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HYDROLOGIC ASPECTS OF NO-TILLAGE VERSUS CONVENTIONAL TILLAGE SYSTEMS FOR CORN PRODUCTION

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PREFACE

The hydrologic aspect of crop growth concerns the capacity of a crop-soil system to utilize available moisture for plant growth and production. The basic parameters which describe this characteristic include soil moisture, precipitation, runoff, temperature, radiation, and evaporation. The no-tillage method of crop production, i.e., planting the crop directly into the existing residue with no prior mechanical seedbed preparation, was developed with the intent of reducing the amount of tillage required and improving the hydrologic characteristics of the system.

This research consisted of a two-year study of the hydrologic aspects of the no-tillage system of corn production compared with the conventional tillage procedures. Particular emphasis was placed on available soil moisture, water use efficiency, plant growth, and crop yields. The results obtained clearly demonstrated the superiority of the no-tillage method, with the conclusion that this method utilized more of the available water for plant production by reducing runoff and evaporation, thus providing a more favorable root zone environment for plant development.

The increased crop yields obtained with the no-tillage method is a major benefit in row crop production. By reducing the rate of evaporation, runoff, and soil erosion, this method minimizes the effects of short, frequent drought periods through more efficient use of soil moisture over longer periods of time.

As an extension to the experimental processes studied, a soil-moisture prediction model is being developed to mathematically similate the hydrologic preformance of an area. This model, in its completed form, should provide a means to study varied soil and climatic conditions, thus predicting crop yields for a specific region.

William R. Walker
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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

HYDROLOGIC ASPECTS OF NO-TILLAGE VERSUS CONVENTIONAL TILLAGE SYSTEMS FOR CORN PRODUCTION

Introduction

For many years one of the goals of tillage research at Virginia Polytechnic Institute has been to develop a system which (a) reduces the amount of tillage required, (b) maintains an open soil structure conducive to good rainfall intake and storage, and (c) makes more beneficial use of the residues of preceding crops for minimizing evaporation, soil erosion and runoff losses. From these investigations evolved the no-tillage system. With this system the crop is planted directly into a chemically killed sod or crop residue with no prior mechanical seedbed preparation, thereby utilizing vegetation from the preceding crop for surface mulch.

The no-tillage system concept was initiated at V.P.I. in 1960. Initial experiments were encouraging, however, many difficulties relating to the control of preceding vegetation, control of regrowth, and planting techniques required basic research before the practice could be implemented or full scale field testing or experimentation made. In general, better crop yields and more vigorous growth were observed. It was assumed that these advantages were for the most part related to the improved hydrologic performance of the area, and were attributable to the no-tillage system. Therefore, the measurement of soil moisture, preciptiation, runoff, temperature, radiation and evaporation should indicate the critical parameters. However, it was recognized that other factors relating to plant physiology, rootbed environment, disease and insect problems could affect the yields, but these under optimum management normally would not be of comparable importance. To aid this assumption extreme care was employed in site selections and in the maintenance of uniform fertility conditions and management procedures.

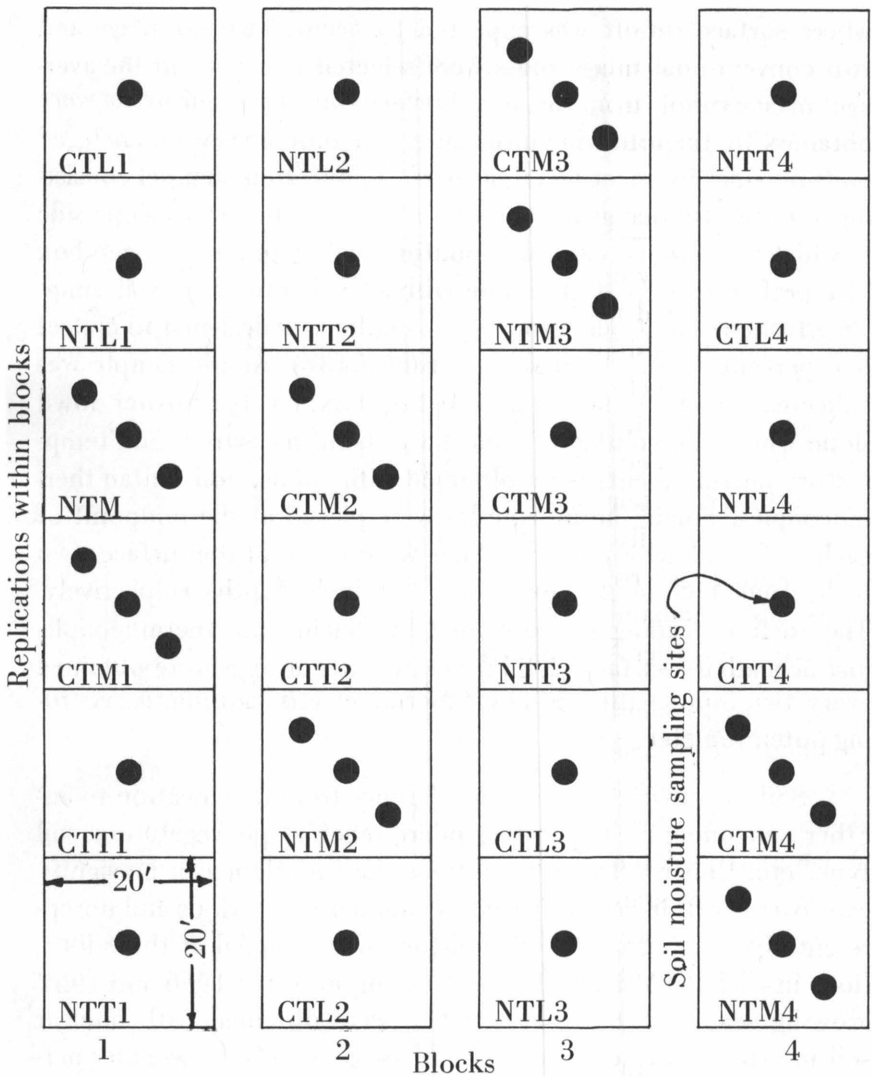
This report presents the results of a two year study of the hydrologic aspects of the no-tillage system. Data are presented on available soil moisture, water use efficiency, plant growth, and crop yields. Finally, a soil moisture prediction model is presented. The application of this model for studying the hydrologic aspects of the no-tillage system under a wide range of simulated climatic experiences will be reported at a later date.

Experimental Procedure

Two radically different row crop tillage systems, conventional (clean) tillage, and no-tillage were studied. In the conventional tillage system the residue of the preceding crop was turnplowed to a depth of seven inches with a standard moldboard plow. The seedbed was prepared by two discings with a standard tractor mounted disc. Chemical weed control was used in lieu of crop cultivation. In the no-tillage system, the residue (grass sod) from the preceding crop was chemically killed. The corn crop was planted with a tractor mounted two row planter that was specially designed to create a desirable seedzone environment during the planting operation without any other soil disturbance.

