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BARD

FINAL REPORT

PROJECT NO. US-666-83

Controlled Traffic for Cropping Systems to Reduce Cost, Energy and Improve Soil and Water Conservation

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1987

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Date: December 1987

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Bet Dagan, ISRAEL

BARD project No. US-666-83

Title

Controlled Traffic for Cropping Systems to Reduce Cost, Energy and

Improve Soil and Water Conservation

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Projects Starting date: December 1984

Type of Report: 1st Annual ☐ 2nd Annual ☐ Final ☒

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630.72

BAR/CAR

2nd copy

631.58 ; 631.43 ; 557.32

631.45 ; 333.91

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ABSTRACT

The project reported here came to study:

- (i) Changes in soil strength, structure and the consequential labour, energy and cost expenditures under conventional, reduced tillage and controlled traffic crop zoning practices.
- (ii) Crop responses to soil conditions changes caused by tillage and traffic caused soil compaction.

The work carried out in three locations - Schafter California - Cotton Research - Station, the National tillage and machinery laboratory, Auburn Alabama in the U.S.A and in Maayan Zvi, Nachsholim settlement, the Technion Haifa and Agricultural Research Organization; Bet Dagan Laboratories in Israel.

The resultant findings can be summarized by:

- (i) Tillage and traffic caused soil compaction leads to delayed or restricted crop development and ultimately to yield reduction, impairment of water infiltrability, roots proliferation and development.
- (ii) Revertment to reduced tillage, controlled traffic management practice has the potential to save labour, energy, reduce soil compaction hazards, lead to soil condition improvement conducive to improved crop development at higher yields.
- (iii) The data so far collected have proven the assumption on which this projects - objectives were based but are too scanty to provide an ample data base on which site, climate or crop tailored controlled, traffic-reduced tillage practices can be developed and recommended.

OBJECTIVES OF THE ORIGINAL RESEARCH PROPOSAL

Main Objectives were:

- a) To study the changes in soil strength, structure and tilth stability under no compaction tillage practices obtained through utilization of the controlled trafficked wide frame tractor technology.
- b) To determine traffic lane characteristics for given field conditions.
- c) To study the possibilities of labour, energy, and cost saving attainable under this new technology.
- d) To measure and study yields and crop response to soil condition attained by this technology application.

Secondary Objectives were:

- (i) To determine changes in bulk density, rain and irrigation infiltration and redistribution in the field as affected by traffic lanes.
- (ii) Measure root proliferation and water extraction patterns from the field as affected by tilled and nontilled, trafficked and nontrafficked soil and,
- (iii) Assess the effects of changes in soil properties on growth, flowering and yields of cotton.

These objectives were based on the following working hypotheses:

- 1) Untrafficked, tilled soil subsides with time, irrigation or rainfall. The bulk density increases and consequently soil properties (e.g., resistance to penetration, aeration, water storage) should change with time and depth, but will not be lower than that obtained on compacted soil;
- 2) Tilled, nontrafficked soil will enable rather simple, profitable management policies to attain optimal tilth;

3) Tilled and untilled trafficked field soils, compacted lanes, impermeable to root and partially impermeable to water will also serve as energy sinks when tilled and impair plant growth;

4) In view of the above assumption, increasing the tilled, noncompacted field area fraction should decrease the amounts of energy required to till the soil, improve water, and fertilizes distribution and root proliferation, will ultimately lead to increasing yields.

In order to achieve the objectives and test these working hypotheses, the following division of responsibilities was decided according to: 1) the site (being near Haifa) 2) the locations, distances to the institutions laboratories and the expertization of the involved institutions:

a) "Granot": Field operations, irrigation, monitoring crop development and crop modeling.

b) Technion: Farm machinery operations, continuous soil water, density determinations, soil mechanical characterization; and

c) Agricultural Research Organization (ARO): Soil physical and chemical properties determinations, seedbed and soil structure analysis, dry matter - wheat and cotton - production and soil density-water content-resistance to penetration analyses.

Body of the Report

The original plan of work involved field and laboratory work to be carried out at three field locations and four laboratory centers.

Field work was planned to be executed at:

a) Shafter California - Cotton Research Station USDA Agricultural Research Station. (Field trials with cotton).

b) Auburn Alabama - National Tillage Machinery laboratory - (traction, compaction trials in soil bins, and fields).

c) Granot Area - field trials with cotton, wheat rotation in Israel.

Laboratory work was to be conducted in the following four locations.

- 1) Cotton Research laboratory, USDA Exp. Station, Shafter California USA
- 2) National Tillage Machinery Laboratory, USDA, Auburn, Alabama USA
- 3) Faculty of Agricultural Engineering, The Technion -Haifa- Israel and
- 4) Institute of Soil and Water, ARO - The Volcani Center, Bet Dagan , Israel

The report will be subdivided into three major parts:

- I. The U.S.A. studies
- II. The Israeli studies
- III. Conclusions and recommendation based on the finding reported in Sections I and II.

ISRAELI STUDIES

The Israeli contribution is reported hereforth and is subdivided into the following parts arranged according to the cropping years:

- a) Characterization procedures of the experimental sites: Maayan Zvi (1985/6 season) and Nachsholim (1986-1987 seasons.)
- b) Validation of predictive models of Soil Compaction by wheels.
- c) Field variability (after tillage, compaction, self subsidence, resistance to penetration, bulk density, texture, chemical properties, infiltration-pondiux time, and final infiltration rates as an estimate of hydraulic conductivity).
- d) Plant response - wheat 1985, wheat 1986. cotton 1985, 1986.

A. Sites Characterization

Several fields were checked as to their suitability for the field trials. Soils ranging from sandy loams to clay were surveyed and the site near Maayan Zvi was selected as the primary choice and a field 5 km to the North of it as an auxiliary field. The general description of the tested sites is given in Table I.

Table 1. General descriptions of four sites wherefrom the experimental site was selected.

Site	Location	Texture			General remarks and description of the area
		clay	silt	sand	
Hamapil	34° 59'E 32° 24'N	43 to 18	29 to 56	28 to 26	Undulating morphology, spots of clayey soil, strips of loam soil, very high variability of soils.
Bochan Metzer	35° 04'E 32° 24'N	61- 64	30- 33	9- 3	Generally flat site, cuts by erosion, during winter partly flooded.
Metzer- Lehavot	35° 04'E 32° 26'N	48- 53	39- 36	13- 11	As above, flat, diagonally cut by natural water conduit
Maayan Zvi	34° 56'E 32° 35'N	50- 42	32- 37	18- 21	Flat site, deep allurial soil, in a valley at the middle.
Nach- sholim	32° 58'E 32° 37'N	50 48	38- 36-	12- 10	As above

The field at Maayan Zvi was sampled at random to a depth of 120 cm and samples were taken to the laboratory for physical, mechanical and chemical properties determinations. Relative location of bores are given in Figure 1.

Some chemical (O.M. content, Cation Exchange Capacity and Exchangeable Sodium Percentage) and physical (soil texture, water relativity) for selected bore holes are given in Table 2. The spatial distribution of clay content at 0 to 15, 25 to 35 cm, water content (g/g) at -1 bar and the hydraulic conductivity (according to Bowers 1966) are given in figures 2 to 6.

The data given in these figures show great diversity and a question rises, is there some order in these distributions or can one detect a trend? In figures 7 to 9 some semivariograms are given for % clay for 0 - 15 and 25 to 35 cm depths and water retention at - 0 bar respectively. The data show a trend of increased variability between clay percentages with increased distance between sampling sites for 0 - 15 and 25 to 35 cm (Fig. 7 & 8) Since the samples for these determinations were taken after the area was deeply plowed and presumably well mixed on one hand and the differences to be small enough on the other hand one can reasonably look on the whole field as a uniform unit.

When the coefficients of variation C.V. of the various parameters given in table 2 are compared are compared to reported C.V. values of corresponding parameters (Warrick and Nielsen 1980) the C.V. for % clay, water content - 1.0 bar tension, fall within the found in the literature range, whereas the C.V. values found for hydraulic conductivities are much greater then those reported by Warrick and Nielsen (1980). These differences can be attributed to the cracks which were still partially active (some were sealed some were still open) in January and after disking and first irrigation of 90 mm in late June (Figures 5 and 6).

Some physical, chemical and mechanical properties for Nachsolim field soil are given in Table 3. This field was sampled at a very low density of sampling bore-holes after consulting a soil surveyor. The slight differences in texture as shown in the given ranges in Table 4 support this procedure.

Shear characteristics of Nachsholim soil are given in Table 4.

The mechanical properties of Maayan Zvi soil can be used also for Nachsholim soil due to the similarity in their physical and chemical properties.

Since no specific spatial variation could be found for water holding capacities at -1.0 bar and clay content, the variation in the soil properties measured in the field - e.g. bulk densities, infiltration structural variation - were taken to result from the agrotechniques and traffic induced variations.

Figure 1: Borelids spread on Maayan Zvi field, 1984.

Figure 2: Clay; contents (%) of 0-15 cm depth layer on Maayan Zvi field 1984.

Figure 3: Clay contents (%) of 25-35 cm depth layer on Maayan Zvi field 1984.

Figure 4: Gravimetric water content [g.g⁻¹ x 100] at $\psi = -1.0$ bar, for 0-15 cm depth layer on Maayan Zvi field 1984.

Figure 5: Hydraulic conductivity [mm.hr^{-1}] determined during January 1985, on blocks 1 and 2 on Maayan Zvi field.

Figure 6: Hydraulic conductivity [mm.hr⁻¹] determined during June 1985 on blocks 1 and 2 on Maayan Zvi field.

Table 2. Physical and chemical properties of selected boreholes in Maayan Zvi: 1985

Depth of layer (cm)		Texture <2			Water characteristics			Organic<3 matter (%W/W)	Cation<4 exchange (mole+/kg)	Sodium<4 exchange (%)
		clay	silt (% W/W)	sand	% W/W at ψ (bars)					
					-1/3	- 1	- 15			
6	0-25	53.0	39.1	7.8	40.5	30.9	28.1	2.3	35.65	5.72
	25-35	54.5	38.0	7.5	39.6	32.9	27.3	1.9	35.65	7.27
	55-65	53.1	39.5	7.4	36.9	32.6	26.9	1.4	35.35	7.52
	85-95	53.2	39.7	7.1	40.8	33.7	27.5	1.4	35.15	8.67
7	0-25	52.5	37.2	10.3	33.7	29.9	25.1	2.2	35.65	6.09
	25-35	51.4	36.5	12.1	35.9	31.3	27.8	1.8	33.97	6.39
	55-65	48.6	38.8	12.6	40.6	31.9	27.7	1.2	33.97	6.65
	85-95	51.3	38.6	10.1	40.5	33.3	10.1	1.1	33.29	7.15
8	0-15	50.1	40.4	8.5	34.8	30.1	26.1	2.3	33.97	7.15
	25-35	54.4	38.3	7.3	40.4	32.9	26.7	2.0	33.65	7.70
	55-65	52.5	38.8	8.3	41.8	33.7	30.7	1.4	35.65	6.82
	85-95	53.3	39.4	8.3	44.2	35.5	31.4	1.1	33.97	9.1
10	0-25	52.2	39.0	8.8	35.6	33.6	26.8	1.8	33.97	6.00
	25-35	52.7	39.4	7.7	44.5	35.6	33.2	1.5	33.17	7.15
	55-65	54.2	38.5	6.3	43.7	34.4	32.9	1.1	33.81	8.36
	85-95	53.3	36.2	10.5	41.2	34.3	31.3	1.0	33.97	9.95
16.30-15	0-15	48.8	39.1	12.1	33.3	28.3	25.2	1.7	30.57	6.22
	25-35	48.7	39.2	12.1	39.4	30.5	29.1	1.6	24.70	9.47
	55-65	51.2	40.4	8.4	41.7	32.9	30.8	1.1	32.3	8.03
	85-95	50.3	40.2	9.3	41.4	32.7	28.8	1.0	24.7	11.50
17	0-15	44.1	37.8	18.1	34.9	29.3	21.5	1.8	28.9	6.83
	25-35	47.6	34.8	17.6	38.8	31.3	22.9	1.4	28.9	7.83
	55-65	47.2	39.3	13.5	37.8	31.3	22.8	1.2	30.57	8.21
	85-95	48.7	40.6	10.7	38.9	32.0	23.3	1.0	32.3	8.02
19	0-25	53.8	38.2	9.0	33.8	31.2	22.4	2.1	37.36	5.73
	25-35	53.9	38.3	8.8	42.9	32.4	23.4	2.2	37.36	5.73
	55-65	53.2	39.0	7.8	43.2	36.6	24.2	1.4	35.65	6.81
	85-95	52.0	40.0	8.0	42.6	33.6	24.9	1.1	35.65	8.67
20	0-15	53.6	38.3	8.1	30.2	27.4	25.5	2.5	33.56	5.33
	25-35	49.8	41.0	9.2	39.2	31.6	28.2	1.9	35.65	6.56
	55-65	51.7	39.7	8.6	38.1	31.8	29.8	1.1	37.36	6.56
	85-95	49.6	42.2	8.2	39.9	32.3	28.8	1.0	37.36	6.72
21	0-15	52.5	34.2	13.3	30.2	26.2	22.3	1.2	27.17	6.74
	25-35	40.9	39.9	19.2	31.1	26.1	21.5	1.7	30.57	6.00
	55-65	45.2	36.8	18.0	35.4	28.2	25.6	1.4	30.57	6.44
	85-95	48.7	37.4	13.9	37.6	25.4	30.5	1.1	30.57	7.95
34	0-15	45.1	37.2	17.7	32.2	28.4	21.9	1.4	33.97	5.21
	25-35	46.7	37.1	16.2	36.8	29.5	21.1	1.6	32.26	5.49
	55-65	44.2	39.8	16.0	38.9	30.7	25.5	1.1	32.26	6.10
	85-95	43.6	35.7	20.7	37.5	30.4	25.8	1.01	28.90	6.83
36	0-25	44.8	38.1	17.1	30.3	27.3	22.9	1.7	32.26	5.05
	25-35	43.2	38.8	17.0	34.5	29.2	24.9	1.4	32.26	5.49
	55-65	46.2	36.9	16.9	34.3	28.9	25.8	1.0	32.26	5.89
	85-95	41.4	33.2	25.4	33.9	27.9	23.3	0.9	25.95	8.25

Table 2: Cont.

38	0-15	44.8	42.4	12.8	37.7	31.5	26.9	2.3	35.65	4.96
	25-35	51.2	39.8	9.0	37.6	31.2	26.3	2.1	34.0	5.80
	55-65	49.8	39.2	10.0	39.0	30.7	26.4	1.5	34.0	6.89
	85-95	51.3	39.7	10.0	42.4	33.4	27.6	1.2	35.65	7.04
40	0-15	51.1	37.9	11.0	39.2	28.2	23.9	2.1	42.45	5.12
	25-35	49.4	37.8	12.8	39.7	34.0	27.4	1.5	45.84	5.73
	55-65	50.5	36.6	12.5	42.4	33.8	24.7	1.3	44.16	5.83
	85-95	48.3	38.1	13.6	39.8	32.6	24.9	1.0	44.16	6.25
42	0-25	44.8	37.0	18.2	32.5	28.9	20.9	1.7	39.05	5.04
	25-35	45.9	37.6	16.5	36.59	29.2	22.4	1.5	39.05	7.07
	55-65	48.0	39.8	12.2	39.1	30.5	23.2	1.3	44.16	7.63
	85-95	48.0	38.8	13.2	37.0	31.0	23.5	.6	40.76	8.19
43	0-15	48.8	41.9	9.3	33.1	29.0	23.5	1.9	44.18	4.85
	25-35	52.3	40.0	7.7	37.2	31.2	22.4	1.5	42.45	5.91
	55-65	51.0	38.8	10.2	38.1	33.7	22.9	1.2	45.84	5.10
	85-95	51.1	40.2	8.7	39.4	3.4	24.3	1.2	44.16	6.07
45	0-15	47.9	39.0	13.1	32.1	27.6	21.6	1.6	39.05	4.87
	25-35	46.6	38.0	15.4	37.8	30.1	22.7	1.6	39.05	5.48
	55-65	45.0	39.1	15.9	39.4	31.8	24.8	1.1	39.05	6.43
	85-95	48.3	37.8	19.9	39.6	32.3	24.8	1.1	42.45	6.10
46	0-15	45.6	36.9	17.5	38.45	28.8	22.6	2.5	40.75	6.36
	25-35	45.8	37.0	17.2	33.6	28.8	22.8	1.6	33.97	5.80
	55-65	44.8	40.4	14.8	36.0	30.0	20.8	1.1	37.36	6.05
	85-95	45.8	39.5	14.7	36.1	31.1	22.3	1.0	37.36	6.72
52	0-15	42.4	34.8	22.8	36.5	26.2	22.5	1.9	32.26	8.56
	25-35	43.4	33.7	22.9	34.7	27.7	21.4	1.6	33.97	7.62
	55-65	42.6	35.8	21.6	29.9	29.4	23.9	1.0	35.67	5.52
	85-95	36.5	28.8	34.7	33.4	28.31	19.4	0.7	27.17	6.51
53	0-15	39.8	31.1	29.1	31.8	26.5	24.7	1.1	37.36	9.05
	25-35	42.6	31.7	25.6	30.2	27.7	22.7	1.4	39.07	9.57
	55-65	42.2	32.4	25.4	32.4	27.6	24.5	.7	37.37	7.84
	85-95	36.5	25.4	38.1	28.5	24.3	20.1	.6	33.97	7.62
57	0-15	46.8	37.2	16.0	36.3	30.5	23.3	1.7	35.65	6.34
	25-35	46.2	39.9	14.0	35.1	30.9	23.7	1.9	44.16	5.30
	55-65	46.9	38.3	14.8	35.5	30.02	24.7	1.4	40.76	6.58
	85-95	46.4	38.8	14.8	37.6	28.4	21.5	1.1	33.76	8.86
59	0-15	47.2	39.2	13.6	35.8	31.4	21.9	1.6	39.05	5.99
	25-35	43.8	40.4	14.8	34.4	-	21.8	1.5	49.45	5.51
	55-65	46.4	40.4	13.2	36.9	31.3	22.3	1.1	39.05	6.63
	85-95	45.3	40.9	13.8	38.7	31.9	21.4	1.1	39.05	7.50
60	0-15	47.8	42.5	9.7	39.3	32.5	24.6	2.6	42.45	6.10
	25-35	51.8	40.9	7.3	40.5	-	23.5	1.7	44.16	6.63
	55-65	51.6	40.6	7.8	-	39.5	23.5	1.2	45.84	7.11
	85-95	49.2	41.5	10.3	41.1	36.8	22.7	1.1	44.16	8.74

<1 Each value given is an average value of three replicates

<2 Texture was determined by the hydrometer method ()

<3 Organic matter content was determined according to ()

<4 Cation exchange capacity and exchangeable Sodium Percentage were determined according to ().

