NATIONAL SOIL CONSERVATION PROGRAM

Methodologies for Assessing Soil Structure and for Predicting Crop Response to Changes in Soil Quality

Final Report

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B.D. Kay, Principal Investigator
A. da Silva
K. Denholm
N. Eshraghi
E. Perfect
V. Rasiah

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EXECUTIVE SUMMARY

The objectives of this study were:

(a) to identify a method(s) for measuring soil structural changes which may be related to soil management systems and which can be shown to be useful for characterizing changes in soil quality across a range of soil conditions and;

(b) to evaluate existing crop productivity models in terms of their suitability for predicting crop response to changes in soil quality.

The budget associated with the contract was directed to field and laboratory studies related to objective (a) and the collection of field data to be used in the evaluation of crop productivity models [obj. (b)]. Further research related to objective (b) has been incorporated into the work plan of an Agriculture Canada Research Branch staff person.

The field studies for the project were located on the farm of Mr. Don Lobb, Huron Country. This site was one of the T-2000 sites investigated during the Ontario Land Stewardship program and is one of the longest running field scale side-by-side comparisons of zero and conventional tillage in Ontario. The comparison is maintained as a strip about 0.5 km in length which traverses soils with clay contents ranging from 7 to 40%. The site was maintained in corn production in 1991 and 1992. (The study has been extended to 1993 and supported by funds from alternative sources). Thirty-six locations were identified on each transect (tillage treatment) for detailed studies on soil structure.

Soil structure can be defined in terms of structural form and structural stability. Structural form relates to the arrangement or "architecture" of solid and void spaces whereas structural stability refers to the resistance of structural form to deformation (including fragmentation) when stress is applied. Structural form can progressively change subsequent to a change in soil or crop management practices through changes in the level of stress applied to a soil or by changing the population of soil organisms (e.g. earthworms). Structural form will also change if the stress remains constant but stability changes. Management practices can cause changes in stability by causing changes in the level of stabilizing materials (primarily organic in origin) in soils. Methodologies to assess both structural stability and structural form were assessed in this study. Pedotransfer functions were developed, where possible, in order to describe the contribution of inherent soil properties to the magnitude of the different parameters that were measured.

Parameters which were used to describe structural stability related to the resistance of soil to deformation by two types of stress: moving water and mechanical stress causing fragmentation. Stability parameters related to moving water were assessed at two different scales: that of aggregates > 0.25 mm, and that of clay-sized particles (< 0.002 mm). The resistance to mechanical stress was assessed using tensile strength and the distribution of aggregate sizes created by tillage.

Preliminary studies using rainfall simulation techniques indicated that the amount of runoff and the amount of sediment in the runoff arising from a rainfall event were related to dispersible clay and time to ponding. Time to ponding is related to infiltration characteristics and was found to be strongly dependent on wet aggregate stability. Stability parameters at the scale of aggregates and at the scale of dispersible clay both appeared, therefore, to be important in describing runoff and sediment load in the runoff. Studies were therefore initiated to assess both characteristics in more detail.

A turbidimetric technique was developed to expedite characterization of dispersible clay across the range of soils on the study site. The technique involved first developing a standard curve (turbidity as a function of concentration of dispersible clay) that can be described as a function of inherent soil characteristics (clay and organic matter content). The standard curve was then used in conjunction with turbidimetric measurements to characterize the dispersibility of clay across the site. Variation in the characteristics of the standard curve with soil properties appeared to be due to the range in concentrations of dispersible clay in which the standard curve was determined and the mean weight diameter of the dispersed clay fraction. A single curvilinear standard curve was found to be applicable to all of the soils on the study site since the curvilinear representation incorporated the influence of both concentration and mean weight diameter. The dispersible clay content was very variable across the site and was found to increase with increasing clay content, increasing water content and decreasing organic matter content. At high clay content, clay was more dispersible under conventional tillage, even after differences due to organic matter were taken into account.

Wet aggregate stability was found to increase with increasing clay, and organic matter contents, and decrease with increasing water content. The reduction in stability with tillage appeared to be related to the reduction in organic matter content with tillage.

The response of soil to mechanical stress was assessed by considering tensile strength measurements and the dry aggregate size distribution created by tillage. Tensile strength increased with increasing dispersible clay, clay content, wet aggregate stability and decreasing organic matter content. When multiple regression analysis was performed, dispersible clay was the only significant predictor of tensile strength; increasing dispersible clay was associated with increasing tensile strength. Aggregate size distributions were assessed using different approaches. A description of the distribution by fractal theory was found to be most accurate. The analyses indicated that the number of aggregates in the largest size fraction increased with increasing clay content, dispersible clay content, wet aggregate stability and decreasing organic matter content. When all of these variables were included in a multiple regression analysis, dispersible clay was the only variable selected. A comparison of tensile strength and aggregate size distribution characteristics showed a highly significant correlation indicating increasing fragmentation with decreasing tensile strength. The analyses suggest that one parameter could be predicted from the other and that, for a given application of stress through tillage, either parameter could be predicted from inherent soil characteristics or from dispersible clay measurements.

Bulk densities and relative bulk densities were measured. The concept of least limiting water range (LLWR) was used to describe the combined effects of structural form on aeration, resistance to penetration and available water and represented measurements under "static" conditions. Structural form was characterized under dynamic conditions using infiltration measurements. Once again the sensitivity of these parameters to inherent soil properties and to management were determined.

