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Tillage and Crop Residue Management Practices for Improved Crop Production and Soil Structure Maintenance

E. Rawitz, J. F. Power, A. Hadas, Y. Chen,

D. Wolf, W. W. Wilhelm

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for Improved Crop Production and Soil Structure
Maintenance

Investigators' Names	Investigators Institutions
E. Rawitz (principal)	The Hebrew Univ of Jerusalem
J. F. Power	USDA-ARS, Lincoln, NE
A. Hadas	A.R.O. The Volcani Center
Y. Chen	The Hebrew Univ of Jerusalem
D. Wolf	The Technion, Israel Inst of Tech
W. W. Wilhelm	USDA-ARS, Lincoln, NE

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Dr. YUVAL ESHDAT
Head, Div. for Research Projects and Budgets
Agricultural Research Organization

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III. Abstract

Two models (NTRM and EPIC) were chosen to evaluate tillage and residue management practices over the broad range of conditions represented by wheat-fallow and cotton crop production systems in the central US and Israel, respectively. Although the models were considered tillage and residue management factor in their algorithms, they proved inadequate for analysis of cropping systems involving these factors. NTRM required modification to be useable in simulating winter wheat. It appears that knowledge of the influence tillage and residue management practices have on basic soil properties and their interaction with crop development and growth is not adequate, or not incorporated into the tested models, to allow their use in identifying potentially useful tillage and residue management systems for field testing.

Eight no-plow tillage and cotton residue disposal treatments in permanent traffic lanes were compared for 2 years with a conventional deep-plowed regime, based on soil structural changes and yield of irrigated cotton. Any effects of residue management were masked by those of tillage. The common farm practice of residue incorporation in a concentrated band gave the lowest yield, had a high energy requirement, and a potentially drastic effect on the field hydraulic properties. Sampling of long-term fertilizer and residue addition experiments showed that heavy applications produced but a minor increase in O.M. content, and produced no changes in soil structural indices. In laboratory incubation experiments, residue and N addition produced a very rapid increase of strength, MWD, and water retention and decrease of hydraulic conductivity within a week, which were completely dissipated during the following 1 - 3 weeks.

IV. Objectives

A. To study the effect of incorporation method and soil moisture regime on the decomposition of crop residues and on soil structural properties.

B. To evaluate the combined effects of tillage-and residue-management method on tillage energy requirements and crop yields.

C. To identify and improve existing simulation models that describe effects of tillage and residue management systems on soil physical properties, soil environment, and resulting effect on crop production.

V. Body of report

A. Introduction

Tillage and crop-residue management systems influence many of the complex array of crop, soil, and water factors in crop production systems. These factors affect crop development and growth directly and indirectly. These numerous factors may influence crop growth processes independently or through interaction with other factors, including time.

Many critical cropping system factors are not readily changed by man (i. e. weather). However, soil and water conditions are greatly influenced by management and cultural practices. Tillage is one of the factors under man's direct control. Tillage and crop-residue management are closely linked management practices. Tillage operations always involve some manner of crop residue manipulation of only affecting the placement of dead plant roots. Likewise, tillage has historically been the most common means of managing crop residues with the possible exception of residue removal for food, feed, or fuel.

Energy requirements for tillage are second only to those for pumping irrigation water within crop production systems. The cost associated with energy used for tillage has been a major incentive for development of less-energy-intensive tillage systems. "Conservation tillage" systems, based on reduced tillage, not only reduce energy used for tillage, but with maintenance of surface crop residues have also been effective in reducing water and wind erosion, runoff, and evaporation of water from the soil surface. This demonstrates the importance of understanding the role of residue management in conservation-tillage systems.

The scientific literature contains contradictory reports on the efficacy of conservation tillage practices. The problems which have arisen in the evolution of tillage practices indicating that no universal prescription exist for achieving both objectives of tillage: Desirable soil physical environment for biological activity and high crop yield. Although many published reports show the immediate effects tillage operations have on soil physical conditions, differential tillage treatments are often not reflected by crop response or by persistent changes in soil structure. Furthermore, a widespread--yet largely undocumented--concern prevails in both the United States and Israel that several decades of intensive irrigated or dryland agriculture may cause degradation of soil physical properties (e.g., low water infiltration, hard impermeable surface crust, imparted aeration, and large, dense soil clods). These symptoms have been found especially in the loessial soils of the southern Coastal Plain and northern Negev of Israel.

In general, tillage- and residue-management practices develop the physical environment that controls biological activity in the soil. Changes in soil bulk density, aeration, soil strength, and location of crop residues result in direct effects on other soil properties, such as soil water content, soil temperature, and nutrient availability, and these in turn affect the biological activity in the soil (microbes and plant roots). Within the limits imposed by nature, man can use tillage, or the lack thereof, as a method of modifying the soil environment to create a specific combination of characteristics to optimize crop growth.

Although tillage practices have been devised and evolved to improve conditions for crop development and growth, determining how the soil physical environment should be altered to optimize crop production, within the site-specific limits imposed by nature, is not an easy task. Varying components of a management system in field trials to quantify output of various crop production systems requires extensive experimentation and is extremely expensive and time consuming. Even if this could be afforded and implemented, results would have site- and crop-specific limitations. Furthermore, variability of soil physical and chemical properties may prevent sound interpretation of such results. Therefore, from a practical standpoint, field trials can only be used to assess strengths and weaknesses of limited numbers of management alternatives which have been screened from a larger set of possible management schemes. Presently, experience and trial and error are used to screen alternative management strategies.

Properly devised and tested simulation models should provide more structured tools to screen the larger set of tillage and residue management practices for ultimate evaluation at the field level. Models can analyze almost any conceivable management condition in the production systems, if they are developed with realistic sensitivity to critical parameters and processes within the cropping system. Determining whether a particular model is appropriately

constructed is a crucial part of the analytical procedure. To this end it is important that candidate models for system analysis be evaluated over widely divergent conditions.

B. Literature review

Models are constructed for many purposes. These purposes may include interpreting experimental results, guiding research, and managing farm operations (Whisler et al., 1986). In all cases, the modeler attempts to provide understanding of the modeled system through the computer simulation. In research guidance and farm management, the understanding is of a very complex system with many components, including soil, water, weather, and crop management.

Although water (Hanks and Rasmussen, 1982) and temperature (Gilmore and Rogers, 1958; Klepper et al., 1982) have been shown to be very critical factors in all crop production systems, their interaction with time in the growing season can also alter the crop response significantly (Wilhelm et al., 1987). Factors within the control of managers, such as tillage and residue management, also influence crop performance through their effects on soil physical properties, such as infiltration (Mielke et al., 1984), evaporation (Unger and McCalla, 1980), strength (Mielke et al., 1984), and soil temperature (Wilhelm et al., 1989). Tillage and residue management impart independent as well as combined effects on the crop response (Wilhelm et al., 1989).

Maintenance of proper soil physical conditions is an essential requirement for optimal crop performance. Among the important properties that might be amenable to manipulation are micro- and macro structure, compressibility, aggregate size distribution and stability to water, bulk density, and resistance to cone and root penetration, water infiltrability and air permeability.

Unfavorable soil physical conditions may be the result of inherently unstable soil structure, inappropriate choice or improper operation of tillage and harvesting implements, and of vehicular traffic. Crop residue management practices, with or without high application rates of fertilizers, composts and manure, have been reported to result in a more stable soil structure, having lower compressibility, greater bearing strength that can better withstand traffic loads, and thus undergo smaller structural changes during a cropping cycle (Trowse, 1971; Fahad et al., 1982; Tate, 1987).

The ways and means for attaining high yields while maintaining long term productivity and proper soil structure under given soil, crop, and climatic conditions, sometimes lumped under the term "conservation tillage", are not clear, let alone proven. This is especially true in semi-arid zones where rainfall is scarce, and moderate to high temperatures prevail. Under these conditions soils tend to have low organic matter content, unstable structure, impaired infiltrability, high susceptibility to crusting, compaction, and self-consolidation (Hillel, 1960, 1967; Chen et al., 1980; Hadas and Wolf, 1984; Wolf and Hadas, 1985; Rawitz et al., 1981).

Heavy traffic loads and mechanical stresses cause these soils to produce large, dense clods (Hadas and Wolf, 1984; Krause et al., 1984). When clods are further broken by subsequent tillage operations, the resultant tilth consists of a finely pulverized matrix containing numerous coarse fragments (Vomocil, 1957; Trowse, 1971; Bowen, 1981). This undesirable condition can not be obliterated by tillage (Hadas et al., 1978, 1985; Fahad et al., 1982; Voorhees, 1983; Wolf and Hadas, 1987), and leads to heterogeneous soil tilth (Frede, 1982; Frede and Meyer, 1981; Hadas et al., 1986), non-uniform crop stand and reduced yield (Hadas et al., 1983, 1985; Rawitz et al., 1981). It is almost impossible to relate clod formation to specific causes such as wetting-and-drying, slaking, or tillage operations (e.g. fallow vs. moldboard or chisel plow). However, clods appear to result from traffic on moist soil following pulverizing operations (Rawitz et al., 1981; Frede, 1982; Hadas et al., 1983, 1986; Voorhees, 1983). The seriousness of these phenomena is illustrated by observations of Rawitz et al. (1964) and Fahad et al. (1982) who reported five-fold increase in soil infiltrability to water brought about by structure-improving crops (e.g. alfalfa, *Medicago sativa* L.) established on fields previously subjected to traffic-intensive tillage and cropping practices which resulted in dense soil and low infiltrability.

C. Materials and methods

1. Model evaluation

a. Model selection criteria

Model validity can be defined as the confidence with which a simulation may be applied outside the range of calibration. Broadly applicable crop production models should simulate the

soil environment and crop growth processes accurately with minimum spatial or temporal specificity. It is important not to rely too heavily on whether the model has a theoretical or empirical basis, but rather to assess the validity of the model as a whole in a broad ranges of field comparisons.

Important attributes of a model, other than predictive accuracy and realistic sensitivity to critical system processes, are availability, ease of use for clientele with diverse interests and technical backgrounds, and ability to execute on a range of computer hardware. Often, even very well developed models, are not easy to use. The usefulness of a complex model to new clientele is strongly related to the quality, thoroughness, and clarity of documentation.

Model selection for system analysis is a critical component of the analytical procedure. The selected model must be assessed to determine if it is appropriate for the evaluation in question. For the current study, selected models had to be: 1) well documented, 2) readily available, 3) constructed to consider processes influenced by tillage and residue management, 4) simulate growth of winter wheat (*Triticum aestivum* L.) and cotton (*Gossypium hirsutum* L.), and 5) executed on available hardware (microVAX II). Nitrogen Tillage Residue Management (NTRM) (Shaffer and Pierce, 1987; Shaffer and Larson, 1987) and Erosion Productivity Impact Calculator (EPIC) (Williams et al., 1983, 1984) models were selected to conduct the cropping system analysis because documentation indicated they satisfied our requirements. Detailed descriptions of submodels used to simulate soil, plant, and water processes have been reported by Shaffer and Pierce (1987) and Shaffer and Larson (1987) for NTRM and Williams et al. (1983; 1984) for EPIC.

b. Description of models

NTRM. A variety of input information is required by NTRM (Table C-1.1). A simplified information flow chart and list of input files are shown in Fig. C-1.1. Each contains a different category of input data.

File A:	Common input file, containing 26 categories of soil crop, and management practice data
File B:	Daily pan evaporation, solar radiation, and wind speed data
File C:	Rainfall data
File D:	General soil temperature input data
File E:	Daily maximum and minimum soil temperature data
File F:	Hourly measured or simulated air temperature data
File G:	Hourly measured or simulated air temperature data
File H:	General output file.

A brief description of steps taken to create and prepare various input files follows. The subprogram, SETUP, creates Files A, B, C, D, and E. Files A, B, and C were created using daily meteorological data from the National Oceanic and Atmospheric Administration (NOAA), National Climatic Data Center data base. Data for Files A and D were entered manually to provide soil, crop, tillage, and management information. Then submodel SOILTEMP was run using information in Files D and E to create Files F and G, hourly soil and air temperature, respectively, and a general output file, File H. Files A, B, C, F, and G are used directly by NTRM.

EPIC. The EPIC model was developed to assess the effect of management alternatives on soil erosion and future soil productivity. The simulation is divided into 49 subroutines which use readily available inputs to evaluate factors within eight general categories (hydrology, weather, erosion, nutrients, plant growth, soil temperature, tillage, and economics). The basic unit for simulation is approximately 1 ha. Within this area, soil characteristics and management practices are assumed constant. However vertically, the soil can be divided into 10 layers to represent differential soil properties with depth. Weather variables, precipitation, air temperature, solar radiation, and wind, drive the model. Systems have been provided for the model to generate these driving variables if their monthly mean and probability of occurrence or coefficient of variation are known (Williams et al., 1983, 1984).

c. Description of data used to test models

Simulation input data and field yield comparison data were collected from a winter wheat-fallow tillage study conducted at the High Plains Agricultural Laboratory near Sidney, Nebraska USA (Fenster and Peterson, 1979) and the main cotton field experiment associated with this BARD project which is described in this report in detail.

Table C-1.1. Summary of NTRM inputs.

Type of data	Data
Climatic	Air temperature (max and min) Precipitation Pan evaporation Solar radiation Wind speed
Soil (by layer)	Depth Initial bulk density Stabilized bulk density Water content at saturation and field capacity Initial water content and temperature Particle size distribution Hydraulic conductivity Water characteristic curve
Management	Tillage-type, date, and depth Residue-type, cover, amount, and date Fertilizer-type, amount, and date
Crop	Planting, emergence, and harvest date Plant population Dates of beginning and end of dormancy Crop coefficients Degree days to flowering and maturity

Figure C-1.1. A simplified input and output configuration of Nitrogen-Tillage-Residue Management (NTRM) model.

Soil at the U.S. site is an Alliance silt loam (fine silty, mixed, mesic Aridic Argiustolls). The experimental site was divided into two sections one planted and one fallow each year. Weed growth in stubble after wheat harvest was chemically controlled, and fallow treatments (moldboard plow, sub tillage, and no tillage) were initiated in mid-April of the next year. Treatment names define the primary tillage tool used in each treatment. A number of secondary tillage operations were performed as required to control weeds in the plow and sub tillage treatments. Wheat, cultivar Centurk, was planted at 50 kg ha^{-1} in mid-September to end the fallow period. Grain harvest occurred in mid-July of the following year. Tillage treatments were split into two subplots for nitrogen applications of 0 or 45 kg ha^{-1} . A detailed descriptions of the experimental site and cultural practices, preceding but similar to those of this study, were published by Fenster and Peterson (1979), Wilhelm et al. (1982), Mielke et al. (1986), and Broder et al. (1984).

The tillage treatments used in this study were plow (moldboard plow), sub tillage (1.5 m-wide "V" blade), and no tillage. Primary tillage tool in the plow and sub tillage treatments were operated at a depth of 100 mm. Secondary tillage tools for these treatments were field cultivator and a rotary rodweeder. These tools were used as needed to control weeds. Weeds were controlled with herbicides in the no tillage treatment.

Dry-matter production was determined by harvesting all aboveground plant parts from a 0.91 m^2 area at intervals during crop development. Harvested samples were oven-dried at 85°C to a constant weight, and dry-matter production calculated. Leaf area index (LAI) was determined at anthesis from 50-culm subsamples. All green leaf blades were removed from each culm and passed through a leaf area meter. The LAI was calculated after determination of the leaf dry weight fraction and the specific leaf weight. Plant material was sampled from a 0.91-m^2 area to determine grain yield.

d. Model testing

Models were tested by first comparing simulation results (obtained with site specific soil, weather, and management input data) to data collected from the field. To further evaluate the applicability of the selected models for cropping system analysis, sensitivity analyses were conducted. Model sensitivity to initial bulk density, depth of tillage, time of tillage, and number of tillage operations were determined.

2. Main field experiment

a. Description of farming system and explanation of problems

The Israeli Farming System. Cotton (*Gossypium hirsutum* L) is Israel's principal irrigated summer field crop, occupying some 50,000 ha. About 65% of this area is drip irrigated, and this percentage is steadily increasing. The common practice is to plant the crop on two-row broad beds with a 97 cm row spacing, the drip laterals being placed between alternate rows, in the center of the bed. Cotton is customarily grown in the same field for three to five consecutive years, with wheat sometimes grown in the winter. The growing season is too short for the grain to mature between two cotton crops, and in that case the wheat is harvested in the spring for silage. The time available between the cotton harvest and the onset of the winter rains, as well as between the wheat harvest and cotton planting in the spring, is a major limiting factor for the execution of tillage operations.

It is a requirement of the production system to control the pink boll worm, and the effective way of doing this is to interrupt its life cycle by denying it hosts for overwintering, such as regrowth of cotton stubble, seeds and other crop residues on the soil surface. It is a legal requirement that all cotton residues be removed from the fields during November. While some cotton spilled during transport from the field to the gin, collects in roadside ditches, and represents a potential focus of infestation, and early rains sometimes make it impossible to finish harvesting and tillage during November, all reasonable efforts are made to observe this rule.

Until about 1980, the standard tillage sequence after harvest consisted of chopping stover with a horizontal blade rotary chopper and turning it under with a moldboard plow to a depth of 35-40 cm. This operation was carried out on dry, compacted soil, turned up large, hard clods instead of a furrow slice, had very high energy requirement, and was time consuming. If wheat were to be sown, the clods had to be broken down in the dry state by repeated disking, pulverizing

a large part of the soil, which then tended to crust under raindrop impact and exaggerate runoff and erosion problems.

The narrow time-window between crops of the intensive farming system, as well as the vagaries of weather, impelled farmers to invest in more powerful and heavier implements on the one hand, and on the other hand forced them to conduct some of the secondary tillage operations in fallow fields (repeated disking, cultivation or harrowing followed by ridging or bed construction) on moist soil following onset of the rainy season, with up to seven trips over moist soil. This resulted in recompaction of the soil, thus actually exacerbating the clod formation problem during the attempt to alleviate its immediate effects. Some of the secondary tillage passes were perpendicular or diagonal to the direction of plowing, and thus over a few years up to 90% of the surface of a field could be compacted in a random pattern, with a steadily decreasing distance between wheel tracks (Frede, 1982). Eventually, several effects such as variability of stand and yields within and between fields, gradual decreases in average yields, increased runoff and declining soil infiltrability were noted. Combined, these facts support the hard-to-prove suspicion that prevailing tillage systems were causing compaction-induced structure deterioration (Hadas et al., 1983). Tentative steps were taken towards precision tillage in permanent controlled traffic lanes and minimum or reduced tillage based on subsoiling and integration of several implements in a "multitiller", e.g., a combination subsoiler-rototiller-ridger. However, field sanitation, especially the elimination of stubble which could regrow, was not as good as with deep plowing.

A tillage system based on an entirely new concept became possible with the development by a local engineering firm of the Uprooter-Shredder Mulcher (USM)¹ shown in Plate 1. This machine basically pulls the cotton plant including the primary root system from the soil, conveys it to a chopper assembly, and ejects the shredded material. Several versions have been built around the basic system, giving the following options:

1. Disposal of chopped residues
 - a. broadcast over the land surface
 - b. blown into a wagon (similar to forage harvester)
 - c. blown into a subsoiler slot (vertical mulching)
2. Additional implements mounted on tool bar, USM, or towed
 - a. mulching shank with funnel (required for 1.c)
 - b. subsoiler shanks of various shapes
 - c. ridgers or bed shaper
 - d. rotary tiller and bed former

Option 1.a requires incorporation of residues in the soil by a subsequent pass of a rotary tiller, which does not leave the soil surface completely free of residues. It is used mainly if the following crop is not cotton. Option 1.b envisages either use of the residues as fuel, or returning them to the land after composting, the heat presumably killing the bollworm eggs. Option 1.c is the one commonly used, in conjunction with options 2.a, b, and either c or d. Option 2.abc accomplishes all the primary tillage operations in one pass, and 2.abd carries out one secondary tillage operation as well. All secondary tillage operations subsequent to the USM pass (rotary tillage, bed forming, cultivations, and sowing) are conducted with 6-row equipment. The immediate benefits of the USM are: fewer traffic passes across the land; compaction limited to permanent wheel tracks; faster coverage of a given area, fewer large clods brought to the surface; and savings of energy and labor. Both the short- and longer term effects of the various versions of this tillage system are among the subjects of this investigation.

¹ Manufactured by Agricultural Machinery Div., Automotive Industries Ltd., P.O.B.535, Nazareth 17105, Israel. Mention of commercial products is for the benefit of the reader and does not imply preferential treatment or endorsement by the authors.

Plate 1. Uprooter-Shedder-Mulcher working in broadcast mode.

b. Site description

The experimental site was located at Kibbutz Nahal Oz 31°28' N, and 34°28'E, 8 km inland from the Mediterranean Sea. Mean annual rainfall is 380 mm, concentrated in the months October - March. Fluctuations of 100 mm or more around the mean are common. The soil is a deep, calcareous, silty loam of loessial origin (Calcic Haploxeralf). The soil profile is structurally amorphous, and aggregates formed by tillage of dry soil have virtually no wet stability. Plowing of intensively cultivated soil in the dry state exposes very large, hard clods. When these are cleaved by secondary tillage, e.g. disking, a large percentage of the soil becomes pulverized, with numerous smaller clods imbedded in this floury matrix. ↓

Two adjacent fields, each about 175 x 175 meters were sampled for soil characterization during June 1986, by 30-cm layers on a 25-m grid. Both fields were under a stand of irrigated cotton. One had been deep-plowed (to 45 cm) with a moldboard, and the other tilled by Paraplow (to 50 cm) in Autumn 1985, followed by identical secondary tillage and seedbed preparation operations. The surface of the moldboard plowed field appeared distinctly coarser to the eye than the one tilled by Paraplow. Aggregate size analysis of surface soil by dry sieving indicated a mean weighted diameter (MWD) of 11.7 ± 3.1 mm for the moldboard plowed plot, and 8.9 ± 1.8 mm for the Paraplow plot, confirming the visual impression. Aggregate stability analysis by wet sieving for 15 minutes with the apparatus described in USDA Handbook 60 showed that less than 5% of the original sample was retained on the finest (0.25 mm) screen. ↑

Saturated soil paste extracts were prepared from all 72 surface layer samples. Electrical conductivity (EC) and sodium adsorption ratio (SAR) were determined. These results were analyzed for spatial variability by geostatistical methods. The area was found to be rather uniform, with variability being entirely random and normally distributed. Mean EC was 0.89 ± 0.047 dS m⁻¹. Mean SAR was 2.49 ± 0.32 .