Addition to Table 2

	% clay	<u>C.V.</u>
0-15	48.84 ± 3.906	8.0%
25-35	48.28 ± 4.119	8.5%
55-65	48.45 ± 3.618	7.5%

Pw (-1/3 bars)

0-15	34.66 ± 3.0796	8.9%
25-35	37.30 ± 3.513	9.4%
55-65	38.15 ± 3.5217	9.3%

Pw (- 15 bars)

0-15	23.83 ± 2.01	8.4%
25-35	24.69 ± 3.13	12.7%
55-65	25.65 ± 3.07	12.0%

CEC [moles +/-kg]

0-15	35.86 ± 4.45	12.4%
25-35	36.51 ± 5.95	16.3%
55-65	36.92 ± 4.65	12.6%

ESP %

0-15	6.05 ± 1.423	18.9%
25-35	6.61 ± 1.236	18.7%
55-65	6.79 ± 0.874	12.9%

Average range and coefficient of variation of hydraulic conductivity (C.V.)

[m·s⁻¹ × 10⁶]

January - 1.78 to 32.1 average C.V. per site = 41.8% for range
 June - 11.30 to 91.2 average C.V. per site = 46.1% for range
 after 1st irrigation

averages 1803%
 80%

Figure 7: Semi-variogram of clay content $[\%]^2$ vs. distance [m] of 0-15 cm depth layer. Maayan Zvi 1984.

Figure 8: Semi variance of clay contents [%]² vs. distance [m] of 25-35 cm depth layer, Maayan Zvi, 1984.

Figure 9: Semivariogram of water contents at $\psi = -1.0$ [bars] vs. distance [m]. Maayan Avi 1984.

Table 3: Some physical, chemical and mechanical properties of Nachsholim soil.

Depth cm	Texture			CaCO ₃ % W/W	C.E.C. Mole +/kg
	Clay %	Silt %	Sand (fine) %		
0 - 30	49 - 54	36 - 39	10 - 12	3.0 - 4.1	34.5 - 36.2
30 - 60	48 - 52	37 - 40	11 - 12	_____	33.1 - 35.8

Atterberg Limits

-----% W/W-----

Plastic Limit	Liquid Limit	Plasticity Index	Coefficient of Linear Extensibility	Proctor Test [Mg.m ⁻³]/%(W/W)
51.0	25.7	25.3	0.212	1.320/32.8
47.8	24.3	23.5	0.193	1.388/32.5

Consolidation Tests Parameters
(According to Larson and Gupta 1982)

C Value	T	Pk [Mg.m ⁻³]	Sk (%W/W)	Source (Site;%Clay)
0.56	3.65x10 ⁻³	1.33	55	Qedma,4,9
0.59	4.16x10 ⁻³	1.25	54	Qedma,52
0.57	5.09x10 ⁻³	1.25	57	Ganshemul 47
Averages				
0.575	4.3x10 ⁻³	1.277	56.0	-----

Table 4: Direct shear characteristics: Cohesion C and angle of internal friction ϕ for precompressed, dramied direct shear tests for Nachsholim sieved through #4 sieve Shear rate 2.38 mm/min. (Technion Lab)

Bulk Density [Mg.m ⁻³]	Cohesion [kPa]	Friction Angle [degrees]	Water Content +/- s.d. PW- (W/W-%)	Correlation Factor
1.0	11.7	35.1	13.1+0.6	.99
1.1	12.1	34.3	10.7+0.2	.99
1.2	15.0	45.9	9.6+0.2	.99
1.3	41.8	53.8	9.6+0.5	.99
1.0	15.2	35.7	18.2+0.2	.99
1.1	16.7	37.5	20.8+1.2	.99
1.2	36.0	40.3	19.2+0.6	.99
1.3	83.5	43.1	19.2+0.4	.99
1.0	10.0	43.2	33.9+0.8	.99
1.1	24.0	35.1	28.9+0.2	.99
1.2	38.0	35.1	27.1+1.2	.99
1.3	41.9	32.7	29.6+0.4	.99
1.0	11.3	29.1	42.8+0.4	.99
1.1	11.3	30.3	41.5+0.3	.99
1.2	18.0	27.3	39.3+0.6	.99
1.3	22.9	32.3	37.0+2.2	.99

This resulting conclusion may not be rigorous with respect to the rather small number of pairs on which the semivariograms were based. The small C.V. values found allow us to neglect possible spatial variability effects.

B. Fields Layout, Agrotechniques and Crops

The plan of work was projected to be carried out on a simple field. During 1984-5 seasons the choice fell on Maayan Zvi. But when toward the fall of 1985 it was realized that the field was infested with nematods, it was abandoned and the experimental field was moved to Nachsholim four kilometers to the north. With the new field being located on the same soil type and almost identical morphological features, it was taken for granted that the extensive laboratory work carried on for the Maayan Zvi field would apply. Yet some checks as to the texture, and mechanical properties were carried out and proved that in a seuse the soils are identical. Furthermore, the lack of spatial variability dependence led to the conclusion that fewer samples would still represent the field, as given in Table 2. The layouts of the Maayan Zvi and Nachsholim fields are given in Figs. 10 and 11.

The same treatments were applied to both fields; yet the area to be tilled by the wide frame tractor was three times wider than that allotted for the conventional tractor (18m vs. 6m respectively). The idea was later to apply differential Nitrogen applications under the wide frame tractor plots.

Due to the Nemotode infestation, the transfer of the experimental site led to the realization that it might be better to use equal sized plots and to reject any future subdivisions of the plots. Therefore the Nachsholim site was arranged into equal plots, 18m wide and 185 m long in four blocks - replicates and the same treatments as before.

The following crops were grown in the two fields.

Winter 1984-5 A third of the field was fodder wheat denoted by subscript C, on figures 10 and 11; the remainder was left fallow for the winter.

Summer 1985 Cotton variety SJ-1.

Fall/Winter 1985 One third of the field-fodder wheat, but this was sown rather late due to the move from Maayan Zvi to Nachsholim.
The stand was bad due to sowing problem on a wet field. No analysis was carried out.

Summer 1986 Cotton v. Pima - a long fiber variety. Cotton picking was delayed due to late ripening, and thus cotton picking, autumn tillage operations and wheat sowing were delayed and carried out on wet soil. The cotton pickers could handle only two rows, thus compacting every furrow except for two blocks, adjacent to the road passing in the middle of the field, which were picked during a rainfall recess on almost dry soil:

Fall/Winter
1986/7

Fodder wheat was sown on one third of the field area but sampling was carried out only on the two blocks left intact by cotton pickers compaction the previous fall. Yet due to wet spring and late rainfall, harvesting fodder wheat and cotton planting destroyed all different patterns of compaction, namely the differential treatments.

The plots were arranged either for multiples of 5.80m width for the conventional tractor (CT) - hence conventional tillage and or traffic or for the wide Frame (WFT) tractor or otherwise known as field power unit (FPU). Typical cross sections of the field sections under these vehicles are given in Figure 12. This schematic presentation shows only the simplified contact positioning but does not show the compaction patterns left behind. Under these simple conditions the compacted-contact areas and the untrafficked spans of a cropping bed were calculated and are given in Fig. 12. The calculated values given in a table below Figure 12 give the lower bound of the area percentage that is compacted or the higher bound of nontrafficked span of a cropped bed, when compared to actual condition of repeated traffic and tillage passes.

C. Preliminary studies and final division of responsibilities

Some preliminary studies were carried out prior to and in parallel to the field experiments. These preliminary tests included:

- a. Bulk density - water content losses and cohesion under direct shear,
- b. Bulk density - water content - resistance to penetration relationships,
- c. Comparison between measured and predicted bulk densities under wheel tracks,

Figure 10: Field plan for Maayan Avi 1984, a) Chisel, b) moldboard plow, c) wheat disk, 2-conventional traffic mode 2-wideframe tractor traffic.

2b	2a	3b	3a	(1)	3a	3b	(1)
3a	3b	(1)	3b	3a	(1)	2a	2b
3a	3c	(1)	2a	3a	2a	3b	(1)
3b	3a	2b	2a	(1)	3b	3a	(1)

Figure 11: Field plan of Nachsholim 1986 field. 1) Interim plots, 2)conventional traffic, 3-wideframe traffic, a) wheat disk, b)moldboard plow and c) chisel plow.

Figure 12: Wheels positioning on conventional and wideframe traffic.

- d. Final infiltration rates as estimates of hydraulic conductivities on wheel track and off wheel tracks after planting and after irrigations.
- a. Bulk density - water content soil cohesion under direct shear.

Soil samples were wetted to "Field Capacity" (27% W/W) and pressed to dry apparent density of 1.22 ± 0.04 and to 1.43 ± 0.03 [Mg.m^{-3}]. Samples were allowed to dry at a slow rate in the laboratory then sheared at different water contents in a direct shear apparatus, and their cohesion was calculated. The results are given in Figure 13. The changes in bulk density during the course of drying were minute, yet the cohesion increased linearly until water content reaches approximately 10% (W/W) and the slope changed. Whereas for the highly compressed samples, the cohesion increased with water content linearly throughout the whole range of water contents. The increase of 11.7% in initial bulk density brought about a similar increase 11.6% in the initial slope dc/dP_w . Yet while this slope was maintained for the high initial densities, it diminished to $dc/dP_w = 0.073$ at $P_w \sim 10\%$ for the lower density samples. These changes in the slopes of the lines shows the increase and decrease in soil cohesion brought about by soil internal stresses caused by surface tension of the soil solution receding in the soil pores and the changes in the pore system continuity. The higher slope for the denser samples signify greater stresses due to narrower pores. Since there is a logarithmic relationship between stress and soil bulk density (Larson et al. 1980) and an exponential relationship (in the range between "field capacity to dryness") between the shrinking soil samples water potential caused internal stresses and water contents, the slope remains linear on a cartesian scale. For the less dense samples, the gradual change over in the dc/dP_w slope signifies a change in the internal rearrangement of particles by shrinkage and water menisci caused stresses. The reduced slope means that micro cracks appear in the samples which still shrink and thus less contact areas of high cohesion are left.

The practical implication suggests that trafficked lanes which are compacted more than their adjacent soil volumes will bring about, upon drying, soil volumes of higher inherent cohesion which will not be broken or only partly so during tillage, leaving a coarser seed bed adjacent to the traffic lanes. Also roots will be less inclined or capable to penetrate these volumes. Infiltration into these higher density soil units will be slower, but where compacted volumes will tend to shrink more due to precompaction and will probably be more inclined to crack,

Figure 13: Cohesion and bulk densities changes under direct shear conditions as affected by gravimetric water content and initial bulk density of a) $1.22 \pm 0.04 \text{ [mg.m}^{-3}\text{]}$ and b) $1.43 \pm 0.03 \text{ [kg.cm}^{-2}\text{]}$.

upon drying than those having lower density to begin with.

These soil samples of 2" x 2" cannot be used for a complete similitude study of field soil behavior, since these samples are too small, yet these findings are pertinent to those subvolumes which shrink severely between the cracks in the field, especially so, on trafficked lanes.

b. Bulk Density - water content - resistance to penetration relationships

In many cases a penetrometer is useful to detect differences in soil resistance to penetration. According to Koolen and Kuipers (1983) penetrometer reading can be used successfully to estimate pore space, bulk density, provided good calibration has been attained. Empirical equation can be obtained by relating the penetrometer reading to produce a void in the soil to the soil bulk density and water contents (Mckeys 1985, Koolen, and Kuipers 1983).

Soil resistance to penetration of a standard core was determined by recording the resistance [kg.cm^{-2}] vs. depth in cm, six penetrations per point, and then samples of bulk density and moisture contents were taken from the same sites at depths of 0-5, 7.5 - 12.5, 17.5 - 22.5, and 37.5 - 42.5 cm. (two samples for each point and depth). Two sets of such calibrations were made, one for Maayan Zvi soil (Jan. 1985), and Nachsholim (Jan. 1987). The resulting data sets of 14 points in each set of determinations (carried out after the top layers were assumed to reach "field capacity") are given in figures no. 14 and 15.

Soil bulk density Y and soil resistance to cavity formation X were related by using the following empirical relationships which are given

$$Y = A + X^n$$

in the figures 14 and 15, where Y is the soil bulk density in [Mg.m^{-3}] and X is given by Penetrometer Reading (Z) - [$A+BZ$]. The bracketed term is the penetrometer rod depth friction in the soil measured separately and found to be:

Freshly Tilled Topsoil

$$A = 0.12 \text{ [kg.cm}^{-2}\text{]}; B = 0.123 \text{ [kg.cm}^{-3}\text{]}; Pw = 19.1 + 1.4\%$$

Settled Soil and Deep Layers

$$A = 0.63 \text{ [kg.cm}^{-2}\text{]}; B = 0.476 \text{ [kg.cm}^{-3}\text{]}; Pw = 27.8 + 2.3\%$$

Figure 14: Measured bulk densities [Mg.m⁻³] as functions of measured cone index determined by penetrometer [kg.cm⁻²] for Maayan Zvi and Nachsholim soil lower set - wideframe tractor plot (Transverse transects).

Figure 15: Measured bulk densities [Mg.m⁻³] as functions of measured cone index determined by penetrometer [kg.cm⁻²] for Maayan Zvi and Nachsholim soils.

c. Comparison between measured and predicted bulk densities under wheel tracks.

In order to verify the possibility to detect either by bulk density determinations or from penetrometer readings signs of wheat traffic caused compaction, the following comparison was made.

Using the compressibility parameters of Nachsholim soil (Table 3) as input parameters with the water contents prevailing during the time of spring tillage in Spring 1987, the distribution of bulk densities under and adjacent to the wheel ruts of the gantry type tractor (wide frame) were determined by sampling in a horizontal and vertical grid of 20 cm by 20 cm. The experimentally determined bulk densities were compared to the forecasted distribution obtained by using the soil parameters (Table 3) and the model of Larson and Gupta (1982). The results are given in figures 16 and 17.

As can be seen the computed bulk densities overestimate the measured values near the center of the ruts and underestimate them elsewhere. In figure 18 the penetrometer readings are given. From the data shown, one has to conclude that penetrometry and bulk density determinations will detect compaction but will not enable quantitative analysis as to the pressure applied to the soil surface or the soil profile state during compressive stress application. Similar results were reported by Hadas et al. (1986) and Hadas (1987). In these works the deviations from the theoretical distributions were attributed to the different insitu soil structure and moisture content distributions, as compared to that of the laboratory small, well-ground and sieved samples, used to obtain the soil compression parameters. Another factor was rate of stress loading, the higher the loading stress rate the lower the compaction strain (Hadas 1987).

d. Final Infiltration rates as estimates of hydraulic conductivities on and off wheel tracks at different periods (e.g., shortly after compaction, after rainfalls and during summer impaction season).

Aluminum cylinders 200 mm diameter and 250 mm long were used to measure infiltration at Maayan Zvi during Jan 1985, April 1985, and late June 1985. Into ten points along two transects, one along a wheel track and the second along the center of untrafficked cropped bed, 2 meters apart, Aluminum cylinders were inserted to a depth of 200 mm. Water was poured into the top and a constant head of ~40 was maintained by adding water sporadically from calibrated cylinders. The final rates after 3 to 5 hours were determined. The cylinders were then taken out and the soil bulk density was determined. The results are given in Table 5.

Figure 16: Predicted distribution of bulk density under a tractor wheel (broken line) and measured values (solid line).

Figure 17: Estimated bulk density values as a function of measured values.

Figure 18: Measured resistances to penetration distributions under and next to a compacted wheel track.

Table 5: Final infiltration rates and corresponding bulk densities determined on three different dates for Maayan Zvi field on tilled bench and trafficked lane.

