides after planting (CS-A) and without herbicide (CS-B). Variants of RR were removal of 66% of previous crop residue (RR-66) and removal of 90% previous crop residue (RR-90).

TABLE I

Experimental approach and cultural practices utilized to evaluate conservation tillage maize production in the southeastern atlantic coastal plains

Exp. No.	Site	Growing season	Research approach	Cover crop	Planting date	Treatments evaluated
1	A	1978	Production	Rye	3-30-78	DE, HL
2	A	1979	Production		3-30-79	DE, HL
3	B	1980	Plot		5- 1-80	DL, HL, RR-90, RR-66
4	B	1981	Plot	None	4- 9-81	DP, ST, RR-90, RR-66
5	B	1982	Plot		4- 9-82	DP, ST, RR-90, RR-66
6	C	1980	Production	Rye	4-16-80	DE, DL, HE, HL
7	C	1981	Production		4-16-81	DE, DL, HE, HL
8	D	1981	Plot		4-13-81	DP, DL, HL, CS-A, CS-B
9	A	1979	Plot		3-30-79	DE, HL
10	B	1979	Plot	None	4- 3-79	HL

Experimental approaches and pertinent cultural practices for each experiment are listed in Table I. All experiments were planted with a Brown-Harden Superseeder which has been described in detail by Campbell et al. (1984). This implement was equipped with in-row subsoil shanks, followed by a smoothing attachment ahead of each planter. Herbicides were tank mixed and surface applied at a rate of 374 l ha^{-1} in aqueous solution as follows: Paraquat (1,1'-Dimethyl -4,4'-bipyridinium ion) at 0.49 kg ha^{-1} a.i.; Atrazine [2-chloro-4-(ethylamino)-6-(isopropylamino)-*s*-triazine] at

1.7 kg ha^{-1} a.i.; Alachlor [2-chloro-2′,6′-diethyl-*N*-(methoxymethyl) acetanilide] at 2.2 kg ha^{-1} a.i. When evening primrose (*Primula* spp.) or marestail (*Conyza canadensis*) were present, glyphosate [isopropylamine salt of *N*-(phosphonomethyl) glycine] was substituted for Paraquat at a rate of 0.9 kg ha^{-1} a.i. A post-emergence application of 2, 4, -D [(2,4-dichlorophenoxy) acetic acid] at 1.6 ha^{-1} a.i. was applied when maize plants were 1.5 m tall for broadleaf weed control.

Populations of *Meloidogyne incognita* and *Pratylenchus scribeneri* nematodes, *Spenophorus madis* and *S. callosus* billbugs and *Conoderus falli* and *C. vespertinus* wireworms were controlled by applying Terbufos [*S*-[[(1,1-dimethylethyl) thio] methyl] 0,0-diethyl phosphorodithioate] or Carbofuran (2,3-dihydro-2,2-dymethyl-7-benzofuranyl methylcarbamate) at 2.2 kg ha^{-1} a.i. Dolomitic lime was applied at a rate of 1200 kg ha^{-1} to maintain soil pH at approximately 6.0. Pre-plant P and K were applied annually at rates of 30 and 170 kg ha^{-1}, respectively. Sulfur, B and Zn were applied prior to planting in 1981 and 1982 at rates of 42, 2.8 and 3.4 kg ha^{-1}, respectively. Pre-plant N rates were 35 or 70 kg ha^{-1} depending upon the pre-plant fertilizer source. Except in the N experiments, total N application was balanced at 170 kg ha^{-1} by side-dressing with anhydrous ammonia approximately 6 weeks after emergence. At mid-anthesis, plant tissue samples were collected, dried at 70°C, ground, and analyzed for N, P, K, Ca, Mg, S, B, Mn and Zn using procedures outlined by Isaac and Johnson (1977). Grain was harvested, weighed, and adjusted to a moisture content of 15.5%.

Detailed soil physical properties were measured on samples from Sites A and B. Qualitative evaluations indicated soils at the other 2 sites were similar. Generalized water balances for non-irrigated conditions were computed for each season by using crop coefficients to calculate potential evapotranspiration (PET) and subtracting these values from plant available water. Crop coefficients were a function of canopy cover and increased linearly from 0.4 to 1.0 between 15 April and 15 May, remained at 1.0 from 16 May to 1 August, and decreased linearly from 1.0 to 0.4 between 2 August and 15 August. Observed rooting depths for 3 periods (15 April—31 May, 1 June—15 June, and 16 June—15 Aug) were used to compute plant available water which was defined as 50% of the total water capacity between −10 and −1500 kPa. Soil-water storage values for the 3 periods of observed rooting were 3.71, 4.89 and 6.07 cm, respectively. Potential evapotranspiration was based upon 85% of the average evaporation from 3 U.S. Weather Bureau open pans located at or within 5 km of Site D.