Based on these results, plot that had received primary tillage by Paraplow was tentatively chosen for the experimental plot. Further samples were collected on three transects, two perpendicular and one parallel to the row direction. Sampling was done at fewer locations but in greater detail: At each location samples were taken from the plant row, the wheel track, and the inter-row furrow. Topographic elevation, soil water content, penetration resistance, bulk density, and strength of dry soil cores were determined. Mass wetness of the soil was very uniform on the day of sampling both with depth (0 - 20, 20 - 40, 40 - 60 cm) and are really. Average water content was $19.86 \pm 0.55\%$, which was no different than the results for the individual layers. Bulk density was determined with a core sampler for the 0-10, 20-30, and 40-50 cm depth layers. Only the 0 - 10 cm layer in the plant row differed perceptibly from the other results, having a mean bulk density of 1.29 ± 0.08 Mg m⁻³. Mean bulk density of all other samples was 1.57 ± 0.04 Mg m⁻³. Water retention characteristics, with depth, for the soil at the site are presented in Fig C-2.1. Average slope of the field in the row direction is 1.7%. In light of these results, this plot was chosen for the experimental site.

c. Description of preliminary experiment: Combined effects of residue disposal and drip-lateral placement on yield (Abstract). See IX B for details

Growers in the region had noticed that in fields where chopped residues were incorporated in the center of the 2-row beds by the Uprooter-Shredder-Mulcher (USM), the residues did not disintegrate physically by the following spring, but remained as a buried "pipe" about 15 cm in diameter at a depth of about 30 cm. Furthermore, in some of these fields there was appreciable non-uniformity of plant height between rows adjacent to the same lateral. It was postulated that since drip laterals were laid with some slack, causing them to "snake" back and forth across the center line of the bed, the very large pores in the residue "pipe" interfered with unsaturated flow across the center line, thus causing water stress and poorer growth in the plants further from the lateral. ↓

Four residue disposal treatments included incorporation at 30 cm, at 15 cm, mixing residues with the 0 - 20 cm layer, and complete removal. The drip laterals were fixed in place either on the center line of the bed, or 30 cm to one side of the center line.

In the plots where the drip laterals were displaced from the center line of the furrow, the rows nearer to the lateral consistently outyielded the far rows by 1.0 Mg ha⁻¹ (about 20% of

Fig. C-2.1. Moisture retention curve of field soil at beginning of experiment.

average yield), regardless of whether residues were incorporated in the soil in various patterns or were removed entirely. However, the average yield of the pairs of rows did not differ from the yields of row pairs with centered laterals, indicating that yield gain in the near row compensated for yield loss in the far row. Since the yield was not affected by the method of residue disposal, the yield difference between neighboring rows was evidently caused only by the uneven distance between the plants and the water supply. ||

d. Experimental design and treatments of main field experiment

Since the farming system called for use of 6-row equipment whenever possible, and the cotton is planted on 2-row broad beds, the smallest basic land unit suitable for an experimental treatment is six rows wide, consisting of three beds. This allows for the two outside beds to act as guard areas between adjacent treatments, with measurements taken on the center bed.

Nine tillage and residue disposal treatments were designed. Eight were based on primary tillage by the Uprooter-Shredder-Mulcher (USM). In the ninth treatment, the USM was used to pull and shred the cotton plants and broadcast them over the soil surface, followed by primary tillage consisting of deep plowing, to 35 cm, with a reversible moldboard plow. Because of the dead furrow left by plowing and the width required by a large tractor, this treatment could not be included in the randomized experimental design. The moldboard plowed area was therefore concentrated in one plot 24 rows wide at the eastern edge of the field (Fig. C-2.2).

The eight USM-based treatments were arranged in a randomized-block design in three replications. Twelve rows between replications and were left as border area to allow installation of temporary irrigation submains without exposing adjacent experimental plots to accidental flooding. The 150-m long rows were divided into two equal 70-m parts by a similar path where a header was placed, supplying water to the sprinkler system used to irrigate the northern half of the field during the first growing season. The southern half was drip-irrigated from manifolds fed by a permanent underground submain along the southern boundary of the field. In the subsequent two years the entire experiment was drip irrigated. The experimental treatments were as follows:

1. USM incorporated chopped residue in center of bed with a special subsoiler shank fitted with a funnel. Residues form a concentrated "pipe" about 15 cm diameter at a depth of 30 cm. Subsoiler shanks in the plant rows.
2. Residue broadcast on soil surface by USM, subsoiler shanks in plant rows. Residue incorporated by rototiller in the spring.
3. All residues removed for composting by USM with forage harvester attachment, subsoiler in plant rows as in preceding treatment. Rotary tillage in spring.
4. USM incorporated residue in center of bed; separate pass with paraplow to a depth of 45 cm in plant rows (in February 1987 the paraplow shanks faced inwards, necessitated by the wetness of the soil, although the plan called for outward facing shanks; in subsequent years shanks faced outwards, to break up the compacted soil under the wheel track). Rototiller in spring.
5. Shallow (0-15 cm) incorporation of residues by USM in center of bed, subsoiler to 30 cm depth in plant rows. Mixing of residues with soil in the spring by rototiller.
6. Vertical mulching in wheel track. Because the USM could only incorporate on its center line, the rig had to run offset by one row, the wheels thus running on the bed center, subjecting it to abnormal compaction. Bed tilled by rototiller.
7. Removal of residues and tillage as in Trt. 3; application on April 1, 1987, of approximately 10 t ha⁻¹ of a 1:1 (v/v) mix of cotton stover and manure, incorporated by rotary tiller.
8. Like Trt. 2, but inward facing paraplow instead of subsoiler.
9. Residues broadcast on surface by USM, incorporated by deep moldboard plowing (35 cm).

e. Crop history

Summer 1984	Fourth year of commercial cotton
Winter 1984/85	Canning peas
Summer 1985	Fallow, deep tillage in August by Paraplow to 50 cm
Winter 1985/86	Fallow

Figure C-2.2. Map of experimental field and experimental design.

Summer 1986	Uniform crop of drip-irrigated cotton. Detailed field measurements and soil sampling to describe initial condition of experimental field
November 1986	Commercial crop harvested. Due to heavy early rains, the harvest was carried out late and on moist soil (approximately at field capacity). This resulted in compaction of bed center by rear wheel of picker
December 8, 1986	Field measurements and soil sampling
January 1987	Field measurements and soil sampling
February 1987	Initial application of differential tillage treatments
April 20-25, 1987	Ridging, herbicide spray, shallow tillage and bed forming by rototiller, planting of cotton
Apr.-May, 1987	Field measurements and soil sampling
July 14, 1987	Penetrometry
October 13, 1987	Harvest (first after imposition of treatments)
November 22, 1987	Field measurements and soil sampling
December 5, 1987	Second execution of differential tillage treatments
January 3, 1988	Field measurements and soil sampling
March 28, 1988	Field measurements and soil sampling
April 11, 1988	Furrow-dam removal and ridge renewal by ridger. Field measurements and soil sampling.
April 30, 1988	Sowing of cotton
May 16, 1988	Field measurements and soil sampling
June 1988	Field infiltrability determinations
October 10, 1988	Harvest
Dec. 1-7, 1988	Primary tillage and seedbed preparation for wheat to be sown on broad beds, preserving the traffic lanes
December 7, 1988	Penetrometry and soil moisture sampling
December 13, 1988	Sowing of wheat
February 27, 1989	Field measurements and soil sampling
April 1989	Field infiltrability determinations

f. Measurements

i. Penetration resistance

Vertical profiles were taken at 5-cm depth intervals to a depth of 40 - 50 cm with a recording resistance penetrometer equipped with a 30° cone and 20 mm base diameter (For pictures and details of the instrument, see Section V.C.2.h and Appendix IX.D). At each site a series of probings were taken along a transect perpendicular to the plant row direction, spanning the space between two wheel ruts. Measurements were taken at least in the center of each rut, in the plant rows, and in the center of the inter-row space (Fig. C-2.3). Occasionally, profiles were taken at 10 cm lateral intervals along the traverse. The periodic measurements were carried out on two transects running across Replication II of the experiment and across the plowed plot.

ii. Bulk density

Bulk density was determined at the same locations as the penetration tests, for the 0-10 cm, 20-30 cm, and 40-50 cm layers, using a core sampler of 4.9 cm diameter, with a volume of exactly 100 mL. Mass wetness of the samples was determined by oven drying.

iii. Tensile strength

The tensile strength of most of the above core samples was determined in an unconfined compression apparatus after oven-drying.

iv. Water infiltrability

The field infiltration function was determined on two dates by a recording double ring flooding infiltrometer using the farm irrigation water. The inside ring was a 0.5 m² steel square (0.707 x 0.707 m) driven about 0.1 m into the ground, and the outside "ring" consisted of a pond bounded by earth levees enclosing three infiltrometers, placed over the wheel rut, the plant row, and the inter-row space, respectively. (For pictures and details of the equipment see Section V.C.2.g.)

Figure C-2.3. Cross-section of broad bed during growing season.

v. Aggregate size distribution

Surface soil samples weighing between 1.5 and 2.0 kg were taken to the laboratory, air dried, and sieved on an oscillating shaker through a sieve stack with the following sieve openings: 0.25, 0.50, 1.0, 2.0, 4.0, 8.0, 12.7, 25.4 and 50.8 mm. The mean weighted diameter was calculated from the weights of fractions retained on each sieve.

vi. Soil moisture characteristic

The moisture retention curve of field and laboratory soil samples was determined in the 0-50 kPa range on a suction table. In the 0-7.5 kPa range the samples were placed on a bed of very fine sand, and suction was applied by means of a hanging water column. In the 10-50 kPa range the samples were placed on a clay membrane on top of the sand bed, and suction was applied by means of a hanging mercury column.

vii. Hydraulic conductivity

Undisturbed core samples taken from the laboratory incubation experiment were saturated from below, and their saturated hydraulic conductivity was determined by placing the sample retainers in a vertical permeameter and measuring flux under a constant downward gradient.

viii. Organic matter content

Organic matter content in the soil was determined by the dry combustion method.

g. A new design for a recording field infiltrometer

The ability to carry out a number of field measurements simultaneously is of obvious importance to the cost of field operations. The possibility of achieving this aim depends on the cost of multiple instruments or primary sensors, the amount of human supervision required, and on the ability to record data automatically. To date most infiltrometers did not have the features required for unattended operation.

We faced the need to determine the field infiltration function under a number of tillage treatments, and of several tillage zones within each treatment. On each date, each replication required a total of 12 separate runs, and preliminary tests showed that in some cases it was not possible to be certain that the final intake rate was reached unless at least 3 hours had passed. Sprinkling infiltrometers were eliminated from consideration because they inevitably result in compaction and trampling in the vicinity of the experimental site, and also due to their high cost. Double-ring infiltrometers were therefore chosen for this purpose.

Water can be supplied to the inner ring of such an infiltrometer either with a falling head device, or with a fluctuating-head (quasi constant head) arrangement. The latter may be a Mariotte bottle, or may simply consist of periodic, manual addition of water to the inner ring. In either case, frequent refilling of water requires the constant presence of an attendant. In principle, the head of water in either the supply container or in the ring can be sensed by a float device and recorded on a drum type chart recorder attached to each infiltrometer. It would also be possible to use a float-activated potentiometer or other type of sensor, which in turn would send electrical signals to a central analog recorder, or through an analog-to-digital converter to a digital recorder. All these options suffer from a number of drawbacks, both technical and economic.

In our case we wished to determine at each sampling location the infiltration function in the wheel rut, the plant row, and the inter-row space in a cotton field. The scale of expected variability due to the action of tillage implements was such that we chose an inner ring in the form of a 0.5 m² steel square (0.707 x 0.707 m) driven about 0.1 m into the ground, and the outer "ring" consisted of a pond bounded by earth levees enclosing three infiltrometers (Plate V-C.1). The water depth in each ring was controlled by an inexpensive float-activated valve of the type used in toilet flush tanks, mounted in a hole drilled through the bulkhead of the steel ring frame. The turn-off point of the valve relative to water depth in the ring was adjustable by means of a screw at the hinged end of the float arm (Plate V-C.2). An additional valve was mounted on a stake and installed in the outer ring to control the depth of water in the buffer area. The float valves in the rings maintained a quasi-constant head of water of approximately 0.05 m, fluctuating less than 0.01 m.

The amounts of water delivered to the rings were measured by precision 1/2" water meters designed to measure injected fertilizer solution in computer-controlled irrigation systems. To

Plate V-C.1. General view of double-ring infiltrometer installation.

Plate V-C.2. Detail of float mechanism and water meter pulse output.

meet this need, the rotating shaft of the meter carries a magnet which activates a microswitch once each revolution, closing a circuit and generating an electrical pulse, thus functioning as an event marker. Each revolution represents 0.1 L. Since these meters are a standard product manufactured in large numbers, they are inexpensive. Each of the three meters was connected to a battery-operated digital micro-logger (Campbell Model 21-X), which recorded the time at which each pulse was received, and also supplied the excitation voltage for the microswitch signal. With the time required for each 0.1 L being known, the discharge can be calculated. With the size of the rings used, each pulse represented an applied depth of 0.2 mm of water, a resolution adequate for our purposes.

The water supply for the infiltrometer installation was taken from the nearest riser of the farm network of underground irrigation pipelines, by means of 32 mm O.D. plastic tubing. The instrumentation made it possible to carry out one to two daytime runs of 3-hour duration. Once a run was started up, which requires some valve adjustments and levee repairs, personnel was freed to install an additional set of infiltrometers for a following run, and to carry out other tasks. An additional, unattended overnight run was activated towards the end of the working day.

The equipment proved to be easy to install and operate, reliable and cost effective. Further data processing of the micro-logger output on a PC type computer was straightforward and convenient. Examples of the results obtained are found in Section V.D.2.a.vi.

h. A new design for an inexpensive recording penetrometer

Execution of the project required a recording penetrometer, but none of those available met our criteria of portability, ease of data handling, and cost.

A compact and inexpensive soil penetrometer with a digital recording system was designed and constructed. Force is measured by a temperature compensated full-bridge load cell, and depth by a proximity switch activated by metal plugs in a plastic slide rod. The concentration of all signal conditioning and data processing functions in a non-dedicated miniature data logger is the key to achieving both major savings in equipment cost and a compact and lightweight field instrument. The cost of the penetrometer itself is less than \$400.

The Campbell CR-10 data logger used can store about 500 lines of information, each including depth, force, and various identification and control codes. However, memory is essentially unlimited as the contents of the logger memory can be dumped to a cassette tape recorder at any time in the field. Field tests have shown that a single operator can easily perform 150 penetrations an hour to a depth of 50 cm. The actual speed depends mainly on the distance to be walked between sampling points.

The data, which are arranged by the logger in tabular form are downloaded at the end of a working day to a spread sheet resident in a personal computer, after which they can be directly processed to calculate various indices and present the results in tabular or graphic form.

A detailed description of the instrument is presented in Appendix IX.D, and detailed results are to be found in Section V.D.2.a.1.

D. Results and discussion

1. Modeling results

a. Wheat yield data

Precipitation for the fallow-cropping seasons investigated were all below normal with the 1978-79 crop experiencing the least cropping season (September-July) rainfall (316 mm, 21% below normal). During the critical spring growth and grain filling period (April-July), the 1979-80 crop experienced only 168 mm precipitation (40% below normal) compared to 226 and 276 mm for the 1978-79 and 1980-81 crops, respectively.

Analysis of data show that grain yield (Table C-1.2) was not affected by tillage during the 1978-79 or 1980-81 cropping season. A 10% reduction in yield was measured for the nonfertilized no tillage treatment compared with fertilized no tillage (Power et al., 1984). Below normal precipitation suppressed grain yield during the 1979-80 growing season when the plow, sub tillage and no tillage treatments produced 81, 78, and 71% of the mean grain produced by the respective treatments during the entire study (1978-1982; Table C-1.2).

b. NTRM

Several modifications were necessary to make the model operational for winter wheat. First, the model was changed to allow simulation from one calendar year to the next. This was

Table C-1.2. Measured and simulated grain yield of winter wheat grown with and without addition of nitrogen fertilizer under three fallow tillage practices.

Tillage	Nitrogen	Measured	Grain yield			
			Simulated			
			NTRM	Deviation [†]	EPIC	Deviation [†]
	kg ha ⁻¹	kg ha ⁻¹	kg ha ⁻¹	(%)	kg ha ⁻¹	(%)
1978-79						
Plow	0	3039	5821	91	4500	48
	45	3035	5802	91	4650	53
Subtillage	0	2901	5434	87	4500	55
	45	3009	5294	76	4650	54
No tillage	0	2917	7533	158	4500	54
	45	3050	7440	144	4170	38
LSD (0.05)-Tillage		NS				
Nitrogen and Tillage*Nitrogen		155				
1979-80						
Plow [‡]	0	2443	2421	-1	3300	35
	45	2458	2294	-7	3280	33
Subtillage	0	2194	2320	6	3300	50
	45	2335	2320	-1	3280	40
No tillage	0	1831	2646	44	2760	51
	45	2187	2698	23	2520	15
LSD (0.05)-Tillage		223				
Nitrogen and Tillage*Nitrogen		158				
1980-81						
Plow	0	3626	6667	84	4100	13
	45	3534	6480	83	4210	19
Subtillage	0	3214	5812	80	4090	27
	45	3761	13980	271	4210	12
No tillage	0	3342	21140	532	4080	22
	45	3596	11180	210	4190	16
LSD (0.05)-Tillage		NS				
Nitrogen and Tillage*Nitrogen		162				

[†] Deviation = [(simulated-measured)/measured]*100

[‡] Data used for calibration of NTRM.

required for winter wheat (as well as any winter annual crop) which is planted in fall and harvested the following summer. Within NTRM a subroutine, YSET, controls initialization of all variables and simulated results. YSET was changed so initialization occurred one day after harvest and not at the end of the calendar year. Thus, simulated results were carried from planting to harvest without disruption of information flow.

A second modification was to set all non-positive soil temperatures in SOILTEMP and NTRM to small positive values. This was done to avoid the undefined calculation of the logarithm of non-positive numbers.

The second modification may have contributed to a third problem; unrealistically great development and growth during the periods of low temperatures (winter). When this problem was presented to the model's author, a third modification was introduced. A parameter was added to define the period of no development and growth, "dormancy". We question the existence of dormancy in winter wheat and feel that in the future the model should be modified to provide a more realistic view of the plant's response to environmental conditions during periods of low temperatures. Low temperatures should interact with the accumulation of thermal time and through it and temperature dependent metabolic activity limit development and growth, not the artificial imposition of dormancy.

The model was calibrated to the site conditions using the most complete field data set available from the wheat-fallow field study, 1979-1980. Soil, plant, weather, and management data for the plow treatment was selected as the calibration data set. While model documentation indicates calibration is necessary, it does not clearly specify steps to use in conducting the calibration. The following calibration procedures (suggested by the model's author) were used in this study.

Three crop coefficients--leaf area, total dry matter, and grain yield--were separately and systematically changed and simulated results compared with field observations [for a description of the coefficients, reader may refer to Shaffer and Pierce (1987)]. Coefficients were changed in the order listed. When the change in a coefficient resulted in $< 5\%$ difference between simulated and measured values for the affected parameter, the coefficient was assumed to be properly adjusted and the next coefficient was changed with the same success criterion. After each coefficient was adjusted to meet the stated criterion, it was not modified during that calibration effort. When all three coefficients, in sequence, met the $\pm 5\%$ criterion the model was considered 'calibrated'. Crop coefficients obtained were 0.0090, 0.45, and 1.70 for leaf area, total dry matter, and grain yield coefficients, respectively. These coefficients were used for all treatment-year combinations, unless stated otherwise.

Simulated total dry matter production for all tillage treatments for the 1979-1980 season followed a similar pattern (Fig.C-1.2). Approximately 30-50% of the total dry matter was produced before winter. Because of the model assumption that wheat has a "dormant" period, no growth occurred during that period. Growth after "dormancy" was nearly linear until about 40 days before harvest. Generally, simulated total dry matter at physiological maturity agreed well with measured mean total dry matter.

Simulated grain yield agreed well ($\pm 7\%$) with measured grain yields for the plow and sub-tillage treatments during the 1979-80 season (Table C-1.3). However, grain yield was overestimated from 23 to 44% for the no tillage treatment for the same season. For the 1978-79 cropping season the model overestimated grain yield by at least 76% for the various treatments. Generally there was no substantial differences in simulated results between treatments with or without N fertilizer except for the sub-tillage and no-tillage treatments during the 1980-81 season. Erratic overestimations, from 80 to 530%, were observed for the 1980-81 cropping season.

In an attempt to evaluate the performance of the model for calibrations with a range of measured yields, the model was recalibrated using data from the plot producing both maximum and minimum measured main yields among the 4 replications for the nonfertilized, plow treatment during the 1979-80 season. In each case the procedure outlined previously was used to recalibrate the model. Calibration for the maximum resulted in 0.0085, 0.50, and 1.85 for the leaf area, total dry matter, and grain yield coefficients, respectively; whereas, calibration for the minimum resulted in coefficients of 0.0080, 0.35, and 1.47, respectively.

Figure C-1.2. Measured and simulated (NTRM and EPIC) dry matter production of winter wheat for all tillage treatments during the 1979-80 growing season. Arrows indicate the date of planting. Observed values are of four replications on two dates (days 366 and 396 of imulation).

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Table C-1.3. Deviation of NTRM simulated grain yield from measured maximum and minimum (among replications) yields when model was calibrated to maximum and minimum yield for the plow treatment during the 1979-80 season, respectively.

Tillage	Measured grain yield		Deviation [†]	
	Maximum	Minimum	Maximum	Minimum
	-----	kg ha ⁻¹ -----	-----	% -----
1978-79				
Plow	3215	2623	72	10
Subtillage	3221	2340	74	19
No tillage	3241	2609	70	79
1979-80				
Plow [‡]	2569	2280	-1	8
Subtillage	2280	1964	-12	-27
No tillage	2004	1715	-44	-45
1980-81				
Plow	3847	3268	153	9
Subtillage	3726	2710	89	32
No tillage	3544	3100	281	378

[†] Deviation = [(simulated-measured)/measured]*100

[‡] Data used for model calibration.