The experimental area was laid out according to a randomized complete block design that consisted of four blocks with the two treatment variables replicated, three times within each block (see Figure 1). The three within reps were used for (a) monitoring soil moisture, (b) soil temperature measurements, and (c) plant growth, dry matter and grain yeild determinations and for laboratory analyses. The plots were located on groseclose silt loam soil, gently sloping phase. An excellent orchard grass sod cover existed in both years

Instrumentation was provided to measure precipitation, air temperature, relative humidity, pan evaporation, total wind speed, and soil temperature during 1966. Net radiation and runoff measurements were added in 1967. Runoff installations were not installed in 1966 because the experimental area was located on very slight slopes. Past experience concerning the hydrologic aspects of this same area have shown that surface runoff will not occur except when the area is subjected to very high intensity storms. The experimental layout for 1967 was located on a gently sloping area



CTL - Conventional Tillage	NTL - No Tillage	(Laboratory)
CTM - ” ”	NTM - ” ”	(Moisture)
CTT - ” ”	NTT - ” ”	(Temperature)

Figure 1. Schematic Illustration of the Experimental Plot Design for the Study of the Hydrologic Aspects of No-Tillage Versus Conventional Tillage Corn Production.

where surface runoff was expected to occur. Two no-tillage and two conventional tillage plots were selected to represent the average surface runoff from the area. Surface runoff measurments were obtained by the following procedure. The plot areas were enclosed on three sides by sheet metal borders. A collection channel consisting of flat-bottomed guttering was imbeded on the down-slope side to which was connected down spouting leading to an approach box of a prefabricated H-type flume with a Cochocton type soil sampler attached. The Cochocton type sampler was designed to collect one percent of the total surface runoff (34). As the sample was collected, it was routed to a collection box, located further down slope where the volume of runoff was hand measured. Soil temperature measurements were obtained with copper-constantan thermocouples. Single thermocouples were placed at the midpoint of each NTT and CTT plot. Readings were taken at the surface, two inch, four inch, eight inch, and 20 inch depths respectively. The surface reading was obtained by placing the thermocouple just beneath the surface (1/8 in.-1/4 in.). Recordings were obtained every two hours with a 40-point thermo-electric automatic recording potentiometer.

Soil moisture can vary considerably from one location to another depending on the surface micro-relief, slope, vegetation, soil type, etc. Under extreme conditions the variations can be significant over short distances. To aid in eliminating spurious and unrepresentative readings the soil moisture was sampled at three locations in each NTM and CTM plot during both the 1966 and 1967 growing seasons. The measurements were obtained with nuclear soil moisture monitoring equipment twice weekly, as weather permitted, at the surface, 12 inch, 18 inch, 24 inch, 36 inch, and 48 inch depths.

In 1967, the experimental layout extended over a much larger area posing the potential problem of considerable plot-to-plot variation in the moisutre content due to variations in slope and surface micro-relief. As a consequence, additional measurements were made once weekly at one location in all NTL, NTT, CTL, and CTT plots. These data were simply to provide a guide as to actual overall plot variation and to substantiate the results obtained from the basic moisture sampling program. To further characterize the moisture variability over the 20 ft. by 20 ft. plots, moisture measurements were obtained once weekly at 12 locations within one CTM plot and one NTM plot.

Soil samples were obtained from each plot and analyzed for fertility level and lime requirements. Subsequent fertilizer and lime applications were based on these tests. Soil samples were secured also from which moisture tension curves were developed by laboratory techniques. The moisture tension curves were required to determine plant available moisture, which for this study was defined as the water held between 1/3 and 15 atmospheres of tension Average moisture tension curves were developed for both the 1966 and 1967 experimental areas. As may be noted from Table 1, these values were quite similar indicating that there were no significant soil type differences in the two areas.

Measurements of plant growth were carried out sporadically during 1966. During the 1967 growing season detailed plant height measurements were obtained weekly beginning June 30. Forty plants selected from four rows were used to determine the average plant height per plot. The following procedure was used in plant selection and height measurements.

a. The four center rows were used in all plots.

b. A distance of one, two, three, or four feet was determined randomly and this distance measured from the edge of the plot for the four rows in a.

c. The leaf extended height was measured for the first 10 plants from the point found in b.

Grain, stover, and cob yields were obtained by sampling a 10 foot section from the four middle rows on each plot. Grain yields were obtained in both 1966 and 1967. Stover and cob yields were determined for the 1967 data.

Table 1. Percentage Soil Moisture by Volume for Indicated Depth and Tension.

Year	Plot	Depth (in.)	1/3 Atm	1Atm	2Atm	4Atm	6Atm	15Atm
1966	NTM	0-6	35.39	24.58	17.79	13.06	10.75	8.55
		6-15	37.65	28.23	22.48	18.64	16.22	13.21
		15-21	44.25	34.92	30.59	27.31	24.81	21.18
		21-30	46.53	37.31	32.84	30.40	27.21	24.49
		30-	42.43	35.52	32.18	30.05	27.19	24.50
	CTM	0-6	31.36	21.48	15.85	11.85	9.80	7.02
		6-15	40.93	29.14	23.75	19.43	17.07	14.64
		15-21	47.87	38.00	33.09	29.63	27.08	24.36
		21-30	50.52	41.51	37.35	34.49	31.88	29.13
		30-	47.17	39.29	35.82	33.19	30.41	27.67
1967	NTM	0-6	30.08	22.78	17.79	12.22	10.15	7.27
		6-15	28.54	23.26	19.31	15.13	13.01	10.34
		15-21	33.13	30.53	26.94	24.35	21.86	19.05
		21-30	44.38	38.78	35.28	32.82	30.28	27.91
		30-	47.99	40.90	37.60	35.04	32.36	30.13
	CTM	0-6	29.13	22.29	17.76	13;27	10.48	7.65
		6-15	31.94	24.62	20.61	16.52	14.35	11.80
		15-21	38.17	31.78	28.69	24.78	23.00	20.38
		21-30	43.20	36.12	33.09	29.78	27.86	25.00
		30-	44.77	37.31	34.39	31.50	29.26	26.38

Table 2. Surface Runoff from No-Tillage and Conventional Tillage Plots during the 1967 Growing Season.

Date[1/]	Surface runoff NTM1	NTM3	CTM1	CTM3
7-1	0.0396	0.0263	0.0288	0.0000
7-8	.0000	.0048	.0000	.0000
7-11	.0000	.0321	.2203	.2245
8-1	.0000	.0772	.2662	.2512
8-3	.0000	.0022	.0405	.0526
8-4	.0000	.0034	.0426	.0242
8-7	.0000	.0010	.0037	.0074
8-24	.0000	.0534	.0028	.2727
Total	.0396	.2089	.6049	.8326

1/ The data given is for the end of the runoff period.