Additional specific experimental details are included in the Results and Discussion section because results or questions raised by 1 experiment often led to modifications in subsequent experiments. However, the reader will find that the 10 site-years of data effectively identifies many of the problems which have been encountered in implementing a conservation tillage program for maize production in the US-SCP.

RESULTS AND DISCUSSION

Experiment No. 1 — production scale evaluation of tillage systems

The first experiment in this program was a production-scale evaluation of treatments DE and HL (Fig. 1) in 1978 at Site A (Table I). Stand establishment was the first parameter in which a significant treatment difference could be identified. Planting rates were equal at 5.8 kernels m^{-2}, but 26 days after emergence (DAE), there were 27% fewer plants in HL strips than in DE strips (3.8 vs. 5.2 plants m^{-2}, respectively). Several factors, including lower seedbed water content, poor soil-seed contact, and preferential feeding by fauna and insects on seedlings in the HL strips, apparently contributed to these differences, but those factors were not evident until data from several subsequent experiments had been collected.

When stand counts were made 26 DAE, infestation of evening primrose was much more severe in HL strips than in DE strips. Therefore, to quantify effects of plant population and weed competition on grain yield, 2 subexperiments were established at Site A. In ½ of the DE strips, plant density was reduced to 3.8 plants m^{-2}, while in both DE and HL strips, replicated

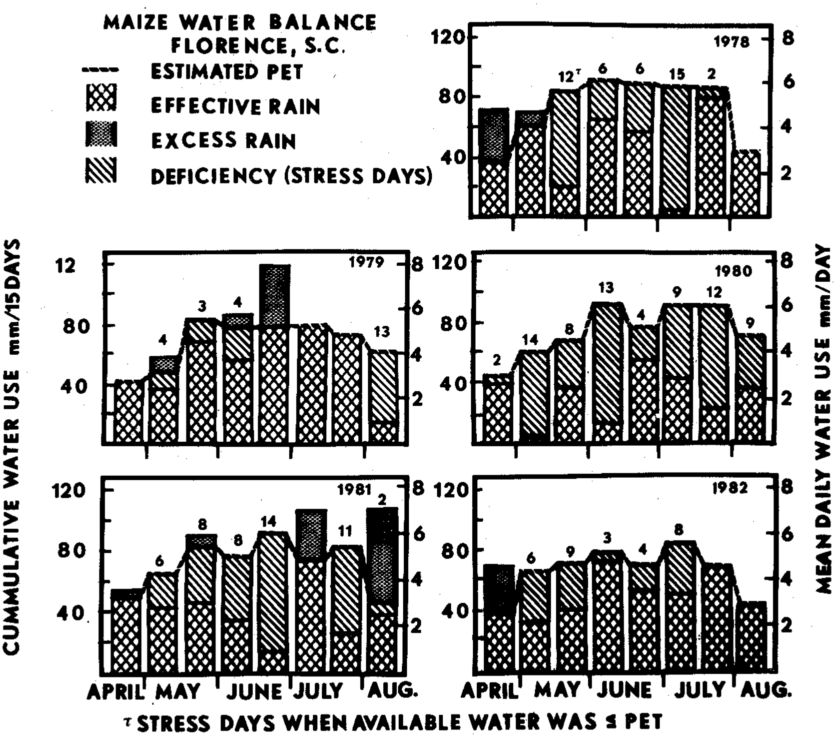

Fig. 2. Seasonal water balances for maize production during 1978 to 1982 near Florence, SC.

44 m^2 sub-plots were hand-weeded. Grain yield was measured with a combine by harvesting 4 0.15-ha sections from the HL strips and from each population within the DE strips. Average yields for DE at 5.2 plants m^{-2}, DE at 3.8 plants m^{-2}, and HL at 3.8 plants m^{-2} were 8.0, 7.3 and 6.2 Mg ha^{-1}, respectively. At $P \leqslant 0.10$, all 3 means were significantly different. In subplots thinned to a population of 3.8 plants m^{-2}, the non-weeded HL treatment yielded 6.6 Mg ha^{-1} which was significantly lower ($P \leqslant 0.10$) than the 8.1 and 7.9 Mg ha^{-1} yields from the weeded DE and HL treatments, respectively. Subsequent orthogonal comparisons using that data showed that weed competition and plant density both contributed to lower maize yields in 1978 where conservation tillage (HL) was used.