<u>Maayan Zvi</u>				
Tilled Bench			Trafficked Lane	
Time	Bulk Density [Mg.m ⁻³]	Final Infiltration [mm.hr ⁻¹]	Bulk Density [Mg.m ⁻³]	Final Infiltration [mm.hr ⁻¹]
Jan. Winter 1985 1]	1.195+0.027	5.1+3.2 C.V=62.7%	1.451+0.037	2.0+1.3 C.V=65.0%
April 1985 2]	1.312+0.034	6.3+6.2 C.V=98.4%	1.436+0.025	7.6+6.3 C.V=82.8%
Late June 1985	1.379+0.025	6.2+4.3 C.V=69.4%	1.415+0.042	4.1+3.1 C.V=75.6%

- 1] After seed bed preparation and 30 mm rain of the rain machine. On the trafficked lane between cracks.
- 2] After 130mm of irrigation. On the traffic lane.
The data given are mean and S. Deviation of 10 measurements.

The data show that on the tilled bench the bulk density at first (Jan. 1985) is much lower then that of the tracked wheel nuts and a rather distinct difference in the final infiltration rate is evident.

But the fine rather unstable material on the bench caused partial sealing in some of the cylinders whereas on the trafficked lane some fine, almost closed cracks could be distinguished. The partial sealing and the slight cracking could have affected and caused the large variability and rather low infiltrability on the low density tilled bench and the relative high infiltrability of the trafficked lane respectively, at later dates.

During spring time of 1985 the lightly compacted seed bed shows an increase in bulk density whereas no real significant reduction in the bulk density of the trafficked lane is observed. The infiltrability of both transects is practically the same and is probably affected by the fine cracks which reappeared. This infiltrability was maintained on the nontrafficked cropped bench inspite of its increased density due to irrigation, but on the trafficked lane which was used during the period between April 1985 to June 1985 twice, the same amount of irrigation water caused a further slight reduction in density yet a lower infiltrability. Practically, the differences for the spring and summer data are not significantly different, yet the trend is there. Infiltration can not be used to discern compaction on the clay soil used at the particular soil conditions prevailing during these tests. In figure 19 the infiltration readings are given in the form a transect. The variations are rather large, yet the number of readings is too small to render a rigorous auto-correlation test.

Another test was carried out to determine the infiltration variations on a large area. The test was marking areas where ponding was attained after 5 minutes of simulated rain under irrigation machine (a walking boom 36m wide). The localized rain intensity was approximately 340 mm hr^{-1} and the predetermined dwelling time while moving above a point was set to be 1/10th of an hour or 6 minutes. Thus the total water given to a unit area was 33-35 mm.

The machine was tested on April 14th 1985. Each water outlet was checked prior to the activation of the machine. Cans were placed on a grid of 12 m (along the moving direction of the machine) and 2 m apart from the machine center toward the boom end. The machine was allowed to move 60 m from the plot border before coming across the grid. During the test, zones with ponded water were visually marked and mapped. Areal water distribution was determined by measuring the water collected in the cans (150 mm diameter / 200 mm high).

In Figure 20 equi-percentage lines of the calibrated amount as of the applied irrigation water are given.

Figure 19: Final infiltration rates [mm. hr^{-1}] dependence on distance bench (O), and wheel tract (O) for January 1985, April 1985 and late June 1985.

Figure 20: Distributions of water machine tracks, iso-lines of
□ Christiansen no. (solid line) and ponded water (shaded area).
Maayan Zvi 1985.

The calibrated amount was set for 332mm of water to be applied, the actual amount measured was 30.9 ± 4.4 mm, thus the C.V.=14.2%. From the analysis of variance, 12%, 52% and 36% of it could be attributed to positioning and direction of orifice on the machine's boom, changes in rate of advance and the remainder to changes in: discharge pressure, wind and boom rocking, respectively. In figure 20 the shaded areas mark the areas drawn by eye where ponded water was observed at the termination of irrigation. As seen ponded water was in the traffic lanes as well as in between, mostly above a total amount of ~ 0.80 of the nominal value of 35 mm, namely after ~ 28 mm of water was taken up.

This set of observation neither gives a quantitative analysis or database of the soil infiltrability, nor of its variability, but it may cast some light as to the great variability found in water contents of the soil profiles during summer (see cotton development).

Final Division of Responsibilities

- a) The sites characterization - physical, chemical properties of soils, soil and seed bed structure analysis, penetrometry soil density - water content studies and plant measurements were done by the Agricultural Research Organization.
- b) Crop modeling, crop development and pest control monitoring; field operation and irrigation control were to be carried out by "Granot"; and
- c) Controlling the Agricultural machinery, tillage operations, soil moisture and bulk density - continuous sampling during growing seasons and determination of soil mechanical properties were carried out by the Technion.

D. Field experiments

Two major crops were grown on the experimental fields -Maayan Zvi and Nachsholim:

A) Wheat for tillage - sown during late autumn, after cotton and harvested either late March or early April for silage.

B) Cotton - under complete summer irrigation of 370 to 420 mm equivalent rain. Cotton was sown by mid April and picked late September or early October. Details of treatments and fields were given in Section 2 (site characteristics). The reported results of the two crop seasons will be presented in two sections:

- a. Wheat for silage - 1984/5 and 1986/7 seasons, and
- b. Cotton - 1985, 1986 and 1987 seasons

D.1. WHEAT

a. 1984 - 1985 SEASON

At the end of a corn crop (late August 1984) the Mayan Zvi site was prepared (plowed, chisled, etc) according to the experimental plan (fig. 1).

During late December 1984 transects of resistance to penetration and water contents across the major treatments were taken. Due to warm February weather (1985) spots of yellowing and enhanced maturity were detected causing earlier harvesting than anticipated (late March).

Wheat plots (1 x 1 m each) were harvested in three traverse transects 50 meters apart along the plots. Each transect covered 3 stretches of 6 meter units of the same treatment from Block 2 which was the least affected by early maturity.

Resistance to penetration was measured every 0.5 m along the transects to a nominal depth of 70 cm or less if impedance to penetration exceeded 70 [kg.cm⁻²]. Gravimetric water content distributions to a depth of 90 cm in layers of 0 to 15, 15 to 30, 30 to 60, and 60 to 90 cm were determined. Samples of bulk density were collected along the transects in the center of the crop beds and trafficked lanes. On one transect, nontrafficked lanes were sampled for water content and bulk density. Some of these bulk density data determined by core-sampling were compared to computed bulk density values using water contents and resistance to penetration correlations.

RESULTS

A cross-section of transects taken in January and the respective gravimetric water contents ($\pm$ s. deviations) are given in Figure 21. From the iso-resistance-density lines, one can discern the traffic lanes under the conventional and wide-frame tractors, as those under which the resistance to penetration is rather higher than at the neighboring points. In general the soil is rather mellow and yielding (low resistances to penetration) which could reflect the mellowing effects of corn root decay and autumnal tillage.

Typical bulk densities distributions under different tillage and traffic patterns are given in figures 22, 23, 24 and 25 for conventional traffic subsoiler; conventional traffic - moldboard plow; wideframe - subsoiler, and wideframe - moldboard plow. A comparison between the computed bulk densities and measured ones is given in fig. 26 for (Maayan Zvi - January 1985).

There is a reasonable agreement between the measured bulk densities and the values computed from the very narrow water contents range (27 - 28 % W/W) and the penetrometer readings calibration equations, given before. Typical cross-sections of soil bulk density distributions are given in figures 27 and 28 for wheat plots for harvest time for the last week of Feb. 1985. These patterns, calculated from resistance to penetration and water content, show distinctly the compaction zones where wheels were in contact with the soil. The bulk density values given are rather high as compared to those given in figures 22 to 25 even though there is a time difference of almost 7 weeks in between which those penetrometer and moisture contents were determined. (Table 5.)

One should expect some alliviation of the compaction by swelling, yet the existance of these rather high values may be attributed to some reinforcement of soil by wheat roots which increase the soil cohesion and thus its resistance to penetration, resulting in overestimated bulk densities. A comparison between measured and computed bulk densities for wheat plots is given in Figure 29.

These data show much smaller intercept - $0.3754 \text{ [Mg.m}^{-3}]$ then that given in fig. 26 - $0.3922 \text{ [Mg.m}^{-3}]$ and the slope is almost doubled 1.3051 vs. 0.6938 . Two conclusions should be drawn from the data given above:

Figure 21: Lines of iso-resistance to penetration under conventional and wideframe traffic plots for Maayan Zvi field (January 1985). Upper set-conventional traffic lower set - wideframe tractor plot (Transverse transects).

Figure 21-a: Lines of iso-resistance to penetration under conventional and wideframe traffic plots for Maayan Zvi field (January 1985).
Upper set-conventional traffic lower set - wideframe tractor plot (Transverse transects).

Figure 22: Bulk density distributions calculated from gravimetric water contents and penetrometer readings for a transverse transect under chisel plow - conventional plot Maayan Zvi, 1985 Jan.

Figure 23: Bulk density distributions calculated from gravimetric water contents and penetrometer readings for a transverse transect under mold board plow - conventional plot Maayan Zvi, 1985 Jan.

Figure 24: Bulk density distributions calculated from gravimetric water contents and penetrometer readings for a transverse transect under chisel plow - wideframe trafficked plot Maayan Zvi, 1985 Jan.

Figure 25: Bulk density distributions calculated from gravimetric water contents and penetrometer readings for a transverse transect under mold board plow - wideframe trafficked plot Maayan Zvi, 1985 Jan.

Figure 26: A comparison between bulk densities calculated from water content-penetrometer reading distributions and measured values - Maayan Zvi, Jan 1985.

Figure 28: Bulk density distributions calculated from gravimetric water contents and penetrometer readings for a transverse transect under wideframe trafficked wheat disk plot at harvest time - Maayan Zvi, Feb. 1985.

Figure 27: Bulk density distributions calculated from gravimetric water contents and penetrometer readings for a transverse transect under conventionally trafficked wheat disk plot at harvest time - Maayan Zvi, Feb. 1985.

Figure 29: A comparison between bulk densities calculated from gravimetric water content - penetrometer reading distributions and measured values from wheat disk plots - Maayan Zvi, Feb. 1985.

1. Although the water content distributions were within the range of penetrometer - bulk density calibration, a large change has taken place due to root swelling and shrinkage of the soil.
2. No reliable bulk density value of a given soil can be deduced by using a single calibration curve as the data presented suggest. Thus one should rely on penetrometer readings only when relative data are discussed or indicative indices are sought.

In view of these conclusions the penetrometer readings based bulk densities given in Figures 22-25, 27 and 28 are indicative to the compaction stress imposed on the soil and the resultant strains. Moreover, the higher the bulk density values are, qualitatively, one can claim the existence of lower air contents in the soil, causing greater energy - synthesates expenditure for root development. These should result in reduced dry matter production as determined by harvesting the above ground wheat biomass for silage.

Wheat dry matter production across the transects, under the two modes of traffic - the conventional and wide framed tractors are given in Table 6. Analysis of the results can be summarized in the following conclusions:

1. The overall wheat dry matter yield under wide frame tractors is greater than that under conventional tractor whereas the variability found under conventional tractors is smaller than that under the wide frame tractor. The differences between the means are practically not statistically significant.
2. Under the wide frame, a distinct trend of reduced yields on the extreme benches, which are adjacent to the traffic lanes. Under conventional tractors these tracks are not as distinct as under the wide frame situation. It does appear in some stretches within the transects while in others, these trends do not exist or even negating trends can be pointed out (e.g. Transect 3 benches 1, 2 and 3; vs. Transect 1 benches 1 and 3 or Transect 2 bench 1).

Since no differences in soil water content distributions were found (0 to 15 cm 18.7+/-3.3%; 15 - 30 cm 26.4 +/- 2.4%; 30 - 60 cm 25.2 +/- 1.6%) for the different location on benches or traffic lanes, the dry matter yields may reflect localized effects superimposed on the traffic caused compaction.

Table 6: Dry matter yields [$\text{Kg} \cdot \text{m}^{-2}$] ^{<1} of wheat for sillage across the transects and conventional or wide frame tractors and traffic modes.

Transect No Bench No Position [m]	1	2	3	1	2	3	1	2	3	Average by position [tons ha ⁻¹]
0 - 1	0.495	0.434	0.668	0.559	0.607	0.454	0.542	0.483	0.512	0.528 ± 0.075
1 - 2	0.468	0.661	0.470	0.605	0.430	0.682	0.662	0.564	0.539	0.565 ± 0.094
2 - 3	0.676	0.707	0.546	0.582	0.576	0.701	0.597	0.648	0.639	0.630 ± 0.058
3 - 4	0.585	0.530	0.468	0.649	0.441	0.547	0.692	0.625	0.618	0.573 ± 0.084
4 - 5	0.541	0.634	0.625	0.574	0.587	0.673	0.633	0.509	0.584	0.596 ± 0.052
5 - 6	0.535	0.500	0.309	0.667	0.437	0.502	0.534	0.473	0.535	0.499 ± 0.095
Average of bench	0.550± 0.074	0.578± 0.106	0.514± 0.129	0.606± 0.043	0.513± 0.085	0.593± 0.105	0.610± 0.064	0.550± 0.074	0.571± 0.051	
Averages of transects	0.589± 0.064			0.547± 0.088			0.559± 0.100	Total average	0.565± 0.086	

Transect No Bench No Position [m]	1	2	3	1	2	3	1	2	3	Average by position [tons ha ⁻¹]
0 - 1	0.495	0.475	0.558	0.426	0.432	0.547	0.556	0.590	0.582	0.518 ± 0.063
1 - 2	0.365	0.451	0.443	0.447	0.468	0.435	0.447	0.491	0.493	0.449 ± 0.038
2 - 3	0.544	0.627	0.490	0.556	0.578	0.495	0.526	0.543	0.621	0.553 ± 0.049
3 - 4	0.420	0.493	0.590	0.583	0.502	0.475	0.468	0.498	0.498	0.503 ± 0.054
4 - 5	0.686	0.586	0.477	0.670	0.437	0.451	0.479	0.512	0.451	0.530 ± 0.095
5 - 6	0.342	0.589	0.439	0.420	0.562	0.589	0.567	0.586	0.485	0.509 ± 0.091
Average of bench	0.476± 0.129	0.537± 0.073	0.499± 0.062	0.517± 0.102	0.497± 0.062	0.481± 0.044	0.511± 0.048	0.537± 0.044	0.522± 0.065	
Average of transects	0.501± 0.095			0.523± 0.060			0.512± 0.058	Total average	0.510± 0.073	

^{<1} In order to obtain yields in Tons·ha⁻¹ multiply the figures in the table by 1.25. This comes from the fact that of a band of 2.00 mm, 1.600 mm are sown and 75-85 cm inbetween the benches were wheat "free."

Nematodes were found to affect severely cotton yields of the same year, and it may well be that the trends found and shown in wheat dry matter production distribution could have been more pronounced had the field been not infested by Nematodes.

b. 1986 - 1987 season

The preceding crop to Nachsholim 1986-87 season wheat was cotton which was machine-picked on moist soil (220 mm of rain fell during October and early November 1986). As a result of the wet soil conditions in three out of the four blocks in Nachsholim field, each farrow was at least trafficked once whereas others were affected by two to five passes of cotton pickers traveling on moist soil. Therefore, during the 1986-1987 season, wheat data was collected from one block only (*3). The soil resistance to penetration, water content, dry matter determinations were carried out as for the 1984-1985 season.

Typical bulk density distributions found under wide frame and conventional traffic modes are given in figures 30 and 31 respectively. In fig. 30, a comparison between measured and computed bulk density for this season is given. In this case the computed values generally do agree rather nicely with the measured ones, but the variability is very large. Thus the conclusions drawn before still hold. Namely, these bulk density values computed from penetrometer - bulk density, water content relationships do show the trends and the distribution patterns but quantitatively are of low accuracy.

Typical resistances to penetration distributions with depth for three transects for conventional and wide frame traffic patterns are given in figures 33 and 34 respectively. Yield patterns of press fresh matter wheat for silage for conventional and wide-frame traffic modes are given in fig. 35, 36 respectively.

Under conventional traffic the soil was less cracked in the traffic lanes as compared to lanes of the wideframe. These cracks form less resistive soil profile as seen in figure 34. Generally the volume averaged soil bulk under the conventional traffic is higher than that under wideframe traffic (fig. 33 and 34). The distinct compaction patterns expected for a known traffic mode are not found in both figures except to one or two stretches. This signifies that the autumnal traffic patterns were more extensive than expected and even this block was unnoticeably trafficked.

Figure 30: Bulk density distributions calculated from gravimetric water contents and penetrometer readings for a transverse transect under wideframe trafficked wheat disk plot, Nachsholim.

Figure 31: Bulk density distributions calculated from gravimetric water contents and penetrometer readings for a transverse transect under a conveniently trafficked wheat disk plot, Nachsholim 1987.

Figure 32: A comparison between bulk densities calculated from gravimetric water content – penetrometer reading distributions and measured values from wheat disk plots , Nachsholim 1987.

Figure 33: Typical resistance to penetration distributions with depth for three transverse transects under conventionally trafficked wheat disk plot, Nachsholim, Jan 1987.

Figure 34: Typical resistance to penetration distributions with depth for three transverse transects under wideframe trafficked wheat disk plot, Nachsholim, Jan 1987.

The patterns of fresh wheat matter given in Figures 35 and 36 conform with the traffic lane positioning but not with respect to the soil resistance to penetration patterns. The latter reflect side effect of soil cracking already observed during harvesting wheat for silage. Generally, one can see that the soil under conventional traffic has a higher volume averaged bulk density than that under the wide frame traffic. Such a comparison is valid since water content distributions were practically the same irrespective of position relative to traffic lane or mode of traffic (Table 7).

Fresh and dry matter data of wheat for silage are given in Tables 8 and 9. The differences in yields (fresh biomass or dry matter yields) between benches adjacent to a traffic lane or a bench bordered by traffic lanes under a conventional traffic are statistically significant (Table 8). Similar yields trends of differences are given for wideframe traffic patterns in Table 9.