Results

Available Soil Moisture

The soil moisture data at selected depths for the two tillage systems are compared in Figures 2 and 3 for growing seasons 1966 and 1967 along with daily precipitation. For the four months (120 days) following planting total rainfall was 12.40 inches and 12.43 inches for 1966 and 1967 respectively. Although the rainfall for both growing seasons was identical, inspection of Figures 2 and 3 will show that the seasonal distribution was dramatically different. In 1966 only 10 percent of the rainfall occurred during the first two months of the growing season while in 1967, 46 percent of the rainfall was recorded during the same period. The influence of these different rainfall distributions on the moisture content is clearly shown in Figures 2 and 3.

With the exception of early in the growing season (drought conditions), Figure 2 does not indicate much difference in the available moisture content for the two tillage systems. However, these curves (Figure 2) do portray several important factors which can influence the moisture relationship between the two tillage systems, namely prolonged drought and abundant rainfall. During periods of prolonged drought the available moisture in both systems will be depleted and crop damage certainly will result. Less damage may be expected on the no-tillage system because, as can be seen in Figure 2, moisture is available for plant use for a longer period.

With abundant rainfall, adequate recharge of the available moisture reservoir is possible under either system. Figure 2 certainly indicates that this indeed did happen during the latter part of the 1966 growing season. Rainfall was able to infiltrate into the moisture reservoir with the only significant losses being those due to evaporation of water intercepted by the plants because, the plots were on areas of very slight slope, the rainfall intensities were relatively low and the corn crop acted as a canopy over the area thereby absorbing much of the energy of the raindrops.

In contrast to the 1966 soil moisture data, significant differ-

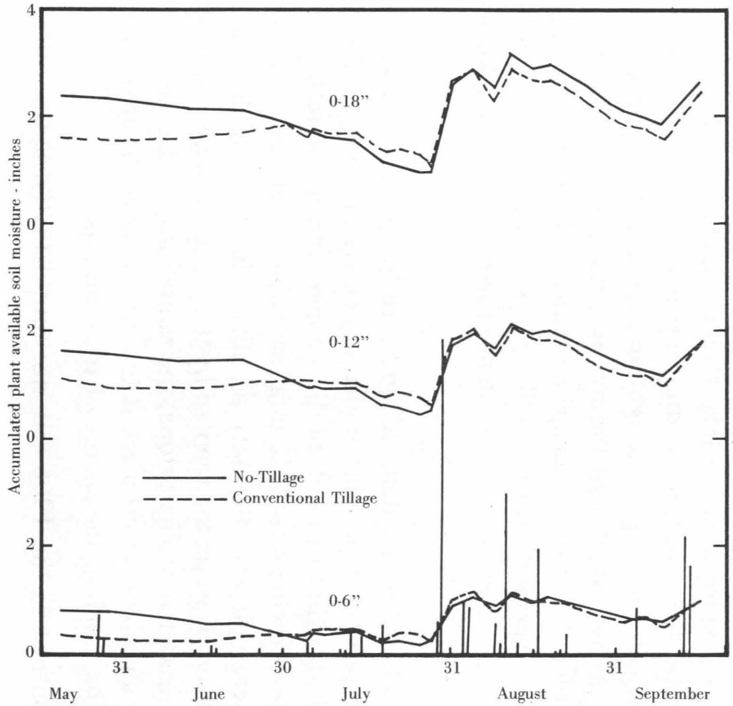


Figure 2. Influence of Tillage System on the Plant Available Soil Moisture at the 0-6", 0-12" and 0-18" Depths during the 1966 Growing Season.

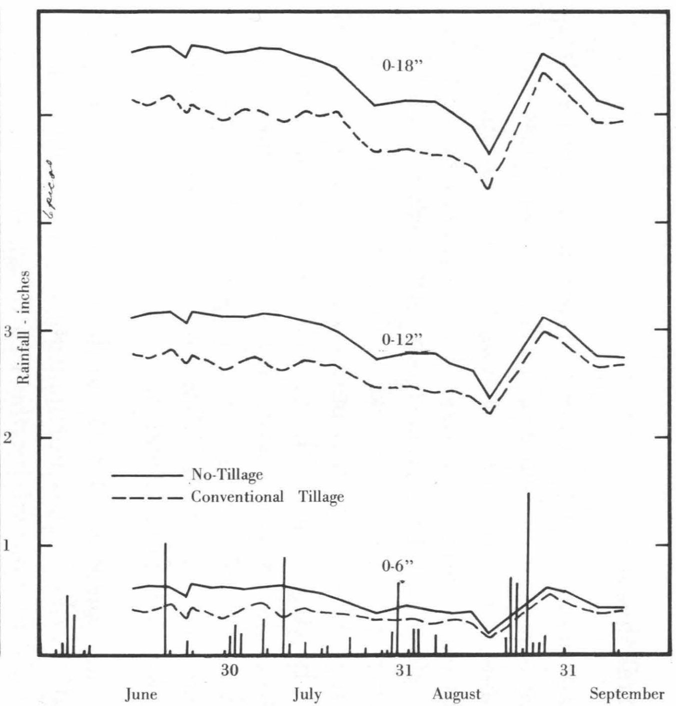


Figure 3. Influence of Tillage System on the Plant Available Soil Moisture at the 0-6", 0-12" and 0-18" Depths during the 1967 Growing Season.

ences are apparent in the 1967 data at the 0-6 inch, 0-12 inch, and 0-18 inch depths. These differences were the greatest during the early part of the growing season and decreased as the season progressed. Several factors interacted to cause this result. During the first weeks of the growing season when the soil is completely exposed on conventional clean tillage plots, evaporation is the dominate factor in moisture relationships. With the no-tillage system the mulch from the killed sod acts as an insulator, thereby greatly reducing evaporation losses. The more vigorous corn plant growth which occurred on the no-tillage system (Figure 4) resulted in the need for additional water. With greater withdrawals for plant development with the no-tillage system the moisture curves tend to merge.

Surface runoff also exerted an influence on the moisture relationship. Runoff data are given on Table 2. These data show that the runoff from the conventional tilled areas was, on the average, seven times greater than that observed from the no-tillage areas. This can account for part of the difference in moisture that appears in Figure 3, from July to the end of the growing season. There was one runoff-producing storm on June 18 that is not reported in Table 2 because instrumentation for the runoff measurements was not complete at that time. Results from other research in the general area in which measurements were obtained indicate that the same ratio was valid for that storm.

One of the most perplexing problems to the agriculturist in Virginia is the occurrence of short drought periods. These short, but frequent drought periods can be extremely damaging to a corn crop, particularly if they hit during the silking and tasseling stage. The occurrence and duration of these short drought events is a random or probabilistic phenomenon which is extremely difficult, if not impossible to predict. That these events do occur even with an excellent seasonal rainfall distribution is evidenced in Figure 2 (late June, mid-July and -August, early September). Since the occurrence and frequency of such events cannot be successfully predicted, the next best solution is a moisture conservation system by which moisture will be available for plant growth during these dry periods. An inspection of Figure 3 shows the additional soil moisture available during these short drought periods with the no-tillage system. This indicates its superior capability for eliminating or minimizing this problem

Statistical Analyses

Statistical analyses were made of all moisture data, to determine if significant differences in moisture existed between the two tillage systems. The total available moisture between the following depth intervals was used in analysis of variance computations: (a) 0-6 inches, (b) 6-15 inches, (c) 15-21 inches, (d) 21-30 inches, and (e) 30-42 inches. A typical analysis of variance breakdown is given in Table 3.