Data from the 1978 experiment also shows that seasonal water balance (Fig. 2) influences maize growth and development in this physiographic region. Plant height measurements 26–40 DAE showed an average daily growth rate of 1.2 cm/day. During this period, there were approximately 12 stress days in which potential evapotranspiration (PET) could not be supplied by available water from the effective root zone. In contrast, during the first 25 DAE when rainfall was adequate, average daily growth was 3.4 cm/day.

To quantify some of the soil physical conditions in this first experiment, 4 pits (3 m long, 1 m wide and 1 m deep) were excavated in both the DE

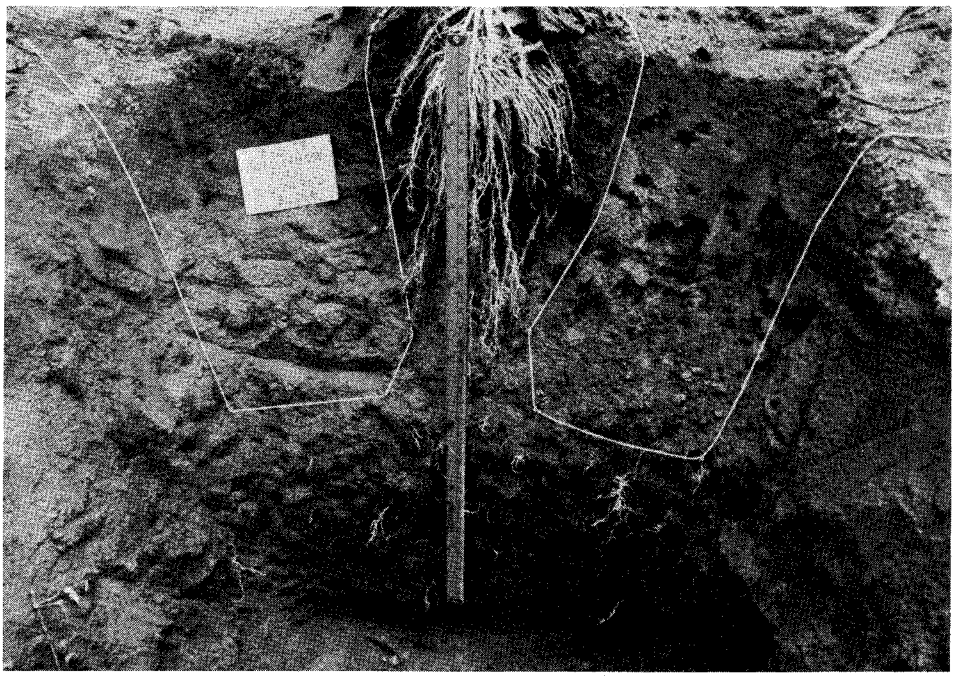

Fig. 3. Rooting characteristics of maize planted with in-row sub-soiling on a Norfolk sandy loam at Site A.

and HL strips at Site A. This showed that maize root growth was confined to the disturbed portion or subsoiled areas (Fig. 3). This restricted rooting was caused by high bulk density and soil strength (Table II) which in these soils are proportional to soil water and vary with horizon (Campbell et al., 1974). Also, those observations were characteristic of coastal plain soils, especially when water is limited (Doty et al., 1975).

TABLE II

Physical properties of 2 Norfolk loamy sand pedons and their effects on plant available water

Site	Horizon	Depth (cm)	Bulk density ($Mg\ m^{-3}$)	Water content (cm^3/cm^3) at selected pressures (kPa)			Plant available water	
				−5	−100	−1500	Unrestricted[a] rooting (cm)	Restricted[b] rooting (cm)
A	Ap	0-17	1.50	0.210	0.075	0.019	2.30	2.30
A	E	18-35	1.78	0.148	0.075	0.016	1.31	0.41
A	Bt	36-100	1.48	0.276	0.198	0.098	4.99	4.22
B	Ap	0-23	1.54	0.215	0.075	0.022	3.22	3.22
B	E	24-44	1.82	0.180	0.105	0.022	1.58	1.05
B	Bt	45-76	1.60	0.325	0.260	0.105	2.08	1.77

[a]Quantity of plant available water between −5 and −100 kPa if soil strength does not limit root exploration.
[b]Quantity of plant available water if soil strength limits extraction to between −5 and −100 kPa in the Ap, −5 and −20 kPa in the E, and −5 to −70 kPa in the Bt horizons, respectively.