Simulation results were sensitive to crop coefficients used in calibration (Table C-1.4). Except for the 1979-80 season and no tillage in the 1980-81 cropping seasons, simulated results from calibration with minimum values gave smaller deviations than results from calibration with maximum or mean values (Table C-1.3).

Tillage operations naturally affect physical properties of the soil layer upon which tillage is performed. Tillage operations are intended to control weeds, loosen the soil, and hence, create a layer of soil which is more desirable for crop development and growth. These conditions may contribute to greater hydraulic conductivity, less surface runoff, and greater water storage. These physical conditions then may be translated into modified crop development, growth, and yield.

NTRM was developed to simulate the effects of several management practices, including tillage, on crop yield. At the time of tillage, the model reduces bulk density in the tillage layer. This layer of soil subsequently reconsolidates over time to approach a predetermined bulk density called "stabilized bulk density" (SBD) in the model. Predicted grain yield was quite sensitive to the input values for SBD (Table C-1.5). Model grain yield predictions ranged from 1253 to 5489 kg ha⁻¹ as SBD was changed from 1.0 to 1.6 Mg m⁻³, a range encountered in most agricultural soils.

Similar to results from changing SBD, no distinct trend in the variation in predicted grain yield was observed when initial soil bulk density was changed systematically while using 1.44 Mg m⁻³ for SBD (Table C-1.6). The model generally simulated grain yield well ($\pm 20\%$) compared with the measured grain yield. However, at specific bulk density (1.10 and 1.45 Mg ha⁻¹) values, NTRM was unrealistically sensitive to extremely small changes in soil density. Such minor changes of bulk density in the field seldom translate to measurable yield differences. Saturated soil water content (another input variable) was changed accordingly with changes in bulk density.

To further evaluate the flexibility of NTRM as a tool for evaluating tillage management systems, depth and number of tillage operations were varied within the general conditions of the 1979-80 plow treatment. Simulation of one tillage operation on either 5 June or 31 July to depths up to 400 mm resulted in essentially no difference in predicted grain yield (Table C-1.7). However, when the tillage depth was increased to 500 mm on either date, predicted yield increased by nearly 100%. A tillage depth of 500 mm may be unrealistic enough to justify the observed difference in yield prediction. Number of tillage (plow) operations (1 to 3) to a depth of 100 mm did not substantially influence predicted grain yield (Table C-1.8). However, addition of a fourth tillage event increased predicted yield by approximately 100%.

c. EPIC

Dry matter predictions for tilled (plow and sub tillage) treatments were the same (Fig. C-1.2). EPIC predicted approximately 2000 kg ha⁻¹ dry matter production for the tilled treatments before the onset of winter slowed growth. In contrast, nearly 5000 kg ha⁻¹ dry matter was predicted in the no tillage treatment. Although no field observations were made at that time, the predicted autumn dry matter production for the no tillage treatment seems unrealistic. EPIC predicted loss of dry matter during the winter. Total dry matter production during the spring and summer growth period agreed very well with field measurements.

Although EPIC over predicted grain yield for the 18 treatment-year combinations tested by 10 to 55% (Table C-1.3), results were nearer the measured yields than those simulated by NTRM, except in the year of calibration (1979-80). As was the case with dry matter, EPIC predicted the same grain yield for both tilled treatments (plow and sub tillage), within a nitrogen rate treatment. Lack of difference between predictions for tilled treatments suggest the model may lack sensitivity to factors critical in separating of crop response to tillage.

Grain yield predictions from EPIC in response to changes in initial soil bulk density were essential the same (Table C-1.6). Predictions ranged from 3300 to 3460 kg ha⁻¹. The change in yield prediction occurred between 1.40 and 1.60 Mg m⁻³. Changes in time, depth, and number of tillage operations produced yield predictions of 3300 kg ha⁻¹ (Tables C-1.7 and C-1.8). The general lack of sensitivity of EPIC to tillage or tillage related factors was a severe disappointment.

Table C-1.4. Sensitivity of NTRM grain yield predictions to varying levels of "stabilized bulk density".

Stabilized bulk density	Predicted grain yield
Mg m ⁻³	kg ha ⁻¹
1.00	1253
1.10	5489
1.20	2494
1.25	2603
1.30	4018
1.40	2896
1.45	2796
1.50	2609
1.60	3734

Table C-1.5. Sensitivity of NTRM and EPIC grain yield predictions to varying levels of initial bulk density.

Initial bulk density Mg m ⁻³	Predicted grain yield	
	NTRM	EPIC
	kg ha ⁻¹	
1.00	1550	3300
1.10	4270	3300
1.15	2560	3300
1.20	2790	3300
1.22	2820	3300
1.24	2860	3300
1.26	2720	3300
1.28	2400	3300
1.30	2470	3300
1.32	2470	3300
1.40	2650	3310
1.45	6630	3310
1.50	2400	3320
1.55	2400	3420
1.60	2200	3460

Table C-1.6. Sensitivity of NTRM and EPIC grain yield predictions to varying depth and date of tillage.

Date	Depth mm	Predicted grain yield	
		NTRM	EPIC
		-----	-----
		kg	ha ⁻¹
5 June	100	2835	3300
	200	2975	3300
	300	2975	3300
	400	2610	3300
	500	5865	3300
31 July	100	2835	3300
	200	2775	3300
	300	2775	3300
	400	2485	3300
	500	5865	3300

Table C-1.7. Sensitivity of NTRM and EPIC grain yield predictions to varying the number of tillage operation (moldboard plow).

Number operations	Predicted grain yield	
	NTRM	EPIC
	-----	-----
	kg	ha ⁻¹
1 (April 15)	3350	3300
2 (April 15, and May 15)	3350	3300
3 (April 15, May 15, and June 15)	3350	3300
4 (April 15, May 15, June 15, and July 15)	5865	3300

Table C-1.8. Measured and simulated seed cotton yield for various tillage and residue management practices during the 1987 season grown at Nahal Oz.

Treatment number	Seed cotton yield		Deviation [†] (%)
	Measured ----- kg ha ⁻¹ -----	Simulated -----	
1	4480	3700	-17
2	5590	3700	-34
3	5990	3700	-38
4	4940	3700	-25
5	4990	3700	-26
6	5050	3700	-27
7	5810	3710	-36
8	4710	3700	-21
9	4950	3700	-25

[†] Deviation = [(simulated-measured)/measured]*100

d. Cotton

Initial evaluation of NTRM identified several problems with the model's capability to be successfully used outside its domain. The model has been developed (Shaffer and Larson, 1987; Shaffer and Pierce, 1987) and used (Swan et al., 1987) to evaluate corn (*Zea mays* L.) management practices. Little effort has been directed to its application to other crops. Results with winter wheat indicated limitations exist; also, the spectrum of tillage tools from which to choose is limited to moldboard plow, chisel plow, tandem disk, and no tillage. These tools cover the range normally used in corn production in the U.S., but not those under investigation in this project. Therefore no attempt was made to evaluate the predictive capability of NTRM under the Israeli conditions.

The EPIC model offers a much broader range of tillage tool options. Unfortunately, some of the new tillage and residue disposal practices evaluated for cotton production were still beyond the range of this model. In these cases, tillage tools which resulted in similar action on the soil were selected.

EPIC under estimated seed cotton yield by approximately 25% (Table C-1.8). Again, the predictions were essentially the same for all treatments. As with the other evaluations of EPIC reported above, it appeared the model lacks the necessary sensitivity to tillage and residue practices to provide insight into the advantages and disadvantages associated with various management schemes.

Although simulation models may provide an economical and convenient method of analyzing crop management practices, the results of these analyses are largely a function of the characteristics of the model employed in the exercise. NTRM and EPIC appear to be the models of choice to analyze tillage and residue management practices. However several situations limit the usefulness of the models.

Although documentation (Shaffer and Pierce, 1987; Shaffer and Larson, 1987) states that NTRM is applicable to a number of agronomic crops, modifications found necessary to make the model functional with winter wheat imply tests of the validity of the statements made in the documentation were not rigorous. Use of algorithms which preclude consideration of temperatures $\leq 0^{\circ}$ C is extremely unfortunate and severely limits the application of the model in temperate climates where these temperatures may occur during the growing season of many crops, including summer annuals. The need to use "dormancy" to limit growth of winter wheat during the winter months suggest the development and growth routines are not sufficiently limited by temperature to provide realistic predictions of growth and yield.

Rather large and erratic deviations between simulated (NTRM) and measured grain yields for the 1980-81 cropping season may have resulted from several factors. One factor contributing to the discrepancy may be the absence of some meteorological data (solar radiation, evaporation, and wind speed) for the experimental site. Data from a station about 80 km north of the experimental site was used.

Comparison of results simulated by the NTRM between treatments within the year of calibration were reasonably accurate. However validity of year-to-year comparison of simulation results may depend upon year-to-year variability of crop coefficients as well as meteorological conditions. This implies that for better and more consistent results the model must to be calibrated for different years, especially if meteorological conditions differ substantially. With limited field data for validation, yearly recalibration is impractical and severely restricts the general usefulness of the model, especially in continental climates which are characterized by large year-to-year variation in weather conditions. These observations of model performance agree with those of Swan et al. (1987) who indicated that large variations between simulated and measured yields can occur from one year to the next based on the total precipitation and its seasonal distribution. Furthermore, they concluded, and we concur, NTRM must be revalidated if it is applied to different climatic, soil, or cultural regimes.

NTRM's sensitivity to soil physical properties is evident. Changing simulated results from changing crop coefficients is reasonable. However large and unexplainable variation in simulated results related to small changes in bulk density do not reflect field observations.

In light of our partial success with NTRM, we conclude major changes in the model are necessary for continued use in assessing potential value of management practices. Specific

suggestions for improvement are: 1. Allow simulation with input temperatures $\leq 0^{\circ}\text{C}$; 2. Generate a more realistic mechanism for low temperature to limit crop development and growth; and 3. Reduce sensitivity of NTRM to both stabilized soil bulk density and initial soil bulk density. Incorporation of these modifications are beyond the scope of this project. Thorough, accurate, and easy-to-use documentation and user interface would also greatly enhance the usefulness of both models by other scientist.

Although EPIC did not predict any crop yields as well as NTRM did within the year for which it was calibrated, EPIC, did not produce the erratic results characteristic of NTRM. However, where NTRM seems overly sensitive to factors influenced by tillage, EPIC appears very insensitive. EPIC predicted yield differences among years and between nitrogen rate treatments. EPIC seems to function with greater emphasis placed on responding to nitrogen fertilization and weather characteristics than impact of tillage and residue management practices on crop yield.

2. Field and residue management results

a. Treatment effects on soil (between and within treatments)

i. Penetrometry

The subjects of interest with regard to the effect of tillage operations on penetration resistance are: 1. Differences between treatments on a given date, i.e. at a particular stage or after a particular operation; 2. Differences between various zones of a given treatment; and 3. Changes in a given treatment with time during the tillage cycle.

The treatments can be separated into several groups based on the implement configuration:

1. Primary tillage by plowing, crop grown on beds, with no attempt to maintain permanently located wheel tracks in either operation (Trt. 9);
2. Primary tillage in permanent traffic lanes by USM, with some sort of subsoiler shanks in plant row, and residue incorporation in bed center by a special subsoiler shank equipped with funnel (Trt. 1, 4, and 5);
3. Primary tillage by USM, but without incorporation in bed center and without subsoiler shank in bed center (Trt. 2, 3, 7, and 8); and
4. Because the equipment was not suitable for the purpose, Trt. 6 reflects undesirable artifacts, and was generally not included in the comparisons.

Changes during time in selected treatments: In all the treatments except Trt. 9 (plowing), the resistance isobars tended to have the general shape of a "W", with resistance peaks in the wheel tracks and the bed center, and resistance minima in the plant rows where the subsoiler shanks were located (Fig. D-1.1). This was sometimes true even for the treatments where residues were incorporated in the bed center, although the height and shape of the middle peak differed from those without subsoiling on certain dates (Fig. D-1.2). While this pattern was modified, especially in the 0-10 cm layer, by secondary tillage operations such as seedbed preparation by rotary tiller, the general pattern tended to persist throughout the entire experimental period. Analysis of the many resistance distribution patterns shows a consistent difference between the shape of the 3- and 5-bar isobars, which are generally parallel and close to each other, and that of the 8- and 10-bar isobars, which also generally form a similar pair. This difference in shape indicates that the boundary between the effect of shallow secondary tillage, e.g. rototiller, and the results of primary tillage lies somewhere between the 5-bar and 8-bar isobars. On the whole, the depth of the 10-bar isobar under the beds fluctuated within a fairly narrow depth range throughout the various tillage cycles - between a minimum of about 20 cm and a maximum of 40 cm. The tillage operations wiped out the effect of compaction on the bed and restored the 10-bar isobar to the greater depth after each primary tillage.

The resistance to penetration on the bed centerline tended to be highest after harvest, immediately before fall tillage. The most likely reason for this is that although harvesting is planned for the period when the soil is driest, prior to the winter rains, in fact many fields are picked only after early fall rains. The vast majority of the cotton pickers used have a single rear wheel which rides on the bed centerline, and if the soil is moist, this no doubt causes some compaction. The soil moisture content below about 15 cm was quite similar on all sampling dates, between 15 and 18%.

Comparison between Trt. 1 and 4 on the one hand (incorporation of residues on the centerline of the beds) with Trt. 2 (no subsoiler on the centerline) shows the effect of the center

Fig. D-1.1. Distribution of penetration resistance (bars) under 2-row bed, Treatment 2, 7-14-87.

Fig. D-1.2. Distribution of penetration resistance (bars) under 2-row bed, Treatment 4, 7-14-87.

shank not only as an additional loosened track of a cut (in most cases), but also in the overall shape and size of the loosened volume, and in a somewhat smaller depth of penetration where the tractor had to pull three subsoiler shanks rather than two.

The USM deposited the chopped cotton residues in a distinct "pipe" under the bed centerline in Trt. 1 and 4, which was easily found in every case by excavation (Plate V-D.1). This pipe had a diameter of about 15 cm, and its axis was at a depth of 25-30 cm. Nevertheless, neither the presence of the pipe nor the effect of subsoiling was clear and prominent in most of the resistance data, although a major effect could have been expected.

Conditions preceding tillage: These are represented by the data of November 1987, taken shortly after harvest. Conditions are similar in all the treatments. Compacted zones are found in the main wheel tracks where machinery passed several times since imposition of the treatments, but also on the centerline of the beds, where only the rear wheel of the cotton picker passed once during harvest. On this date the compacted zone under the main wheel tracks was already 60 cm wide. Under the plant rows there is a zone of low resistance, probably caused by a combination of factors: Absence of wheel traffic, effect of decayed roots, and the passage of a subsoiler shank (Fig. D-1.3).

Conditions following tillage: If tillage has an effect on soil structure, this should be most pronounced immediately after tillage. A detailed comparison will be made between the measurements of January 24, 1988 and of December 7, 1988 (Figs. D-1.4, D 1.5).

1. In general, the observed effect of tillage was less deep in December than in the previous January. Since no change had been made in the adjustment of the implements, the probable cause is that on the later date the soil was appreciably drier: About 16% vs. 23% in the 0-10 cm layer, and 14% vs. 19% in the 20-30 cm layer (Figs. D-1.4, D-1.5).
2. In Trt. 1 (incorporation in bed center) one sees in December 1988 both the tracks of the subsoiler shanks in the plant row and a large friable area in the center of the bed, indicating soil shattering by the center shank. In contrast, in January 1988 there is an island of high resistance between the center a shank and one of the side shanks, indicating inadequate shattering, and more cutting effect. This is attributed to the soil being moister in January (Figs. D-1.6, D-1.7).
3. In Trt. 4 (incorporation in bed center, Paraplow shank facing outward in each plant row) the effect of all three subsoiler shanks is discernible in December 1988, while in January 1988 the effect of the center shank is not as clear. The tilled volume is wider and generally also deeper in this treatment than in Trt. 1, which shows the effect of the outward-facing Paraplow shank (Figs. D-1.8, D-1.9).
4. Trt. 2, 3, and 7 should be similar at this stage, since all of them were tilled by subsoiler in the plant row only (no incorporation), and they differ from each other only by the manner of residue management. The results of these treatments were indeed similar. Comparison with Trt. 1 and 4 shows that the bed center is equally friable in both groups, in spite of the fact that no subsoiler worked the bed center in these treatments.
5. In Trt. 8 (inward-facing Paraplow shank in plant row) the cut of the shank is narrower than that of the subsoiler shank in the comparable Trt. 2, with little evidence of lateral shattering or mixing of soil. The central area of the bed is less well loosened than after the subsoiler (Fig. D-1.10).
6. Trt. 5, with shallow incorporation (0-15 cm) of residues and shallower setting of subsoiler shanks, does not show a difference in depth of subsoiler action as compared to Trt. 1, but depth of tillage in the center of the bed is indeed shallower than in Trt. 1.
7. On both dates (January and December 1988), as well as in February 1989, after another deep plowing and seedbed preparation for wheat, there are visible "cells" of high and low resistance (Fig. D-1.11), each roughly 200 cm wide. The cause of the alternating cells is not clear, and may be due to the tractor or plow slipping off its course or poor steering by the driver. Before tillage, the "W-pattern" described for

Plate V-D.1. Buried residue "pipe" one year after incorporation.

Fig. D-1.3. Distribution of penetration resistance (bars) under 2-row bed, Treatment 4, 11-22-87.

Fig. D-1.4. Distribution of penetration resistance (bars) under 2-row bed, Treatment 2, 1-24-88.

Fig. D-1.5. Distribution of penetration resistance (bars) under 2-row bed, Treatment 2, 12-7-88.

Fig. D-1.6. Distribution of penetration resistance (bars) under 2-row bed, Treatment 1, 1-24-88.

Fig. D-1.7. Distribution of penetration resistance (bars) under 2-row bed, Treatment 1, 12-7-88.

Fig. D-1.8. Distribution of penetration resistance (bars) under 2-row bed, Treatment 4, 1-24-88.

Fig. D-1.9. Distribution of penetration resistance (bars) under 2-row bed, Treatment 4, 12-7-88.

Fig. D-1.10. Distribution of penetration resistance (bars) under 2-row bed, Treatment 8, 12-7-88.

Fig. D-1.11. Distribution of penetration resistance (bars) under 2-row bed, Treatment 9 (plowed), 1-24-88.

the other treatments was seen here as well, reflecting the wheel traffic pattern associated with secondary tillage operations for broad bed planting and harvesting.

Conditions at planting time: Another date of interest is immediately before or after sowing in the spring, as this represents the conditions faced by the young crop. Two sets of data are available for this analysis, taken in May 1987 and 1988, respectively. Comparison with conditions after primary tillage in the fall gives an indication of the persistence of the primary tillage effects after exposure to winter rains and secondary tillage operations.

In general, the fall tillage effects persisted through May, and were perceptible to a somewhat shallower depth in 1988 than in 1987. In contrast to the dates analyzed above, Trt. 1 clearly shows the effect of the incorporating subsoiler shank on the bed centerline (Fig. D-1.12) on both sampling dates, although the depth of tillage is distinctly shallower in 1988 than in 1987 in this treatment. Qualitatively, the patterns of both years are very similar, in that three minima are seen instead of the "W" pattern.

In Trt. 4, comparable to Trt. 1 in that residues were incorporated by subsoiler in the bed center of both treatments, the effect of the middle shank is less pronounced in 1987, and not discernible at all in 1988.

Treatment. 5, also comparable to Trt 1 and 4, though to a shallower depth of incorporation, clearly reflects the imposed difference in 1987, displaying three minima in the upper layer, and a "W" pattern below 20 cm (Fig. D-1.13). The 1988 data do not show the effect of tillage on the bed centerline.

As could be expected, Trt. 2, 3, and 7 were similar to each other in both years. Treatment. 8 is also comparable to these three, with any expectable difference being due to the shape of the subsoiler shanks. The effect of the Paraplow shanks is confined to a narrower and more sharply defined soil volume than the regular subsoiler shanks, and the loosened volume includes the 5-bar isobar, in this case definitely due to the Paraplow rather than secondary tillage operations.

Conditions in the plowed plot in May 1987 and 1988 are very similar. Since the observation was taken after planting and not immediately after tillage, one can see the effects of planting and cultivation operations in the form of compaction in the new wheel track position. By November 1987, after harvest but prior to tillage, one clearly sees the development of compacted zones in the main wheel tracks and in the bed center where the third wheel of the picker passed. In January 1988 one sees a deep "cell" of loosened soil, as was mentioned above. It should be noted that at the time of penetration tests there was no way of identifying where the wheel tracks of the previous season had been.

ii. Bulk density

Core samples for bulk density determination were taken prior to imposition of differential treatments, and on six dates during the experiment. The initial sampling was done on December 8, 1986, after harvesting. The land was in broad beds, with a shallow furrow on the bed centerline resulting from the rear wheel of the cotton picker. Samples were taken from the wheel track, the furrow on the bed centerline, and from the plant row at each of 25 grid nodes in the field, from the 0-10, 20-30, and 40-50 cm depths. These samples served for a uniformity test and to define the initial condition of the field. All the data except for those from the 0-10 cm depth in the plant row were found to come from the same population, having a mean bulk density of $1.55 \pm 0.02 \text{ Mg m}^{-3}$. The bulk density of the 0-10 cm layer in the plant row was $1.31 \pm 0.07 \text{ Mg m}^{-3}$. In parallel, samples were taken from an adjacent nature preserve, which can therefore be viewed as samples of virgin soil. The bulk density was found to be 1.56 Mg m^{-3} . During the experiment samples were generally taken on the same dates as penetration tests, from Trt. 1, 3, 4, 6, and 9, in the central of the three replications, along two transects 50 and 125 meters from the northern field boundary. Inspection of the data showed that while the bulk density of the 40-50 cm layer seemed to fluctuate slightly with time, no evidence was found of any effect due to tillage or location with respect to the traffic lanes. Since this soil does not exhibit appreciable volume changes due to swelling and shrinking, and since the soil wetness stayed within rather narrow limits, the fluctuations of the values are most likely due to differences of technique between operators on the various dates. The data for the 40-50 cm layer are thus not presented here. The data from the 0-10 and 20-30 cm layers are summarized in Fig. D-2.1. The upper layer shows larger changes with time as well as larger differences between treatments on a given date than is

Fig. D-1.12. Distribution of penetration resistance (bars) under 2-row bed, Treatment 1, 5-17-87.