As would be expected from an inspection of Figure 2, the data for the 1966 season showed no statistically significant difference between the two treatments at the five percent level except for the 0-6 inch depth in the early part of the growing season. For the 1967 data (Figure 3), differences were significant at the one percent level at the 0-6 inch and 6-15 inch profiles respectively. No statistical significance at the five percent level could be detected for the remaining three intervals. The same statistical analysis was performed on the data collected from the NTL, NTT, CTT, and CTL plots. These analyses also showed that the moisture content in the no-tillage plots was significantly different at the five percent level for the 0-6 inch and 6-15 inch depths. This confirms that the data from the CTM and NTM plots were representative. Moisture variation across individual plots was studied using data collected from 12 locations per plot. The primary objective was to determine the number of sampling locations required to adequately represent the plot moisture content. A statistical evaluation of these data showed that a combination of three moisture readings randomly located within the plot give a good indication of the average moisture content at the 6 inch, 12 inch, 18 inch, and 24 inch depths.

Table 3. Analysis of Variance Breakdown for Soil Moisture Data collected during the 1966 and 1967 Growing Season.

Source of Variation	Degrees of freedom 1966	1967
Sampling date	25	22
Block	3	3
Treatments	1	1
Sampling date x block	75	63
Sampling date x treatments	25	21
Block x treatments	3	3
Sampling date x block x treatments	75	63
Within replicates	416	352
Total	623	527

Table 4. Total Dry Matter Yields for Corn grown on No-Tillage and Conventional Tillage Systems during 1967.

Treatment	Dry matter yields (lb./ac.)			
	Stover	Cobs	Grain	Total
No-tillage	4653.9	1109.2	5005.2	10768.6
Conventional tillage	3011.5	854.4	3655.0	7520.9

Table 5. Grain Yields for Corn grown on No-Tillage and Conventional Tillage Systems during 1966 and 1967. Yields based on 15.5% Moisture Content.

Treatment	Grain yields (bu./ac.)	
	1966	1967
No-tillage	108.28	97.45
Conventional tillage	83.87	71.00

At the 36 inch and 48 inch depths one sampling point was sufficient.

Water Use Efficiency

A partial explanation of why greater yields were produced on the no-tillage system in 1966 yet statistical evaluation of the moisture data indicated no difference may be found in analyzing the moisture required to produce dry matter. As previously mentioned the more vigorous growth on the no-tillage system requires additional water for support. Rhoades and Nelson (38) suggest that 400# water is required to produce 1# dry matter when the fertility level is high. The fertility level is extremely important, because corn grown in soils of low fertility may require an additional 150-170# of water to produce 1# dry matter. Detailed fertility analyses were made on the experimental plot area and these results showed that a high fertility level existed.

Estimates of water use efficiency for both tillage systems using Rhoades and Nelson's results accentuate the ability of the no-tillage system to better utilize the existing water supply for plant production. In the no-tillage system 19 inches of water were required to produce the corn crop, whereas in the conventional tillage system only 13.3 inches of the available water was utilized for corn crop production. Rainfall plus soil moisture storage provided a total of 23.5 inches of available water during the season. Based on this amount the water use efficiency for the no-tillage and conventional tillage systems was found to be 81 and 57 percent respectively. The difference between the two systems totaled 24 percent, which reflects vastly better moisture conservation and beneficial use with the no-tillage system. These advantages are attributed to the significantly less runoff and evaporation and to the generally more favorable physical root zone environment for superior plant development which this system provides.

Plant Growth and Yields

A graph depicting plant growth from June to September on the two tillage systems is given in Figure 4. A difference of four inches was recorded on June 30, followed by significantly larger

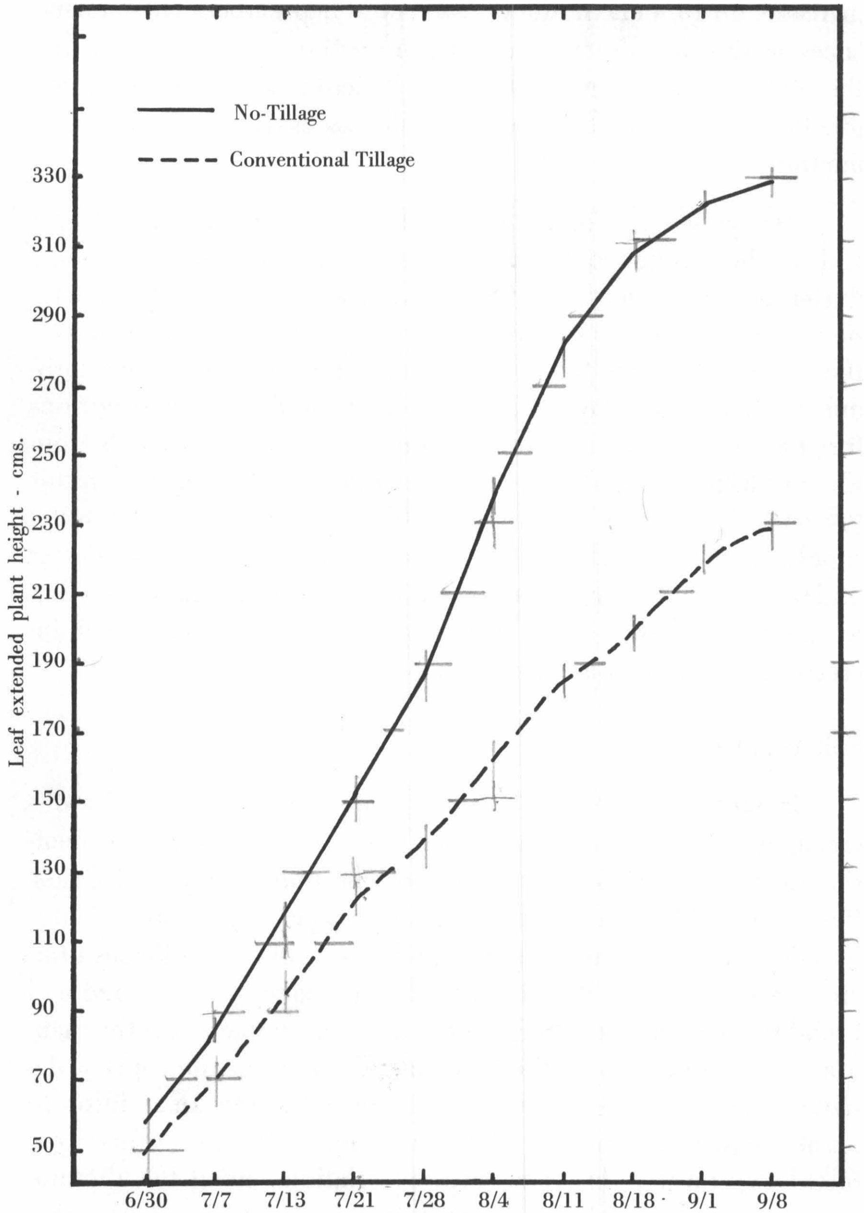


Figure 4. Growth of Corn on Conventional Tillage and No-Tillage plots during 1967 Growing Season.

increases up to a maximum of 2.5 feet in September. These differences were quiet dramatic and again portray visual evidence that the no-tillage system not only is an efficient moisture conservation practice but also greatly enhances water use efficiency in crop production.