Interactions between soil strength and matric potential are accentuated in US-SCP soils because high sand and low organic matter contents result in a low volume of plant available water. Data in Table II show that imposing soil strength limitations on effective rooting volume can further reduce plant available water by 12 to 19%. That relationship emphasizes the importance of deep tillage such as in-row subsoiling so that available water retained in the Bt horizon can be utilized. Failure to disrupt tillage pans or compacted genetic (E) horizons can severely limit crop yield potential of US-SCP soils (Campbell et al., 1974; Trouse, 1983).

Experiment No. 2 — cross-row subsoiling evaluations

Following grain harvest at Site A in 1978, maize stover was incorporated by disking. A cross-row subsoiling experiment was then initiated because of the restricted rooting that was observed in the previous maize crop. Three treatments (non-subsoiled, cross-subsoiled every 48 cm, and cross-subsoiled every 96 cm) were imposed during autumn of 1978 when the soil profile was relatively dry. Winter rye (*Secale cereale* L.) was then broadcast over the entire 7.5 ha field and grazed through February of 1979. Biomass samples collected approximately 30 days later showed an average production of 1.7, 2.0 and 2.5 Mg ha^{-1} for the 3 treatments, respectively. Lower yields for the 48 cm cross-subsoiled treatment were caused by a less uniform stand in those areas. Gravimetric measurements showed increased water extraction by the rye from the Bt horizon in cross-subsoiled areas, but this did not stress the subsequent maize crop because winter rainfall was above normal.

In late March of 1979, four 3.8-ha strips of the rye cover crop were incorporated by disking to establish the DL tillage treatment. The remaining cover crop was untouched prior to planting which established the HL treatment. Both tillage systems were imposed perpendicular to the strips that were previously cross-subsoiled. Hybrid maize was planted at 8.0 kernels m^{-2}. Approximately 20 DAE, stand density averaged 7.6 plants m^{-2} and was not significantly different for the DL and HL treatments. However, periodic observations during the growing season indicated that in the HL strips there was preferential feeding on maize seedlings by raccoons, field mice, rabbits, and birds (data not presented). There was also greater damage by corn-ear worm (*Heliothis zea*) in those areas. Therefore, at physiological maturity, stand density was significantly different at $P \leqslant 0.05$, averaging 6.7 and 5.7 plants m^{-2}, respectively. This difference in stand density appeared to cause the difference ($P \leqslant 0.05$) in grain yields, which averaged 6.5 and 5.4 Mg ha^{-1} for the DL and HL treatments, respectively.

The 1979 water balance (Fig. 2) shows 3 limited periods of early-season water stress, but in general rainfall was adequate for non-irrigated maize production. Tensiometer data (not presented) showed water extraction to a depth of approximately 100 cm for both tillage systems. They also showed soil-water tension was greater in DL strips than in HL strips which was probably caused by plant population differences during grain fill, although differences in evaporation or infiltration could have also been involved.

Cross-subsoiling significantly increased maize grain yield ($P \leqslant 0.05$) for both tillage systems, but there was no difference between the 48- and 96-cm treatment. Increased rooting volume and thus plant available water was presumably responsible. Cross-row subsoiling in autumn was beneficial to both the winter cover crop and subsequent maize crop, but several factors need careful consideration before implementing this practice. These factors include: severity of soil compaction; soil-water content and thus potential for effective profile shattering; tendency and rate of natural recompaction; the net energy cost/profit ratio associated with the crops to be grown. These factors vary with soil type and physiographic region, and therefore, should be carefully evaluated before making generalized recommendations for this practice.

Experiments 3—8 — plot-scale evaluation of surface residue effects

The production-scale experiments raised many questions about surface residue effects on maize growth, development and yield when conservation tillage systems were used in the US-SCP. Therefore, in 1980, 1981 and

1982, 3 plot-scale evaluations of the ST, DP and RR tillage systems (Fig. 1) were made for maize grown with and without supplemental irrigation at Site B. Five other tillage systems (DE, DL, HE, HL and CS) were evaluated without irrigation on similar Norfolk soils at Sites C and D (Table I). In non-irrigated experiments, water stress was severe in 1980 and 1981 (Fig. 2) because rainfall amounts were not sufficient to meet the water requirements for maize. Those seasonal rainfall deficits not only limited maize yield of all treatments, but also accentuated effects the various tillage systems had on the early-season soil-water content.

Tillage system significantly influenced profile water content in these experiments. With an average of 4.0 plants m^{-2} in 1980, early-season water stress (Fig. 2) significantly reduced plant growth (Table III) and ultimately grain yield at Site C. Similar water stress was measured at that site in 1981 and is reflected in measurements of profile water content and plant growth (Table III). At Site D in 1981, significant growth and yield responses were also measured (Table IV). Early-season soil-water content (Fig. 4) was highly correlated with those responses and was also proportional to the amount of actively-transpiring vegetation on the soil surface.