A proper comparison to be made is given in Figure 39. Under conventional tractors, the central bench is bordered by compaction produced by the two tractor wheels, thus, the severest impact of compaction is reflected by the lowest yields. The extreme bench of both traffic modes reflect the impact of Uniboarder compaction and the yield is practically the same and has the same variability. The central bench under the wide frame tractor has not been or has been least affected by traffic caused compaction and the yield is the highest. The total yield of a field will be for conventional: 45.8 ± 1.02 [Tons ha⁻¹] and for the wide frame: 49.4 ± 1.11 [Tons ha⁻¹] - an increase of 8% in yields.

Yields resulting along trafficked lanes under the two traffic modes are given in Figures 37 and 38 for fresh biomass, dry matter percentages and dry matter yields across the field at intervals of 10ms. The average fresh biomasses, and dry-matter yields for the wheel boarded, uniwheel boarded and nontraffic affected benches (from Figures 37, 38 and 39) were 52.7 ± 3.4 ; 58.4 ± 3.3 ; 57.4 ± 2.8 and 61.2 ± 3.2 [Tons ha⁻¹]; and 14.2 ± 0.9 ; 15.9 ± 1.2 ; 15.9 ± 1.4 ; and 17.5 ± 1.4 [Tons ha⁻¹] respectively. The average dry matter yields for the conventional and wide tracked traffic fields equal 46.0 ± 1.1 and 49.3 ± 1.2 [Tons ha⁻¹], respectively. These values almost coincide with the respective values obtained from the tranverse transects.

Figure 35: Fresh matter of silage wheat and resistances to penetration distributions under a conventionally trafficked plot, March 1987, Nachsholim.

Figure 36: Fresh matter of silage wheat and resistances to penetration distributions under a wideframe trafficked plot, March 1987, Nachsholim.

Table 7: Gravimetric water contents w/w, taken at Nachsholim site during wheat for silage harvest.

TRAFFIC MODE	CONVENTIONAL			WIDE FRAME		
Position Depth [cm]	Traffic Lane (middle)	Bench Next to traffic Lane	No Traffic Bench	Traffic Lane (middle)	Bench Next to Traffic Lane	No traffic Bench
0 - 10	28.3	27.5	29.7	29.1	28.1	28.7
10 - 20	29.4	27.7	27.9	29.0	27.9	28.1
20 - 30	29.0	27.0	27.3	28.4	27.8	27.5
30 - 40	26.8	27.0	26.9	27.3	27.2	26.9
40 - 50	27.3	26.5	27.4	27.4	27.5	26.8
50 - 60	27.7	26.5	27.3	26.9	26.9	27.1

The values are averages of 9 position replicats two samples 1 m apart for each positon.

Table 8: Fresh wheat biomass, dry matter percentage and wheat dry matter yields [Tons·ha⁻¹] for coventional traffic - Nachsholim, 1986-1987 season. Traffic lane border bench No. 2 on its two sides (transverse transects)

a) fresh biomass [Tons·ha ⁻¹]									
Bench No.	1	2	3	4	5	6	7	8	9
Transect No.				1	2	3	1	2	3
1	58.0	52.0	5.40	62.0	52.0	57.0	55.0	45.0	53.0
2	51.0	55.0	56.0	54.0	50.0	57.0	61.0	52.0	57.0
3	54.0	54.0	57.0	54.0	56.0	52.0	66.0	56.0	62.0

Average fresh matter yields for wheel track boarded bench (*2) = 52.6 ± 3.4 [Tons·ha⁻¹]

Average fresh matter yields for uni-side wheel track boarded bench (*3) = 56.7 ± 3.8 [Tons·ha⁻¹]

b) Dry matter percentages of biomass									
Bench No.	1	2	3	4	5	6	7	8	9
Transect No.				1	2	3	1	2	3
1	29.6	28.1	27.7	25.1	27.5	28.2	32.7	27.4	27.8
2	28.1	26.3	27.1	28.7	26.2	27.6	27.2	27.2	25.6
3	27.7	27.4	27.1	27.1	28.1	27.6	26.3	24.7	26.3

c) Dry matter yields [Tons·ha ⁻¹]									
Bench No.	1	2	3	4	5	6	7	8	9
Transect No.				1	2	3	1	2	3
1	17.2	14.6	15.0	15.6	14.2	16.1	18.0	12.3	14.7
2	14.3	14.5	15.2	15.5	13.1	15.7	16.7	14.1	14.6
3	15.0	14.8	15.5	14.6	15.7	16.9	17.4	13.8	16.3

Average dry matter yields for wheel track boarded bench (*2) = 14.2 ± 0.9 [Tons·ha⁻¹]

Average dry matter yields for uni-side wheel track boarded bench (*3) = 15.8 ± 1.0 [Tons·ha⁻¹]

Table 9: Fresh wheat biomass, dry matter percentage and wheat dry matter yields [Tons·ha⁻¹] for wide frame traffic - Nachsholim 1986-1987 season. Traffic lane boarder outer boarder of benches No. 1 and 3 (transverse transects).

a) fresh biomass [Tons·ha ⁻¹]									
Bench No.	1	2	3	4	5	6	7	8	9
Transect No.				1	2	3	1	2	3
1	58.2	59.0	49.2	55.2	57.8	51.6	48.0	59.0	54.0
2	56.4	59.0	58.8	56.4	59.0	51.6	55.2	54.3	54.0
3	51.6	63.7	51.6	54.0	59.0	55.2	60.0	70.8	55.2

Average fresh biomass yield for wheat track boarder bench = 54.2 ± 3.1 [Tons·ha⁻¹]
Average fresh biomass yield for wheat inner bench = 60.2 ± 4.4 [Tons·ha⁻¹]

b) Dry matter percentages of biomass									
Bench No.	1	2	3	4	5	6	7	8	9
Transect No.				1	2	3	1	2	3
1	28.0	28.4	31.4	29.5	31.3	29.4	31.3	28.9	28.6
2	25.5	28.0	30.4	26.7	30.5	28.4	28.4	28.7	28.9
3	28.3	29.6	30.1	29.8	30.4	28.9	29.8	29.8	30.1

c) Dry matter yields [Tons·ha ⁻¹]									
Bench No.	1	2	3	4	5	6	7	8	9
Transect No.				1	2	3	1	2	3
1	16.3	16.8	15.4	16.3	18.1	15.2	14.9	17.0	15.4
2	14.4	16.5	17.8	15.1	18.0	14.8	15.7	15.7	15.5
3	14.6	18.9	15.5	16.1	18.0	16.0	17.9	21.1	16.0

Average dry matter yields for wheel track border bench = 15.8 ± 0.97 [Tons·ha⁻¹]
Average dry matter yields for inner bench = 17.8 ± 1.5

Figure 37: Fresh biomass yields, dry matter percentage and dry matter yield distributions along a longitudinal transect for a conventionally trafficked plot, March 1987, Nachsholim.

Figure 38: Fresh biomass yields, dry matter percentage and dry matter yield distributions along a longitudinal transect for a wideframe trafficked plot, March 1987, Nachsholim.

Figure 39: Average yields [Tons.ha⁻¹] and S.D. of dry matter for silage on benches as affected by their relative position with respect to wheel trafficked lanes and mode of traffic, Nachsholim 1987.

COTTON - SEASON OF SUMMER 1985 - MAAYAN ZVI

The second crop in the planned sequence was cotton. After the winter, the plots on which wheat for silage was sown (1/3rd of the area) were rototilled to a depth of 15 - 20 cm, as the rest of the area which was left fallow during the winter.

The complete field was planted with cotton (var. S.J - 1) at a density of 10 - 12 [seeds m^{-1}]. To enhance uniformed emergence an equivalent rainfall of 35 mm was applied by irrigation after planting.

Two weeks after planting first stand count was performed and another count was carried out two weeks later. On the same date, water content of seed beds, benches bulk densities and aggregate size distribution of seed bed was determined by sieving 5 samples of approximately 5 kg. soil scooped from 0 to 5 cm depth off the planted rows, per each treatment and block. Stand counts were carried out by counting the plant density per meter length for 10 meters length of two adjacent rows, along the plots in four sectors 25 - 35, 65 - 75, 105 - 115, 145 - 155 m from the borders of the plots.

During the season plant samples were taken from rows along the traffic lanes and untrafficked lanes. The plants were taken along 1 m row taken at random along the plots. These plants were partitioned at Bet Dagan laboratories into their smaller limbs (bolls, flowers, leaves, stems, buds) counted weighed and their dry weight was determined.

The field was irrigated four times during the season and a seasonal total of 350 mm of water was applied. After the third irrigation (late July 1985) severe stress signs became apparent across the whole field. Soil samples were sent to a laboratory for phytopathological analysis. The soil

samples were found to be infested with virulent nematods, and to the cotton to which the observed stress and the great reduction in yields at the end of the season could be attributed.

The cotton yields were picked by a cotton picking machine - the two central rows of each trafficked - nontrafficked strip, weighed and the yield was computed and corrected for the whole field area.

RESULTS AND DISCUSSION

Cotton stand counts, water content distribution and median aggregate diameter under the various treatments in Maayan Zvi are given in Tables 10, 11, 12 and 13, respectively.

As a general rule stands densities were higher on the conventionally trafficked plots than on those trafficked and tilled by the wide frame tractor (Tables 10, 11). On the second count, previous, initial plant densities were found to have changed, yet the general trend remained - higher plants stand on conventionally trafficked plots, and there is a trend toward lower stands on all plots. The area was found to be weed- and field mice-infested (especially blocks 1 and 2) and many plants were damaged or destroyed by root rots. On the silage wheat-disk plot, the stand was the lowest and two reasons may have caused it:

- a. coarser surface with wheat debris which clogged and hampered planting units and colters;
- b. coarser seed bed and lower water contents (Tables 12 and 13) at planting level on the benches (Table 13). On all plots the means and the standard deviations do not represent the actual seedling bunching along the planted rows. These were at times one, two or even three seedlings per nest.

A follow up of dry matter accumulation and total cotton yields are given in Tables 14, 15 and 16.

As one can see larger plants were observed at the beginning of the growing season on the plots where sparser stand was observed (silage wheat-disk plots). As the season progressed the total dry matter evened out within the standard duration units. Two distinct trends are discernable:

- a. On the conventionally trafficked plots the variability is somewhat higher than that found for wide frame trafficked plots.
- b. There is a definite trend for more dry matter produced on rows less affected by wheel caused compaction. (Table 14).

When the total dry matter produced is broken into its plant components, it is interesting to note the following trends:

- a. From the 65th day plants height is statistically the same, yet on the silage wheat-disk plots, the plants are higher;

Table 10: Cotton stand* on Mayan Zvi field - April 26, 1985

<u>Field block No.</u>						
<u>Traffic mode</u>		1	2	3	4	Overall of the field
<u>Primary tillage</u>						
Moldboard plow	Conventional	9.2±1.4	9.3±1.8	9.7±1.9	8.0±1.5	8.6±1.6
	Wide frame	6.7±1.9	6.6±1.7	6.1±1.6	6.4±1.6	6.4±1.7
Chisle- Ridging	Conventional	8.0±1.8	9.2±2.0	5.5±1.6	6.7±1.9	6.2±1.8
	Wide frame	7.5±2.0	6.3±1.8	3.8±1.6	4.5±1.8	5.5±1.9
Wheat disk	Conventional	6.4±2.1	4.0±1.8	5.5±2.1	4.8±2.0	5.2±2.0
	Wide frame	4.0± 2.3	5.1±2.4	4.6±1.9	2.6±1.8	4.1±2.1

* The data given (mean ±5 deviation) represent 3 strips, each 50 m long on each center bed of each treatment (150 m length per block and tillage treatment).

Table 11: Cotton stand* on Mayan Zvi field - May 6, 1985.

<u>Field block No.</u>						
<u>Traffic mode</u>		1**	2*	3	4	Overall of the field
<u>Primary tillage</u>						
Moldboard plow	Conventional	7.7±2.6	10.7±2.5	9.3±1.8	9.6±1.7	9.3±2.2
	Wide frame	8.6±2.7	6.6±2.2	7.6±2.0	7.3±2.3	7.5±2.3
Chisle- Ridging	Conventional	7.8±2.1	5.9±1.7	6.9±2.1	9.2±2.1	7.5±2.0
	Wide frame	8.2±2.5	6.4±2.4	4.6±2.2	5.8±1.7	6.3±2.3
Wheat disk	Conventional	5.3±3.3	5.0±2.5	6.5±2.5	4.5±2.1	5.3±2.6
	Wide frame	3.8±3.4	4.5±2.6	5.1±2.4	4.8±2.2	4.6±2.7

* Each data set (mean ± S. Deviation) represents 4 double rowed strips, each 10 m long chosen at random on each center bed of each treatment (namely 240 m on each block and primary tillage treatment).

** On blocks 1 and 2 a severe infestation by weeds and field mice was observed.

Table 12: Seedbed finess as determined by the median aggregate size [mm]
- Maayan Zvi - May 1985.

Primary Tillage Mode of Traffic	Moldboard Plow	Chisle - Ridging	Wheat - Disk
Conventional	5.78±0.51	4.18±0.57	5.77±1.90
Wideframe	4.20±0.42	3.80±0.99	6.31±2.12

Each data set represents (median diameter ± S. Deviation of 16 replicates) four determinations, randomly spaced along the central bed on each treatment and block.

Table 13: Gravimetric water content [$\text{g}\cdot\text{g}^{-1} \times 100\%$] and bulk densities [$\text{Mg}\cdot\text{m}^{-3}$] for Mayan Zvi (April 26, 1985) field.

Primary tillage Depth [cm]	Chisle - Ridging		Wheat - Disk		Moldboard plow	
	$P_w^{(1)}$	$bd^{(2)}$	$P_w^{(1)}$	$bd^{(2)}$	$P_w^{(1)}$	$bd^{(2)}$
0 - 5	19.4±5.4	0.860±0.072	19.5±1.2	0.916±0.095	15.7±1.9	0.932±0.031
5 - 10	27.7±0.7	0.848±0.148	26.4±0.7	0.821±0.179	27.4±1.3	0.888±0.035
10- 30	28.0±0.3	1.300±0.023	26.2±0.9	1.354±0.020	27.4±1.1	1.280±0.052
30- 60	27.5±0.3	1.415±0.065	25.9±2.0	1.437±0.071	26.9±1.1	1.431±0.082
60- 90	25.8±0.5	-	17.9±1.5	-	24.9±1.0	-
90 - 120	26.6±0.8	-	18.6±1.8	-	23.7±0.6	-

(1 Gravimetric water content in [$\text{g}\cdot\text{g}^{-1}$]

(2 Bulk density given in [$\text{Mg}\cdot\text{m}^{-3}$]

Each data set represents (mean ± S. Deviation of 16 replicates of four determinations along each center bed on each treatment and block (each is the yield of 16 samples).

Table 14: Total dry matter produced mean $\pm$ S. Deviation of 5 plants, four replications by cotton plants on Mayan Zvi field - 1985 season [gr.m⁻²].

Day after planting		36	50	65	92
Row*					
Mode of traffic					
Chisle					
Conventional	bi traffic	2.0 $\pm$ 0.8	14.7 $\pm$ 3.3	76.3 $\pm$ 27.5	310.0 $\pm$ 99.1
	non traffic	2.5 $\pm$ 0.4	18.6 $\pm$ 3.9	91.7 $\pm$ 26.5	324.1 $\pm$ 92.5
Widefram	uni traffic	1.7 $\pm$ 0.4	18.3 $\pm$ 2.3	69.5 $\pm$ 12.8	172.7 $\pm$ 65.9
	non traffic	2.2 $\pm$ 0.3	20.9 $\pm$ 1.9	77.1 $\pm$ 12.0	204.3 $\pm$ 60.9
Wheat-Disk					
Conventional	bi wheels	3.6 $\pm$ 0.5	10.8 $\pm$ 2.6	62.3 $\pm$ 16.7	208.9 $\pm$ 36.1
	non traffic	4.3 $\pm$ 0.3	12.5 $\pm$ 1.7	68.1 $\pm$ 12.4	218.8 $\pm$ 59.9
Widefram	uni traffic	3.1 $\pm$ 0.5	12.7 $\pm$ 0.9	66.4 $\pm$ 9.7	196.3 $\pm$ 54.0
	non traffic	3.7 $\pm$ 0.7	13.4 $\pm$ 1.0	79.1 $\pm$ 17.3	253.6 $\pm$ 60.0
Moldboard plow					
Conventional	bi traffic	3.6 $\pm$ 0.6	29.0 $\pm$ 10.0	92.2 $\pm$ 14.5	187.9 $\pm$ 50.3
	non traffic	4.1 $\pm$ 0.3	33.9 $\pm$ 9.3	97.7 $\pm$ 16.4	231.8 $\pm$ 53.9
Widefram	uni traffic	4.0 $\pm$ 0.4	24.4 $\pm$ 6.6	72.8 $\pm$ 12.3	171.6 $\pm$ 10.2
	non traffic	4.1 $\pm$ 0.5	26.0 $\pm$ 10.9	94.1 $\pm$ 10.7	188.7 $\pm$ 34.8

* Rows as defined follow the attached drawing:

Table 15: Breakdown to cotton plants components - dry matter production* for different mode of traffic, primary tillage operation, traffic positioned row and days after planting - Maayan Zvi - 1985.