The yield data for the two systems are compared in Tables 4 and 5. The difference in grain yields was approximately the same during both the 1966 and 1967 growing season. A complete analysis of dry matter was not available for the 1966 season. However, the 1967 data show that 43.1 percent more dry matter was produced on the no-tillage plots. Recalling the rainfall distributions for the two seasons, it is readily seen that the superior yields from the no-tillage system during two diverse rainfall distributions result primarily, because the no-tillage system utilizes the available water supply much more efficiently than the conventional system. Better utilization resulted in 1.6 tons per acre additional silage on a dry weight basis or 26 bushels of corn per acre. The value of such increases to the farmer are quite obvious.

Soil Temperature

Detailed analysis of the soil temperature data revealed a discrepancy in the measurements obtained by the previously mentioned thermo-electric 40 point recording potentiometer. Exhaustive searching by the University instrumentation section and later by laboratory performance tests under controlled conditions utilizing an environmental chamber the discrepancy was isolated and found to be a machine malfunction. Further contact with the manufacturer revealed that the instrument had been improperly designed and was being discontinued by the company. In addition to unsatistactory design and selection of materials, the errors were further aggravated by temperature variations along the thermocouple hookup panel caused by improper placement of heat-producing internal components of the instrument.

Exhaustive efforts toward the development of appropriate calibration curves to apply to the data failed. Additional equipment has been secured and the needed soil temperature data will be collected on a similar experiment during the 1968 growing season. Results of this work will be reported at a later date.

Soil Moisture Model

The data presented in Figures 2, 3 and 4 in conjunction with the hydrologic and climatic data collected at the experimental site were used to develop a soil moisture prediction model. In its very basic form the model can be likened to an accounting system and is expressed as:

$$SM_t = SM_{t-1} \pm \Delta SM_t \qquad (1\text{-}1)$$

where

SM = available soil moisture in a given profile (inches of water)

t = time

Model Development

The model states that the available soil moisture on a given day is equivalent to the available soil moisture for the previous day plus or minus changes that have occurred in storage. Rewriting (1-1) and including the appropriate parameters for determining ΔSM_t:

$$SM_t = SM_{t-1} + P_t - Q_t - PC_t - ET_t + I_t \qquad (1\text{-}2)$$

where

P = rainfall (inches)
Q = runoff (inches)
PC = deep percolation (inches)
ET = evapotranspiration (inches)
I = irrigation (inches)

Equation (1-2) is the basic prediction relationship. It is easily solved by accounting techniques when all variables are known. However, considerable difficulty can be encountered in predicting the variables involved in determining ΔSM_t. In this model it is assumed that rainfall (P) and irrigation (I) are known. Deep percolation when it exists is accounted for in the runoff prediction model. With these assumptions runoff and evaportranspiration are the only remaining variables to be estimated. Exact theoretical relationships for estimating Q or ET under field conditions are non-existing. Consequently empirical relationships which have been shown to give adequate results are employed.

The infiltration concept was used to estimate runoff. An empirical relationship developed by Holtan (20) can be expressed as:

$$f = as^n + fc \qquad (1\text{-}3)$$

where

f = infiltration rate (in./hr.)
s = remaining unfilled pore space above some datum (inches)
fc = final infiltration rate (in./hr.)
a & n = constants that depend on surface conditions, soil type, root development, etc.

Equation (1-3) has been found to give very close approximations of both temporal and spatial variations of runoff (7, 21, 33).

Actual evaportranspiration (ET) was estimated from potential evaportranspiration (PE) using an empirical procedure developed by Thornthwaite (41), which can be expressed as:

$$PE = ct^a \qquad (1\text{-}4)$$

where

PE = monthly ET (cms)
t = mean monthly temperature (°c)
a & c = constants

Thornthwaite suggests that exponent a is best defined by the polynomial:

$$a = 6.75 \times 10^{-5} I^2 + 17.92 \times 10^{-3} I + 0.49239 \quad (1\text{-}5)$$

where

I = annual heat flux which is equal to the sum of the monthly heat indices i where $i = (t/5)^{1.514}$

Coefficient C varies inversely with I. With the appropriate substitution equation (1-4) becomes:

$$PE = 1.6 \; (10\, t/I)^a \quad (1\text{-}6)$$

Equation (1-6) can be converted from metric to English units by utilizing the relation $°c = 5/9\ (°F - 32)$ and the appropriate factor for reducing centimeters to inches.

$$PE = 17.49 \times 10^{-4} \, [5.55\,(°F - 32)/I]^a \quad (1\text{-}7)$$

Estimates given by equation (1-7) are based on a 12-hour day and 30-day month. Modifications for the actual day length and the number of days per month lead to the result:

$$PE = 17.49 \times 10^{-4} \, [5.55\,(°F - 32)/I]^a \; HN \quad (1\text{-}8)$$

where

H = actual daylight hours
N = actual number of days per month

Equation (1-8) is the final form of Thornthwaite's original equation for estimating potential ET. The only unknowns in (1-8) are mean daily temperature (°F) and actual day length. Temperature is determined from on-site measurements and the actual day length for a given location can be obtained in abbreviated form from meteorological tables (27). An example of daylight hour data computed from the abbreviated meteorological tables is given in Table 6.

With an adequate tool available for estimating PE, the question now posed is how to apply PE to field conditions. Classical PE

Table 6. Actual Day Length at the V. P. I. Agricultural Engineering Farm, Blacksburg, Virginia.