TABLE III

Effects of tillage system on early-season plant growth, profile soil-water content and yield of maize in 1980 and 1981 non-irrigated experiments at Site C

Tillage system	1980		1981							
	Plant[a] height (cm)	Grain yield (Mg ha^{-1})	Profile water content (%w)[b] at depth (cm)					Plant height (cm) after planting (days)		
			0–15	15–30	30–45	45–60	Mean	29	36	53
DE	110a	6.40a*	6.75	6.88	7.42	10.92	7.99a	31a	54a	230a
HE	96b	6.40a	6.20	6.28	6.89	10.32	7.42a	31a	54a	229a
DL	95b	5.77b	4.44	5.27	5.94	10.18	6.46b	24b	45b	212b
HL	84c	5.96b	4.32	5.27	6.30	9.86	6.44b	24b	44b	214b

[a]Measurements 40 days after planting.
[b]Measurements 15 days after planting.
*Means within a column followed by the same letter are not significantly different at $P \leq 0.05$.

Data presented in Fig. 4 show that because winter rainfall was low, there was an additional 3.8 cm of available water in the upper 60 cm of soil where the DP tillage system was used compared to where the HL system was used. This difference in early-season soil-water content slowed plant growth, development, and ultimately reduced grain yield by 1.3 Mg ha^{-1} in the HL treatment. The greatest soil-water depletion occurred where tillage system CS-B was utilized. This system allowed rye to grow between maize rows, and therefore, 15 days after planting, there was 5.8 cm less available water than in the DP treatment. As a result of this water deficit, plant growth (Table IV) and yield were lowest for the CS-B tillage system. These data

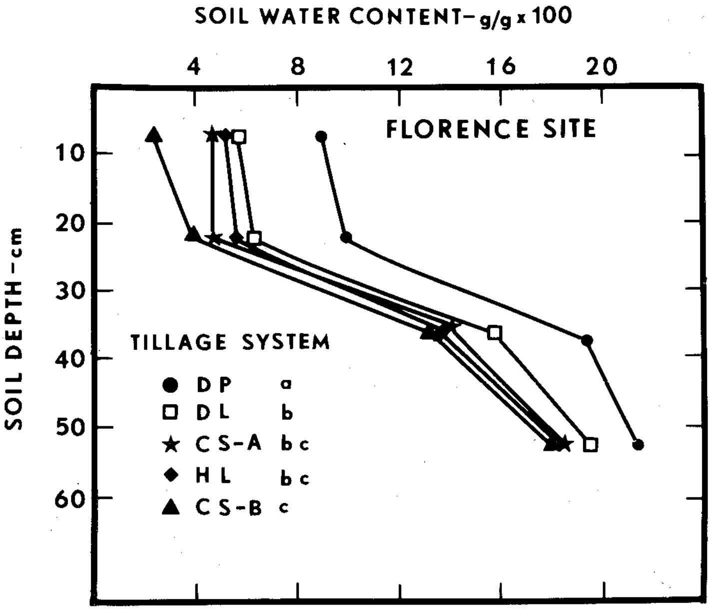

Fig. 4. Soil-water content 15 days after planting maize into various surface soil conditions. (Treatment symbols followed by the same letter were not significantly different at $P \leq 0.05$.)

TABLE IV

Tillage system effects on early-season growth and yield of maize at Site D in 1981

Tillage system	Plant[a] height (cm)	Grain-yield (Mg ha^{-1})
DP	214a*	6.92a
DL	179b	6.16a, b
HL	168b, c	5.66b
CS-A	163b, c	5.53b
CS-B	153c	4.40c

[a]Measurements made 60 days after planting.
*Means within a column followed by the same letter are not significantly different at $P \leq 0.05$.

show the importance of quickly killing cover crops or weeds on these soils, because even after systemic herbicides are applied, transpiration declines only gradually and can continue to significantly reduce available soil water if rainfall does not occur.

Surface roughness and stand establishment were also influenced by tillage system. Data from 1980 at Site B (Table V) show that planting into 1-m tall rye (HL system) resulted in the greatest surface roughness and lowest plant density. Plant spacings were also less uniform in HL plots (D.L. Karlen, unpublished observations, 1980), but grain yields were not significantly different. Mechanical removal of the cover crop (RR treatments) provided a better seedbed which was similar to HE treatments in other studies and caused less problems with stand establishment.