Fig.D-I.13. Distribution of penetration resistance (bars) under 2-row bed, Treatment 5, 5-17-87.

Bulk Density by dates & treatments
0 - 10 cm layer, Bed center

Bulk Density by dates & treatments
20 - 30 cm layer, Bed center

Bulk Density by dates & treatments
0 - 10 cm layer, Plant row

Bulk Density by dates & treatments
20 - 30 cm layer, Plant row

Bulk Density by dates & treatments
0 - 10 cm layer, Wheel track

Bulk Density by dates & treatments
20 - 30 cm layer, Wheel track

Fig. D-2.1. Bulk density of field soil in selected treatments as a function of depth, tillage zone and date.

the case for the deeper layer. The open bar at the left of each graph shows the bulk density in the initial state. In general, the density in the wheel track is higher than the original value, around 1.65 Mg m^{-3} in the upper layer, and slightly less in the second layer. The relation between sampling dates and field operations was as follows:

December 8, 1986	After harvest, before tillage, following uniform treatment
April 28, 1987	After primary and secondary tillage, spring planting
November 22, 1987	After harvest, before tillage
January 3, 1988	After harvest and primary tillage only
March 28, 1988	After primary tillage and ridging
May 9, 1988	After seedbed preparation and planting
February 27, 1989	After harvest, primary tillage, seedbed preparation and sowing of wheat

In the bed center, the bulk density is on the whole lower than the original density, especially so in the upper layer. After one tillage cycle, in November 1987, the bulk density returned more or less to the original state, after having been lower than the original on April 28, following all tillage and planting operations. An exception to this general picture is Trt. 6, where incorporation of residues in the wheel track necessitated a tractor wheel pass on the bed centerline, something which would not normally be done if appropriate equipment were available. In contrast to the penetrometer data, the compaction on the bed is clearly visible in the surface layer, as is the lower density in this treatment in the wheel track.

Similarly, one can discern the desirable effect of residue incorporation in Trt. 1 after tillage, and also that the ridging operation preceding the sampling of March 28, 1988 apparently dispersed the residue pipe and exposed more compact underlying soil. Comparison with Trt. 3 (broadcasting of residues) shows that incorporation in a "pipe" has an effect on bulk density. On the other hand, Trt. 4, which should be similar to Trt. 1, does not show clearly the effect of residue incorporation.

Preparation of the land for wheat largely erased the effects of preceding differential treatments. When the land was after the cotton harvest and before tillage, compaction was at its worst, and yet bulk density generally did not exceed the original value on the broad beds, nor is there any evidence of a continuing long-term compaction process discernible over the period of observation.

In the plowed plot there was no possibility of identifying the location of the previous season's beds except immediately after harvest, as in November 1987. Nevertheless, there is a clear tendency for bulk density to be higher in the beds of the plowed plots. In the plant row differences between treatments were smaller than in the bed center. This is to be expected, since all except the plowed treatment received identical tillage by subsoiler shanks. Again, there is a trend towards higher bulk density in the plowed treatment, and bulk density in the 20-30 cm layer did not depart appreciably from the original state.

In the wheel tracks the bulk density exceeded the original value on most sampling dates, and since the wheel tracks themselves were not tilled, no recovery is seen after tillage, except of course in the plow treatment. It is also seen that the loosening achieved by plowing is quickly obliterated by subsequent tractor passes in the field.

In general, the bulk density results are consistent with the penetrometry data. However, due probably to differences in sampling technique (e.g. depth of layer per sample, radius of sampled volume, number of samples per unit width of bed), the two determinations evidently have a different sensitivity and spatial resolution. Thus the penetrometer showed the effect of the subsoiler shanks more clearly and to a greater depth. In general, bulk density response seemed to be limited mainly to the 0-10 cm depth layer. On the other hand, in a number of cases the penetrometer data did not reflect the presence of the residue "pipe" at the bed center, or the effect of vertical mulching in Trt. 6, whereas the bulk density showed this effect quite clearly.

iii. Aggregate size distribution

Aggregate size distribution by dry sieving was carried out twice: In the initial state, taken in June 1986, and at the end of May 1988. In June 1986 there was a stand of young cotton in the field, before imposition of differential treatments, and before the final choice of plot was made. One-half the area had received primary tillage in the fall of 1985 by deep plowing with a

moldboard plow, and the other half by Paraplow with the shanks mounted in parallel as a gang. Both halves were subjected to an identical series of secondary tillage operations such as ridging, cultivation, and rototiller during the course of the preceding winter and during seedbed preparation. By the sampling date the field had been subjected to all the operations that could have caused aggregate breakdown. Nevertheless, the plowed area gave a visual impression of being coarser and more cloddy than the area tilled by Paraplow. Surface soil samples were taken from 18 grid nodes in each half of the area for aggregate size analysis by dry sieving. The results indeed confirmed the visual impression: The MWD of the plowed half was 11.7 ± 3.1 mm, and that of the subsoiled half, 8.9 ± 1.8 mm.

The second sampling was taken at the end of May 1988, which was the last occasion when the field was in a condition comparable to the first sampling. Five surface soil samples each were taken from three treatments: Trt. 1 (control), where the cotton stalks had been uprooted, chopped, and incorporated in the bed center by the USM, and tilled in the plant row by subsoiler shanks mounted on the USM; Trt. 8, where the chopped material was broadcast on the soil surface, and tillage was done by two Paraplow blades facing inward under the bed; and Trt. 9 (plowed), where the residues were processed as in Trt. 8, and tillage was by deep plowing. The MWD values were 6.66, 5.75, and 8.15 mm for Trt. 1, 8, and 9, respectively. It can be seen that plowing consistently produced the coarsest seedbed, and Paraplow the finest. This is consistent with the results of resistance measurements by penetrometry (Section V.D.2.a.i), which also show the greatest soil disturbance by plowing and the narrowest cut by the Paraplow shank. It is important to note that at the level of secondary tillage intensity chosen each year by the farmer, the residual effects of primary tillage on aggregate size were not erased by the secondary tillage operations. While it is difficult to compare the two years quantitatively, since soil condition and the intensity of secondary tillage energy inputs are never quite the same from year to year, it can nevertheless be stated that there is no evidence of a cumulative effect leading to coarser aggregation that might be attributed to compaction. If anything, the clod size is smaller in 1988, but over such a short period this can not be taken as evidence of a trend.

iv. Organic material content

Soil samples for determination of organic material content were taken in triplicate on December 8, 1988, and on June 10, 1989. The December 1988 sampling was done immediately after the primary tillage and residue incorporation, and the samples were taken from the relevant soil layer: From the 10-30 cm depth on the center line of the bed of Trt. 1, and from the 0-30 cm layer from a trench across the bed in Trt. 2 and 9. In June 1989, after the wheat harvest, the samples were taken from the surface 10 cm, since the buried band in Trt. 1 had been scattered during seedbed preparation for the wheat. A similar sample was taken in April 1989 from virgin soil in an adjacent nature preserve, covered by a thin stand of herbaceous vegetation.

After removal of coarse plant fragments, samples were crushed to a fine powder, oven-dried at 105°C , weighed, and processed by dry combustion at 550°C for 8 hours, and weight loss was determined. We report this as "organic material" to emphasize that this is not stable Organic matter (humus) which is usually regarded as an intrinsic soil property at equilibrium with a particular site and land use. It must be assumed that some of the samples contained appreciable amounts of undecomposed plant residues, especially those from Trt. 1. As we mentioned in other sections (e.g. V.D.2.a.i and ii, Plate V-D.1), incorporated material was found physically intact as long as one year after incorporation. The intrinsic, stable organic matter content of this soil at equilibrium with an intensive irrigated crop rotation is in the range of 1.0 - 1.5%.

In the December 1988 sampling, the organic material content of Trt. 1, 2, and 9 (band incorporation at 30 cm; chopped residues scattered on surface and incorporated with rotary tiller; scattered on surface and deep plowed) was 7.16 ± 0.31 , 4.42 ± 0.06 , and $4.56 \pm 0.11\%$, respectively. In June, 1989, the values for the same treatments were 4.21 ± 0.06 , 3.85 ± 0.07 , and $4.40 \pm 0.20\%$, respectively. The sample from the nature preserve contained $2.91 \pm 0.21\%$ organic material.

It is estimated on the basis of the nature preserve data that stable organic matter content would be 50% or less of the above values. Residue disposal by scattering chopped straw on the soil surface and incorporating it by shallow rotary tillage resulted in a concentration of organic materials of about 4.5%, which decreased to about 4.1% during the following 6 months, a period

when soil moisture and temperature conditions were favorable to microbial activity. These values are distinctly higher than for virgin soil, and reflect the incorporation of about 4,000 kg ha⁻¹ of cotton straw, which contains a large proportion of material that does not decompose easily. The results from Trt. 1 in 1988 clearly show the effect of concentrated residue incorporation, which reverts to normal after mixing of the soil in the following spring. These results are consistent with those of the long-term observations on the permanent plots (Appendix IX.E), which show that continuous additions of fertilizer and organic residues produced but a very small increase in soil organic matter, and no persistent improvement of structure.

v. Soil strength

Soil core tensile strength was determined on six occasions between January 1987 and May 1988. The cores used were the same ones on which bulk density was determined, and were in the oven-dry state when tested with an unconfined compression apparatus.

Overall, the soil strength data had a much higher coefficient of variability than did the bulk density (36% vs 6%). Inspection of the data and their standard deviations led to the conclusion that with a few exceptions, no differences between treatments could be detected. In the few exceptional cases, e.g., the bed center in Trt. 6, where there was wheel compaction due to an artifact discussed elsewhere, or in the wheel track and bed center after ridging, which removed friable soil, the results were expectable and obvious and added no new information. Therefore henceforth the discussion relates to values averaged over Trt. 1, 3, 4, 6, and 9.

The data were tested for a relation between bulk density and strength (Fig. D-5.1). A linear regression model of strength on bulk density yielded a correlation coefficient $r=0.8619$, and a regression of log strength on bulk density yielded $r=0.9015$. The logarithmic model is therefore moderately superior to the linear model. In terms of utility, soil strength is not an excellent estimator of bulk density, and since additional work is required above and beyond that required for determining the density, there is no practical advantage to the strength determination.

As was the case for bulk density, no differences can be detected in the 40-50 cm layer between the wheel track, bed center and plant row soil strength on any given date (Table D-5.1). Likewise, while there seem to be some differences between the average values of different dates, (different stages in the tillage cycle), they are not statistically significant, except for the higher strength in the initial, pre-treatment stage in January 1987.

The soil strength in the plant row was consistently, and in most cases significantly, lower than either in the wheel track or the bed center in the 0-10 and 20-30 cm layers. The differences are particularly pronounced in the 0-10 cm layer. Since the plant row reflects the combined and presumably additive effects of the root system, the mechanical effects of uprooting the plant, and the passage of the subsoiler shank, it is not surprising that tillage was best in this zone, as indeed it is intended to be. Seasonal changes show that the tillage operation made an appreciable contribution to the strength decrease (e.g., January 1987 vs. April 1987; November 1987 vs. January 1988).

The strength values of the bed center seem to form two distinct populations: Values <50 kPa, and values >150 kPa. The difference can be explained by reference to the tillage cycle. The high values are characteristic of the state after harvest but before tillage, or immediately after a ridging operation. Harvesting is the only operation where wheel traffic (the single rear wheel of the cotton picker) passes over the bed center, often on moist soil. The ridging operation scrapes up loose soil and throws it into the ridges, with the ridging tool generally penetrating to the lower boundary of loose soil, thus exposing more compact deeper layers. This is reflected by all the structural indices that were used. Prior to spring planting the ridges are destroyed and the surface reformed into broad beds, thus returning loose soil to the bed center, which explains the group of lower values after planting (April 1987, May 1988). The fact that the higher values in the bed center range between about 60% and 125% of the strength of the soil in the wheel track after only one traffic pass, demonstrates again that most of the compaction takes place after a single loading event.

The soil strength in the wheel track is generally somewhat lower in the 0-10 cm layer than in the 20-30 cm layer. This may be due to two causes: The top layer is generally drier than the underlying ones, and thus less prone to compaction; If tire slippage took place, the churning

Fig. d-5.1.1. Relation between log tensile strength and bulk density of undisturbed core sample of field soil.

Table D-5.1. Summary of soil strength by zone, averaged over treatments.

			----1-10	cm----	---20-30	cm---	--40-50	cm--
Date	Status	Zone	Strength	CV	Strength	CV	Strength	CV
			kPa	%	kPa	%	kPa	%
1987								
Jan 25	Initial state	Wheel track	159	7.5	255	30	209	40
	post-harvest	Ridge	73	29	141	13	233	9
	pre-tillage	Bed center	204	28	251	32	316	13
Apr 28	After tillage	Wheel track	147	42	260	23	160	45
	and spring	Ridge	36	108	79	43	135	77
	planting	Bed center	35	86	150	47	151	22
Nov 22	Post-harvest	Wheel track	256	53	241	26	176	42
	pre-tillage	Ridge	33	64	165	41	169	32
		Bed center	146	41	249	39	144	41
1988								
Jan 3	Post harvest	Wheel track	252	58	310	46	248	24
	post-tillage	Ridge	6	13	158	89	249	22
		Bed center	20	83	234	58	316	18
Mar 28	Post harvest	Wheel track	373	29	254	14	182	2
	post-tillage	Ridge	19	26	200	30	206	15
		Bed center	270	30	232	24	264	50
May 16	Post harvest	Wheel track	187	33	235	21	256	27
	post-tillage	Ridge	23	79	212	39	214	22
		Bed center	34	85	121	32	188	15

action of the lugs may have produced an effect similar to shallow tillage in the top layer. Expectably, the wheel track is the zone with the highest soil strength.

vi. Field infiltrability and effect of residue "pipe"

Infiltration runs: Infiltration determinations were carried out in June 1988 and in April 1989. At both times the field had undergone all the primary and secondary tillage operations according to the experimental design and was under a crop. In 1988 the crop was a young stand of cotton, which had received one cultivation after emergence. In 1989 the cover was wheat, planted on broad beds in the fall of 1988. A description of the equipment and procedures is given in Section V.C.2.g. Infiltration runs were made in Trt. 1, 2, 8, and 9, in order to obtain comparisons between concentrated incorporation of residues in the center of the bed by subsoiler and incorporation of broadcast residues by rotary tiller; between the action of conventional subsoiler shanks and inward-facing Paraplow shanks run in the plant row; and comparison between random plowing and permanent traffic lanes. With the exception of Trt. 2 in 1989, where only one run could be carried out, all runs were carried out in triplicate in 1988 and in duplicate in 1989. The averages of the results are summarized in Table D-6.1. The final rate by itself does not give all the relevant information, since the infiltration functions did not all have the same shape. This is demonstrated by the data on the time required to reach the final rate in the above table. Additional important information reflecting the shape of the functions is contained in the cumulative infiltration during the first 100 minutes, also given in the table. A number of trends are discernible in the data:

1. The final rates are consistently lower in 1989 than in 1988 (Table D-6.1. and Fig. D-6.1). Also, the differences between zones within treatments and differences between treatments are much less clear in 1989. The most probable cause of this is crusting. In 1988 whatever crust appeared in the field was due to a pre-irrigation by sprinkling. This crust was disrupted by the subsequent cotton planting operations and the cultivation. In the fall of 1988 wheat was sown in dry soil, and it germinated only following the early winter rains. These are more effective in crust formation than sprinkler irrigation because the rain drops have a higher terminal velocity, and because the distilled water is more effective in dispersion of the clay. Since no further tillage operations were carried out on the wheat, each rain which fell before the crop covered the soil surface contributed something to crust formation. With the crust being the dominant factor in 1989, the effect of the treatments is understandably smaller and less clear.
2. Within each tillage treatment, the wheel ruts had by far the lowest infiltrability (Table D-6.1). With the exception of Trt. 2 (no replications), infiltrability in the wheel ruts was less than 15 mm h^{-1} .
3. The center of the bed had a generally higher infiltrability than the plant row, with the exception of the plowed treatment. The effect is particularly pronounced in Trt. 1 in 1988 (Table D-6.1). This is consistent with the nature of the treatments. Both the loosening of the soil on the centerline by the subsoiler shank, and the incorporation of chopped residues in the center of the bed would be expected to increase infiltrability. A special effect of the incorporated residues is discussed in greater detail below.
4. Both the final infiltrability and cumulative infiltration of all the no-plow treatments clearly show that the different tillage zones within a treatment are performing their task in accordance with the philosophy underlying zone tillage: The bed center, which is subject to the least compactive stresses, is the major zone of water intake; The plant row provides the conditions required for seed germination and seedling establishment, which requires some moderate compaction of a shallow layer in the actual seed row to improve seed-water contact. At the same time, this zone has a quite high infiltrability, thus making a contribution to the moisture requirements of the root zone; the wheel track is sacrificed from the point of view of supporting plant growth, is the major potential contributor to runoff, and should be kept as narrow as possible, consistent with the requirements of essential traffic. The residual effect of the wheel track in the plowed treatment demonstrates the desirability of permanently located wheel tracks, so as to affect as small a portion of the field as possible.

Fig. D-6.1. Sample infiltration functions of Treatment 8, 1988 & 1989.

5. The bed centers and plant rows of the plowed treatment had the lowest infiltrability among the treatments, and the highest variability. This is consistent with the theory proposed by Frede (1982) that the random traffic of a plowing regime causes compaction of a rapidly growing proportion of the soil surface. Furthermore, any of the tillage zones of a current bed has a higher probability of being located on a previously compacted zone (e.g., an old wheel rut) than is the case with permanent traffic lanes, where this is avoided with almost complete certainty. This is the cause of the high variability.
6. In both years Trt. 2 had a moderately higher infiltrability than Trt. 8 both in the plant row and in the bed center. In the plant row this can be explained by the fact the the subsoiler shank was thicker than the Paraplow shank, and thus may have created more of a shattering effect over a larger area. However, in the bed center the Paraplow was expected to have more of an effect since the shank bent inwards, and in addition had a share at its tip which was expected to create more soil disturbance than the chisel tip of the subsoiler. The difference between the two treatments is almost indiscernible in the cumulative data. No good explanation is presently available for the observed difference.
7. The time required to reach the final rate was longer for the centerline of Trt. 1 than for the other treatments, but the differences between the final rates were relatively smaller. Thus while the 2-year average final infiltrability of Trt. 1 was not clearly higher than in Trt. 2 and 8, cumulative infiltration during 100 minutes was nevertheless highest in Trt. 1 due to the shape of the infiltration function (Table D-6.1). Considering only the 1988 data, the final rate on the bed center of Trt. 1 was distinctly the highest among all the treatments.
8. The infiltrability values are generally very high. Rawitz et al. (1981) found final rates around 10 - 15 mm h⁻¹ in random-tilled sprinkler-irrigated tillage treatments on an essentially identical soil at Gilat, and values of this magnitude or smaller have been accepted as characteristic of these loess soils. However, Rawitz et al. (1964) also found final infiltrability of 42 mm h⁻¹ at Gilat on an old alfalfa plot, parts of which had been flood-irrigated and others sprinkled. This provides evidence that the profile itself can have a very high infiltrability. Cohen² (1988) reported rates of the same order of magnitude (40 - 200 mm h⁻¹) for a nearby alluvial soil with a large loess component. These results therefore confirm that when these soils are neither crusted nor compacted, their characteristic infiltrability is in the range found in this experiment.

Eighteen sets of data, including some data from every treatment, were analyzed by non-linear regression procedure for compliance with the infiltration equation developed by Philip (1957):

$$i = 1/2 St^{-(1/2)} + A.$$

The correlation coefficients ranged between 0.900 and 0.993, the average value being 0.955. A sample comparison between the calculated and observed data is shown in Fig. D-6.2. The goodness of fit is further confirmation that the observed very high infiltration rates reflect normal soil behavior and are not due to some artifact.

Effect of buried residue "pipe": On a number of occasions it was noticed that one of the runs of Trt. 1 had an appreciably higher flux than the other replications. For example, in 1988 the final rates on the bed center were 100, 135, and 210 mm h⁻¹, respectively, and in 1989 they were 135 vs 40 mm h⁻¹ in the plant row, but 58 mm h⁻¹ in both replications on the bed center. In addition, some of the runs had to be terminated early or canceled due to what initially

² H. Cohen, Kibbutz Sde Yoav, Personal Communication.

Fig. D-6.2. Sample of fit between observed (*) and calculated (---) infiltration functions using the Philip equation.

appeared to be spuriously high fluxes, some of which appeared suddenly during a run that had been proceeding normally.

It was soon discovered that the surface soil in the bed center a number of meters downslope from the infiltrometer installation had become saturated, with water even rising to the surface and proceeding as surface flow in the shallow center furrow. After some time, a 5 - 7 m section of soil became saturated up to the surface (Plate D-6.1). In one case, probing the inner ring with an iron reinforcing rod to determine depth of the wetting front caused a very rapid disappearance of the water from the ring through the probe hole, accompanied by the formation of a pronounced vortex. Excavation on the bed centerline showed that rapid mass flow of water was taking place through the highly porous "pipe" of woody cotton stover residues. Another excavation about 5 m downslope from an infiltrometer installation where infiltration was apparently proceeding normally also exposed a residue "pipe" flowing partly full, discharging about 150 mL min⁻¹. If this discharge were attributed to the entire surface of the infiltrometer ring, it would amount to an equivalent infiltration rate of 18 mm h⁻¹. This is too low to indicate the presence of a "short circuit" due to macro-pores.

From these observations it is possible to explain the apparently spurious data, to predict the potential effects of the residue "pipe", and to evaluate its possible practical significance. Wherever there is a continuous macro-pore between ponded surface water and the residue "pipe", there will be very rapid, turbulent flow into the residue "pipe", which will be orders of magnitude faster than the infiltration flux through the soil layer between the surface and the buried residue. In the absence of such macro-pores, downward flow through the unsaturated soil may actually be impeded by the residue layer which is at atmospheric pressure, i.e., at a higher potential than the water in the unsaturated soil. Under these conditions, infiltration rate will be equal to or lower than that into soil not underlain by a layer with very large pores. As the overlying soil becomes saturated, water will enter the residue "pipe", at a rate consistent with the saturated hydraulic conductivity of the layer.