	Month											
Day	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
1	9.644	10.353	11.374	12.604	13.723	14.556	14.697	14.062	12.990	11.811	10.632	9.801
2	9.656	10.385	11.411	12.642	13.757	14.573	14.687	14.031	12.953	11.770	10.597	9.782
3	9.668	10.418	11.448	12.681	13.790	14.590	14.677	14.000	12.916	11.729	10.562	9.763
4	9.680	10.451	11.485	12.720	13.823	14.606	14.666	13.969	12.879	11.688	10.572	9.744
5	9.692	10.484	11.522	12.759	13.857	14.623	14.656	13.938	12.842	11.646	10.491	9.725
6	9.708	10.519	11.564	12.801	13.890	14.653	14.644	13.907	12.801	11.607	10.461	9.711
7	9.725	10.554	11.606	12.842	13.922	14.647	14.631	13.876	12.760	11.568	10.430	9.696
8	9.742	10.590	11.647	12.884	13.955	14.659	14.619	13.845	12.719	11.528	10.400	9.682
9	9.758	10.625	11.698	12.926	13.988	14.671	14.606	13.814	12.678	11.489	10.369	9.668
10	9.779	10.660	11.730	12.963	14.019	14.684	14.585	13.781	12.638	11.452	10.338	9.658
11	9.800	10.695	11.771	13.000	14.050	14.696	14.565	13.748	12.599	11.514	10.307	9.647
12	9.921	10.730	11.811	13.037	14.081	14.709	14.544	13.715	12.560	11.378	10.276	9.637
13	9.842	10.765	11.852	13.074	14.112	14.721	14.523	13.683	12.520	11.341	10.245	9.627
14	9.862	10.802	11.891	13.111	14.141	14.721	14.507	13.646	12.483	11.304	10.217	9.619
15	9.882	10.839	11.931	13.148	14.169	14.721	14.491	13.609	12.446	11.267	10.188	9.610
16	9.903	10.877	11.970	13.185	14.198	14.721	14.474	13.572	12.409	11.230	10.159	9.602
17	9.923	10.914	12.009	13.222	14.227	14.721	14.458	13.535	12.372	11.193	10.131	9.594
18	9.948	10.950	12.048	13.259	14.254	14.725	14.433	13.502	12.331	11.152	10.101	9.594
19	9.972	10.987	12.087	13.296	14.281	14.729	14.408	13.469	12.290	11.111	10.072	9.594
20	9.997	11.023	12.126	13.333	14.307	14.734	14.383	13.436	12.249	11.069	10.043	9.594
21	10.021	11.060	12.165	13.370	14.334	14.738	14.358	13.403	12.207	11.028	10.014	9.594
22	10.048	11.097	12.206	13.407	14.357	14.738	14.334	13.364	12.168	10.995	9.991	9.594
23	10.075	11.135	12.248	13.444	14.380	14.738	14.309	13.324	12.129	10.963	9.969	9.594
24	10.102	11.172	12.290	13.481	14.402	14.738	14.285	13.285	12.089	10.930	9.946	9.594
25	10.129	11.210	12.331	13.518	14.425	14.738	14.260	13.246	12.050	10.897	9.923	9.594
26	10.160	11.251	12.370	13.553	14.446	14.729	14.233	13.211	12.009	10.859	9.901	9.602
27	10.192	11,292	12,409	13.588	14.467	14.721	14.206	13.175	11.968	10.822	9.878	9.610
28	10.223	11.333	12.448	13.623	14.487	14.713	14.180	13.140	11.926	10.784	9.855	9.619
29	10.255	11.374	12.487	13.659	14.508	14.704	14.153	13.105	11.885	10.747	9.832	9.627
30	10.287		12.526	13.680	14.524	14.702	14.123	13.067	11.861	10.709	9.822	9.633
31	10.320		12.565		14.540		14.092	13.029		10.670		9.638

formulations are derived either with the explicit or implicit assumption that moisture is not limiting for the evaporative process. For the most part moisture will be limiting under natural field conditions. Difficulty arises when moisture is limiting in that the PE rate may change with the available moisture remaining. Many theories have been advanced to explain ET when moisture is limiting. Among these are: (a) depletion by PE until wilting point at which time the rate abruptly drops to zero, (b) a linear depletion rate from field capacity to wilting point, and (c) non-linear depletion rates between a and b. A discussion of these and other theories can be found in reference 40.

The ET loss from areas in corn will be entirely by evaporation until emergence, at which time transpiration will commence and will become a dominant factor when foliage becomes dense. Reports by several investigators indicate that the average loss by ET and evaporation will be about equal for the entire growing season (16, 35, 36).

It is generally excepted that the first 1-inch of available moisture in the 0-12 inch profile will deplete at the potential rate (25). This is approximately equivalent to the amount of water held between field capacity and 1 atmosphere of tension for a wide range of soil types.

Available soil moisture between 1 and 15 atmospheres of tension was assumed to deplete as a function of the moisture remaining, e.g. if the PE rate was 0.20 and the percentage soil moisture remaining was 50 percent than the adjusted ET rate was 0.10.

With the above criteria the soil profile was subdivided into 3 zones or categories. Zone 1 (SMO) contains only free water which includes the moisture held between 0 and 1/3 atmosphere tension. Water in this zone is free to drain from the profile by gravity. However, evaporation can take place from this zone because the free drainage process can take several days in some soil types. Evaporation is assumed to continue at the potential rate. Zone 2 (SM1) is the upper segment of plant available water. This zone, as previously defined, has a maximum capacity of 1 inch from which the ET rate is assumed to be equal to PE. Zone 3 (SM2) contains the remaining moisture in the plant abailable range and is assumed to be equivalent to the soil moisture held between 1 and 15 atmospheres of tension. The ET from this interval can be expressed as:

$$ET = PE \frac{SM2_R}{SM2_R}$$

where

$SM2_R$ = soil moisture remaining in Zone 3
$SM2_M$ = maximum moisture possible in Zone 3 for the profile being consedered

During periods of precipitation and at night ET was assumed to be negligible. Depletion by ET was assumed to take place by layers, i.e. SMO would be depleted first, followed by SM1 and SM2. Negative depletion rates were not allowed. Recharge was assumed to take place first in SM1, followed by SM2 and SMO, respectively.

The above relationships were programmed for an IBM 7040 computer. In effect the program is a mathematical simulation of the hydrologic preformance of an area. Since the required results are "local", estimates of ground water flow and determination of correct spatial and temporal distribution of excess precipitation by routing techniques were not included. Such estimates would be necessary in a complete watershed model. The model uses an iterative scheme to arrive at the hydrologic preformance of the soil profile, given precipitation, mean daily temperature, and initial soil physical properties.

The simulation process is illustrated schematically in Figure 5. Precipitation excess is represented by the symbol EXCESS and includes depression storage. This storage will later infiltrate into the moisture resevoir at some rate f that is determined by iterative solution of equation (1-3). For practical purposes FC was assumed to take place only from Zone 1 and ET was assumed to be essentially zero at 15 atmospheres of tension. The available storage (SAV) at any given time is equivalent to the total porosity above wilting point minus the quantity SMO + SM1 + SM2.