TABLE V

Tillage system effects on plant density, midseason surface roughness, and maize yields at Site B in 1980

Tillage system	Surface residue at planting ($Mg\ ha^{-1}$)	Population (plants m^{-2})	Midseason surface roughness SD (cm)[a]	Grain-yield ($Mg\ ha^{-1}$)
DE	—	5.6	2.01	7.09
HL	2.71	3.7	3.79	6.53
RR-66%	1.75	4.6	2.28	6.56
RR-90%	1.46	4.8	2.33	6.84
LSD (0.05)	0.34	0.6	0.15	NS

[a]Standard deviation from the mean distance between the soil surface and a plane 1 m in height, measured across 3 maize rows or a linear distance of 3.5 m.

Results of these plot-scale evaluations emphasize the need to prevent weeds or cover crops from depleting available soil water before the maize is established. This can be accomplished by early application of herbicide, animal grazing, or mechanical harvesting. If quantities of surface residue are well-managed, beneficial aspects of increased surface roughness such as decreased runoff and increased infiltration can be preserved by using conservation tillage techniques in the US-SCP. Utilizing irrigation water can minimize soil-water related problems provided plant density and spacing are adequate. For non-irrigated maize production on these soils, measuring the amount and effectiveness of spring rainfall and knowing the available soil-water status are essential for acceptable conservation tillage maize production.

Experiments 9 and 10 — nitrogen studies

Plot-scale N rate experiments were conducted at Sites A and B in 1979 and at Site B in 1980. Anhydrous ammonia (NH_3) was used as the N source to prevent volatilization losses which can occur when ammonium or urea N sources are placed in contact with plant residues, on the soil surface, or when exposed to the atmosphere (Terman, 1979). Response curves for maize grown using clean tillage (DP) and conservation tillage (HL and RR) are shown in Fig. 5. Water exerted a large influence on N response,

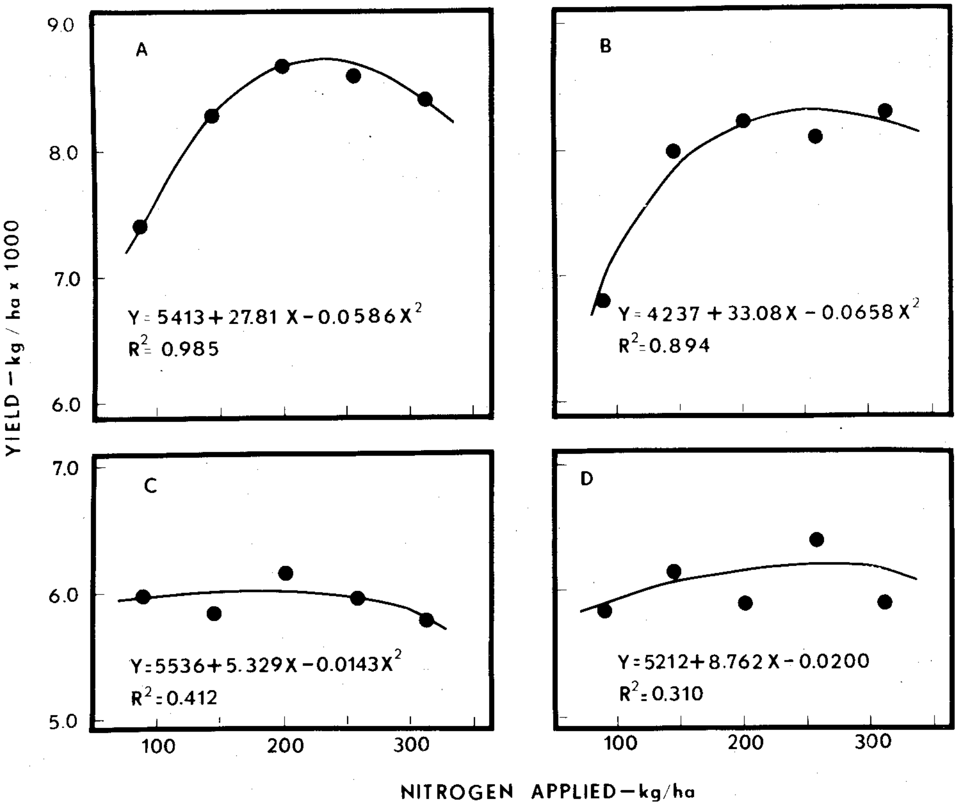

Fig. 5. Maize yield responses to N rates with conventional (A and C) or conservation (B and D) tillage and adequate (A and B) or limited (C and D) seasonal water regimes.

therefore, data were pooled for regression analyses according to tillage system and water availability. This technique provided 36, 76, 5 or 15 observations for each mean plotted in Figs. 5a–d, respectively. When rainfall or irrigation met the evapotranspirational demand, yields increased regardless of tillage system until total N application exceeded 200 kg ha^{-1}. However, when water was very limited, there was essentially no response to N rates.