Days from planting	row	36				50			
		Height [cm]	Dry matter [g·m ⁻²]		Height [cm]	Dry weight [g·m ⁻²]		Height [cm]	
			leaves	stems		leaves	stems		
	Bitraffic lane boarders	5.1±2.3	1.6±0.7	0.4±0.2	17.6±4.3	11.9±3.1	2.6±0.4	30.1±10.1	
	Unitraffic lane	6.1±1.4	2.2±0.3	0.3±0.2	18.0±3.9	14.6±3.1	3.9±0.9	36.0±10.2	
	Unitraffic lane	7.2±1.8	1.5±0.3	0.4±0.1	15.1±4.4	14.5±2.5	3.8±0.7	30.3± 4.4	
	No traffic	8.3±1.2	1.8±0.3	0.5±0.2	18.1±2.1	16.8±1.7	4.2±0.5	33.5± 8.3	
	Bitraffic lane boarders	6.6±2.4	2.9±0.4	0.7±0.2	13.0±2.4	8.7±2.3	2.2±0.4	31.0± 7.0	
	Unitraffic lane boarders	6.5±2.5	3.3±0.3	0.9±0.2	14.7±2.4	9.7±1.5	2.6±0.5	33.6±11.0	
	Unitraffic lane boarders	6.8±2.4	2.3±0.5	0.8±0.2	12.0±1.4	10.1±1.4	2.5±0.5	35.1± 3.5	
	No traffic	10.0±2.4	2.8±0.6	0.9±0.1	14.1±1.9	10.4±1.4	3.2±1.1	34.6± 5.7	
	Bitraffic lane boarders	7.1±2.1	3.0±0.7	0.6±0.2	23.8±3.8	23.2±7.2	6.8±3.1	34.0± 7.2	
	Unitraffic lane	8.0±2.6	3.3±0.2	0.8±0.1	26.4±1.8	26.1±8.2	7.8±1.8	39.3± 4.1	
	Unitraffic	8.2±3.1	3.4±0.5	0.9±0.3	19.5±5.5	17.4±6.1	6.2±2.0	42.2± 9.3	
	No traffic	8.7±5.1	3.6±0.2	1.0±0.1	22.8±3.8	18.7±8.3	7.3±2.3	47.7± 8.1	

* Mean deviation at four randomly chosen points along the center bed (1 mm long).

65					92						
Dry weight [g·m ⁻²]			No. flowers		Height [cm]	Dry weight [g·m ⁻²]			Flower buds	No. flowers per meter	
Leaves	Stems	Roots	Flower buds	per meter		Leaves	Stems	Roots			
53.4±21.8	18.7± 7.5	11.2±4.4	3.3±2.5	90±35	59.6±10.7	170.2±40.7	86.7±40.7	-	16.4± 6.5	187±39	
60.7±22.4	26.5±12.4	11.6±3.6	4.3±3.2	98±41	69.0±10.9	202.9±93.6	96.8±29.1	-	21.6± 5.8	184±34	
47.9±15.9	17.1± 6.3	9.2±3.1	2.1±1.3	82±32	55.4±15.5	99.3±24.5	53.3±38.4	-	18.7± 9.4	172±22	
52.5±10.6	21.4± 5.6	9.2±3.2	3.2±1.5	102±12	58.3±11.2	106.2±27.6	72.5±49.3	-	19.6± 5.8	178±18	
43.3±14.8	16.3± 7.5	9.0±4.3	1.9±1.0	630±22	50.3±13.1	135.8±38.5	48.5±24.8	-	14.5± 6.9	174±60	
48.1±16.1	18.2± 4.7	7.5±2.9	2.1±1.2	640±25	56.8±10.6	144.9±38.9	59.3±20.2	-	14.8± 7.4	187±41	
47.4±11.4	16.1± 5.9	11.0±2.8	2.8±1.2	88±14	57.7±10.3	123.6±33.6	59.4±16.8	-	16.6± 5.9	175±22	
53.9±14.1	21.3± 5.7	12.2±3.5	3.6±1.0	112±13	67.6± 9.5	134.6±30.4	92.2±37.8	-	13.8± 4.8	161±24	
58.5±13.6	25.6± 9.1	11.9±2.7	4.5±1.6	98±26	61.0± 8.8	101.9±44.9	67.5±25.3	-	17.1± 5.9	186±45	
66.0±10.6	26.2± 9.5	14.5±2.2	5.6±1.1	110±32	58.8±11.8	135.0±32.2	74.8±29.7	-	22.4±10.7	189±34	
38.4±15.3	24.0± 3.2	11.3±2.5	4.1±1.2	93±17	52.0±11.0	98.9±38.6	56.6±27.0	-	16.2± 6.4	164±44	
51.9±11.2	33.4± 9.6	10.9±6.7	5.0±1.4	940±15	57.1±11.2	108.4±36.5	63.2±26.4	-	17.6± 8.0	188±46	

Table 16: Mean seed cotton yields in [Tons.ha⁻¹] for idfferently traffic positioned of rows * and total yields for Maayan Zvifield, 1985. (neither standard deviations nor statistical analysis are given due to the nematode cause variability.

Rows No	[Tons. ha ⁻¹]			Total **
Traffic Mode and Primary Tillage	1	2	3	
Chisle Plow Conventional	2.939	2.503	2.701	2.718
Chisle Plow Wideframe	4.021	2.826	2.484	3.110
Moldboard Plow Conventional	3.016	3.120	3.155	3.097
Moldboard Plow Wideframe	3.818	2.950	2.449	3.073
Wheat - Disk Conventional	3.323	3.567	2.939	3.278
Wheat - Disk Wideframe	3.061	3.019	3.057	3.046

* See Tables 15,14.

** Total yield was obtained as the mean of the whole field.

b. Amounts of dry matter produced either as leaves, stems, number of flower buds or flowers are greater on less or no trafficked rows as compared to traffic affected rows.

The trends are distinct, the differences are statistically not significant (Table 15). These trends suggest that less dry matter is produced per plant and less flowers are to be found on the traffic-affected rows. In other terms, traffic-induced compaction may lead to delayed development of flowers, bolls and eventually to reduced yields if cotton is picked on a predetermined date at which lately produced bolls are not fully matured and open and therefore their lint is not picked. This logical conclusion should eventually be reflected by lower yields on rows adjacent to traffic lanes, as compared to those on rows further off these lanes. The cotton yields given in Table 16 do not support this supposition but rather the relative combined effect of compaction and soil born nematode damage.

COTTON SEASON 1986 - NACHSHOLIM

The nematodes enforced the move of the experimental site from Maayan Zvi to Nachsholim 4 kms north of the previous site. As the decision was taken rather late, in the fall of 1985, wheat for silage was sown and the fallowed plot were tilled in a hasty manner.

Late rains followed wheat for silage harvest and caused problems in maintaining the predesignated traffic lanes design. In some cases especially on blocks A and D (the extreme ones), local inaccessibility to tractors and low trafficability caused the planners to mark field segments that were put out of the experimental design due to over puddling and compaction.

Cotton (var. Pima S-4) was planted after two thirds of the experimental fallowed field was rototilled (chiseled to 30 cm and rotovated to 15 - 20 cm). The silage wheat plots were disks and then cotton was planted directly into the reduced stubble. In places due to planter clogging by wet soil the planters heads were cleaned and cotton was replanted. Once the cotton was established, stand counts were performed and the previous years program was adhered to.

RESULTS

Prior to planting soil water contents and soil bulk densities of the seed-bed were taken and these are given in Table 17(a). During the late season bulk densities were taken once more and are given in Table 17 (b). Comparison of the values obtained for 1 to 10 cm layer show some densification of the top layer due to wetting and drying caused by irrigation and evaporation.

Cotton plant stands densities are given in Table 18. The stands are rather thin, around 5 to 6 plants per meter and no significant statistical differences exist between the primary tillage plots nor for the traffic pattern treatments. The rather uniform seedling densities are in contrast to the finess of the appropriate seed beds given in Table 19 (a). According to Hadas et al (1983) coarser seed bed should lead to sparser stand but in this case, probably due to high soil moisture content Table (17a) establishment of uniform, though a bit sparse, stand was attained. This is in conformity to trade-off possibilities between water content and seed bed coarseness mentioned by Hadas and Russo (1974 a,b).

A follow up of the structural finess of the top layer later in the season (Table 19b) show that the median aggregate diameter remained the same, except:

- a. for the wide frame chisel plow plots, where the median aggregate diameter and its geometrical deviations increased too,
- b. moldboard plow wide frame traffic where the median aggregate diameter decreased as well as its geometrical deviation. These trends in structural changes may suggest that where least traffic and complete soil fragmentation and mixing is maintained (wide frame, mold board plowed) the surface structure will tend to mellow into smaller particles whereas on chisle plowed the structure tendency toward larger clods is unexplained.

Cotton plants development as determined by total dry matter accumulation and in major plant organs were determined as done in the previous season (1985) by sampling plants. This season samples were taken from the extreme compaction zones, namely from rows inbetween the wheels of a conventional tractor (conventional in Table 20) and at the center, nontrafficked wheel base of the wide frame tractor (wide frame in Table 20). In accordance soil resistance to penetrometer readings were recorded and mean lines are given in figures 40 (a, and b). In these penetrometry recordings one can see that by traffic lane the soil resistance to penetration is higher than that away from the trafficked lane to the tillage depth (35 to 45 cm) whereas below that level both readings are practically the same (from 35 to 45 cm and below).

Table 17: Soil water contents [$\text{g}\cdot\text{g}^{-1}$] at different depths and bulk densities on block #3, Nachshalim prior to sowing cotton on April 10, 1986 (a) and after irrigation(?) on August 11, 1986 (b).

(a)							
Distance [m]		Water contents P_w [$\text{gr}\cdot\text{gr}^{-1}$]					Averages
Depth [cm]	30	40	50	60	70	$P_w[\text{g}\cdot\text{g}^{-1}]$	b.d $\text{Mg}\cdot\text{m}^{-3}$
0-10	0.320	0.313	0.362	0.364	0.354	0.343 ± 0.024	0.827
10-20	0.375	0.372	0.386	0.381	0.379	0.378 ± 0.6	1.071
25-35	0.369	0.364	0.363	0.374	0.363	0.366 ± 0.006	1.499

(b) Depth of 0-10 cm

Primary tillage	Mold board	Clude plow	Wheat disk
Traffic mode	plow		
Conventional	1.034	1.099	1.060
Wide frame	1.267	1.010	1.084

Table 18: Cotton seedlings stand of Pima (S4) May 1986 - Nachsholim, under different primary tillage operations.

		Moldboard		Chisle		Wheat-Disc		
		A	B	A	B	A	B	
*	1.	5.3±2.1	6.7±1.3	4.4±2.0	7.2±1.3	4.7±2.4	5.7±1.9	
	2.	7.0±2.4	5.9±2.0	7.4±1.1	7.1±1.2	7.5±2.6	6.4±0.8	
	3.	7.5±2.7	6.5±1.2	6.4±2.3	8.3±1.3	5.0±3.2	6.4±2.7	
	4.	6.3±2.7	3.8±1.6	6.7±2.4	6.3±3.1	4.6±2.5	6.8±1.3	
	Aver.	6.5±2.6	5.8±1.9	6.2±2.2	7.2±2.0	5.4±3.0	6.4±1.9	6.3±2.4
**	1.	6.4±2.0	6.9±2.1	7.2±1.5	9.0±2.7	7.8±1.9	4.3±1.4	
	2.	7.0±1.7	9.3±2.0	7.7±1.3	10.0±1.5	8.4±4.6	8.2±0.8	
	3.	6.2±2.0	-	6.1±1.3	5.7±1.1	4.3±1.4	6.8±2.1	
	4.	5.1±1.7	5.4±0.5	5.8±1.9	6.5±1.6	5.8±1.7	5.7±2.0	
	Aver.	6.2±2.0	7.2±2.4	6.7±1.7	7.8±2.5	6.6±3.2	6.2±2.2	6.8±2.4

* For conventional traffic - it is the central bed, compacted on both sides and not trafficked for wideframe.

** For wideframe, trisided compacted bed and the same for conventional traffic.

A. Wideframe tractor traffic.

B. Conventional tractor traffic.

Table 19: Seedbed finess, given as the median aggregate diameter $\emptyset$ [mm] and its geometrical deviations Tg. a) At sowing time April 1986 and b) at the end of the irrigation season, end of July 1986 . Nachsholim 1986. (block #3).

1) According to Gardner 1956.

(a)						
Primary Tillage Traffic	Moldboard $\emptyset$ [mm] Tg		Chisle Plow $\emptyset$ [mm] Tg		Wheat - Disk $\emptyset$ [mm] Tg	
Conventional	9.2	5.1	17.9	3.8	17.0	6.4
Wideframe	17.1	4.2	16.8	3.3	12.3	5.9
(b)						
Primary Tillage Traffic Mode	Moldboard Plow $\emptyset$ [mm] Tg		Chisle Plow $\emptyset$ [mm] Tg		Wheat Disk $\emptyset$ [mm] Tg	
Conventional	9.0	3.7	13.1	6.1	17.2	5.7
Wideframe	9.4	2.9	24.2	5.3	11.9	5.3

Table 20: Total cotton dry matter produced and its plant organs break down for different primary tillage operations, time after planting and traffic pattern is given Nachsholim field 1986.

63					
Days after planting					
Dry matter partitioning	[Kg·m ⁻²]				
Traffic mode	leaves	stem	buds	total cm	height
Conventional	82.5± 4.8	35.2± 2.8	4.5± 0.7	122.2± 6.9	38.8± 4.3
Wideframe	68.6± 11.0	28.8± 7.4	3.5± 1.1	101.0± 19.5	37.9± 3.8
Conventional	68.0± 22.0	27.9± 11.7	2.9± 1.1	98.9± 34.6	34.4± 12.3
Wideframe	89.5± 22.0	40.4± 12.1	5.7± 2.8	135.5± 36.6	41.4± 5.5
Conventional	72.9± 15.6	29.8± 7.7	3.41± 1.8	106.2± 24.1	34.7± 5.2
Wideframe	65.7± 10.1	26.5± 6.4	2.58± 1.2	94.8± 17.3	32.4± 13.8
76					
Leaves	Stems	Buds	Total	Height [cm]	No of flowers per m
165.5± 23.8	106.2± 21.6	24.9± 2.5	279.9± 31.5	57.8± 7.8	321.3± 33.2
136.4± 12.5	90.0± 12.3	21.4± 3.4	247.8± 26.2	57.9± 6.9	301 ± 57.7
150.1± 24.3	96.8± 25.2	26.5± 8.2	273.9± 56.9	52.6± 16.0	302.3± 51.0
167.4± 26.7	114.7± 20.6	30.4± 4.9	312.7± 50.6	60.9± 7.3	327.5± 68.2
130.4± 15.1	80.6± 15.7	24.1± 9.1	235.6± 28.3	53.0± 8.3	263.8± 71.2
133.9± 21.3	80.0± 18.6	17.3± 3.6	231.2± 42.0	54.4± 10.0	270.5± 48.1

Table 20: Cont.

90						
Leaves	Stems	Buds	Bolls	Total	Height cm	No. flowers per m
169 ± 97.5	175.8± 28.7	53.9± 5.5	28.8± 7.1	469.7± 63.8	71.0± 8.0	338.3± 84.9
198.0± 15.9	167.1± 10.3	52.3± 6.8	38.6± 15.4	456.1± 19.3	64.2± 22.9	322.3± 51.0
231.1± 29.4	178.8± 32.1	56.2± 2.0	31.7± 11.3	497.7± 55.6	70.4± 4.5	380.8± 68.0
250.9± 37.7	220.2± 48.7	76.0± 18.7	33.5± 6.4	580.6± 108.7	72.7± 5.9	384.8± 22.8
176.1± 24.8	131.6± 23.7	48.5± 3.5	25.7± 9.7	381.9± 42.7	61.8± 9.3	299.5± 50.6
193.9± 48.9	147.3± 35.7	44.7± 4.5	14.5± 9.3	401 ± 86.8	63.2± 9.5	365.8± 80.8
113						
Leaves	Stems	Buds	Bolls	Total	Height cm	No. flowers per m
266.5± 68.1	265.5± 98.9	36.8± 19.7	228.0 ± 31.8	769.8± 188.6	92.8± 18.3	162.3± 103.1
280.6± 66.1	283.4± 79.9	37.6± 10.7	219.97± 33.5	857.7± 169.7	96.3 14.5	164.3± 63.3
262.3± 18.9	246.4± 24.8	29.2± 12.4	288.0 ± 64.5	825 ± 75.8	86.9± 10.6	125.8± 65.7
273.9± 22.3	280.4± 35.6	37.9± 3.9	242.2 ± 47.7	834.4± 93.6	97.8± 8.1	158.8± 27.5
306.1± 115.8	286.7± 114.2	38.3± 21.4	241.1 ± 34.5	872.5± 230.6	94.3± 17.4	192.0± 109.8
317.8± 60.0	291.9± 49.6	40.7± 12.6	116.7 ± 43.2	757.1± 25.3	98.1± 10.9	238.0± 54.7

These readings suggest greater resistance to cotton rooting on beds next to a trafficked lane as compared to those further away from them. No particular differences were discernable between conventionally trafficked or non trafficked beds to those of the wideframe until concerning depth distribution of soil resistance to penetration. Cotton plants were sampled, partitioned and their dry matter accumulation during the season and the results are given in Table 20.

The expected effects of delayed cotton development noted during the previous year (1985) are not discerned in the results of 1986 season. Only on leaves - dry matter a trend appears toward larger dry matter amounts accumulated as leaves on nontrafficked, uncompacted lanes. Any other measure does not follow that pattern, e.g., total dry matter, stems, no of flower, bolls or height. This lack of previously detected trends holds at least till the 113 day after plantime, whereas the cotton was harvested on the 193rd day after planting.