The practical results of the above phenomena depend on a very complex set of circumstances. In the above case, water was entering the soil over a small area only, surrounded by dry soil, and its distribution was observed within a relatively short distance from the source. If one assumes that the residue pipe is continuous along the entire plant row and discharges into free air, while the entire length of the pipe acts as a sink, then the residue "pipe" would be operating like a conventional drain, abstracting rainfall or irrigation water from the field, representing a water loss. If, however, the end of the pipe was closed, as would be the case where the tractor driver raised the implement at the end of the row, the residue pipe would quickly fill, and the water in it would be at some small, positive pressure. This would create a potential gradient away from the pipe, causing water to flow out into the surrounding soil, very much as is the case with sub-irrigation or reverse drainage. This could be expected mainly in the lower parts of a field.

The assumption of a continuous pipe in the field is however not a realistic one. It is common to find gaps in the plant stand along a row, which in itself would cause a discontinuity of buried residues. In addition, it is a common occurrence that the USM becomes blocked occasionally, requiring the operator to raise the implement, clear it manually, and resume work. Furthermore, large clods may roll down into the trench made by the subsoiler and funnel before it is backfilled, thus again causing a discontinuity. It is to be expected that the distance between such breaks in the pipe would be highly variable, on the order of several meters to several tens of meters. In such a case it is expected that the "pipe" would run full for some distance upstream from each obstruction, creating a series of wet spots along the row. Just exactly what wetting patterns would result in different situations requires further investigation. However, it may be assumed as a first approximation that the presence of a residue pipe introduces an undesirable heterogeneity in soil moisture distribution with a characteristic scale of perhaps 5 - 25 m. It may furthermore be assumed that incorporation of broadcast chopped residues by a separate rotary tiller pass (as in Trt. 2) will result in more uniform residue distribution in the soil, and will entirely eliminate the effect of a "pipe" of macropores. This is one of several reasons why the latter treatment is recommended for adoption rather than Trt. 1.

Plate D-6.1 Capillary wetting of surface soil from buried residue "pipe".

b. Crop response to imposed treatments

Stand density: Stand counts were taken each year a number of weeks after germination, when it could be safely assumed that seedling emergence and establishment were complete. The first survey was taken in May, 1986, when the field had not been subjected to any treatments. The number of plants along 3 meters of row was counted at 48 grid nodes, 16 in each of the future blocks. The mean stand densities were 38.8 ± 3.5 , 37.3 ± 2.7 , and 39.0 ± 3.2 per 3 m, respectively. For the entire field, mean stand density was 38.4 ± 3.2 for 3 meters, or 12.8 ± 1.0 per meter. The spatial distribution of the variability was entirely random, displaying no discernible pattern. This is a uniform stand of more than adequate density.

The next count was taken in May, 1987, the first spring after imposition of differential treatments. The measurements were taken in two areas of Block II, 50 and 80 m south of the field boundary. In each area the four outside rows of each 6-row treatment were counted, so that two rows were adjacent to a wheel track on one side, while the other two rows had uncompacted inter-row spaces on both sides. Counts were made of the number of plants in each of 10 consecutive meters of row, for a total of 2×40 m per plot. There were no systematic differences between the four rows of a plot, nor between the 50-m and 80-m locations. Variability was very high, due mainly to occasional gaps extending across several rows, so that the stand density of the entire 4×10 m sampling plot was affected. Average stand densities in the various treatments ranged between 1.1 and 9.0 plants m^{-1} . Of the nine treatments, five (Trt. 2, 3, 5, 6, and 8) had a stand of >7.4 plants m^{-1} , which is more or less accepted as the minimum stand required for achievement of maximum yield. The results are summarized in Table Db-1. It should be noted for future reference that the densest stand was found in Trt. 2 and 3, the plowed treatment was one of two treatments with very poor stand due to gaps, and that Trt. 1, while hardly affected by gaps, nevertheless had one of the poorer stands.

In May, 1988, ten consecutive 3-m row segments were sampled in each treatment of Block II, and the results are also summarized in Table Db-1. It is noteworthy that this year there were almost no large gaps in the stand, that the range of population densities was narrower, and the mean stand density was higher. Nevertheless, only three treatments had a stand denser than 7.4 plants m^{-1} and the average yield in 1988 was lower than in 1987. The previously observed relation between stand density and yield was evidently masked by some other, more dominant factor. Treatments 1 and 9 again ranked low among the treatments. On the same date, large soil samples were taken for dry sieving from Trt. 1, 8, and 9, which are representative of three distinct tillage systems. The aggregate MWD values were 6.66, 5.75 and 8.15 mm, respectively. In the light of previous work by Rawitz et al. (1981) and Hadas et al. (1985), the poor stand in Trt. 9 may be attributed to the much coarser aggregation of the plowed treatment. However, Trt. 1 was certainly not the only one tilled by subsoiler in the plant row, and there is no evident cause why incorporation of the residues in a concentrated band under the bed center could interfere with germination and establishment.

While it can be stated that in both years Trt. 1 and 9 had the thinner stands and that Trt. 2, 5, and 6 tended to rank near the densest ones, the high variability and the lack of consistency in the ranking of the treatments preclude the drawing of clear conclusions regarding any possible cause-and-effect relationship between stand density and the characteristics of the tillage-residue management treatments, excepting the effect of aggregate size in the plowed treatment.

Yields: Yield was determined by harvesting an entire plot by a commercial cotton picker, and transferring the raw cotton from the basket of the harvester to a wagon equipped with a weighing mechanism. In 1987, when half the field was irrigated by sprinkling and the other by drip, the size of a plot was close to 500 m^2 , and in 1988, 1,000 m^2 . In this way any random sampling errors due to local variability were eliminated, and the entire population of a plot was used to determine yield. The yield data are presented in Table Db-2.

The most pronounced feature of the results is that Trt. 1 (incorporation to 30 cm in the bed center and subsoiler in the plant row), which was the treatment used by the farmers, consistently gave the lowest yield, which was about 85% of the maximum yield. The second consistent result is that all drip treatments outyielded the parallel sprinkler treatments in 1987, by 400 $kg\ ha^{-1}$. This is in accordance with the general experience, and the yield difference is about what is required to offset the higher equipment cost of drip systems.

Table Db-1. Ranked stand density and standard deviations in 1987 and 1988.

1987			1988	
Rank	Treatment	Stand plants/m	Treatment	Stand plants/m
1	3	9.1±2.0	7	8.3±2.1
2	2	8.0±2.8	5	7.7±2.0
3	6	8.4±2.4	6	7.4±1.8
4	8	8.1±2.7	2	7.2±1.3
5	5	7.4±2.0	4	7.1±2.3
6	7	4.9±3.2	3	6.1±1.8
7	9	3.6±2.5	8	5.6±0.7
8	1	3.4±3.7	1	4.8±1.9
9	4	1.0±2.0	9	3.8±1.6

Table Db-2: Ranked treatment yields by year and irrigation method

1987 Sprinkled			1987 Drip		1988 Drip		Avg. (1987 + 1988) Drip	
Rank	Trtmt.	Yield	Trtmt.	Yield	Trtmt.	Yield	Trtmt.	Yield
———— Mg ha ⁻¹ ————								
1	7	4.89 a	2	5.59 a	8	4.34 a	2	4.90 a
2	9	4.89 a	3	5.43 ab	6	4.32 a	3	4.78 ab
3	3	4.87 ab	7	5.18 abc	5	4.23 ab	6	4.69 ab
4	2	4.78 ab	6	5.05 bc	2	4.20 ab	5	4.61 ab
5	6	4.70 ab	5	4.99 bc	3	4.13 ab	7	4.56 ab
6	4	4.62 ab	9	4.95 bcd	9	4.09 ab	8	4.53 ab
7	5	4.51 ab	4	4.94 cd	4	4.00 ab	9	4.52 b
8	8	4.26 ab	8	4.71 cd	7	3.95 ab	4	4.47 bc
9	1	4.21 b	1	4.48 d	1	3.85 b	1	4.17 c

Values in a column followed by the same letter are not different at the 0.05 probability level according to Duncan's Multiple Range Test.

Limiting further comparisons to the drip treatments, it is seen that Trt. 4, which is similar to Trt. 1, ranks in the class just above that of Trt. 1. In the average of both years, Trt. 4 ranks immediately above Trt. 1, and in the individual years, it is one rank removed (Table Db-2). There does seem to be some effect of the residue "pipe", rather than of stand density or in addition to it, that has a negative effect on yield under drip irrigation. In the sprinkler plot, where water is applied more or less uniformly from above over the entire soil surface, Trt. 4 ranks much higher than Trt. 1. While no prominent differences in growth were noted between adjacent rows during the growing season, and the preliminary experiment did not prove an effect of the residue pipe as such, the fact that the two deep-incorporation treatments gave the lowest yields which are not clearly a function of stand density, does lend support to the suspicion that the concentrated residues interfere with optimal water distribution. The plowed treatment (Trt. 9) was also among the lower yielding ones under drip irrigation. It may be that large clods, interspersed with macropores and cleavage planes, remained intact after shallow secondary tillage and interfered with water distribution similarly to concentrations of undecomposed residues in Trt. 1 and 4. Here again the more uniform wetting by sprinkling would explain the higher yield under sprinkling.

In contrast to some consistency at the low-yield end of the range, there is no treatment that appears to be consistently superior to the others. If there is a treatment of superior quality, two years' data were insufficient to bring it to light. As of now, it appears that the farmer could choose any treatment that leads to shallow residue incorporation or mixing with the soil that is the most economical to perform with the equipment at hand. Likewise, no medium-term effects were found due to either compost incorporation or complete removal of all residues. This is not to say that none existed, but only that under the conditions of this experiment, and the time span of observation, no effects were detected.

c. Implement-soil interaction

A series of measurements were carried out in December 1988, to determine tractor draft required for execution of the primary tillage operations. The tractor used was a John Deere Model 4450 with 4-wheel drive engaged during all operations. Each measurement run was 20 m long, and was done in triplicate. The true velocity was measured, and theoretical velocity was calculated from wheel r.p.m. and diameter. The cone index was determined in the wheel track along the measured strip. The measurements were carried out in Trt. 1, 2, 4, 6, and 8. The average draft was calculated by the Wismer and Luth (1973) equation without accounting for load transfer during operation, since all operations were carried out with the tractor-drawn USM supported on its own wheels.

The average draft forces calculated were 37.8, 17.2, 51.0, 41.6, 52.7, and 48.5 kN for Trt. 1, 2, 4, 5, 6 and 8, respectively. It is interesting to note that Trt. 1 (one subsoiler shank in each of two plant rows and an incorporating shank with funnel on the center of the bed) required 20 kN more draft than Trt. 2, where the center shank was not used.

A comparison between Trt. 1 and 4, where the parabolic, straight in-row standards were substituted by Paraplow shanks facing outward under the wheel track shows that the Paraplow required an additional 13.2 kN of draft.

Trt. 5, using the identical implement as Trt. 1, but set for a shallower depth, required 3.8 kN more draft. While the subsoiler chisel acted on a drier and harder soil layer than in Trt. 1, one would expect this to be more than compensated by the shallower depth required, and the difference may be due to experimental error.

Comparison of Trt. 2 and 8 again shows the extra energy required by the Paraplow, in this case without the incorporating center shank. Here the bend of the Paraplow standard faced inward under the bed center, without the benefit of loosening by the incorporating subsoiler as is the case in Trt. 1. The highest draft requirement was in Trt. 6, where the residues were incorporated in the compacted wheel track, where the highest resistance was to be expected.

Reference to the yield data (section V.D.2.b) shows that in every comparison Trt. 2 was preferable to Trt. 1 and 4, in addition to requiring less energy. There was thus no benefit in banded residue incorporation. In 1988, Trt. 8 was significantly, but only marginally so, better than Trt. 2, whereas the two-year average shows a significant and economically appreciable superiority of Trt. 2. While the performance of the Paraplow made a visual impression of good

tillage, the data obtained do not support this impression. It is nevertheless possible that such an effect might appear over a longer period, but for the moment this is in the realm of speculation.

3. Laboratory incubation experiment with soil from experimental field

a. Introduction

A laboratory experiment was carried out in order to determine short term effects of cotton residue decomposition on aggregate size distribution, aggregate strength, soil compressibility, tensile strength, water retention and hydraulic conductivity. Observation of field conditions, beginning with far from uniform distribution of the chopped crop residues, led us to suspect that there was little chance that any existing differences in the above properties could be detected by a logistically feasible sampling program. We therefore chose to supplement the field data with a more detailed look at processes under more controlled conditions.

The hypothesis was that during various stages of residue decomposition biomass excretions and decay, effective in creating or stabilizing aggregates and possibly blocking of pores, should affect the structure and physical properties of the soil. Furthermore, introduction of high C/N ratio organic material should result in some gradual changes in the observed physical properties. Alternatively, if a part of the microbial population acts specifically on certain components of the decomposing residues, there should occur a flush type of reaction, i.e. a peak in the changes of soil physical properties.

b. Materials and methods

Bulk surface soil from the Nahal Oz field site was brought to the laboratory, air dried, and passed through a 2 mm sieve. Plastic trays measuring 54x13x10 cm were filled with 7.5 kg of soil on the air-dry basis after mixing with additives to obtain the following treatments:

Control	No additive
OM-1	Finely shredded cotton residues equivalent to 4 t ha ⁻¹
OM-1 + N	As OM-1, plus 150 kg ha ⁻¹ of N as urea
OM-2	Cotton residues equivalent to 8 t ha ⁻¹
OM-2 + N	As OM-2, plus equivalent of 150 kg ha ⁻¹ of N as urea

The air-dry mixtures were brought to a mass water content of $18 \pm 1\%$ (approximately "field capacity") with the appropriate fertilizer solution, gently mixed and packed in the trays, and covered with perforated plastic film that allowed gas exchange but inhibited water loss. Each treatment was carried out in duplicate, and a pair of trays was prepared for each sampling date. Water loss was determined by periodic weighing and replaced as needed. The soil was allowed to incubate for one, three, six, and twelve weeks at 25° C.

On each sampling date the following samples were taken:

1. Undisturbed cores for water retention and hydraulic conductivity
2. Undisturbed cores for compressibility and tensile strength
3. Bulk samples for aggregate size distribution and strength indices

Hydraulic conductivity was determined by the constant head method (Klute, 1965), and water retention in the 0 - 10 kPa (0 - 100mb) range was subsequently determined on the same samples on a suction table (Klute, 1986). Separate core samples were subjected to compression loads of 49, 98, 196 and 392 kPa, and the compressibility coefficients were determined. The cores were then oven dried, and the bulk densities at the various loads were back-calculated. The same cores were then subjected to the tensile strength test (Kirkham et al., 1958).

The bulk samples were air dried and sieved to determine the mean weighted aggregate diameter (Gardner, 1956). Three replicate aggregates from each treatment and size class were then subjected to the tensile strength test (Hadas and Wolf, 1984).

c. Results and discussion

i. Aggregate size distribution

The results are given in Figs. D-3.1 and D-3.2, presenting the weighted geometric mean diameter and the geometric standard deviation, respectively. The treatments receiving low OM addition (control, OM-1, and OM-1 + N) displayed a distinct peak after one week of incubation, with the added N increasing the diameter only slightly over that of the OM-1 treatment. This peak dissipated by the third week, and by week 6 the size ranking of the treatments changed. After the first week the ranking by size in diminishing order was: (OM-1 + N) > (OM-1) > control > (OM-2) > (OM-2 + N) but after the third week the order became: (OM-2) > (OM-2 + N) > (OM-1 + N)

Fig. D-3.1. Geometric mean aggregate diameter as a function of organic matter treatment and incubation period.

Fig. D-3.2. Geometric standard deviation as a function of organic matter treatment and incubation period.

> (OM-1) > control. This order of ranking qualitatively confirms the model described in Appendix IX.A, and shows the effect to depend on the amount of OM added and probably also on the rate of decomposition, K_i .

Where little or no OM was added, the small amounts present produced a "flush" of fungal growth, the most active part of the microbial population, producing extensive but probably ephemeral mycelia capable of tying soil particles and micro-aggregates into larger but inherently unstable aggregates by wrapping them with a netlike mesh (Y. Henis, personal communication). Doubling the OM addition should have produced an even greater effect, but the process was apparently limited by lack of available N. We have no explanation why the fungi should not have used whatever available N there was to increase aggregation at least as much as in the control or low-OM treatments. This question is further discussed in connection with the model (Appendix IX.A), but obviously calls for further investigation in future research.

The larger OM additions did eventually cause an improvement in soil structure, as shown by a slight increase in aggregate size which persisted at least as long as the maximum period of incubation (12 weeks). This may be due to slower-acting bacteria, nourished by the gradual mineralization of fixed nitrogen.

Figure D-3.2 shows a general trend of increasing geometric standard deviation. This trend shows the effect of scale. As decomposition of the added OM progresses, fewer undecomposed fragments are scattered in the soil mass, whereas the effect of those decomposed earlier may have already diminished. In other words, the data suggest an increase in the scatter of aggregate size as the decomposition sequence processes progress. As ever less material (which at the same time becomes less digestible) is more scattered, mean aggregate diameter will decrease, but the size scatter will increase. Towards the end of the sequence the scatter may diminish as well, but the duration of this experiment was probably too short to reach this stage.

It may be concluded that:

- 1) Large effects on soil structure as determined by aggregate size distribution are produced by addition of OM, provided this is not limited by a deficiency of N or other nutrients. The effect depends on the nature and composition of the decomposing substance, and is probably short lived.
- 2) If a practical recommendation is to be given, then in order to improve soil structure by adding OM, particularly with a high C/N ratio, it should be applied with sufficient nitrogen to support decomposition by the microbial population. This has indeed been known for a long time with regard to plowing under of wheat straw. It would be desirable to find a way of stopping the decomposition process when the effect is at its peak.

ii. Aggregate tensile strength

Aggregates taken from the sieved size fractions were subjected to the unconfined compression test to determine their tensile strength. Twenty aggregates per test group, two test groups per treatment and incubation period were used for this set of measurements.

The analysis followed the procedure described by Hadas and Wolf (1984) and the equations used were:

$$[1] \quad \sigma = 0.711 (4 F) (\pi d^2)^{-1} \quad (\text{Hadas and Lennard, 1988});$$

$$[2] \quad \bar{\sigma} = \left(\frac{V}{V_0} \right)^{1/m} \sigma_0 \Gamma \left(1 + \frac{1}{m} \right) \quad (\text{Braunack et al. 1979});$$

$$[3] \quad \sigma_{\text{variance}} = (\sigma_0)^2 \left(\frac{V}{V_0} \right)^{1/m} \left(\Gamma \left(1 + \frac{2}{m} \right) - \Gamma^2 \left(1 + \frac{1}{m} \right) \right)$$

Where σ , σ_0 , $\bar{\sigma}$, and σ_{variance} are the stress at failure of single aggregates, the characteristic stress, the mean stress and the variance of stress at failure, respectively for each aggregate group, F the force applied at failure, d the diameter, V, V_0 the volume of single aggregates, and the characteristic volume of the aggregates in the group, Γ is the gamma function of the argument in

brackets, and m a factor related to the uniformity and internal pore system of the sample aggregates.

Figures D-3.3 - D-3.5 show the mean tensile strength at failure of aggregates in the 2 - 4 mm, 4 - 5.6 mm, and 8 - 16 mm size fractions as a function of OM and N addition and incubation time. In the 2 - 4 mm fraction no change was observed except for a moderate surge between three and 12 weeks at the heavy OM application rate (OM-2 + N). The same effect was obtained in the 4 - 5.6 mm fraction, but not in the largest fraction. The surge may be due to a higher probability of contact between small aggregates and the scattered OM particles.

Large peaks in aggregate strength occurred after one week of incubation in the OM-1 treatment of the two larger size fractions, the effect being very much stronger in the largest size class. While there is a decrease in strength thereafter, this treatment retained its higher strength throughout the 12-week period. The increased strength of the larger aggregates can not be attributed to bacterial secretions produced during the decay of added OM, since under these conditions secretions can only strengthen contact points. Had this been the mechanism involved, then the smaller aggregates would have had to show the same phenomenon. Similar to the behavior of aggregate size discussed above, the explanation for the increase in strength of the larger aggregates is that fungal mycelia enmeshed them with a fine network of "strings" (Metzger et al., 1987; Gupta and Germida, 1988). Fungal mycelia were observed in the incubated soils, but no specific details of amount, local concentrations, penetration of aggregate interior, or identification were obtained. The very high strength values found for the 4 - 16 mm aggregates suggest that the mycelia strengthened the aggregates in two ways: By the physical effect of surrounding them with a net, and then reinforcing this shell by chemical secretions.

The characteristic strength of aggregates and the characteristic volume V_o calculated for the aggregates at failure under tensile stress are given in Figs. D-3.6 - D-3.11. The peaks in τ follow the same trend found for mean aggregate strength, especially so for the larger aggregate sizes.

The characteristic volume V_o of the stronger aggregates tends to approach the average aggregate volume. However, the fluctuations are large, and no specific trend is discernible. The general trend of increasing V_o supports the model of external reinforcement of the aggregates by mycelial nets.

In conclusion, aggregates were probably reinforced by fungal mycelia and their secretions. The only treatment greatly affected according to strength criteria was OM-1. No good explanation was found why just this treatment should be so affected.

iii. Compressibility and resultant tensile strength

Two undisturbed core samples were taken from each replication on each sampling date and subjected to confined compression. The data are presented in Table D-3.1. Bulk density data were correlated with applied pressure according to:

$$[4] \quad (bd) = (bd)_1 + C \ln P$$

where (bd) and $(bd)_1$ are the bulk density attained under pressure P and 1 kPa, respectively, and C is the compressibility coefficient. The calculated values of $(bd)_1$, C , and the regression coefficients are given in Table D-3.2. The data show that:

1. $(bd)_1$ values tend to be lower than the initial values at time 0.
2. The C values, or the indicator of soil tendency to compact under pressure, do not show a clear pattern of changes with time or amounts of residues and fertilizer applied.