Response curves in these experiments were similar to those reported by Langdale et al. (1981). Yields at low N rates, where crop residues were left on the soil surface, were slightly lower than where crop residues had been incorporated. These lower yields were probably not caused by volatilization losses because the NH_3 was injected at a depth of approximately 20 cm. Thomas et al. (1973) have suggested N may be subject to loss by leaching or denitrification although sub-surface placement of N has been shown to be the most efficient method of side-dressing no-till maize by Fox and Hoffman (1981) and Touchton and Hargrove (1982). Our data support those findings and agree with conclusions by Mengle et al. (1982) that injected NH_3 is an acceptable method for side-dressing no-till maize.

However, injection of NH_3 was not without problems because surface residues often accumulated between shanks if plot lengths exceeded 30 m. Accumulating surface residues subsequently broke some plants at the soil surface and also interfered with closing the N-injection slit. To minimize those problems, NH_3 applicators should have a cutting coulter and also some type of covering disks where substantial amounts of crop residues remain on the soil surface. Coulters will insure that trash does not prevent proper injection depth or cause mechanical damage to plants. Disks would insure that the injection slits are properly sealed and that NH_3 volatilization losses are minimal.

In 1979, injected urea ammonium nitrate (UAN) solution, NH_4NO_3, and NH_3 placed on both sides of the maize row (48-cm spacings) were also compared as methods of side-dressing maize. The N-rate response curves were essentially the same as those reported for NH_3 injected between rows on 96-cm spacings. NH_3 injection every 96 cm, NH_3 injection every 48 cm, UAN injection every 96 cm and broadcast NH_4NO_3 produced mean yields of 7.72, 7.47, 8.29 and 7.79 Mg ha^{-1}, respectively, and an LSD at $P \leqslant 0.05$ of 0.44 Mg ha^{-1}. This indicated that injecting NH_3 within 24 cm of the row may have caused root pruning and thereby reduced the grain yields. The reason for the positive response to injected UAN is unknown, although it may have been related to the rate of nitrification (Tomasiewicz and Henry, 1982) or to the need for N to "move" to the plant roots because soil strength limited inter-row root penetration. These limited data indicate that further investigations are needed to determine optimum placement and sources of side-dress N for conservation tillage production of maize in the US-SCP.

Maize leaves were collected from opposite and below the primary ear at silking and chemically analyzed to assess the plant nutrient status in these experiments. When water was adequate and total N application was greater than 90 kg ha^{-1}, N concentrations averaged 3.2% regardless of tillage system. Concentrations of P, K, Ca, Mg, Mn and Zn averaged 0.29%, 2.55%, 0.36%, 0.16%, 47 ppm and 34 ppm, respectively. These nutrients were not significantly changed by tillage system or N fertilization rate. Langdale et al. (1981) identified B as a potential-limiting plant nutrient in their conservation tillage N experiments. Without B fertilization, leaf analyses averaged 2.3 ppm B, emphasizing the need to apply this nutrient annually where rainfall or irrigation is sufficient to leach B from the root zone. All other plant nutrient concentrations were within the sufficiency ranges reported by Jones and Eck (1973).

Tillage—water relationship summary

The importance of water conservation for maize production in the US-SCP was evident in all non-irrigated tillage experiments. Estimated seasonal

PET (Table VI) shows that there were stressed and unstressed periods each year although no interval of water stress was severe enough to kill the maize plants. Stress periods calculated from PET or by summing stress days from Fig. 1 were equally effective in identifying periods of plant water stress.

TABLE VI

Estimated potential evapotranspiration (PET) for maize and relative stressed and non-stressed periods occurring in each of 5 growing seasons

Year	Calculated (mm)	PET (%)	Unstressed period		Stressed period[a]		Drought days[b]	
			mm	%	mm	%	days	%
1978	579	100	370	64	209	36	41	34
1979	533	100	436	82	97	18	24	20
1980	593	100	247	42	346	58	71	58
1981	564	100	321	57	242	43	49	40
1982	517	100	394	76	122	23	30	25
Mean	557	100	354	64	203	36	43	35

[a]Computed from water deficit/calculated PET.
[b]Summation of stress days from Fig. 1.