Cotton was picked two weeks after a heavy, unexpected October rain, which caused some damage. In Table 21 seed cotton machine picked yields are given. When these values are compared to those picked by hand (Table 22 and 23), the degree of damage done by the rain can be estimated. Furthermore, it is quite obvious that yields of rows next to a traffic lane are lower than those of untrafficked lanes (see Figure 41). A spatial row differentiation of cotton yields is given in Figure 42.

Since no significant differences were found between deeply tilled plots, another comparison is given in Table 24a and 24b where total yields are given by rows and total field for two modes of crop rotation as affected by traffic

modes. The trafficked lanes obviously affect the yields on beds next to them. Yet, when yields are compared, cotton yields are higher on the deeply - monocultured plots than on their traffic equivalent with wheat for silage. Moreover on the average, cotton yields on conventionally trafficked plots are somewhat higher than those on the wide frame less trafficked plots. This comparison was made on hand picked data.

If similar comparison will be made on the machine picked yields by rows (as the farmer actually picks), the following values are obtained for conventional traffic: 4.622 vs. 4.061 [Tons ha⁻¹] and wide frame traffic: 4.997 vs. 3.880 [Tons ha⁻¹] for deeply tilled and wheat for silage treatments respectively.

Summing up the 1986 cotton season the following conclusions can be drawn:

Figure 40-a: Resistance to penetration with depth plots as affected by primary tillage operations and position relative to trafficked lanes for a) conventional tractor plot

Figure 40-b: Resistance to penetration with depth plots as affected by primary tillage operations and position relative to trafficked lanes for b) wideframe tractor.

Table 21: Cotton seed yields [Tons.ha⁻¹] determined by machine picking, Nachsholim (1986) These yields show the effect of heavy rain damage prior to picking.

Primary tillage	Chisel plow	Moldboard plow	Wheat-disk
Mode of traffic			
Wideframe	3.775	4.293	3.338
Conventional	4.023	3.795	3.180

Table 22: Cotton seed yields [kg/5m row] hand-picked as affected by relative position to traffic sheels, primary tillage operations and traffic mode.

Primary tillage	Chisel plow			Moldboard plow			Wheat disk		
Row*	1*	2*	3*	1*	2*	3*	1*	2*	3*
Wideframe	3.448± 0.279	4.50± 0.619	5.26± 0.604	3.604± 1.414	4.927± 0.574	5.605± 0.528	3.719± 0.692	4.232± 0.585	4.024± 0.497
Conventional	4.912± 0.54	5.417± 0.472		4.859± 0.307	5.303± 0.368	-	3.750± 1.216	4.261± 0.811	-

* See Figure 41

Table 23: Seed cotton yields [Tons.ha⁻¹] hand-picked by "Granot"-Nachsholim 1986

Row	Chisel Plow			Moldboard Plow			Wheat - disk		
	1*	2**	3*	1*	2**	3*	1*	2**	3*
Wide frame	4.870	5.050	4.950	3620	5.560	4.900	3.750	3.980	3.910
Convent.	4.420	4.700	--	4.400	5.370	--	3.780	4.680	--

* 5m² plots

** 2m² plots

Row - See Figure 41

Table 24 a: A comparison of tilled and non-tilled plots , seed cotton yields [Tons.ha⁻¹], determined from hand-picked plots of 5m² on Nachsholim field (1986) as affected by traffic mode.

Tillage	Deep Tillage			Wheat - desk			Deep Tillage		Wheat - disk
	1	2	3	1	2	3	1	2	
Wide frame	3.256 ±0.837	4.714 ±0.546	5.433 ±0.505	3.719 ±0.692	4.231 ±0.585	4.024 ±0.497	4.557 ±0.647	3.991 ±0.597	
Conven- tional	4.886 ±0.397	5.359 ±0.352	--- ---	3.750 ±1.216	4.261 ±0.811	---	5.044 ±0.383	3.921 ±1.098	

* Row - See Figure 41

Table 24 b: Seed cotton yields [Tons.ha⁻¹], on bisided compaction, machine-picked from compacted row conventional traffic - unisided compaction, unicomaction-wide frame traffic (a), mid row - unisided compaction on conventional traffic, no compaction (b), as for mid-row of wide frame (c).

(a)			
Primary Tillage	Chisel	Moldboard	Wheat-disk
Traffic Mode			
Wide frame	4.876	3,619	3.754
Conventional	4.423	4.406	3.778
S.D. of mean = 0.346 [Ton.ha ⁻¹]			
(b)			
Tillage Traffic	Chisel	Moldboard	Wheat-disk
Wide frame	5.054	5.567	3.979
Conventional	4.705	5.367	4.686
S.D. of mean = 0.562 [Ton.ha ⁻¹]			
(c)			
	Chisel	Moldboard	Wheat-disk
Wide frame	4.947	4.899	3.907
Conventional	—	—	--
S.D. of mean = 0.243 [Ton.ha ⁻¹]

Wide frame traffic - compaction

Conventional - traffic compaction

Figure 41: Spatial cotton rows positioning with respect to trafficked lanes under conventional and wideframe traffic modes.

Figure 42: Mean seed cotton yields and respective S.D. distributions with respect to wheel compacted, traffick modes and primary tillage operations A-chisel plowed, B-moldboard plowed and C-wheat disk plots, Nachsholim 1986.

- a) The trend of compaction or traffic caused cotton development delay, observed the previous year was not observed until the 113th day after planting.
- b) Traffic or compaction reduction of cotton yields are evident, even though there are no high statistical differences between traffic and nontraffic affected cotton rows' yields.

In view of conclusions a) and b), one is led to assume that if there is no specific stress e.g. nematods or water stress, compaction caused yield reductions may be caused by other mechanisms, rather than direct effects reflected by delayed development.

- c) The fact that the soil has a high clay content, soil swelling and shrinkage, probably alleviated soil compaction caused by traffic as found in Maayan Zvi (penetrometer and bulk density changes with time and by 1987). And thus, the other factor causing changes in yields due to soil compaction may be induced by excessive cracking on more compacted zones. More cracks may lead to severer roots pruning effects and probably to boll shedding and reduced yields. This assumption was not tested and thus requires further research.

1987 COTTON SEASON

Since the cotton yields of 1986 season were picked after heavy early rainfalls, tillage operations were ruled out and thus the area was disked and left bare till the first opportunity enabling tillage during Winter of 1987. Winter 1987 proved to be the wettest since many years Spring tillage by rototillers of the plots (except silage wheat disk plots) produced an extremely coarse seed bed and the whole field was practically compacted to varying degrees. The plots were still referred to as if tilled.

Due to seed bed coarseness, cotton was planted twice and as extra seeds were not available the silage wheat-tilled plots were sown with Pima S-4 variety, whereas the bare-tilled plots were planted with cotton (var. Acala SJ-2)

In view of the severe compaction caused by spring traffic prior to and during planting, a drastic change in plans had to be enforced. Instead of the regular plant dry matter analysis as carried out in previous seasons only two dry matter analysis were performed, and a greater emphasis was given to water contents and penetrometry analysis.

This season ended by a torrential early October rain (172 mm) which destroyed most of the crop which was ready to be picked. Thus the yields measurements do not reflect effects caused by treatments or traffic.

RESULTS

The residual effects, spring compaction could have caused, were examined by taking two transects of soil water contents and soil bulk densities after first irrigation was applied (Table 23). The results show rather low variability along each transect and between the transects. These data led to conclude that spring compaction was alliviated by a) emergence irrigation (30-35mm) and b) the first full irrigation of the season (100 -11 mm). In view of this lack of variation, the soil water contents data were combined per plots as given for different dates during the season in Table 24a and 24b.

Cotton seedlings stands were counted and are given in Table 25. The data indicate that there is a tendency toward higher stand densities for the less trafficked wide frame plots as compared to their equivalents under conventional traffic (for moldboard plow and wheat-disk), whereas no such tendency can be observed on chiseled plots. The reasons for these observations are not known since no primary tillage operations were applied. Stand densities tend to be slightly higher on rows near the wheels on conventional trafficked plots yet no such tendency could be discerned on the less trafficked moldboard plots.

Resistances to penetrations were measured on several transects five transverse 15m apart and two longitudinal 60 m long. The results are given in Figures 43 and 44.

In Figure 43, I the residual effects of "regular" conventional traffic evident as is on 43-II, 43 V whereas on 43 - IV there is a "complete cover" of compacted layers. These transverse transects were taken from a plot supposed to be under a wideframe traffic pattern. These transects show the damage spring traffic operations caused to the field. In figure 44-A, taken on a nontrafficked lane, no particular irregularities in soil resistance to penetration is distinguished whereas on 44-B, taken along a trafficked lane greater variability in soil resistance to penetration can be observed.

Table 25: Water contents (gravimeter $\text{g}\cdot\text{g}^{-1}$) distribution for Nachsholim (1987) field as determined after first irrigation, along a transect of 60 m, determinations were taken at 10 m intervals.

a) Row adjacent to wheel

Distance m	Gravimetric water content [$\text{g}\cdot\text{g}^{-1}\times 100$]								Average bulk density [$\text{Mg}\cdot\text{m}^{-3}$]
Depth cm	0	10	20	30	40	50	60	Average	
0-15	9.2	11.4	10.2	15.3	10.7	9.2	14.3	11.5 ± 2.4	1.173
15-30	29.5	28.9	30.1	33.4	30.7	29.4	33.5	30.8 ± 1.9	1.346
30-45	33.4	31.7	32.1	32.9	31.4	32.9	32.9	32.4 ± 0.7	1.423
45-60	34.0	32.4	31.9	32.7	32.0	31.9	31.7	32.4 ± 0.8	-
60-90	29.9	30.8	29.4	28.8	29.7	30.4	29.2	29.7 ± 0.7	-

b) Third row away from wheel

Distance m	Gravimetric water content [$\text{g}\cdot\text{g}^{-1}\times 100$]								Average bulk density [$\text{Mg}\cdot\text{m}^{-3}$]
Depth cm	0	10	20	30	40	50	60	Average	
0-15	9.6	8.9	10.2	10.4	10.0	9.7	9.8	9.8 ± 0.5	1.125
15-30	20.2	31.1	30.6	29.2	30.4	31.2	29.8	30.4 ± 0.7	1.339
30-45	29.7	30.7	31.4	30.1	30.8	30.2	31.3	30.6 ± 0.6	1.417
45-60	33.4	32.9	31.8	32.4	31.4	32.3	33.0	32.5 ± 0.7	-
60-90	32.1	31.4	30.9	31.6	32.5	31.7	30.9	31.6 ± 0.6	-

Table 26: Cotton seedling stand densities* on different rows with respect to wheel positioning, Primary tillage operations, on Nachsholim field (June 1987) - For Row Positioning see Figure 41.
Comparison of equally trafficked rows will be for conventional 3,2 and 1 wide frame for one-sided trafficked and 1 (conventional) and 2 (wide-frame) for no traffic.

Prim. Till.	Chisel plow			Mold board plow			Wheat-disk		
Row Posit.	1	2	3	1	2	3	1	2	3
Traffic Mode									
Con-	7.4±2.0	4.8±1.7	7.3±1.8	3.8±1.8	4.8±1.7	7.3±1.8	12.7±2.7	13.4±1.3	10.4±1.2
ven-	3.0±2.3	1.9±1.1	5.4±2.2	2.9±1.7	1.9±1.1	5.4±2.2	11.1±1.6	12.1±2.0	11.7±3.3
tion-	4.4±1.6	7.4±2.2	5.8±2.7	4.3±2.1	7.4±2.2	5.8±2.7	7.9±1.5	7.2±2.1	6.4±1.4
al	4.0±2.4	5.0±1.7	5.5±3.0	4.0±2.4	5.0±1.1	5.5±3.0	5.9±3.1	6.4±2.2	5.1±1.7
Wide	7.4±2.0	7.1±2.2	7.5±2.5	7.0±1.9	6.0±1.9	9.0±2.3	10.5±1.7	9.9±2.1	11.9±1.7
	7.8±2.4	7.9±2.2	7.9±1.5	7.9±1.7	8.7±2.3	7.5±1.8	12.1±1.9	14.9±1.8	12.4±1.6
frame	6.8±1.8	6.3±1.6	6.1±2.4	9.9±2.1	10.0±1.6	1.9±2.1	8.3±1.8	8.8±1.6	10.0±1.4
	6.0±1.7	4.5±1.0	4.7±2.7	8.9±1.9	9.7±2.3	6.7±2.2	8.9±2.7	8.7±2.6	9.5±2.1

* In each block and treatment four 10m long strips of the appropriate rows were chosen at random and seedlings were counted for each meter length. Replicates (1, 2, 3, 4) are the average and S. D. for the 10m strips.

Figure 43: Resistance to penetration distribution for five transverse transects, cotton season 1987, Nachsholim.

Figure 43-a: Resistance to penetration distribution for five transverse transects, cotton season 1987, Nachsholim.

Figure 44: Resistance to penetration distribution for five longitudinal transects, cotton season 1987, Nachsholim.

Figure 44-a: Resistance to penetration distribution for five longitudinal transects, cotton season 1987, Nachsholim.

Table 27: Dry matter of various cotton Pima (S-4) organs at two different data July 2, 1987, two combined samples (row-next to traffic lane. Center-non trafficked zone), and August 17, 1987, along two transects - Nachsholim 1987.

Relative No per plant site to traffic lane	Height [cm]	Dry Matter [g.m ⁻¹]							
		Leaves	Roots	Stems	Bottoms	Bolls	Total Plant	Bottoms	Bolls
7 - 22 - 1987									
Center (1)	84.9±15.9	53.5±32.5	10.3±3.8	39.4±21.0	8.7±8.3	4.2±3.1	116.1±57.1	20.2±10.9	3.5±2.6
Row (2)	85.0±9.9	23.6±7.0	6.7±2.7	23.9±14.9	4.7±7.8	2.8±4.7	62.4±37.5	14.4±17.8	3.6±5.3
8 - 17 - 1987									
1 (1)	129.2±22.6	52.7±18.6	11.8±4.0	62.0±30.3	-	57.5±27.4	186.3±70.3	-	13.4±5.1
2	121.1±8.1	30.2±18.6	7.5±1.5	33.2±7.0	-	48.7±34.9	106.6±40.3	-	5.8±4.6
3	116.8±14.7	28.4±8.5	8.4±3.2	31.8±10.7	-	50.8±22.9	120.1±34.7	-	6.8±2.2
4	108.3±14.7	29.5±9.0	8.0±2.2	26.7±14.5	-	25.3±16.5	94.6±30.9	-	4.8±1.9
5	129.2±17.7	55.7±24.9	10.9±3.7	58.1±18.0	-	155.4±133.6	279.6±179.1	-	12.6±5.3
1 (2)	118.3±7.5	29.5±14.2	8.7±2.7	39.4±15.6	-	49.9±33.1	126.7±59.1	-	7.6±2.5
2	107.0±9.7	26.4±7.3	8.7±1.9	33.0±10.5	-	57.6±22.4	119.8±36.5	-	7.4±2.9
3	107.4±7.8	24.8±4.7	9.0±3.4	32.3±14.9	-	21.3±7.0	88.7±19.8	-	5.8±1.4
4	109.6±15.9	26.3±7.3	7.6±2.3	31.1±11.1	-	21.3±10.8	87.5±19.8	-	5.6±1.0
5	122.4±18.2	50.1±14.9	11.8±2.2	60.3±13.9	-	31.6±13.0	154.5±30.0	-	8.2±3.0

Table 28: Total seed cotton yields * [Tons ha⁻¹] Nachsholim field 1987 season as affected by primary tillage and mode of traffic.

Primary Tillage Mode of Traffic	Seed Cotton Yields [Tons ha ⁻¹]		
	Chisle Plow	Moldboard Plow	Wheat - Disk **
Conventional	2.848±0.482	2.893±0.261	3.218±0.265
Wideframe	2.378±0.709	2.435±0.559	3.181±0.546

* The yields were picked by machine after a heavy early rain of 107mm which caused uneven shedding of cotton from the opened bolls.

** Due to planting failures after the wheat was harvested the field had to be resown and shortage of seeds compeled the farm to use "Akala SJ-2" instead of Pima S-4 as for the plowed plot.

In view of the rather uniformity in water and bulk density values found (Tables 13, 17, 23, 24) these trends in soil resistances to penetration as given in figures 43 and 44 may serve as a rather sensitive method to distinguish field- structure - or density variability. Yet, this supposition should be taken with caution, because data collected during the 1985 and 1986 season in wheat and cotton (figures 14, 15, 17, 21, 26 29, 40, a-b;) show the inaccuracy in deducing bulk densities from water contents - bulk density - penetrometer reading calibrations.

Total dry matter produced values and their partitioning for two dates are given in Table 26 and the final yields in Table 27. The data in Table 26 show once again the trend of delayed development due to compacted zones proximity, as found in Maayan Zvi 1985. Yet there is no final evidence that such a delay in plants development may lead to yield reduction. The reason is that the damage the early rain caused to the final yield (Table 27). and Pictures 1 and 2 attest to it,

but in picture 2 one can see more unopened bolls on the plants. This picture was taken from a row next to a traffic lane. This fact strongly supports the possibility of yield decrease due to delayed development and ultimately less mature bolls caused by compaction.