Gupta et al. (1987) also found that addition of corn residues to the soil under field and laboratory conditions practically did not change the soil compression index, C . Anger et al. (1987) reported a 12% higher C value for soil cropped to brome grass for 15 years as compared to that cropped to corn for 15 years. Furthermore, when cropping practices were changed, rapid changes appeared to occur in the C value. Soanes (personal communication, 1988) pointed out that organic matter is more likely to have greater influence on the compaction index C at low rather than high compressive stress. This influence can be attributed to: Organic molecules binding the aggregates, which will tend to reduce C , or will impart greater elasticity to the soil structure, thus relieving response to pressure.

Fig. D-3.3. Mean tensile strength as a function of organic matter treatment and incubation period.

Fig. D-3.4. Mean tensile strength as a function of organic matter treatment and incubation period.

Fig. D-3.5. Mean tensile strength as a function of organic matter treatment and incubation period.

Fig. D-3.6. Characteristic tensile strength as a function of organic matter and incubation period.

Fig. D-3.7. Characteristic tensile strength as a function of organic matter and incubation period.

Fig. D-3.8. Characteristic tensile strength as a function of organic matter and incubation period.

Fig. D-3.9. Characteristic volume as a function of organic matter treatment and incubation period.

Fig. D-3.10. Characteristic volume as a function of organic matter treatment and incubation period.

Fig. D-3.11. Characteristic volume as a function of organic matter treatment and incubation period.

Table D-3.1: Bulk density and strength changes of cores taken from incubation experiment subjected to different compactive stresses.

		<u>Compactive stress applied, kPa.</u>					
		0	50	100	200	400	
<u>After one week of incubation</u>							
Treatment	Ww, %	----- Bulk Density, Mg m ⁻³ -----					Strength kPa
Contr.	21.4	1.20	1.32	1.42	1.53	1.59	216
OM-1	22.0	1.22	1.33	1.42	1.53	1.60	178
OM-1+N	22.6	1.13	1.27	1.35	1.41	1.55	135
OM-2	22.6	1.10	1.22	1.33	1.45	1.60	120
OM-2+N	20.6	1.03	1.22	1.33	1.44	1.52	217
<u>After three weeks of incubation</u>							
Contr.	17.0	1.05	1.17	1.27	1.39	1.57	51
OM-1	17.3	1.04	1.17	1.27	1.40	1.56	---
OM-1+N	17.8	1.08	1.19	1.30	1.41	1.54	56
OM-2	17.3	1.09	1.20	1.27	1.38	1.51	60
OM-2+N	17.8	1.01	1.15	1.26	1.40	1.51	43
<u>After six weeks of incubation</u>							
Contr.	12.8	1.10	1.21	1.31	1.45	1.61	31
OM-1	13.2	1.04	1.19	1.29	1.44	1.60	78
OM-1+N	14.0	1.12	1.21	1.31	1.46	1.61	63
OM-2	15.2	1.10	1.22	1.33	1.48	1.61	45
OM-2+N	13.7	1.14	1.24	1.33	1.46	1.56	61
<u>After 12 weeks of incubation</u>							
Contr.	16.0	1.09	1.16	1.22	1.35	1.50	---
OM-1	18.4	1.07	1.15	1.24	1.39	1.55	---
OM-1+N	18.7	1.15	1.25	1.32	1.46	1.62	---
OM-2	18.4	1.14	1.24	1.32	1.45	1.50	---
OM-2+N	17.2	1.09	1.19	1.27	1.39	1.54	---

Table D-3.2: Bulk density and compressibility values calculated from Eq.[4].

A. Calculated bulk density of uncompressed sample, Mg m^{-3}

Incubation Time, wks.	0	1	3	6	12
Treatment					
1	0.91	0.81	0.43	0.68	0.48
2		0.81	0.40	0.47	0.36
3		0.78	0.54	0.44	0.53
4		0.50	0.57	0.57	0.55
5		0.66	0.48	0.59	0.51

B. Calculated bulk density after compression at 100 kPa.

1	1.35	1.44	1.29	1.31	1.25
2		1.43	1.28	1.30	1.27
3		1.35	1.31	1.33	1.35
4		1.34	1.29	1.34	1.34
5		1.30	1.27	1.34	1.29

C. Calculated compressibility values "C"

1	0.13	0.14	0.19	0.14	0.16
2		0.13	0.19	0.18	0.20
3		0.12	0.17	0.19	0.18
4		0.18	0.16	0.17	0.17
5		0.15	0.17	0.16	0.17

D. Correlation coefficients for regression of observed bulk density on pressure applied (Eq. 4).

1	0.974	0.992	0.981	0.907	0.961
2		0.996	0.964	0.960	0.984
3		0.878	0.928	0.976	0.926
4		0.983	0.959	0.957	0.981
5		0.997	0.927	0.911	0.938

It is interesting to note from our data that the changes in C noticeable after the first week persisted for at least 12 weeks. Rebound was negligible during the compression test once the load of 392 kPa was released.

Tensile strength of compressed samples. After drying, the compressed cores were loaded using the unconfined compression test to determine their tensile strength. The results are shown in Fig. D-3.12. The general trend is for strength to diminish with time, even in the control. It seems likely that voids left after decomposition of organic fragments, causing more cracks and failure planes in the soil, are the reason for reduced tensile strength of the compressed soil cores.

From the above data it may be concluded that:

1. Decomposition of cotton residues apparently affected the soil so as to render it more susceptible to compression, and the supposed elastic behavior reported in the literature was not observed, nor was there any effect of undecomposed residues left in the cores.
2. The compressed cores, which all approached almost the same bulk density after 12 weeks (Table D-3.2), show a reduction in tensile strength, probably due to residual undecomposed organic debris or increased void volume upon decay of part of the residues. However, this does not explain the behavior of the control treatment, which did not contain any residues.

iv. Hydraulic conductivity

Undisturbed cores taken from the different treatments after different incubation periods were presaturated and their hydraulic conductivity (K_{sat}) was determined in a constant head permeameter. The results (Fig. D-3.13) show a sharp decline between the first and third weeks, followed by a recovery, converging around 100 - 200 mm hr⁻¹. The similarity of the K_{sat} values suggests that the originally similar packing of all treatments was retained during incubation, and that the changes with time reflect fungal and bacterial activity. The minimum at three weeks is indicative of pore clogging by biodegradable fungal mycelia or secretions, which dissipated between the third and sixth weeks. After this, K_{sat} is practically the same for all treatments, irrespective of OM or nitrogen additions. The general pattern of large changes early in the incubation period is consistent with the behavior of other parameters discussed above, although there seems to be a time lag in the response of hydraulic conductivity.

v. Water retention at high potentials

There is a common belief that addition of organic materials to soils will increase their "water holding capacity". When subjected to scientific tests, it has generally been found that the addition of practically feasible amounts of OM had but a negligible effect on water retention, let alone on the range of plant-available water. Soil scientists regard water retention primarily as a function of soil texture rather than structure, and truly vast amounts of additive would be required to appreciably change the average texture of the plow layer in the field. The exception is the high water potential range, where the large pores are capable of retaining water. It is the percentage of these pores which is most affected by changes in soil structure. The main potential benefit attributed to the addition of OM to the soil is its ability to promote formation of, or stabilize existing aggregates and macropores, i.e., to improve soil structure. It is therefore logical to look for effects of incorporated crop residues on retention in the high-potential moisture range as well as on the saturated hydraulic conductivity.

The data in Figs. D-3.14 - D-3.16 are essentially a mirror image of the hydraulic conductivity results (Fig. D-3.13). The proffered explanation is that the same early transient flush of fungal activity that caused the trough in the conductivity by partial pore clogging, also produced a transient peak in water retention attributable to either pore clogging or the hydrophilic properties of the decomposition products. The second increase in retention toward the 12th week may be due to subsequent, or slower bacterial activity. The question of the exact mechanism involved can not be resolved without further research stressing the details of the organic matter cycle and real-time changes in soil physical properties. This is qualitatively dealt with by the model described in Appendix IX.A.

No very clear and consistent differences were found between the treatments. In weeks 1, 3, and 6 the control treatment retained the least water, and the highest retention in week 1 was

Fig. D-3.12. Tensile strength of cores as a function of organic matter treatment and incubation period.

Fig. D-3.13. Hydraulic conductivity as a function of organic matter treatment and incubation period.

Fig. D-3.14. Soil mass wetness as a function of organic matter treatment and incubation period.

Fig. D-3.15. Soil mass wetness as a function of organic matter treatment and incubation period.

Fig. D-3.16. Soil mass wetness as a function of organic matter treatment and incubation period.

found in treatment (OM-2), which is consistent with expectations. However, in week 12 the control retained the most water, with treatment (OM-2 + N) retaining the least, and no good explanation has been found. It should be pointed out that the greatest difference in retention between the various treatments on any sampling date is no more than 3%, so that some of these differences may lie within the range of experimental error.

d. Summary

All the major parameters show the same general trend of a transient "flush" of activity early in the incubation period and a subsequent decline, followed by a secondary recovery approaching, or even somewhat exceeding, the initial value. In fact, this pattern is consistent with the theoretical trends exhibited in Fig. D-3.2, where $K_1 \gg K_2$ for low OM additions, and $K_1 < K_2$. The K_i as given in Appendix A is not a unique coefficient but a lumped one. This becomes obvious in view of the following arguments.

When a substrate is added, the microbial population will react, and its reaction will follow a sequential order, like the reaction observed for OM, so long as no limiting factor comes into play. The reaction is indicated by a high rate of activity, probably large production of biomass, exudates or secretions. This in turn is the start of a secondary decay process with its own characteristic K_2 , and after the third or fourth week most of the effects are dissipated, except possibly for a more persistent bacterial activity. In simple terms our qualitative K_1 implicitly includes, besides the actual decomposition rate, changes in the active biomass of various population components involved in a given decay process, as well as controlling or limiting factors such as O_2 , N, S, or micronutrients.

The results of the incubation experiment show that organic matter can cause very pronounced transient effects on soil physical conditions in addition to whatever medium- and long-term effects it produces. By better knowledge of the processes involving added organic residues and the physical and biological phases of the soil one may be able to optimize the OM effects, and perhaps even tailor them to meet given objectives. For example, timing of residue incorporation with reference to the soil moisture regime, e.g. scheduled irrigations or the expected start of a rainy season, might be a way of improving water intake rate and minimizing runoff.

E. Conclusions

1. Model evaluation

Crop production system analysis is a much needed tool to identify factors within the physical environment which affect optimum crop production. Simulation models devices to be sensitive to factors affected by tillage and residue management systems should provide an attractive mechanism to identify optimum conditions for crop development. The Nitrogen Tillage Residue Management (NTRM) and Erosion Productivity Impact Calculator (EPIC) models were selected to evaluate the influence of tillage and residue management practice on winter wheat and cotton growth and yield.

Results from NTRM displayed large deviations between predicted and measured yields outside the year of calibration. Predictive accuracy of NTRM was affected by crop coefficients selected in the calibration process. Wheat grain yield predictions by NTRM were very sensitive to initial and stabilized soil bulk density within the range of 1.1 to 1.6 $Mg\ m^{-3}$. Incorporation of several modifications into the model (including use of algorithms which allow input of temperatures $\leq 0^\circ\ C$ and realistic sensitivity to bulk density) may enhance its usefulness in crop production system analysis.

Although simulation results from EPIC showed sensitivity to variation in yearly weather pattern and nitrogen fertilization rate, the spectrum of tillage and residue management practices investigated in this study were not simulated as have any effect on crop yields.

In conclusion, results of the modeling effort within this project indicate two extreme responses to lack of knowledge of crop response to changing tillage and residue management practices. NTRM was so sensitive as to be unrealistic; conversely, EPIC was generally not sensitive enough to be useful in identifying potentially useful management schemes to be further tested in field situations. It appears that critical knowledge of the influence tillage and residue management practices have on basic soil properties and their interaction with crop development

and growth is not adequate, or not incorporated into the tested models, to allow their use in identifying the "ideal" soil environment for crop production.

2. Main field experiment

The main findings of the field work were: (a) Any differences between interactive tillage and residue management treatments were completely dominated by the effects of tillage per se, with the exception of the treatment characterized by placement of a concentrated band of chopped residues under the center of the inter-row space. Since the effect of this treatment was also primarily physical in nature, it could in a way be included among the tillage effects. If there were any effects on soil structure caused by residue decomposition, they were of secondary importance compared to the tillage treatments; and (b) Incorporation of chopped residue in a concentrated band can profoundly modify the hydraulic properties of the field, with the specific consequences being a function of a complex set of conditions. In the present experiment, this treatment consistently gave the lowest yields.

Penetration resistance: Resistance across a 2-row bed had a typical "W" shape, with highest resistance in the wheel track, lowest in the plant row, and generally a secondary peak on the bed center line. While this pattern was modified by different secondary tillage treatments, it was not obliterated. The depth of the various parts of the "W" changed in a seasonal cycle that accurately reflects the sequence of field operations. The pattern itself corresponds to the three principal zones in the field and their functions: Wheel track, plant row, and inter-row space. The relatively high resistance in the center leg of the "W", which occurred mainly after harvest, is due to a single pass of the rear wheel of the cotton picker over moist soil. This confirms the observation that most of the compaction takes place during the first of a series of stress applications.

The shape and volume of soil affected by subsoiler tillage was dependent on soil moisture: In dry soil there is a large, diffuse area of shattered and friable soil around the subsoiler track, whereas in wetter soil there is a clear and narrow cut, with the surrounding soil relatively unaffected by the implement passage.

Although modifications due to secondary tillage may be evident, the effects of autumn primary tillage persist at least until the following summer. In particular, residues incorporated as a "pipe" by the USM retain their physical (though possibly not their chemical) integrity throughout at least the following summer, at the end of which the band is scattered by the subsequent primary tillage.

Bulk density: Initial post-harvest bulk density was areally and vertically uniform, 1.55 Mg m^{-3} , except for a value of 1.31 in the 0-10 cm layer in the plant row. Throughout the experiment, no effects of tillage or systematic changes with time were detected in the 40-50 cm depth layer either by penetrometry or by bulk density determinations.

The condition of the 0-40 cm layer reflects both primary and secondary tillage operations and their cyclic sequence. Density was consistently lowest in the plant row (locus of subsoiler track), highest in the wheel track, and intermediate in the bed center. The 0-10 cm layer underwent the most frequent and the largest changes during the cycle.

Bulk density of the wheel track was around 1.65 Mg m^{-3} at most times to a depth of 30 cm, and did not recover appreciably after tillage, excepting one date in the plowed treatment. This is also reflected by the penetration resistance and infiltration data, and both density and infiltrability values point to structure degradation. This accentuates the importance of maintaining permanent traffic lanes, and also the need to avoid as much as possible a gradual widening of the rut with repeated operations. From the point of view of limiting the area subjected to compaction damage, it would be desirable to use narrower tractor tires, possibly with a longer but narrower "footprint", with a shape resembling a crawler track.

In contrast to the wheel tracks, the density of the bed center, where some compaction was done by the cotton picker rear wheel, shows definite density recovery during the tillage cycle in the top layer, and to some extent in the 20-30 cm layer as well. In addition, the maximum density values are lower on the bed center than in the wheel track, and even in the lower layer do not generally exceed the original density. This aspect of the compaction problem might be solved by using cotton pickers with two rear wheels traveling in the path of the main wheels. There is good correspondence between the density results and the infiltrability and penetration resistance

data. It is expectable that this relation is specific to each soil, but with proper calibration or possibly normalization, there is a good prospect that penetration resistance can serve as a convenient indicator or predictor of infiltrability, at least in non-crusting soils.

Aggregate size distribution: Plowing produced a coarser final seedbed than the no-plow treatments, and the Paraplow the finest. This is also consistent with penetration resistance results, which show greatest soil disturbance by plowing and least by Paraplow. The coarser aggregation under plowing was not obliterated by subsequent secondary tillage, and appeared to affect plant stand and yield.

Soil tensile strength: A fairly good linear correlation was found between strength of soil cores and bulk density, and a good correlation between the logarithm of strength and bulk density. While this measurement was consistent with all the other indices and therefore confirms their results, it offers no particular practical advantage as a method for field characterization.

Infiltrability: Overall, infiltrability was very much higher than what is generally considered normal for these loessial soils under intensive conventional tillage and either sprinkler irrigation or rainfall. This is nevertheless in agreement with findings of other workers, and demonstrates that when the soil is not compacted, dispersed or crusted, it definitely does not have an intrinsically low infiltrability. The infiltration functions conform closely to the inverse square-root relation described by Philip (1957). Infiltrabilities of less than 10 mm h⁻¹, as were observed in the wheel rut, are indicative of soil physical degradation, as was also shown by bulk density and penetration resistance. The dynamics of degradation and reclamation, especially the role of the geometry and continuity of large pores, and the extent to which reclamation is possible, require further study.

The infiltrability of the plowed plots was much lower than that of the other treatments. This is attributed to the random pattern of compaction in a plowing regime, which progressively affects an ever larger percentage of the land surface. Ultimately, the entire field could approach the conditions prevailing in the wheel tracks. The residual effect of the wheel track demonstrates the importance of permanently located traffic lanes, so as to affect as small a portion of the field as possible.

In the no-plow treatments, infiltrability is highest in the bed center, lowest in the wheel ruts, and intermediate in the plant row. This is in accordance with the philosophy of zone tillage and demonstrates the functioning of the different zones.

The bed center infiltrability in the treatment where chopped residues were incorporated as a band was much higher than in the other treatments. Exceptionally high values were caused by "short circuiting" of water through macropores directly to the residue pipe, which acted like a conventional drain. The practical implications of this phenomenon depend on a complex set of factors, but are potentially of great importance.

Yields: The treatment where chopped residues were incorporated by a hollow subsoiler shank as a buried "pipe" consistently gave the lowest yield. While the preliminary experiment suggested that yield variability was caused by differences in distance of plants from the drip lateral rather than by mode of residue disposal, in the main field experiment there is no relation between treatment execution and the random location of the drip laterals. Nevertheless, this treatment consistently gave significantly the lowest yield. It must therefore be concluded that there was after all something about the concentrated placement of the residue band that affected yield. While statistical differences between the other treatments were found in all the analyses, the ranking of the treatments is inconsistent between the various analyses, and thus no clear conclusions can be drawn. Unlike the clearly lowest yield of the band incorporation treatment, no treatments could be identified as giving consistently highest yields.

To sum up, all the field tests except for yield were essentially point measurements representing small soil volumes. The results were found to reflect the effects of tillage method rather than of residue management method. Therefore, the effect of residues on soil structure and crop performance was either non-existent, or required a period longer than the two years of this experiment to appear, or appeared and dissipated during a period shorter than the interval between field sampling dates.

3. Supplementary laboratory experiments

a. Long-term effects

To identify possible long-term effects, the structural characteristics of samples from two permanent plot experiments were examined. Long-term fertilization of a clay soil with high rates of NPK fertilizers did not change the organic matter content of the soil. In spite of differences in N, P, and K added and the amounts of plant residues incorporated in the soil, soil strength and water stability were likewise not affected. The high rates of Ca addition with the P may have made the bulk soil more friable, as indicated by estimates of the tensile strength of the soil bulk.

Long-term organic matter and nitrogen application to a silty arid-zone soil, accompanied by a general management intensification (irrigation, increased fertilizer, compost and manure applications) produced a gradual increase in the organic matter content, from 0.4% to approximately 1.5%. The estimated period required to attain 95% of the final organic matter content varied between 7.5 and 12.5 years, depending on cultural practices and rates of organic matter and fertilizer application. However, no changes in soil structural indices were detected.

Summing up the long-term NPK and residue trials, very heavy applications of organic matter and fertilizers resulted in some increase of organic matter and bulk soil friability to tillage, but did not improve soil structural stability or friability on the aggregate size scale.

b. Short-term effects

Since no changes in soil physical properties were detected in the long-term experiments, the next step was to examine the effect of possible short-term processes initiated by residue and fertilizer application. In the first experiment, active organic substances contained in leachate obtained from urban refuse compost, were added to the soil. Changes in shear strength were found to depend on type of soil clay fraction, time of incubation, and CaCO_3 content. In kaolinitic and illitic soil there was an immediate increase in strength, which decayed to its original value within a week. No immediate change in shear strength was observed on smectitic and highly calcareous soil, but some increase was observed to take place within one to two weeks.

In the second experiment, various amounts of chopped cotton residues and urea nitrogen were added to Nahal Oz soil and incubated for various periods up to 12 weeks. Aggregate formation, measured by the MWD, increased with organic matter addition. At a rate equivalent to the normal annual straw yield in the field, the process was short-lived: A fast increase in aggregate diameter for a week or two, followed by a decline. Heavier application rate caused a delayed response, reaching a peak at 6 weeks, followed by a slow decline to the twelfth week.

A definite increase in the strength of medium and large aggregates was found, again only with the addition of a normal amount of cotton residues. A very pronounced peak occurred between the first and third weeks, followed by a decline. No such effect was found with higher residue application rates. The observed structural effects during the 12-week incubation experiment are attributed to the binding action of fungal mycelia and secretions, which dissipates after an initial burst of activity. No explanation can be given at this stage why only the normal field yield of straw was effective.

A reduction in the saturated hydraulic conductivity occurred during the first week or two after organic residue application, after which it increased again toward its original value. This behavior was independent of the amount of organic matter added. Moisture retention gave a mirror image of the hydraulic conductivity function. As the added residues decomposed, hydrophilic byproducts and secretions are presumed to have caused pore clogging on the one hand, and increased water retention on the other hand.

To summarize, when normal field yields of crop residues are incorporated in moist soil, changes in soil structure or structure-related properties may be expected to appear during a period between one and six weeks after incorporation. In order to better understand the processes involved, it is considered necessary to investigate why application of larger residue amounts produced a weakened or delayed response. Another important research topic is the timing and amount of residue application in order to obtain a desirable, temporary change in certain soil properties.

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VI. Description of cooperation

A. The two parties are in frequent communication via electronic and regular mail to coordinate various aspects of project business.

B. Israeli and US representatives met at the American Society of Agronomy and International Soil Tillage Organization meetings to compare and discuss project results and chart project activity.

C. Dr. Rawitz traveled to the US to report project activity to date, coordinate collection of data needed for simulation exercises, and plan future project work.

D. Data from the cotton tillage and residue management experiment conducted in Israel provided essential information to broaden the range of condition used to evaluate the applicability of the selected simulation for cropping system analysis.

E. Dr. Wilhelm traveled to Israel to view on going research activity, gain a better appreciation for the cropping practices used for cotton production to aid in evaluation of modeling results, and discuss interpretation of results from completed field, laboratory, and simulation studies.