Effects of tillage system and water management on maize yield at Site B are summarized in Table VII. Utilizing conservation tillage on that well-drained Norfolk soil significantly increased non-irrigated grain yields in 1981 and numerically increased them in 1980. However, when water was

TABLE VII

Maize yield as influenced by tillage system and water management at Site B from 1979 through 1982

Year	Tillage system			
	Conventional ($Mg\ ha^{-1}$)		Conservation ($Mg\ ha^{-1}$)	
	Irrigated	Non-irrigated	Irrigated	Non-irrigated
1979	—	—	9.86a*	8.23b
1980	8.26a	5.93c	6.93b	6.13c
1981	10.69a	5.89c	10.47a	8.11b
1982	11.34a	10.62b	10.82a, b	9.83c

*Yield values within any one year (row) followed by the same letter are not significantly different at $P \leq 0.05$.

not the most limiting production factor, maize yields under conservation tillage were lower than maize yields produced using conventional tillage.

Tensiometers were used to monitor soil-water tension at Site B. Analyses of 1981 and 1982 data (not presented) showed that profile soil-water content from tasseling through physiological maturity was generally greater where residues were left on the soil surface than where residues were incorporated. Those data indicated that infiltration was greater and evaporation lower where conservation tillage was used and agree with findings of Jones et al. (1969), Blevins et al. (1971), Gallaher (1977) and Phillips et al. (1980).

Hill and Blevins (1973) reported that effective rain plus seasonal changes in soil-water storage accounted for 40.8, 26.2 and 45.0 cm of water and produced average yields of 8.25, 5.93 and 10.32 Mg ha^{-1} in 1969, 1970 and 1971, respectively. Their results show an average of 219 kg ha^{-1} of grain for each cm of available water. Estimated water use in our studies show an average of 201 kg ha^{-1} of grain for every cm of water used between planting and harvest.

Finally, water will increase yield during anthesis and early earfill at a higher rate, but on a seasonal basis, 1 cm of available water will produce approximately 200 kg ha^{-1} of grain. Therefore, excluding runoff and deep percolation, production of 10 Mg ha^{-1} of grain would require 50 cm of plant available water during the growing season in this physiographic region. Due to low soil-water retention and poor root penetration in US-SCP soils, any tillage/production system which provides less water will probably result in proportionally lower maize yields, despite high annual rainfall.

CONCLUSIONS

Interpretation of these experiments is not intended to disclaim benefits associated with conservation tillage for maize production, but to show that on the well-drained soils of the US-SCP, a higher level of management is required to produce maize yields which are equal to those produced using conventional tillage.

These experiments have shown that an interaction between seasonal water balance and crop residue management practice determines the ultimate success of conservation tillage maize production. Water conservation aspects of plant residue on the soil surface were confirmed, but when early-season rainfall was limited, water extraction by a cover crop or winter weeds reduced the early-season growth, vigor, and yield of maize under conservation tillage. Yield reductions occurred because soil-water and soil-strength interactions in these soils are physical relationships which greatly influence yield of maize. Rooting volumes are reduced because soil strength increases when drought, weeds, or a competing cover crop limit available soil water. This restricted rooting reduces soil-water and plant-nutrient availability, which slows plant growth and limits potential maize yields.

The importance of achieving a uniform plant stand was confirmed. Results show that when maize is subsoil-planted into surface residues, there are many factors including soil-seed contact and pests which may decrease stand and reduce potential yield. Fall subsoiling increased winter forage and maize yield, but before implementing this as a production practice, detailed economic, energy use, soil and other site-specific analyses should be made.

Water availability was the predominant factor influencing the N response in these experiments. When water was adequate, conventional tillage resulted in greater yields at lower levels of N, but when approximately 200 kg ha^{-1} of N was applied, maximum yields occurred regardless of tillage system. Anhydrous ammonia was an acceptable N source, but care must be taken to close the injection slit when applying it where heavy surface residues are present. Nutrient analyses of ear leaves showed that supplemental B was needed, but other nutrient concentrations were within acceptable ranges regardless of tillage system.

When irrigation was used to prevent water stress in the maize crop, yields under conventional tillage production were always numerically greater than under conservation tillage production. When limited water was a factor, yields produced under conservation tillage were significantly greater in 1981 and numerically greater in 1980. However, in all other non-irrigated experiments, conservation-tillage maize yields were lower than conventional tillage yields.

Conservation tillage did conserve water. However, in the absence of slope-related problems and when water deficits at anthesis or grain-fill were not limiting production, a summation of other yield losses associated with the more critical management made conservation tillage of maize less successful than conventional tillage. These findings should emphasize the importance of refining management practices until the conservation merits are uniformly evident in final yields.

ACKNOWLEDGEMENT

This paper is a contribution of the Coastal Plains Soil and Water Conservation Research Center, USDA-ARS, Florence, SC, in cooperation with the South Carolina Agricultural Experiment Station, Clemson, SC, U.S.A.

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