Compatibility of Results

Our ultimate goal was to estimate the soil moisture at a given time. To achieve this objective through accounting techniques, esti-

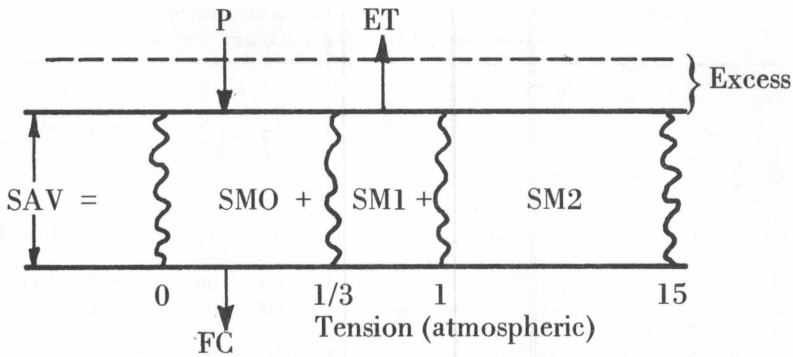


Figure 5. Schematic Representation of the Soil Moisture Prediction Model.

mates of ET and runoff were required. These estimates were obtained through equation (1-3) and an adjustment of the results from equation (1-8). The soil moisture status was then determined by equation (1-2).

Table 7 illustrates the parameters and computations for corn grown on a groseclose silt loam soil, gently sloping phase with a conventional tillage practice. Total prosoity above wilting point was found to be 6.71 inches. SMO was estimated at 3.28 inches and SM1 plus SM2 was estimated at 3.43 inches. Antecedent conditions at planting date were determined from field measurments to be 3.16 inches available moisture. Depression storage was assumed to be zero. The final infiltration rate was estimated at 0.20 in./hr.

In Table 7 columns 6, 7, and 8 were developed from an iterative solution of equation (1-3). Column 8 is a potential infiltration rate for the indicated available storage. It is only equivalent to the actual infiltration rate when $\Delta P/\Delta T$ is equal to column 8
where ΔT = time in hours
ΔP = precipitation occuring in ΔT
When $\Delta P/\Delta T >$ column 8 iteration of equation (1-3) proceeds until the condition $\Delta P/\Delta T \leq$ column 8. The excess becomes columns 9 and 10. If $\Delta P/\Delta T$ was initially $<$ column 8, it was assumed that conditions were sufficient for somplete infiltration of ΔP.

Column 11 resulted from equation (1-8) and column 15 resulted from equation (1-2). Columns 12, 13, and 14 resulted from intermediary moisture balances using equation (1-2).

Table 7. Computations of Soil Moisture Prediction Equation for Corn grown on Groseclose Silt Loam Soil, Blacksburg, Virginia.

Month	Day	Year	Hour	Precipitation	Available storage	Infiltration rate	Average infiltration rate	Depression storage	Runoff	Evapo-transpiration	SMO	SM1	SM2	Soil moisture
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)
5	8	67	8.4167	0.00	3.55	3.68		0.00	0.00	0.00	0.00	0.73	2.43	3.16
5	8	67	10.4167	.11	3.44	3.53	3.60	.00	.00	.00	.00	0.84	2.43	3.27
5	8	67	14.3333	.00	3.46	3.55	3.54	.00	.00	.02	.00	.82	2.43	3.25
5	8	67	15.0500	.23	3.23	3.25	3.40	.00	.00	.00	.05	1.00	2.43	3.43
5	8	67	17.4167	.00	3.29	3.33	3.29	.00	.00	.01	.00	0.99	2.43	3.42
5	22	67	9.0000	.17	3.11	3.10	3.21	.00	.00	.00	.17	1.00	2.43	3.43
5	22	67	24.0000	.00	3.31	3.36	3.23	.00	.00	.03	.00	0.97	2.43	3.40
5	23	67	24.0000	.00	3.38	3.45	3.40	.00	.00	.07	.00	0.90	2.43	3.33
5	24	67	24.0000	.00	3.45	3.54	3.50	.00	.00	.07	.00	0.83	2.43	3.26
5	25	67	24.0000	.00	3.54	3.67	3.60	.00	.00	.09	.00	0.74	2.43	3.17
5	26	67	24.0000	.00	3.64	3.81	3.74	.00	.00	.10	.00	0.64	2.43	3.07
5	27	67	24.0000	.00	3.77	3.98	3.89	.00	.00	.12	.00	0.51	2.43	2.94
5	28	67	24.0000	.00	3.93	4.21	4.10	.00	.00	.17	.00	0.35	2.43	2.78
6	18	67	12.0000	.00	5.17	6.06	6.02	.00	.00	.05	.00	.00	1.54	1.54
6	18	67	12.0500	.01	5.16	6.05	6.05	.00	.00	.00	.00	.00	1.55	1.55
6	18	67	12.1167	.06	5.10	5.95	6.00	.00	.00	.00	.00	.00	1.61	1.61
6	18	67	12.1500	.00	5.10	5.95	5.95	.00	.00	.00	.00	.00	1.61	1.61
6	18	67	12.1667	.24	4.99	5.77	5.86	.00	.12	.00	.00	.00	1.72	1.72
6	18	67	12.1833	.15	4.87	5.58	5.68	.00	.03	.00	.00	.00	1.84	1.84
7	11	67	24.0000	.00	4.31	4.75	4.66	.00	.00	.13	.00	.00	2.40	2.40
7	12	67	24.0000	.00	4.51	5.05	4.90	.00	.00	.20	.00	.00	2.20	2.20
7	13	67	24.0000	.00	4.66	5.27	5.16	.00	.00	.15	.00	.00	2.05	2.05
9	10	67	24.0000	.00	4.45	4.96	4.89	.00	.00	.11	.00	.00	2.26	2.26
9	11	67	24.0000	.00	4.53	5.06	5.01	.00	.00	.07	.00	.00	2.19	2.19
9	12	67	24.0000	.00	4.58	5.15	5.11	.00	.00	.06	.00	.00	2.13	2.13
9	13	67	24.0000	.00	4.64	5.24	5.20	.00	.00	.06	.00	.00	2.07	2.07

Table 8. Comparison of Potential and Actual Evaportranspiration computed by Thornthwaite's Empirical Relationship and a Modified Penman Concept developed by C. H. M. van Bavel.

Period	Potential ET		Actual ET	
	Thornthwaite	Penman	Model	Lysimeter[1/]
	(in./day)	(in./day)	(in./day)	(in./day)
6/20-6/29	0.15	0.14	0.12	0.09
7/3 -7/5	0.13	0.17	0.09	0.12
7/11-7/30	0.16	0.13	0.10	0.11
8/1 -8/7	0.15	0.12	0.10	0.16
8/8 -8/21	0.13	0.12	0.07	0.14
9/1 -9/13	0.09	0.10	0.08	0.12

1/ Average ET values from three hydraulic lysimeters with Kentucky 31 fescue, Kentucky 16 tobacco, and Kentucky 16 mammoth tobacco vegetative covers respectively. The lysimetry data courtesy of J. N. Jones, Jr., USDA, ARS, Blacksburg, Virginia.

A comparison of potential and actual evapotranspiration computed by Thornthwaite's empirical relationship and Penman's equation as modified by C. H. M. van Bavel (42) is illustrated in Table 8. In van Bavel's procedure ET is assumed equal to PE. The lysimeter values were not for the same cover conditions as was the data given for the model. However they can be considered as "ball park" conditions and therefore give reasonable relative comparisons. Inspection of the data indicate that acceptable agreement does exhist between all comparisons.