VII. Evaluation of research achievements

A. Although documentation indicated the chosen models were designed to be sensitive to tillage and residue management practices, they proved inadequate for analysis of cropping systems involving these factors. It appears that critical knowledge of the influence tillage and residue management practices have on basic soil properties and their interaction with crop development and growth is not adequate, or not incorporated into the tested models, to allow their use in identifying the "ideal" soil environment for crop production.

B. Random plowing and no-plow tillage regimes were found to have different, and in some respects persistent effects on soil friability, compaction and hydraulic properties. Plowing generally led to less favorable soil conditions than precision tillage in controlled traffic regimes.

C. The common farmer practice of residue incorporation in a concentrated band was less successful than incorporation that mixed residues with the soil, in terms of yield response, depth of tilled layer, energy requirement and effect on soil hydraulic properties

D. It was not possible to identify short-, medium-, or long-term effects of residue application amounts, placement in the profile and degree of mixing with the soil on the structure and physical properties of the soil under the field conditions described in this report.

E. Short-term effects of organic residue additions on soil structure, hydraulic properties and strength could be identified and were measured in supplementary and incubation experiments.

F. A possible reason for the inability to discern changes of soil conditions due to residue addition under field conditions may be that the effect of aggressive soil tillage operations is far greater than that produced by decomposition of the organic residues.

G. Another reason may be that the timing of our sampling schedule by which we tried to detect the effect of residue addition on soil structure missed the time span during which there was such an effect. Here is the place to state that had we changed our plan exactly in compliance with the referees' remarks (suggesting elimination of all laboratory investigations and exclusive concentration on field work), we would not have detected any effects of added organic matter on soil structure, nor would we have found that they were a short-lived phenomenon.

H. While the results of the research reported here do not describe the complete picture, they do make it possible to summarize what is known and point to future research required to clarify and extend our knowledge and apply it under field conditions. Our recommendations in this respect are as follows:

1. To carry out a detailed study under controlled conditions of the interaction between amounts of residue additions, timing of application, duration of incubation, soil moisture and aeration regime, and soil physical conditions.
2. To determine which microbial populations attack various residue components, and under what soil conditions.

3. To examine in the field those treatments found to be promising for improvement of soil structure or other physical properties and to test the reliability and correlation of field results against those of laboratory experiments under controlled conditions.
4. To determine the effects of differences between field conditions and controlled laboratory conditions on the results in the field and on the duration of the observed changes.
5. To study the relation between various residue incorporation modes, aggregation, and the geometric and continuity characteristics of macropores and channels in the soil.

VIII. List of Publications

- Davidoff, B., W.W. Wilhelm, and J. Skopp. 1989. Use of NTRM to evaluate sensitivity of winter wheat yield to soil physical environment. Agron. J. (in journal review).
- Rawitz, E., H. Lior, and M. Rimon. 1989. The effect of drip-line placement and residue incorporation on the growth of drip-irrigated cotton. Soil Tillage Res. (in press).
- Rawitz, E., and Margolin, M. 1989. An economical hand-held recording penetrometer. Soil Tillage Res. (in journal review).

IX. Appendices

A. A conceptual model describing organic matter decay processes

Any addition of plant residues, compost, or manure introduces a mixture of substrates into the soil which a heterogeneous microbial population starts decomposing to produce biomass, to respire, and to secrete substances which may on the one hand affect soil structural properties, or on the other hand become the lowest rung on the next higher stage of the food chain. Provided no rapid soil water flow or leaching take place, all the substrates and species involved in these processes are practically immobile. Thus all activity is localized around the organic parcels introduced into the soil.

According to this view, description of the soil condition affected by the added material involves problems of heterogeneity, relation between affected and measured volume, and the effect of scale. Additionally, the question arises of which theory applies to particular soil volumes. In other words, one may expect to encounter difficulties in projecting parameters of field behavior to processes taking place in small voids. As a consequence, the only way of studying the effect that addition of organic residues have on soil properties, is to observe and measure at or very near the scale of either the debris or the organisms. Experimental study of the systems is technically impossible at the latter scale. The model presented here will therefore be applied to small soil volumes about the same size as the plant residues (in this case, shredded, chopped cotton stalks).

A simple model relating the decomposition of organic residues to their surface area was proposed by Gregory et al. (1985). Several assumptions were made by this model which apply to almost all current models:

1. The processes involve a heterogeneous, active microbial population and a mixture of organic compounds. Thus the parameters used to describe this complex system represent the mean value of the relevant parameters.
2. Temperatures are above freezing and below the upper limit of biological activity.
3. If nitrogen is the limiting factor, rate of decomposition is inversely proportional to the C/N ratio.
4. The decomposition rate is a decreasing function of the moisture content of the soil-residue mixture.
5. The residue fragments have a uniform geometry and dimensions, and decomposition proceeds inwards from their surface.

According to Gregory et al. (1985), if the radius R is such as to maintain the length of the fragment $L \gg R$, then we can describe the system by:

$$[1] \quad dR = -u \, d\tau$$

where u is a proportionality factor and τ is a time-related parameter. The change in mass of the residue input dM is given by:

$$[2] \quad dM = 2 \pi R L \rho N \, dR,$$

where ρ is the residue density and N the number of fragments per unit surface area. The total residue mass M at time $t = 0$ is given by:

$$[3] \quad M = \pi R^2 L \rho N.$$

Rearranging Eq. 1, 2, and 3, one obtains the following relationship:

$$[4] \quad \frac{dM}{M} = -\frac{2}{R} u \, d\tau$$

Integrating Eq. 4 for $t = 0$, $\tau = 0$, and for $t > 0$, $t = \tau$, and $R = R_0$ at time zero and rearranging, we obtain:

$$[5.1] \quad R = R_0 - u\tau$$

$$[5.2] \quad \int \frac{dM}{M} = - \int \frac{2 u}{(R_0 - u\tau)} d\tau$$

$$[6] \quad \frac{M}{M_0} = \left(1 - \frac{u}{R_0} \tau\right)^2$$

Gregory et al. (1985) defined τ , the time-dependent parameter, as directly proportional to the temperature T , average water content dI_i/i , where I_i is the rainfall amount for a given time period and i is the number of days, and inversely proportional to the C/N ratio. For u/R_0 in Eq. 6 they used values of 1.37×10^{-4} , 1.18×10^{-4} , 1.19×10^{-3} and 2.11×10^{-2} for soybean, corn, sunflower, and wheat, respectively. They assumed the same density of about 0.7 Mg m^{-3} for all the residues, and the diameter of cotton stalks to be three times that of wheat. The value of u/R_0 of cotton was thus one third that of wheat, about 0.7×10^{-3} . In their correlations for wheat, Ghidey et al. (1985) used a value of 9.55×10^{-4} for u/R_0 in Eq. 7.

$$[7] \quad \left(\frac{M}{M_0}\right)^{0.5} = 1 - \frac{u}{R_0} \tau$$

$$[7a] \quad \left(\frac{M}{M_0}\right)^{0.5} = 1.0 - 9.55 \times 10^{-4} \tau$$

For cotton, the value of u/R_0 should be approximately one-third of that for wheat, or 3.17×10^{-4} . The value of τ was calculated from:

$$[8] \quad \tau = \frac{T A_m}{[C/N]} t,$$

where A_m is the water content factor, C/N the carbon to nitrogen ratio, and t the time. Since C/N of wheat is about 100 (Ghidey, 1985) and that of cotton about 400, then for cotton decomposition, a value of 0.8×10^{-4} would be appropriate, instead of 9.55×10^{-4} for wheat under similar conditions. In their article they reported the following percentages of wheat residues remaining between February and November: 96.5, 94.4, 97.9, 93.4, 87.9, 69.9, 73.8, 67.8, 59.2, 63.9. For cotton, these residual values should be 98.8% for February and 87.1% for September. In other words, decomposition should be approximately $(12)^{0.5}$ slower than that of wheat during the same period and conditions. Field observations in Israel confirm this finding qualitatively.

The model of Gregory et al. (1985) seems to be the most appropriate one to describe decomposition of long cylindrical fragments like those of cotton. However, it does not relate decomposed amount to some simply measurable factor such as N accumulation or CO_2 emission. Furthermore, no soil physical condition except surface cover can be directly correlated with Eq. 6.

A different yet classical approach was presented by Reddy et al. (1980), who assumed that overall decomposition can not be described by a simple kinetic equation, but rather by a sequence of equations each describing a separate stage of the process:

$$[9] \quad -\frac{dC_i}{dt} = k_i C_i,$$

where C_i is the amount of organic carbon present in stage i , and C_{ii} the remaining organic C_i at time t , as obtained by integrating Eq. 9:

$$[10] \quad C_{ii} = C_i e^{(-k_i t)}.$$

This approach assumes a first order rate constant for each stage. This model contains an oversimplification in that it ignores the fact that several different processes may proceed simultaneously at each stage, and assumes that a discrete sequential order exists without either overlapping or gaps between stages. Consequently, their analysis assumes the decay process to follow the straight line segments in Fig. 1 rather than the observed smooth curvilinear function.

For k_1 , k_2 , and k_3 they obtained values of 0.0212, 0.0078 and 0.003 day^{-1} respectively, and percentages of residual C (originally added as farmyard manure) of 36%, 17% and 57%,

Fig. 1. Relative amount of first residue decay products as a function of K_2/K_1 and dimensionless time scale.

respectively. They observed only two stages of decomposition for plant residues incorporated into the soil, and found the following results:

Crop	C/N	k ₁	k ₂
soybean	15	0.0168	0.0007
wheat	73	0.0058	0.0012
corn	100	0.0070	0.0013

The percentages of organic C decomposition at each stage were 53 and 47%, 23 and 77%, and 27 and 73%, respectively for the three crops. These values indicate that the higher the C/N ratio of the added organic residues, the smaller is the part that decomposes during the initial stage. It is interesting to note that their estimates of the half-life of organic C added by the three crops were 866, 495, and 462 days, respectively.

Although this approach indirectly examines a sequential order of decomposition, it does not consider the buildup of biomass that may:

1. Block pores to water flow (Allison, 1947; Pillsbury and Appelman, 1945), affect air permeability (Christiansen, 1944), change soil compressibility (Anger et al., 1987; Gupta et al., 1987), or shear strength and tensile strength among other properties.
2. Excrete organic substances which stabilize soil structure, add strength on drying.
3. Decay itself in the course of time along with some of its secretions.

A more comprehensive approach is desirable, which would simultaneously take into account the processes involving both decomposition of the original residues and of the products of subsequent stages. This will be based on the following assumptions:

1. On a scale larger than the chopped crop residues, a simple first order decay type equation describes the changes occurring in the residues, their decomposition products, and ultimately of CO₂ emission.
2. The added crop residues are finely chopped and uniformly distributed in the soil, so that the sequential degradation processes have a uniform effect on the soil matrix.
3. At time $t = 0$, the soil microbial population is in equilibrium with the organic matter and its constituents, e.g. in very dry soil at the end of a growing season.
4. All process stages are continuous, and there may be overlap between stages.

The following rate equations describe the transformations of added OM through a number of stages:

$$[11] \quad \frac{d}{dt} R = -k_1 R$$

$$\frac{d}{dt} B_1 = +k_1 R - k_2 B_1$$

$$\frac{d}{dt} B_2 = \quad + k_2 B_1 - k_3 B_2$$

$$\frac{d}{dt} B_n = \quad + k_n B_{(n-1)} - k_{(n+1)} B_n,$$

where R is the amount of "raw" residues added, B_1 to B_n are the amounts of decomposition products along the sequence, and k_1 to k_n are the proportionality coefficients or apparent first order rate constants, which also include an efficiency term for each process stage. These equations form a system of ordinary linear differential equations to be solved simultaneously for the relevant initial conditions.

Let us examine a case where a liquid, labile organic matter is mixed with soil at time $t = 0$, and is decomposed to produce a given product which affects soil properties, and is in turn respired and lost as CO₂ at the same rate as it produced. In this case the relevant equations are:

$$[12] \quad \frac{d}{dt} R = -k_1 R$$

$$[13] \quad \frac{d}{dt} B_1 = + k_1 R - k_2 B_1$$

$$[14] \quad \frac{d}{dt} B_2 = \quad + k_2 B_1.$$

While Eq. 14 can be obtained by integrating Eq. 13, the solution sought for Eq. 12 and 13 becomes simpler, for the following initial conditions:

$$\begin{aligned} R &= R_0 \\ B_1 &= 0 \end{aligned} \quad t = 0$$

The solutions for Eq. 12 and 13 then become:

$$[15] \quad R = R_0 e^{-k_1 t}$$

$$[16] \quad B_1 = \frac{R_0 k_1}{(k_2 - k_1)} (e^{-k_1 t} - e^{-k_2 t})$$

and that of Eq. 14 is given by:

$$[17] \quad B_2 = k_2 \int_0^t B_1(t) dt = R_0 - \frac{R_0}{(k_2 - k_1)} (k_2 e^{-k_1 t} - k_1 e^{-k_2 t})$$

Since in our case B_2 is the cumulative loss of added organic matter as CO_2 , let us look at the behavior of these solutions. Fig. 1, was derived for $R_0 = 1$. If the decomposition rate of the original residues (k_1) is very low compared to k_2 , then the effect on the soil can not be expected to be large ($B_1 < 0.1$), but as k_1 approaches k_2 the effect should increase, and when $k_1 \gg k_2$ a peak in B is reached a short time after the introduction of the residues, after which decay becomes dominant.

In Fig. 2 the solutions for R , B_1 and B_2 are given for $R_0 = 1$, $k_1 = 1.0$, and $k_2 = 0.05$. B_1 reaches a peak and starts decreasing, while B_2 starts increasing. If during mass transfer from R to B_1 or B_2 a certain portion were lost to respiration, then B_2 would have had to include terms of R and B_1 to account for respiration. Time lag usually encountered in biomass involvement in organic matter transformations has been neglected here in view of the assumed time interval of days or weeks, whereas biomass time lags are on a scale of hours, at most.

When three simultaneous microbial processes leading to a final respiratory loss are considered, no peak, one, or more peaks may occur, depending on the different values of k_i . Since we are dealing with complex organic matter, and with a heterogeneous microbial population metabolizing the organic matter, one should monitor changes in soil microbial populations, changes in OM content and composition. These data are needed for calculation of the various rate constants (k_i). Such an undertaking was beyond the scope of this project, but needs to be included in future research. The present model is a qualitative model which will be applied to analysis and understanding of the effects of addition and decomposition of crop residues on soil physical properties.

Fig. 2. Relative amount of original residue (R), first decay product (B1), and final decay product (B2), as a function of dimensionless time scale.

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B. Preliminary experiment

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THE EFFECT OF DRIP-LINE PLACEMENT AND RESIDUE INCORPORATION ON THE GROWTH OF DRIP-IRRIGATED COTTON.

E. RAWITZ¹, H. LIOR², AND M. RIMON³

¹Faculty of Agriculture, The Hebrew University of Jerusalem, Rehovot (Israel)

²Agric. Extension Service, Israel Ministry of Agriculture

³Kibbutz Bror Hayil

ABSTRACT

Much of the cotton in Israel is grown under alternate-row drip irrigation. Conventional tillage systems based on deep plowing are giving way to precision tillage with a single implement that uproots, shreds and incorporates residues, chisels the soil and shapes beds in one pass. We investigated the relation between observed variability of growth in adjacent rows and several methods of residue incorporation, some of which were presumed to interfere with water distribution if the drip lateral is not placed directly over the buried residue band. Large yield differences were indeed found between centered and eccentric lateral placement, but these were independent of the method of residue disposal. The yield differences are attributed to water availability as a function of distance between the plant row and the water source. However, the average yield of row pairs was the same regardless of lateral location, indicating complete compensation between the more and less favored rows of a pair.

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INTRODUCTION

Cotton (*Gossypium hirsutum*) is Israel's principal irrigated summer field crop, occupying some 50,000 hectares. About 65% of this area is drip irrigated, and this percentage is steadily increasing. The common practice is to plant the crop on two-row broad beds with a 97 cm row spacing, the drip laterals being placed between alternate rows, in the center of the bed. Cotton is customarily grown in the same field for three to five consecutive years, with wheat sometimes grown in the winter. The growing season is too short for the grain to mature between two cotton crops, and in that case the wheat is harvested in the spring for silage. The time available between the cotton harvest and the onset of the winter rains, as well as between the wheat harvest and cotton planting in the spring, is a major limiting factor for the execution of tillage operations.

It is a requirement of the production system to control the pink boll worm, and the effective way of doing this is to interrupt its life cycle by denying it hosts for overwintering, such as regrowth of cotton stubble, seeds and other crop residues on the soil surface. It is a legal requirement that all cotton residues be removed from the fields during November. While some cotton spilled during transport from the field to the gin collects in roadside ditches and represents a potential focus of infestation, and early rains sometimes make it impossible to finish harvesting and tillage during November, all reasonable efforts are made to observe this rule.

Until about 1980, the standard tillage sequence after harvest consisted of chopping the stover with a horizontal blade rotary chopper and turning it under by plowing to a depth of 35-40 cm. This operation was carried out on dry, compacted soil, turned up large, hard clods instead of a furrow slice, had a very high energy requirement, and was time consuming. If wheat were to be sown, the clods had to be broken down in the dry state by repeated disking, pulverizing a large part of the soil, which then tended to crust under raindrop impact and produce runoff and erosion. In fallow fields, secondary tillage after onset of the rains was by repeated disking, cultivation or harrowing followed by ridging or bed construction. Thus the seedbed was prepared gradually during the winter, with up to seven trips over moist soil. During winters with frequent rains many farmers did not manage to prepare the seedbed by sowing time without either working at non-optimal moisture or omitting some of the steps. Some of the secondary tillage passes were perpendicular or diagonal to the direction of plowing, and thus over a few years up to 90% of the surface of a field could be compacted in a random pattern, with a steadily decreasing distance between wheel tracks (Frede, 1982). Eventually, several effects were noted such as variability of yields within and between fields, gradual decreases in average yields, increased runoff and declining soil infiltrability. These added up to the hard-to-prove suspicion that the prevailing tillage system was causing structure deterioration due to compaction (Hadas et al., 1983).

Tentative steps were taken towards precision tillage in permanent controlled traffic lanes and minimum or reduced tillage based on subsoiling and integration of several implements in a "multitiller", e.g., a combination subsoiler-rototiller-ridger. However, field sanitation, especially the elimination of stubble which could regrow, was not as good as with deep plowing. A tillage system based on an entirely new concept became possible with the development by a local

engineering firm of the Uprooter-Shredder-Mulcher (USM)³. This machine basically pulls the cotton plant including the major root system out of the soil, conveys it to a chopper assembly, and ejects the shredded material. Several versions have been built around the basic system, giving the following options:

1. Disposal of chopped residues
 - a. broadcast over the land surface
 - b. blown into a wagon (similar to forage harvester)
 - c. blown into a subsoiler slot (vertical mulching)
2. Additional implements mounted on tool bar, USM, or towed
 - a. mulching shank with funnel (required for 1.c)
 - b. subsoiler shanks of various shapes
 - c. ridgers or bed shaper
 - d. rotary tiller or bed former

Option 1.a requires incorporation of residues in the soil by a subsequent pass of a rotary tiller, which does not leave the soil surface completely clean of residues. It is used mainly if the following crop is not cotton. Option 1.b envisages either use of the residues as fuel, or returning them to the land after composting, the heat presumably killing the bollworm eggs. Option 1.c is the one commonly used. The immediate benefits of the USM are fewer traffic passes across the land, compaction limited to permanent wheel tracks, faster coverage of a given area, fewer large clods brought to the surface, and savings of energy and labor. The long-term effects of the various versions of this tillage system are not yet known, and are presently under investigation. However, it was soon observed that the USM deposits the shredded residues as a "pipe" at a depth of about 30 cm in the center of the beds, and that the material preserved its physical integrity into the following summer. It was recognized that this could affect the soil wetting pattern by water delivered from the drip lateral, also placed in the center of the bed. Indeed, in the summer of 1985, following a winter with low rainfall which did not wet the profile deeply, reports were received of uneven growth in many fields, with the variability apparently random and affecting small areas. The hypothesis was proposed that this was due to the combined effect of the residue "pipe" and drip lateral placement. The laterals can not be placed perfectly in the center of the bed and in a straight line, some slack being required to allow for thermal expansion and contraction. It appeared that if the lateral crossed over from one side of the residue "pipe" to the other, the water flowing through unsaturated soil could not enter and flow through the very large pores between the residue chips, and thus alternately one or the other of a pair of plant rows on a bed would get less water, producing the observed spotty growth. This was perceived as undesirable, although no clear effect on yields was determined. An experiment was therefore initiated in the autumn of 1985 to investigate the relative effects of drip lateral placement and residue disposal method.

METHODS

The experiment was conducted on a young, deep, clay-loam, calcareous alluvial soil with an appreciable admixture of aeolian dust. The previous cotton crop was harvested in October 1985. Tillage and residue disposal were carried out at the end of November, 1985, by one pass of the Uprooter-Shredder-Mulcher, adjusted to work in the mode appropriate to the treatments described in "A" below. Final seedbed preparation was done in March, 1986, by a rotary tiller working to 5 cm depth, with a bed-former attached at the rear. Cotton was sown on beds at a 97 cm row spacing on April 15, 1986.

The experiment included four residue disposal treatments and two drip lateral placement treatments in a split-plot design, with four replications of the disposal treatments and two replications of the lateral placement treatments. Each plot was 2 rows wide and 15 m long:

³ Manufactured by Agricultural Machinery Div., Automotive Industries Ltd., P.O.B.535, Nazareth 17105, Israel. Mention of commercial products is for the benefit of the reader and does not imply preferential treatment or endorsement by the authors.

A. Residue Disposal Treatments

1. complete removal of residues
2. incorporation at 30 cm depth in a slot on bed centerline
3. shallow incorporation (15 cm), as above
4. shallow incorporation as above, mixed with soil by rototiller

B. Drip Lateral Placement Treatments

1. drip lateral fixed on centerline of bed
2. drip lateral fixed 30 cm off center

While drip laterals wander randomly across the bed centerline in commercial fields, they were fixed in place in the experiment in order to get a clear separation of factors. Data obtained included stover yield in the autumn preceding the experiment, plant population density, plant height, and yield of seed cotton determined separately for each row of the pair irrigated by a given lateral. The central 10 m of the 15-m plot were harvested by hand.