E. Soil Structure Studies - Israel

The apparent finding in this report and by () in Texas, which states that on a clay soil (montmorillonitic clay), swelling and shrinking of the soil alleviate compaction damages led to the following studies carried out by A. Hadas (A.R.O.) during his sabbatical leave in the Dept of Soil Science, University of Minnesota St Paul MN U.S.A. during 1986.

The questions asked were:

- a. Can autumnal tillage done on air dry soil break - down compacted layer?
- b. Do soil constituents govern air dry soil strength? and
- c. How rain, irrigation and drying cycles affect soil structure mellowing.

Part of these questions were answered by the following works: attached in Appendix A.

Picture 1: Damage caused by rain to cotton crop. Nachsholim 1987.

Picture 2: Trafficked lane row.
Note the density of unopened bolls.

Picture 3: Tafficked lane

Picture 4: On right- cotton stand on wheat-disk plot, on left- cotton stand on regular tillage (moldboard). Traffic mode on both plots- conventional. Nachsholim 1987.

Picture 5: Water way and a division sector between moldboard plow and chisle plow plots. Nachsholim 1987.

F. Acknowledgements

The authors would like to thank Dr. I. Shmulevich of the Faculty of Agricultural Engineering for his support, help and great assistance in bringing this report to print. Thanks are due to Mrs. A. Newman, M. Rosner and A. Picken for their help in field and laboratory work concerning this project. The authors wish to thank Mrs. R. Bortman for printing this report and Mrs. R. Zarkina for preparing the drawings illustrating this report.

Reprinted from the *Soil Science Society of America Journal*
Volume 51, no. 1, January-February 1987
677 South Segoe Rd., Madison, WI 53711 USA

**Dependence of "True" Surface Energy of Soils on
Air Entry Pore Size and Chemical Constituents**

A. HADAS

Long-term Tillage Practice Effects on Soil Aggregation Modes and Strength

A. HADAS

ADVANCES IN MODELING MACHINE-SOIL-PLANT INTERACTIONS¹

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ABSTRACT

Hadas, A., Larson, W.E. and Allmaras, R.R., 1988. Advances in modeling machine-soil-plant interactions. Soil Tillage Res., 00:000-000.

Modern agriculture involves mechanized operations which affect crop growth and yields through change in soil environment. Field research to study the phenomena involved in the soil-machine-crop system is usually site-specific with respect to edaphic, climatic, and management factors. Field experiments are often expensive to conduct, and generalization to other sites or practices is usually tenuous at best. Computer-based techniques to simulate machine-soil-plant (or crop) systems can test many combinations of site characteristics and management practices, and screen the most promising combinations. Once these promising combinations are validated, the simulation techniques together with stochastically supported data bases can be used to predict tillage management systems suitable for specific sites and crops.

¹Contribution from the Agricultural Research Organization, The Volcani Center, Soil Science Department Bet Dagan 50250, Israel, No-E series; the Minnesota Agric. Exp. Stn., St. Paul, MN 55108; Paper no.15491, Scientific Journal Series, and U.S.D.A., A.R.S. Soil and Water Management Unit, St. Paul, MN 55108, U.S.A.

Current efforts to model plant response to soil conditions created by tillage and machines have serious shortcomings, because the link between tool action, subsequent soil structure, and the parameters that describe fluxes of water, heat, and gas need further development for deterministic modeling. Machine-soil models focus on efficiency of the tillage operation, while soil-plant models focus on soil structure and related parameters influencing plant growth. While current models for simulating the machine-soil-crop system have limitations, an approach to bridge between the two model applications offers great promise and should be a high research priority. When used with improved measurements of tool action and of soil structural properties before and after tillage and traffic, including position or placement of the crop residues, current models can be doubly effective for improving tillage management.

INTRODUCTION

An array of soil factors are involved in a crop production system and many of these are significantly modified by machinery and associated traffic, both intentionally and incidentally. The machine system is not only used for tillage, but also to add and strategically place pesticides, soil amendments, fertilizers, crop residues, and the seeds or other reproducing parts of the crop. At harvest of root crops, the machine system must dislodge the roots. Such is also the case for weed control. Traffic is produced by traction and transport associated with these machine inputs. These inputs with machinery systems must be applied while

conserving soil, water, energy, and labour. Thus the management approach must be based upon systems analysis.

Weather factors, such as soil and air temperature, precipitation, wind and air humidity significantly influence interactions in this system, but they cannot be predicted for periods more than a week except in a stochastic sense. Climatic effects can be modified only partially as with such practices as irrigation, the application of a surface mulch of crop residue, or field windbreaks.

Tillage and cropping practices have developed by trial and error at specific sites. Field research has most frequently solved problems that will improve the system in place, but attempts to transfer the system to another site have often failed. Usually the soil, climate, and management factors were not identified fully so that quantitative transfer of the results to another site was not possible.

A model of the machine-soil-plant interaction must use computer simulation because of the many complex interactions involved. Successful application of the model will predict plant performance given the use of some machine or tillage system. Such a computer-based simulation should produce an interpretation of the main factors influencing the choice of tillage and management practices and give a site-specific prediction for a set of practices. Most existing soil-plant models simulate the interactions of soil, water, and nutrients in a system with climatic or weather inputs and a developing plant. The soil properties are those measured after some sequence of tillage.

Special emphasis is given to root and shoot development, water and solute transport in the soil and plant systems, and transformations of carbon and nitrogen sensitive to placement of crop residues. These models must have weather and climate input, otherwise the simulation cannot be generalized in both a deterministic and stochastic sense. Research results from different locations are usually needed to develop appropriate input for these models. Missing in most of these soil-plant models is the interaction between machine (or an individual tillage tool) and the soil properties that may later control the interactions of soil and plant. However, the models which emphasize machine-soil interactions in tillage are designed to predict or describe efficiency of the tillage operations. Models emphasizing machine-soil interactions in traction have been more successful than those in tillage to predict efficiency and subsequent soil properties.

For general application of these models, a mechanistic, or process-oriented simulation is almost a must. Only in this way can these complex systems be simulated adequately, include the crop-environment interactions mentioned above, and provide extrapolations beyond existing data sets. These models, once validated deterministically, can then use stochastic input data along with the range of variability in the parameters to generate frequency distributions with respect to response of the system. This approach assists to search for weakness of theory and data base.

Because soil-plant models are required to simulate a system

of interactions, the simulation system is complex with a large number of parameters, equations, and interactive feedback loops. They may include many subroutines and their interfacing. Such a model dictates lengthy computer runs and complex sets of tests to validate the model's capabilities and its prediction. Several such complex simulation models have been developed, including NTRM by Shaffer and Larson (1987), GOSSYM by Baker et al. (1983) and SOYMOD by Meyer et al. (1979).

Models which include machinery or tillage effects on tillage or traction efficiency and subsequent soil properties vary with respect to model approach, complexity, hierarchy of submodels within the combined model, initial soil properties and the relative importance of various submodels on the final outputs. In the present paper various models are evaluated for their capabilities, infrastructure, and approaches to continued improvement of current modeling efforts.

MODELING TILLAGE EFFECTS

Management of the soil environment, including soil water, heat, tilth, soil strength, and location of nutrients is usually carried out by tilling the soil. The challenge is to model the tillage- soil-water-nutrient effects and their interactions with plant growth and climate. The various models available today differ in their specific goals and scope.

Soil tillage requires large amounts of energy, labour, and time, even if good soil conditions exist and appropriate tillage implements are used. When correct techniques are consistent with

a well balanced tractor-implement combination, and existing soil conditions are appropriate (including soil water content, soil structure, and soil mechanical properties), the new soil structure will be attained while no impairment of soil properties is caused. Much experimental information is available about the performance of implements and tractors on various soils, but few attempts have been made to integrate this information (Meiborg and Perdok, 1979; Perdok and Van de Werken, 1983); thus only limited progress has been made in the selection of an appropriate combination of machine-soil conditions. Schafer et al., (1985) pointed out the importance of specifying agronomic or conservation needs so that the correct machine-soil combinations can be determined to achieve efficiency. They used the term custom prescription tillage. In the event that the exact needs are not known, their flow chart might be used repeatedly via modeling and soil-plant system to achieve the most acceptable machine-soil combination to achieve desirable soil properties and the least amount of energy required in the operations.

Soil-plant modeling of tillage effects

Fig. 1 presents a general outline of one of the most complex and complete models available to relate tillage to crop response. The model has been labeled the Nitrogen-Tillage- Residue Model (NTRM) and includes 13 submodels (Shaffer and Larson, 1987).

Shaffer et al. (1983) detailed the tillage submodel and its exchange of data between submodels (see Fig. 2). The tillage submodel requires input of soil properties after tillage. The

soil temperature submodel shown in Fig. 1 receives data from the tillage submodel, but also requires independent input. Such an interface reduces sensitivity to joint heat and water flow in the soil. Moreover, the model uses hydraulic properties calculated from such soil properties as organic matter content, composition of mechanical constituents, and dry bulk density, unless the hydraulic properties are specified through independent measurement after the tillage operation.

Soil-implement modeling in tillage

To till a soil a tool or an implement (machine) must provide energy to the soil. A tillage tool is an individual soil working element and a tillage implement (or machine) is a single or a group of soil working tools together with the power transmission structure, control, and protection systems present as an integral part of the machine (see ASAE standard EP291.1, 1983). A model for simulating or predicting a tillage operation from sets of implement-soil interactions may yield either energy required to move the implement through the soil, changes in soil structural state, or both. Implements may be subdivided into (a) tines (operating depth much greater than tool width), (b) ploughing bodies (operation depth and width approximately equal), and (c) rotary implements (energy applied through rotary blades or tines). To model the machine-soil interaction, the following soil relationships must be known (Koolen, 1977; Koolen and Kuipers, 1983; McKyes, 1985): a) stress-strain responses; b) mode of deformation, rotation, failure, and rearrangement-processes (Spoor

and Godwin, 1979; Stafford, 1982) during passage of the tillage tool; and c) spatial variation of texture, apparent density, water content in the soil matrix, all of which affect the spatial soil strength characteristics of shear strength, compressibility and adhesion.

Draft force required to pull an implement

Models developed to predict draft forces required for operating a soil-engaging implement can be divided into three groups:

a) Empirical models - Empirical relationships are established for a given implement between characteristic implement parameters (shape, hitching mode, dimension), operational mode (speed and depth of operation), and soil conditions (soil bulk density, water content, degree of aggregation). Such relationships were developed and presented for ploughs (Söhne, 1960; Söhne and Möller, 1962; Poesse and Van Ouwerkerk, 1967; Zoz, 1974), and for tines (Wismer and Luth, 1972). Because these relationships are empirical, they yield draft-force values specific to site (soil properties), operational conditions, and implement characteristics. A large data base, if available, would allow generalization of recommended ranges of draft forces for various implements through development of tabulated or graphed field application. Examples are given by Perdok and Van de Werken (1983 and shown in Figure 3), Ellen (1984), or to be found in the Agricultural Engineering Yearbooks of the ASAE (marked as ASAE D230.4).

b) Scale modeling and dimensional comparison - Similitude is

a rigorous methodology from engineering mechanics used for modeling and predicting prototype response. The methodology uses scale modeling and dimensional techniques and has been applied to model machine-soil interactions (Freitag et al. 1977). A scaling approach is similar to that with the full-scale empirical models mentioned above because a diminutive form of the implement under consideration is operated in the soil, forces are measured, and the energy needed for the real-sized implement is then estimated. Although this approach is used as a lower priced experimentation to yield values similar to the full scale approach (Wisner et al., 1976), accuracy of this modeling approach is seriously reduced by the inability to develop scaled soil properties.

Dimensional techniques are used to simplify modeling a prototype by reducing the number of factors (Freitag et al. 1977). Machine parameters including those describing geometry have not been limiting to similitude, rather the parameters related to dynamic soil reaction are the most difficult to specify. This technique has been applied to highly specified tillage prototypes such as a plane blade moving in a soil without cohesion and with mainly frictional forces (Luth and Wisner, 1971) or moving through a cohesive soil with a minimum of frictional forces (Wisner and Luth, 1972). Even though the procedures of similitude are highly analytic, similitude lacks general application because of the difficulty to understand and therefore rigorously model soil reaction dynamics.

A modified similitude modeling approach was used by Evans et al. (1985) to estimate draft changes produced by interaction of

adjacent tillage tools (chisel points). Model predictions agreed with measurements from a prototype operated in a sandy loam using various proximity configurations and operational depths.

Disagreement in a clay loam demonstrated that the type of soil influences how proximity of chisel points affects interaction.

c) Draft forces estimation from machine-induced stress/strain in soil - Soil stress-strain characteristics during failure can be used to solve equations of stresses and strains developed when an implement is operated in a given soil body. Most of these models were developed for wide vertical bodies or two-dimensional models, such as earth moving scrapers (Reece, 1965; Yong and Chen, 1970; Hettiaratchi and Reece, 1967, 1974), or for three-dimensional bodies such as narrow tines (Hettiaratchi and Reece, 1967; Godwin and Spoor, 1977; McKyes and Ali, 1977; Perumpral et al., 1983). McKyes (1985) made a comparative prediction of draft forces using field data for sand (Luth and Wismer, 1971) and a clay soil (Payne, 1956). Generally, the predicted values followed the same trends as the measured ones, and the agreement was better for the clay soil. Most models developed for narrow tine-shaped tools yield moderately accurate estimates of the draft force required.

Modifications must be made in these analytical models if they are to account for dynamic changes, i.e. changes in forward velocity of the implement, rate of stress loading as it changes shear strength, shear or compressive strains, and spatial changes in soil strength. The 'theoretical' models (analytical or computer solutions) are adequate for assessing very simple tool shapes, including tines, chisels, and to some extent more complex

tools shaped like shovels and sweeps. Consequently, sweep or duck-foot cultivators and subsoilers can be handled by these models (Koolen, 1977; Koolen and Kuipers, 1983; McKyes, 1985). However, a similar modeling approach cannot be utilized for the mouldboard plough which is a non-symmetrical twisted plane (Koolen and Kuipers, 1983; McKyes, 1985). In fact that 'family' of implement tools has not been modeled successfully as yet.

Modeling soil structure after machine-soil interaction

All models mentioned above deal with forces acting on the machine and the resultant energy or draft required, yet no model attempts to predict the tilth or the structural condition of the soil once the implement has passed through soil elements. Changes in soil structural state, or tilth in response to implement and tillage combinations have been measured by many workers. Some of these are: random roughness of the surface (Allmaras et al., 1977); relative loosening, change in the soil bulk density, or 'upheaval' (Van Duin, 1956; Allmaras et al., 1977; Ojeniyi and Dexter, 1979a b; McKyes and Desir, 1984; Cassel and Nelson, 1985; Kouwenhoven, 1986); changes in hydraulic properties and infiltration (Van Duin, 1956; Ehlers, 1976; Edwards, 1982; Klute, 1982; Mielke et al., 1986); soil temperature and heat balance (Van Duin, 1956; Allmaras et al., 1977; Cruse et al., 1982; Gupta et al., 1984); changes in mechanical impedance (Bradford, 1980; Cassel, 1982; Cassel and Nelson, 1985); and aggregate-size distributions (Hadas et al., 1978; Hadas and Wolf, 1983). Many of these measured properties have characteristic ranges

associated with particular implement types.

Although not a soil material, crop residues may impart significant changes in soil structural conditions, conditions such as soil strength and bulk density. Recent measurements (Greb et al., 1974; Christian and Miller, 1986; Allmaras et al., 1988) show characteristically different depth distributions of crop residue as related to type of implement.

Dexter (1976) proposed a prediction of tillage-induced soil porosity, a prediction which uses a stochastic procedure to predict voids and solid. This soil tilth prediction accounts for implement characteristics, management practice, soil water content at the time of tillage application (or soil workability state), consecutive implements passes, depth of operation, and compaction or rearrangement of soil units. Applicability has not been tested adequately because many measurements are needed to provide a new calibration for each crop management site and parameter involved.

Rawls et al. (1983) integrated tillage-induced porosity with other soil properties (contents of organic matter and mechanical constituents) to predict water flow-related properties in a soil subjected to tillage operations such as mouldboard ploughing, chiseling, and wheel traffic after mouldboard ploughing. Brakensiek and Rawls (1983) then used typical values of random roughness to compute soil crust effects on infiltration. Unfortunately, these integrated projections of water flux parameters in the soil have not been evaluated in models such as in NTRM (Shaffer and Larson, 1987).

A need exists for improved prediction of the post-tillage

soil structural state, and consequent soil mechanical, hydraulic, and thermal properties. We are limited by an incomplete understanding of the modes of soil deformation and ultimate failure during machine interaction as affected by previous loads on the soil, kind of stress system applied, rate of stress loading, and the initial soil structural state (Spoor and Godwin, 1979; Stafford, 1982).

An extension of the recently developed "Critical State" concept about drained aggregated soils (stresses produced within a typical unit of soil structure) may lead to a better understanding of soil response to tilling implements, a better prediction of forces produced by the operating implement (Hettiaratchi and O'Callaghan, 1980; Stafford, 1981), and therefore a forecast of the soil tilth produced by the implement passage. Until this knowledge becomes available, one must: a) rely on the tabulated ranges of energy for evaluating the machines used for tillage operations; b) determine the post-tillage tilth and decide if it is the desired one; if not, consider additional operations; and c) choose the proper machine-tractor combination which can deliver the wide range of energy required. One must also make sufficient measurements in a given machine-soil-crop combination to generalize on the parameters for the models, such as in Fig. 1.