Figure 6 is a comparison of predicted versus actual soil moisture that was developed for the two tillage systems from the computations started in Table 8. Note that two prediction curves are presented–curve No. 1 for the no-tillage and curve No. 2. for conventional tillage. The procedure previously discussed applies to curve No. 2. Curve No. 1 was developed by assuming a uniform step function for ET, which started at 0.05 PE for periods prior to June 15, stepped to 0.17 PE from June 15 until June 30, and increased at this rate by two-week increaments until PE was reached in late August. The maximum error between the predicted and computed for either curve was found to be approximately 0.40 inch of water for the 0-18 inch depth.

General Discussion and Summary

The data presented show that soil moisture was the dominant factor affecting the differences in yield in the two tillage systems. At plant emergence the available soil moisture was always significantly greater in the no-tillage system because the mulch resulting from the killed sod acts as an insultator over the surface which results in very little evaporation from the no-tillage areas. These findings although much more dramatic are in close agreement with results found by others in different mulch studies (5, 6, 9, 12, 22, 28, 31, 43, 44, 45). In general any material placed over a surface that will reduce temperature will tend to suppress evaporation. The mulch from the no-tillage system has a decided advantage over artifically applied mulch in that it is in effect

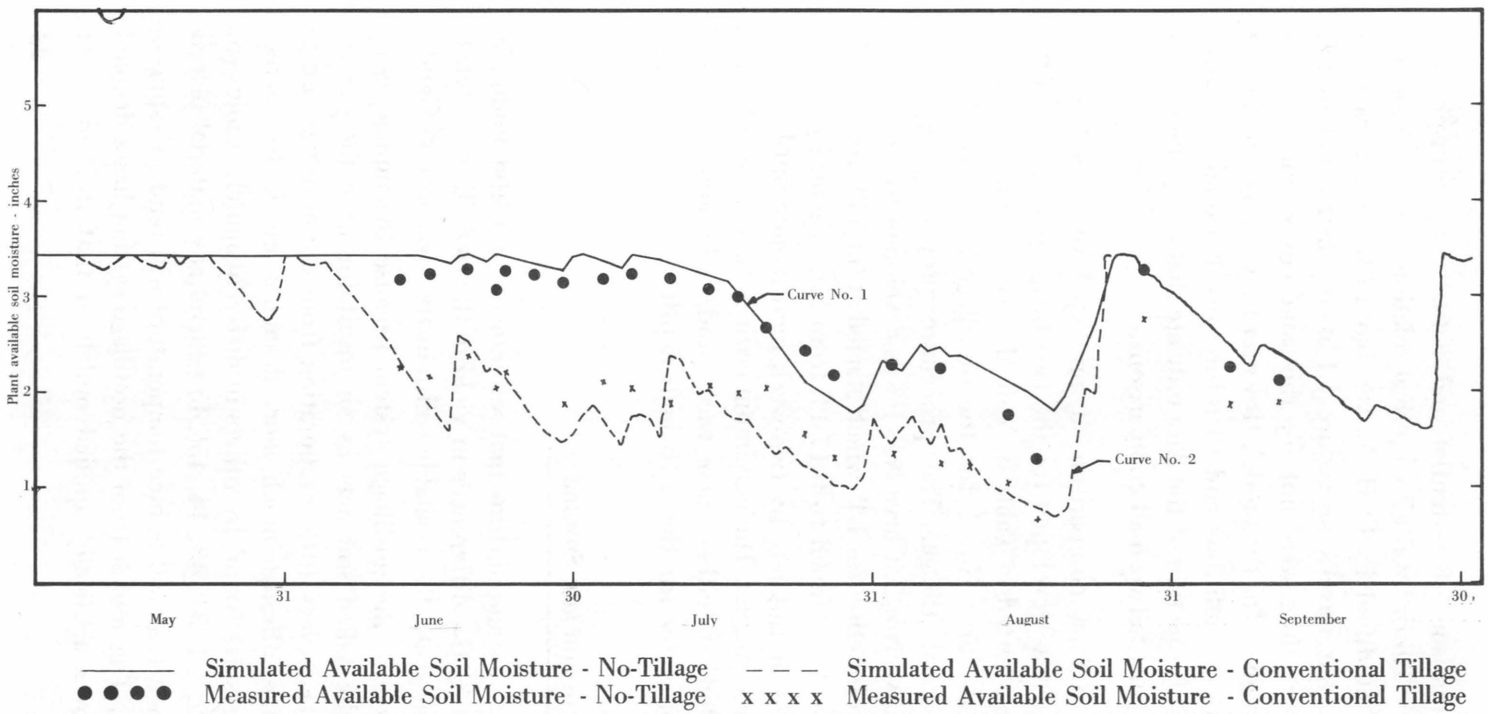


Figure 6. Comparison of Predicted and Measured Available Soil Moisture on No-Tillage and Conventional Tillage Systems for Corn grown on a Groseclose Silt Loam Soil at Blacksburg, Virginia.

fastened in place by its own root system. The advantage is that weather elements will not readily dislodge and remove the mulch from the area.

The type of tillage practice definitely can affect the infiltration rate and consequently erosion and runoff (5, 10, 15, 17). The no-tillage system greatly reduces both runoff and soil erosion. Experimental evidence indicates a ratio of 7 to 1 in favor of no-tillage over conventional methods. The decaying root system provides open channels for infiltration and permeability through the soil profile (4). It is hypothesized without experimental verification that the grass mulch absorbs considerable quantities of dew during the night and that during the following day the cooling effect is sufficient to reduce the net evaporation rate from the soil profile to less than 10 percent. The experimental data do in fact show that the moisture loss from the no-tillage system prior to emergence was near zero. This loss became progressively larger as transpiration increased due to increased corn growth.

For the climatic condition studied the data definitely indicate that the no-tillage system is the superior practice. Better yields, less runoff, erosion and evaporation were observed. Coincident with the absolute minimum tillage requirements, the system most certainly appears to offer exceptional merit in Virginia as well as in other areas. In Virginia it would appear that the facility of being able to alter the farm management plan would be exceedingly advantageous. Steeper slopes in good grass sods could be planted to corn with reduced danger of erosion due to excessive runoff.

Because of the difficulty in securing a sufficient supply of experimental data on a wide variety of soil types subjected to a range of climatic experience, a mathematical model was developed to simulate the moisture conditions. As previously shown this model has fit the actual conditions for the 1966 and 1967 data exceptionally well. Equal agreement has been obtained for soil moisture data collected in related experimental work. The next step will be to simulate the soil moisture conditions under a wide range of climatic experiences, different soil types and depths. These data will be extrapolated to give the range of yields that the farmer can expect from a no-tillage system relative to conventional practices. The results of this study will be reported at a later date.

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