RESULTS

Plant density in the spring of 1986 was 9.0 ± 0.8 per meter of row with no significant differences between the two rows of a bed. Maximum plant height, at the beginning of August, likewise showed no treatment effect. A summary of the yields of raw cotton (fiber + seeds) is given in Table I.

Analysis of variance and Duncan's multiple range test show that yield differences between residue disposal treatments were not significant on the 5% level, although there does appear to be a slight superiority of the shallow mixed treatment. The differences between the right and left rows on beds with centered lateral placement were likewise not significant. However, with eccentric lateral placement, the rows nearer the lateral gave significantly higher yields (5.12 ± 0.16 vs. 4.12 ± 0.23 Mg ha⁻¹).

DISCUSSION

The yield data clearly show that eccentric drip lateral placement between a pair of rows on a bed produced a large difference in yield between the rows, on the order of 1 Mg ha⁻¹. However, the averaged yield of two rows on the same bed was equal to that of beds with centered laterals, so that the higher yield of the row nearer the lateral fully compensated for the lower yield of the far row.

The data also indicate that in this case the method of residue management had no effect on yield. The residue "pipe" apparently did not interfere with soil water distribution in a way that would depress yield, although this is not to say that it did not or could not affect the water or root distribution pattern. Since the yield difference between adjacent rows on the beds where all residues were removed was similar to that found in the various incorporation treatments, the effect of lateral placement must simply be attributed to the distance between the water source and the near and far plant row, respectively. The placing of drip laterals in only every other interrow space was adopted by the growers in order to save on equipment costs. It is known that somewhat higher yield can be obtained by placing a lateral in every interrow space, but this does not pay for the additional equipment (Oron et al., 1981). The result is that the plants in each row receive irrigation water only from one side, and thus the plants develop a pronouncedly asymmetrical root system. In addition, the high irrigation frequency (3-4 day interval) and small application size commonly used limit the depth of water penetration to about 60 cm. The combined result is a root system whose extent is much smaller than that dictated by the plant's genetic makeup. Thus the deliberately limited and asymmetrical root system is associated with an optimal yield which is somewhat less than maximum yield, due to slightly inadequate water availability. This makes the plant sensitive to any additional factor affecting the water supply, in this case distance between the plant and the water source, which can thus be expected to affect yield.

If one could rely on full compensation between more and less favored plants in adjacent rows under all expectable conditions of lateral displacement from the center, uniformity of stand, and initial soil water storage, the suspected problem could be declared to be non-existent. However, Hadas et al. (1985) have shown that stand heterogeneity may have greater or lesser effect on yield, depending on the presence of other limiting factors such as average stand density, nutrient and water availability. In fields with a high yield potential, heterogeneity is generally

Table I. Comparison of raw cotton yield (Mg ha^{-1}) from rows within a pair as a function of lateral placement and residue disposal.

Residue disposal treatment	Centered					Eccentric						
	I			Block		number			Eccentric			
	III	I	III	avg	II	IV	avg	II	IV	avg	Grand	
	Row			position		position			position			
	left	right	all	left	right	all	left	right	all	left	right	all
1. Removal	4.89	4.67	4.45	4.36	4.59	5.15	5.34	5.25	4.06	4.34	4.20	4.66
2. Buried 30 cm	4.33	5.54	5.46	4.02	4.84	5.15	4.61	4.88	4.13	4.76	4.45	4.75
3. Buried 15 cm	4.19	4.03	4.94	4.32	4.37	5.10	5.05	5.08	3.93	3.76	3.85	4.41
4. Shallow mixed	4.99	5.95	4.03	5.03	5.41	5.15	5.28	4.43	4.43	3.56	4.00	4.83
Average	4.64	4.81	5.20	4.18	4.71	5.20	5.04	5.12	4.14	4.10	4.12	4.66
S.D.	0.39	0.55	0.56	0.16	0.25	0.12	0.27	0.16	0.18	0.47	0.23	0.16

more deleterious. There appear to be at least potential advantages in eliminating heterogeneity due to drip lateral positioning.

CONCLUSIONS

1. Imperfectly centered drip laterals between adjacent cotton rows produced large yield differences between the rows, indicating that yield of the far rows was limited by insufficient water supply.
2. The above yield differences occurred regardless of various residue disposal practices, including complete removal, different placement depths and degree of mixing with the soil. Residue placement was therefore not the cause of the yield differences.
3. The yield differences are attributed to distance between the plant and the water supply.
4. The average yield of row pairs was the same for centered and eccentric drip laterals, which may however not be the case under all conditions.

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C. Short-term effect of organic matter leachate on the shear strength of three soils.

I. Shmilowitz, A. Wolf, D. Wolf, and A. Hadas

Land application of slurry from cattle feed lots and dairy barns is one of the preferred disposal methods for these agricultural wastes. The slurry contains suspended undecomposed organic material as well as decomposition products, polyanions such as proteins, carbohydrates and other materials which may affect the soil matrix, its mechanical properties and strength. Experiments were carried out to test the hypothesis that addition of very active organic material will immediately affect the soil structure, and that these effects will change with time.

Materials and Methods

The soils used in the experiment were a silty loam from Kfar Aza (Calcic Haploxeralf), a clay loam from Yagur (Typic Chromoxerert) and a clay loam from Elrom (Typic Rhodoxeralf). Representative soil properties are given in Table 1. Soil from the upper 20 cm layer was air dried and passed through a 2 mm sieve. Then the control treatment was well mixed with 0.25 L of distilled water per kilogram of soil, to be compared with addition of 0.09 L of compost leachate plus 0.16 L of water. The soils were then each split into three sub-treatments: One part was dried again to the air-dry state; the second and third parts were packed in plastic bags and left to incubate at 25° C for 7 and 14 days, respectively, after which the soil was also brought to air dryness.

The compost leachate was prepared by taking a recommended urban compost⁴ and extracting it with warm water. One part of compost was mixed with two parts of warm water by volume, shaken for one hour, filtered, and the filtrate stored in air tight bottles under refrigeration until used. It is assumed that most of the solutes in the extract consisted of polysaccharides, uronic acids, amino sugars and free acids such as citric, maleic, fumaric, etc.

The treated air dry samples were rewet, the silty loam to 10% w/w, and the clay soils to 20% w/w. The samples were packed into direct shear cells and brought to low, medium and high bulk density (Table 2), and then stressed to failure in a Soiltest Model D-120-B4 direct shear apparatus under normal loads of 50, 100, and 200 kPa.

Results and Discussion

The charts from the direct shear apparatus giving shear stress τ as a function of displacement were used to calculate the cohesion "c" and the angle of internal friction " ϕ " using the Coulomb-Mohr equation fitted by statistical regression models, where σ_n is the normal applied load and τ the measured shear stress.

$$[1] \quad \tau = c + \sigma_n \tan \phi$$

The τ values were taken either at their peak value when the chart displayed a peak, or at the 20% displacement mark. A sample chart is shown in Fig. 1, and the calculated "c", " ϕ ", and regression coefficients are given in Table 2. The pressures required to bring the samples to the required bulk densities are given in Table 3. The data in Table 2 show different responses of soil shear strength to addition of organic matter and incubation. In the untreated silty loam the cohesion increased with bulk density and incubation time. The angle of internal friction also increased with incubation time (with the highest value at 7 days). Addition of organic matter does not seem to change the pattern or order of magnitude of the values except that at 7 days incubation the calculated cohesion of the leachate-treated samples was lower than that of the untreated samples.

In the clay soil (Typic Chromoxerert) where Smectite is the dominant clay mineral, cohesion and angle of internal friction peak at 7 days, and there is practically no difference

4 Personal communication, Y. Avnimelech, Faculty of Agric. Engng., Div. of Soil Organic and Inorganic Chem., The Technion, Haifa, Israel.

Table 1. Selected physical and chemical properties of the experimental soils.

Soil designation	Sand —— %w/w ——	Silt —— %w/w ——	Clay —— %w/w ——	Clay* (pot)				Surface m ² /g	OM %w/w	C.E.C. mole/Kg
				S	K	I	O			
Calcic Haploxeralf	54.0	18.0	18.0	5	2	2	1	70	22	0.151
Typic Chromoxerent	5.0	44.0	51.0	8	1	1	?	280-310	trace	0.414
Typic Rhodoxeralf	38.0	17.0	45.0	4	4	-	2	135-188	none	0.198

* S - Smectite, K - Kaolinite, I - Illite, O - Other
 pot - Parts out of Ten

Fig. 1. Shear stress as a function of displacement for treated and untreated soil under two levels of normal stress.

Table 2. Response of soil strength parameters to organic matter addition, incubation time and bulk density.

Soil \ Index	Incub. period (days)	With or without Compost leachate	Bulk density of sample (Mg·m ⁻³)	Cohesion "C" (kN·m ⁻²) (calcul.)	Angle of internal friction (degree)	Regression Coefficient n x 1
Calci Rhodo xeralf	0	(-)	1.21	0.00	24.6	1.000
	0		1.42	2.31	24.4	0.997
	0		1.61	23.51	27.8	0.997
	0	(+)	1.21	3.19	25.2	0.990
	0		1.42	3.60	23.4	1.000
	0		1.61	19.92	22.2	0.993
	7	(-)	1.21	0.00	46.1	1.000
	7		1.42	21.52	40.1	0.978
	7		1.61	43.83	43.2	0.998
	7	(+)	1.21	6.37	42.6	0.999
	7		1.42	11.95	42.8	0.996
	7		1.61	18.33	41.3	0.986
	14	(-)	1.21	1.59	43.7	0.993
	14		1.42	10.36	41.4	0.991
	14		1.61	37.45	37.8	0.991
	14	(+)	1.21	8.77	42.9	0.980
	14		1.42	13.55	38.9	1.000
	14		1.61	57.38	30.6	0.999
Typic Chromo xerent	0	(-)	1.02	1.99	48.0	0.968
	0		1.34	1.19	29.1	0.992
	0		1.65	58.97	19.6	0.984
	0	(+)	1.02	5.18	25.8	0.986
	0		1.34	7.97	22.8	0.999
	0		1.65	57.38	16.9	0.916
	7	(-)	1.02	27.31	48.0	0.968
	7		1.34	28.37	29.1	0.992
	7		1.65	51.00	19.6	0.984
	7	(+)	1.02	15.14	30.1	0.998
	7		1.34	27.09	26.6	0.982
	7		1.65	39.85	25.3	0.991
Typic Rhodo xeralf	14	(-)	1.02	5.98	23.7	1.000
	14		1.34	11.56	19.1	0.980
	14		1.65	29.31	19.5	0.950
	14	(+)	1.02	7.97	18.5	1.000
	14		1.34	9.96	19.6	0.997
	14		1.65	21.52	18.5	0.952
	0	(-)	1.02	8.77	19.4	1.000
	0		1.34	10.36	21.1	0.989
	0		1.65	19.52	13.0	0.982
	0	(+)	1.02	10.44	22.9	0.999
	0		1.34	8.77	21.0	0.989
	0		1.65	12.12	17.9	0.992
	7	(-)	1.02	0.79	40.8	1.000
	7		1.34	22.31	34.9	0.975
	7		1.65	27.89	29.8	0.973
	7	(+)	1.02	17.53	34.5	0.979
	7		1.34	20.75	37.7	1.000
	7		1.65	25.50	34.9	0.975
	14	(-)	1.02	0.0	28.3	1.000
	14		1.34	5.68	22.1	0.979
	14		1.65	25.10	21.9	0.985
	14	(+)	1.02	0.39	28.4	0.996
	14		1.34	7.57	23.7	0.987
	14		1.65	42.23	19.9	1.000

Table 3. Pressure required to bring experimental soils to various denssities (kPa).

Soil Desigation	Bulk Density Mgm ⁻³					
	1.02	1.21	1.34	1.45	1.61	1.65
Calcic Haploxeralf	-----	0.4±0.3	-----	1.4±0.3	4.5±0.8	-----
Typic Chromoxernt	0.3±0.2	-----	2.2±0.7	-----	-----	5.4±0.6
Typic Rhodoxeralf	0.3±0.1	-----	2.3±0.5	-----	-----	4.2±0.6

between the control and and O.M. treated samples. In the Rhodoxeralf, where the dominant clay minerals are Kaolinite and Illite, cohesion increased with bulk density and slightly with incubation time, in both treated and untreated samples. The angle of internal friction diminished with bulk density, increased somewhat to the 7th day and declined thereafter.

The trends observed for shear strength parameters reflect the changes in the highest values of shear stress used for the correlation equation (namely the peak τ value or τ at 20% displacement). The different modes of shear strength changes with respect to displacement or deformation are ignored. As the rheological behavior of the soil samples is not accounted for, the calculated values of cohesion and internal angle of friction include effects of strain hardening of sheared samples as well as their plastic deformation (See Fig. 1). Consequently, the effects on soil shear strength of active organic material added to the soil or induced in the soil by incubation and activating its own organic matter, are confounded.

In order to get a different view of the effects of organic matter addition and incubation time, we applied the approach of shear energy displacement analysis. The energy dissipated in shearing the samples was computed as the integral of the shear stress $\tau(r)$ - displacement r curves (e.g., Fig. 1).

$$[2] \quad E_{sh} = \int_0^r \tau(r) \, dr$$

Since the functional relationships between τ and r are not known, the integration was carried out graphically by planimetry of the actual recorded τ - displacement relationships.

The E_{sh} data for the silty loam soil (Fig. 2 - 7) were incomplete. Nevertheless, it is evident that immediately after adding the slurry, the energy required to shear the samples for any range of initial bulk density and normal stress did not change. There is a general tendency of increased energy requirement for shear with incubation time, and where sufficient data were obtained for a comparison, practically no differences were found between treated and untreated soil. The general tendency for increased energy requirement for shear with time may be connected with carbonate cementation or decomposition of the small, background amount of organic matter (about 0.5% w/w) present in the soil. Since organic matter content and composition were not determined, no clear explanation can be given for the changes in energy requirement with incubation time.

In Figs. 8 - 13 are shown the energy requirements for shearing the clay soil (Typic Chromoxerent). At the high bulk density (the pre-shear consolidation pressure exceeded the normal stress imposed during shear) there exist two distinct trends: 1) Practically no difference between control soil and soil treated with organic matter; and 2) Energy required to shear was highest in the initial state (zero incubation time), decreased towards the 7-day incubation time, and subsequently increased again (Figs. 8 - 10). This pattern can be explained as follows: Since the leachate contains mainly organic acids, sugars, carbohydrates and uronic acids, it tends to be anionic, and as such may not affect the soil immediately upon application.

As incubation proceeds, acidic decomposition products of the added organic matter (leachate) after 7 days of incubation may affect the electrical double layer activity. When rewetted prior to shear, the repulsive forces of the double layer of the treated soil increase due to anionic decomposition products which adhered to the negatively charged surfaces as the soil dried. The same materials can only slightly increase binding forces when adhering to or being adsorbed onto the few broken positively charged edges of the smectite minerals. The expected gross effect is of reduced strength due to net increase in repulsive forces due to the fact that the magnitude of negatively charged area is much greater than the positively charged edge area in smectitic minerals. When incubation is extended to 14 days the effect of decomposition products diminishes, probably due to decomposition or disappearance of the decay products. As a consequence there some regeneration of shear strength which increases with normal stress during shear.

In the case of the initially low bulk density (Figs. 11-13), the shear pattern is affected both by the above factors and by the additional effect of the imposed normal stress during the shear test, which is greater than the pressure imposed on the sample to attain the initial bulk density. When organic matter is added and the sample is immediately subjected to the test under

Fig. 2. Shear energy for treated and untreated samples as a function of incubation time at three levels of displacement, under a normal stress of 50 kPa and an initial bulk density of 1.61 Mg m^{-3} .

Fig. 3. Shear energy for treated and untreated samples as a function of incubation time at three levels of displacement, under a normal stress of 100 kPa and an initial bulk density of 1.61 Mg m^{-3} .

Fig. 4. Shear energy for treated and untreated samples as a function of incubation time at three levels of displacement, under a normal stress of 200 kPa and an initial bulk density of 1.61 Mg m^{-3} .

Fig. 5. Shear energy for treated and untreated samples as a function of incubation time at three levels of displacement, under a normal stress of 50 kPa and an initial bulk density of 1.21 Mg m^{-3} .

Fig. 6. Shear energy for treated and untreated samples as a function of incubation time at three levels of displacement, under a normal stress of 100 kPa and an initial bulk density of 1.21 Mg m^{-3} .

Fig. 7. Shear energy for treated and untreated samples as a function of incubation time at three levels of displacement, under a normal stress of 200 kPa and an initial bulk density of 1.21 Mg m^{-3} .

Fig. 8. Shear energy for treated and untreated samples as a function of incubation time at three levels of displacement, under a₃ normal stress of 50 kPa and an initial bulk density of 1.65 Mg m⁻³.

Fig. 9. Shear energy for treated and untreated samples as a function of incubation time at three levels of displacement, under a normal stress of 100 kPa and an initial bulk density of 1.65 Mg m^{-3} .

Fig.10. Shear energy for treated and untreated samples as a function of incubation time at three levels of displacement, under a normal stress of 200 kPa and an initial bulk density of 1.65 Mg m^{-3} .

Fig.11. Shear energy for treated and untreated samples as a function of incubation time at three levels of displacement, under a normal stress of 50 kPa and an initial bulk density of 1.02 Mg m^{-3} .

Fig.12. Shear energy for treated and untreated samples as a function of incubation time at three levels of displacement, under a normal stress of 100 kPa and an initial bulk density of 1.02 Mg m^{-3} .

Fig.13. Shear energy for treated and untreated samples as a function of incubation time at three levels of displacement, under a normal stress of 200 kPa and an initial bulk density of 1.02 Mg m^{-3} .

a normal stress of 100 or 200 kPa, more energy is required to shear the sample than for the control treatment. This may be attributed to an initial gluing effect of the original dissolved organic materials. However, when the soils are incubated, the trend is reversed at 7 days, and disappears completely by the 14th day. When a normal load of 50 kPa was applied to low density samples, addition of organic matter had no effect on the shear strength, as if no gluing effects acted at all.

Under normal loads of 100 or 200 kPa the bulk density should have increased from its original value. For normal load of 100 kPa, addition of organic matter caused some "gluing" effect reflected by greater shear energy for all incubation times and displacement percentage smaller than 25%. The total shear energy for complete 25% displacement was greater with added organic matter only for zero incubation time, while for longer incubation times no differences were observed. These results suggest that the "gluing" effect can retain some of its strength, alike to a "spring", until a displacement percentage of about 15%. At 25% this gluing effect disappeared as if the "spring" was torn or broken.

When initial low density samples were subjected to shear under normal load of 200 kPa, there was a change in the pattern. For zero incubation time added organic matter increased strength when compared to non-treated samples. No difference was found between treated and non-treated samples incubated for 14 days, but after 7 days of incubation non-treated samples showed greater strength than the treated ones.

The absence of differences after 14 days of incubation probably reflects the disappearance of active organic materials added, and decomposition products of the original organic matter from both treated and untreated samples.

In the case of the kaolinite-smectite clay the trends are somewhat different (Figs. 14-19). For samples with a high initial bulk density the general trend is that at time zero the added organic matter increases the energy required to shear the sample (Figs. 14-16). This indicates the improved binding ability of the organic matter when added to a soil with a larger percentage of lattice edges which will bind with anionic compounds.

The trend reversal after 14 days of incubation may be due to decay of the added organic material and "edge contamination" by newly decomposed products of the soil organic matter. The trend of these changes as seen in the figures shows an almost complete switch of positions. At $t=0$, the energy required for shearing the untreated soil reflects the inactivity of the soil organic matter, which is probably at equilibrium with respect to decomposition processes. By the seventh day the energy required for shearing the control soil had risen somewhat, whereas that of the treated soil had markedly decreased - almost equal to the final value found after 14 days of incubation. At this time the energy required by the untreated soil reached a value almost equal to that of the treated soil at time zero. This pattern at high density suggests that the high activity of added organic material is related to greater edge bonding on kaolinite clay, which is however highly unstable in this soil. On the other hand, the original organic matter present in the control soil can decompose slowly and increase soil strength with time. It is probable that had the incubation process been continued past 14 days, the trend of increased energy required with time would have peaked and then declined, as indicated by the model presented in Appendix IX.A. In other words, the behavior of organic matter of the untreated soil conforms to the model when K_2 very large compared to K_1 , whereas for the added organic matter in treated soil K_1 is very much larger than K_2 .

In the case of initially low bulk density (Figs. 17-19), the same general trend appears, with "noise" due to the normal loads applied. Under these conditions highly dense packing is not attained, and thus the effect of increased strength due to organic matter is less distinct, although the same general trend is present.

In summary, the results obtained so far suggest that:

- a. Added organic matter, if anionic in nature, will initially increase soil strength under shear if the dominant clay mineral is of the two layer type, like kaolinite, less so for smectites without free calcium carbonate, and not at all in soils with free calcium carbonate.
- b. The initial effect is dissipated after a rather short time. On the other hand, in soils where the original, endemic organic material decomposes slowly, the soil will gain

Fig.14. Shear energy for treated and untreated samples as a function of incubation time at three levels of displacement, under a normal stress of 50 kPa and an initial bulk density of 1.62 Mg m^{-3} .

Fig.15. Shear energy for treated and untreated samples as a function of incubation time at three levels of displacement, under a normal stress of 100 kPa and an initial bulk density of 1.62 Mg m^{-3} .

Fig.16. Shear energy for treated and untreated samples as a function of incubation time at three levels of displacement, under a normal stress of 200 kPa and an initial bulk density of 1.62 Mg m^{-3} .

Fig.17. Shear energy for treated and untreated samples as a function of incubation time at three levels of displacement, under a normal stress of 50 kPa and an initial bulk density of 1.02 Mg m^{-3} .

Fig.18. Shear energy for treated and untreated samples as a function of incubation time at three levels of displacement, under a normal stress of 100 kPa and an initial bulk density of 1.02 Mg m^{-3} .

Fig.19. Shear energy for treated and untreated samples as a function of incubation time at three levels of displacement, under a normal stress of 200 kPa and an initial bulk density of 1.02 Mg m^{-3} .

strength with time if it is of the non-smectite type. Smectitic clays will show no response to added organic material, but will gain strength with time due to decomposition of its endemic organic matter.

- c. The effect of added organic matter is short lived.