Soil-machine interactions of traction vs. soil compaction

Machine performance capabilities can be matched to a required range of draft forces by considering traction as a machine-soil interaction and accounting for the associated soil compaction.

The draft force needed to pull an implement through the soil at a desired speed reflects the net transfer of useful energy from the engine to the implement through the interaction of tractor wheels or tracks with the soil. This net energy or work available at the drawbar is the difference between the torque work of the driving wheels and the work to overcome resistance against wheel movement across the soil, friction or shear (slip) at the contact interfaces, and the amount of work exerted to compact the soil (sinkage).

Modeling machine-implement traction capabilities, also termed as drawbar draft or pull, has been done based upon an approach of dimensional analysis and correlative calibrations, which depend upon whether wheels or tracks supported the machine. For wheeled machines (Wismer and Luth, 1973, 1974), the parameters used for calculating the traction (T) produced by a driven wheel or pull force (P) required for a towed wheel were wheel numerics or ratio of resistance to penetration (CI) divided by wheel loading stress, wheel width (b), wheel diameter (d), weight carried per wheel (W), and wheel slip (s). T/W or P/W is a representation of slip at the wheel-soil interface:

$$(P/W) = [(1.2/C_n) + 0.04] \text{ for a towed wheel} \quad [1]$$

$$(T/W) = 0.75 (1 - e^{0.3s \cdot C_n}) - [(1.2/C_n) + 0.04] \quad [2]$$

for a driven wheel

where $C_n = CI \cdot b \cdot d / W$. For a tractor with rear-wheel drive only, the net traction or draft will equal the difference between the total traction produced by the rear wheel with its appropriate C_n (including the corrected CI after the front wheel caused soil

compaction) and the required force to pull it across the field. When the tractor is driven by both sets of wheels (front and rear), the net traction is the summation of traction produced by the appropriate wheel and soil conditions.

A combined empirical-mathematical model has been attempted by formulating a relationship of shear-stress to shear-deformation for wheel tracks (Bekker, 1956, 1960; Janosi and Hanamoto, 1961). This approach is based on the normal pressure at the contact plane and the tangential stresses for shear at the contact plane between wheel and soil surface (slip). By summing up the tangential displacements, the traction or resultant drawbar pull is calculated.

Karafiath and Nowatzki (1976) and Yong et al. (1984) gave a detailed treatment of Janosi's approach in a Finite Element Model for wheeled or tracked vehicles in an off-road mode. In all of these models, soil mechanical characteristics such as peak shear strength, compactability, effects of pore water pressure, rate of loading, are of great importance. Thus, if the approach of finite elements is found to be satisfactory, the only handicap which may remain is the quality and reliability of soil samples tested under laboratory conditions to represent the behavior of field soils under dynamic situations of tillage and traffic. Another concern is how adequately the laboratory tested samples represent field spatial variability of soil strength properties, either natural or man made. Whereas for wheeled tractors the front wheel either compacts (pushed) or shears and compacts (driven) the soil and the rear wheel follows in a more compacted soil with improved

traction, the tracked vehicle develops its shear in a similar mode by increased shearing displacement from the front part of the track toward its rear part.

As shown above, traffic across the field with or without implements causes compaction, which is usually looked upon by farmers as an unavoidable evil. Traffic is often applied when the soil is moist and plastic, and thus produces more compaction than needed for traction.

Hadas et al. (1986) developed a stepwise computational model to estimate compaction and draft. This procedure can be used to predict draft force available based on existing soil conditions, load, and tractor wheel numerics. The procedure also calculates the soil compaction produced. The calculation is based on a model to compute stress distribution within the soil, soil compression characteristics, and soil resistance to penetration using relationships of bulk density and water content. The schematics of the model are given in Fig. 4. Predicted draft forces were compared to measured ranges of draft forces in Fig. 5. Measured soil compaction represented as resistance to penetration or bulk density distribution is given in Figs. 6 and 7, respectively.

The above procedure yielded reasonable agreement between prediction and field-observed values of bulk density distributions and draft, although the predicted bulk densities were higher than the measured ones. In this model bulk densities were calculated according to Gupta and Larson (1982) and based on compression characteristics of sieved soil samples. Soil structure states and stress-strain relationships in field soils differ from samples of

crushed, sieved, and repacked soil samples (Culley and Larson, 1987). Due to differing structural states, soil response to stresses might be different (Hadas et al., 1986), and probably more so for different stress combinations (deviatoric vs. spherical stresses) and loading rates (Hadas, 1987). Several other models of stress-strain (Perumpral et al., 1971; Soane et al., 1981a, 1981b, 1982; Gupta and Larson, 1982; Bailey et al., 1986) can facilitate theoretically-based predictions of soil compaction.

Even though the surface area affected by tractor wheels or tracks in the field is rather small for each tillage operation (e.g., 15-25% of the total area), this compaction-affected soil volume has direct and indirect effects on field management inputs (energy, labour, machinery, fertilizers), crop establishment, and growth responses to differing soil conditions. Improved measurements of soil bulk density in depth increments as small as 20 mm have permitted a more critical and extensive evaluation of these compaction effects in the field (Wilkins et al. 1985).

Modeling changes in soil physical properties caused by compaction or soil loosening processes related to traction

As mentioned before, tillage implements when operated in tilled fields, produce machine compacted strips and tilled beds. In some cases, the implement is equipped with devices to retill the compacted lanes. This procedure leaves a field which is sectionally non-uniform with respect to soil properties and crop yields (Hadas et al., 1983, 1985). A typical example, shown in

Figure 8, demonstrates the potential significance of spatially variable compaction.

Changes in soil physical or mechanical properties caused by tillage or traffic-induced compaction have been reported in many published articles. Some of these were discussed above as related soil structural changes; some are notably sensitive to tillage implement and or traffic-induced compaction, but some are not. Those properties that are depth dependent in soil often have different depth distributions as affected by traffic and the tillage machine (Wilkins et al. 1985; Allmaras et al. 1988).

Parameters used frequently to show the tillage or compaction induced changes in soil properties are: bulk density, mechanical resistance to penetration, saturated and unsaturated conductivity, water retention characteristics, thermal conductivity and heat capacity, air and oxygen diffusion coefficients, air permeability, and specific resistance to tillage implement passes. One should not be surprised that each of these parameters may have a depth function unique to the tillage system. All of these parameters reflect a response to rearrangement of soil particles, structural units, and the pores or voids between them. Given the textural analysis of soils and theoretical packing arrangements of associated spherical or ovular-shaped particles, Farrell and Larson (1972) and Gupta and Larson (1979) predicted soil matrix and porosity properties. Such processes as bridging associated with soil structure could not be predicted. Thus, pore space geometry and pore size distributions can be estimated only roughly and, as a consequence, the same applies to the estimated transport

and capacity parameters, such as water retention, conductivity and permeability to air and water, gaseous diffusion (Marshall, 1958; Millington and Quirk, 1961; Mualem, 1978). While progress is being made in developing mechanistic and process-oriented models, currently reliance must be placed on empirical relationships between timely measured soil physical properties and pore geometry distributions, or transport parameters. When compiled, these data provide tabulated time and space related values of the above-mentioned parameters.

These empirical relationships should be utilized only for the time period in which they are accurately known. For example, soil tilth produced by tillage without traction-induced soil compaction is short-lived (Kouwenhoven, 1986; Larney and Fortune, 1986; Schofield, 1986), while soil structure changes related to an adverse amount of compaction are long-term and regeneration is slow (McKibben, 1971; Low, 1972; Blake et al., 1976; Allmaras et al., 1982; Hadas, 1982; Voorhees, 1982; Wolf and Hadas, 1984; Bullock et al., 1985; Hadas et al., 1985). Soil structural states determined by selected single values or by distributions of a selected soil parameter with depth are often momentary (Ehlers, 1973, 1976; Bouma et al., 1975; Cassel, 1982; Ehlers et al., 1983; Ellen, 1984; Hoogmoed, 1984; Wolf and Hadas, 1984, 1985; Cassel and Nelson, 1985; Stroosnijder and Hartge et al., 1985; Mielke et al., 1986). Yet depth distributions of these parameters are essential to the modeling activity.

Summing up, we are limited, in most cases, to empirical relations that have been established between soil structural state

or tilth and soil parameters characteristic of physical processes. These, in turn, can be used to assess the soil-machine performances (Gill and McCreery, 1960; Hadas and Wolf, 1983; Wolf and Hadas, 1987) and to ultimately model soil-crop systems.

Interactions of soil tilth with seeds and roots

Mechanical operations on cropped fields change soil physical properties which, in turn, influence seed germination (Hadas and Russo, 1974 a, b; Hadas et al., 1978; Hadas et al., 1983, 1985), development and activity of the root system (Taylor and Klepper, 1978; Hadas et al., 1981) and, ultimately, crop yields (Hadas et al., 1981; Hadas et al., 1985; Reddy et al., 1987). Because the root system is the plant organ which is mainly responsible for interacting with the soil environment, modeling efforts involving the soil-plant interactions should take into account the response of the root system to the soil environment.

Major modeling efforts of soil-root interactions emphasize water uptake by roots, localized hydraulic balance, and nutrient uptake (Molz and Remson, 1970, 1971; Nimah and Hanks, 1973 a, b; Feddes et al., 1974, 1976, 1978; Taylor and Klepper, 1978; Wagenet, 1980; Narda and Curry, 1981; Whisler et al., 1982; Huck and Hillel, 1983; Klepper et al., 1983; Larson et al., 1983; Molz, 1975; Shaffer and Larson, 1987; Hoogenboom and Huck, 1986). In these models evapotranspiration is incorporated as a flux constraint. Emphasized also are soil-water conductivities and resistance to water flow in plant tissues. Water potential in the leaves, roots and soil is emphasized also to represent a driving force or

water potential constraint. In these models, roots are treated as quasi-stationary sink terms (Nimah and Hanks, 1973a, b; Feddes et al., 1974, 1978; Whisler et al., 1982) that change with depth, either with depth distribution of relative activity for water withdrawal (Feddes et al., 1974, 1976, 1978; Wagenet, 1980), or with changes in soil resistance to penetration, aeration conditions, and available photosynthates (Whisler et al., 1982; Hoogenboom and Huck, 1986; Reddy et al., 1987).

Seed germination and seedling establishment is usually dealt with as an empirically determined regression equation (Wanjura, 1975), or is totally omitted (Feddes et al., 1978), and the soil-crop model starts after plant emergence. Seed germination and seedling emergence is highly sensitive to soil tilth and associated soil physical properties. Coarse tilth may reduce total seedling stand and increase stand variability (Hadas et al., 1983, 1985). This response may be caused by diminished water supply to the germinating seed (Hadas and Russo, 1974a), impaired seed-soil contact, differential hardening of the soil crust as affected by tillage (Hadas and Stibbe, 1977) or a combination of high transpirational demand and impaired contact between soil and radical or moderate to high soil resistance to penetration (Williams, 1974).

Several recent models, with only limited simulation, related to corn germination, emergence, and development of sixth leaf stage demonstrates the relative impact of soil tilth and crop residue cover. Schneider and Gupta (1985) demonstrated interactive effects of soil temperature, matric potential, and aggregate size

distribution and have utilized the model to predict the influence of several tillage systems on time for emergence in the Corn Belt. Swan et al. (1987) modeled the growing-degree days for sixth leaf emergence; crop residue cover over the row was much more important than other tillage-related factors, such as soil structural arrangements affecting thermal diffusivity.

The relative effects of root activity to withdraw water as related to soil-root contact, mechanical impedance, and aeration change for soil layers which differ from one another in soil tilth and water content. Generally, root contact with soil water greatly affects water uptake when roots penetrate a coarsely structured layer such as the Ap horizon, but when the root grows in a nontilled and naturally or artificially dense soil layer, resistance to penetration and reduced aeration become restrictive factors.

Configuration and depth distribution of the root system may affect nutrient and water uptake by plants as measured in the field (Barley, 1971; Feddes et al., 1974; Hadas et al., 1981) and as simulated (Feddes et al., 1978; Reddy et al., 1987). Because soil-crop models usually require many parameters and employ a combination of empirical and multivariate interactions, it is extremely difficult to perform a sensitivity analysis of factors related to root distribution with depth and time (size, shape, and branching of roots), and of the utilization of water and nutrients. Therefore, it seems that for the time being, it is impossible to decide which of the following modes should be employed to calculate root distributions and activities: a) time

and space measured distributions (Feddes et al., 1974, 1978; Wagenet, 1980), or b) partitioning net photosynthate between shoots and roots and assuming a predetermined root mortality (Huck and Hillel, 1983; Hoogenboom and Huck, 1986). However, we speculate an improved understanding of root proliferation and associated activity distribution in a soil environment model will be gained by computationally building a root system (Hackett and Rose 1972a, b; Lungley, 1973) with a dynamic system of factors, including soil-root contact and root activity for nutrient and water uptake related to soil water conductivity (Barley, 1971; Williams, 1974). For instance, Passioura (1984) has suggested that root function for water uptake may be modeled using an integration of single root models. While such an improvement in our modeling practices will reflect an improved knowledge and understanding of the processes, interactions, and parameters involved, it will again lead to more complex and time-consuming models. These, in turn, will be more difficult to validate.

A small digression will help to assure that limited models are useful to identify special objectives for tillage machines and systems. Laflen et al. (1985) have modeled the C (or crop) factor for water erosion control by tillage systems based upon random roughness, surface cover with crop residue, crop residue incorporated in the upper 10 cm layer of soil, and soil pulverization. Discussion above cites numerous studies to show that the first three of these factors are indeed characteristically produced by certain tillage implements.

CONCLUSIONS

Current capabilities of modeling the machine-soil-crop interactions as a system include empirical, theoretical, and simulation models to predict segments of the total system, but none covers the full system. Yet this system is sufficiently complex to warrant more extensive use of a systems analysis.

Those machine-soil models that attempt to model machine behavior in the soil system are usually more satisfactory for predicting efficiency of energy conversion than for predicting the structure of the soil after a pass by an implement through the soil. Machine-soil models related to traction dynamics have predicted resultant soil properties better than those related to tillage dynamics.

The NTRM model (Shaffer et al., 1983; Shaffer and Larson, 1987) developed in Minnesota is the most comprehensive simulation model of the soil-crop (or root) system. It has not yet been applied in a sufficiently wide range of situations to adequately evaluate its effectiveness. It does not include a component that focuses on the machine as it passes through the soil, but it can be used to predict and describe agronomic and conservation needs. Ongoing improvements in measured soil structure responses to tillage and models such as NTRM are mutually supporting.

Numerous less comprehensive models of the machine-soil or soil-plant type were discussed to encourage their use for more restricted objective and for continued development of theory to understand the machine-soil-crop interaction.

Continued improvement of relationships between machine and soil structure, as well as stress-strain relationships of the soil and distribution of stresses around a machine in a soil body may be the best method to estimate the spatial distribution of particles and voids involved in soil tilth. These spatial properties are crucial in determining the soil physical parameters needed to model the flow and content parameters in the root zone and the properties that control soil strength and mechanical resistance to root growth.

The problems caused by natural and artificially induced spatial variability of field soils were not discussed. Yet, inclusion of these variations by use of a probabilistic approach - with respect to time and space - will improve the incorporation of parameters related to machine, soil, and crop.

The interface between the machine and the soil properties produced by the machine is the interface in most need of improved understanding for managing the machine-soil-plant system. It is an interface in which there are many processes and a deficiency of theory to organize predictions. This interface is also one that suggests increased interdisciplinary research among soil scientists and engineers interested in tillage management. Research on this interface has much promise for the development of tillage systems to meet needs of production, conservation, and monetary expediency.

Acknowledgment

This work was partially supported by a grant from the United States-Israel Binational Agricultural Research and Development Fund (BARD) No. US-666-83.

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FIGURES

Figure 1. General flow chart of the NTRM model (from Shaffer and Larson, 1987).

Figure 2. Exchange of tillage data between submodels of NTRM (from Shaffer et al., 1983).

Figure 3. Tractor energy, fuel consumption, main time, and tractor power (per unit width of implement) required for tillage of soils with various texture, seven different tillage implements, and under good, normal, and bad traction conditions (from Perdok and Van de Werken, 1983; MbP - moldboard plow, CP-chisel plow, RTs-rotary tiller (spike), RTb-rotary tiller (blade), PH-powered harrow, OH-oscillating harrow, and STC-spring tooth cultivator).

Figure 4. Flow chart for step-wise computational model to estimate tradeoffs of compaction and draught (adapted from Hadas et al., 1986).

Figure 5. Measured ranges of draft forces for selected tillages in a silty clay loam compared to predicted draft forces using the model of Hadas et al. (1986) with input of ballasted and non-ballasted front wheels of a tractor, variable slip and variable bulk density of a silty clay loam at about 12% (w/w) water content (from Hadas et al., 1986).

Figure 6. Isopenetration resistance lines measured in a silty loam at a water content of 20% (w/w) after one pass of a tractor traveling at speeds of 3.2 and 8.0 km h⁻¹ (from Hadas et al., 1986).

Figure 7. Measured distribution of bulk density in a silty clay soil, at an initial water content of 20% (w/w), after one pass of a tractor traveling at 3.2 and 8.0 km h⁻¹ (from Hadas et al., 1986).

Figure 8. Field variation of wheat dry matter yields on a silty clay as related to penetrometer resistance after conventional or controlled traffic (soil water content when trafficked was 28%, w/w).

FIGURE NO. 1

FIGURE NO. 2

FIGURE NO. 3

FIGURE NO. 4

FIGURE NO. 5

FIGURE NO. 6

FIGURE NO. 7

FIGURE NO. 8