Bulk density was found to vary with clay and organic matter contents and was higher on the no till than the conventional till treatment. The relative bulk densities were determined by dividing the observed bulk density of each soil by the bulk density determined after compacting each soil using a compressive stress of 200 kPa. The bulk density after compaction was also found to vary with clay and organic matter content. The relative bulk density was however constant across all soils for a given tillage treatment and was 11% higher on the no till treatment. This type of analysis has not been done before and obviously has important implications for all laboratory studies in which bulk density and inherent soil properties are variables.

Values of LLWR were determined by establishing the functional dependence of the water release curve (potential versus water content) and the soil resistance curve (resistance to penetration versus water content) on bulk density, clay and organic matter content. Limiting values were then assigned, using generally accepted criteria in the literature, for aeration (10% air filled porosity), field capacity (0.01 MPa), permanent wilting point (1.5 MPa) and resistance to penetration (2.0 MPa) to these functions in order to define the LLWR for each soil. Analyses showed a wide variation in LLWR with clay and organic matter content for a given tillage treatment. Correlation of LLWR with plant growth parameters indicated a strong correlation between LLWR and plant population. Integration of LLWR data with soil water content was necessary before the LLWR could be related to yield.

Infiltration was measured in the non-trafficked inter-rows on all 36 locations under both tillage treatments. The field saturated hydraulic conductivity, Kfs , was found to be higher under the no-till treatment than under conventional till and may reflect greater continuity in macropores in the no-till treatment. A statistically significant, but poor, correlation existed between Kfs and inherent soil properties.

Soil water content measured regularly throughout the growing season is a reflection of precipitation, evapotranspiration, and soil structural characteristics. The mean water content was found to be a more predictable hydrologic characteristic than infiltration characteristics. Mean water contents at 0-20 cm depth varied with clay and organic matter contents, tillage and row/interrow position.

An analysis of the sensitivity of structural characteristics to management on different soils and the possibility of correlations between characteristics suggest that the following parameters represent the minimum data set that should be measured under the climatic conditions encountered in Ontario:

- dispersible clay
- relative bulk density
- soil water content
- least limiting water range

In the case of freshly tilled soil some measure of the fragmentation characteristics such as dry-aggregate size distribution is also recommended.

These parameters exhibit different degrees of temporal stability. The non-limiting water range is the least dynamic of the variables if defined as a function of bulk density. The relative bulk density is slightly more dynamic - particularly where tillage is involved. Both of these parameters are less dynamic than dispersible clay which, in turn, is less dynamic than soil water content. The dry-aggregate size distribution is highly dynamic. Further work on the relation between least limiting water range and plant response is strongly recommended.

Data were collected that could be utilized in evaluating plant growth models. Climatic records were obtained from a weather station maintained on the site. Additional information on plant response parameters (yields, root distributions) were also recorded. The 1992 growing season was wetter and cooler than the previous year. Measurements of the root length density in the 0-20 cm depths indicated a consistently lower root length density in 1992 than in 1991.

Adaptation of current crop productivity models is being undertaken by Mr. Ken Denholm, Agriculture Canada Research Branch, Guelph as part of this project. This activity has not progressed as rapidly as originally anticipated. However, once the models are developed a complete data set is available to assess the models in terms of their ability to predict yield response on soils of different structure and under the dramatically different climatic conditions that existed in 1991 and 1992. Assessment of existing models, and restructuring them as required, is part of Mr. Denholm's current workplan.

1. INTRODUCTION TO STUDY

The structure of soil can determine both the effectiveness and the impact of farming practices. Soil structure influences the extent to which crop breeding and the management of weeds, insects, disease, soil fertility, and water are manifested in increased crop yields. Soil structure also influences the loss of agricultural chemicals through erosion and leaching and can, therefore, have a significant bearing on the environmental impact of some management practices.

Soil structure is very sensitive to management and the impact of soil structure on crop productivity varies with both soil and climatic conditions. A multitude of parameters have been used to characterize soil structure and the quality of soil for crop growth. The ultimate agronomic meaningfulness of these parameters lies in their value in predicting crop response but few of these parameters have been rigorously evaluated from this perspective.

The paucity of studies relating soil structural characteristics to yield arises, in part, from the strong influence of climatic conditions on soil-plant interaction and would suggest that a large number of years of data would be necessary at one site before yield could be predicted from one or more structural characteristics. It is unrealistic to expect that such data will be readily obtained for a range of soils and crops. The alternative to long term studies for the purpose of accessing the meaningfulness of structural characteristics is to develop a computer model in which soil physical conditions are adequately built into the model and then analyses carried out to determine the sensitivity of yield to variation in soil physical properties under the range of climatic conditions which may be experienced at that site. The extension of such models to a range of sites would only be limited by the data available on soil and climatic characteristics on these sites.

1.1 Objectives

The general objectives of the studies were:

- to identify a method(s) for measuring soil structural changes which may be related to soil management systems and which can be shown to be useful for characterizing changes in soil quality across a range of soil conditions
- to evaluate existing crop productivity models in terms of their suitability for predicting crop response to changes in soil quality.

1.2 Site Selection and Description

The nature of the general objectives dictated that the following criteria be met in selecting the principal research site. The site would:

- have a broad range of textures with a minimum of two distinctly different management practices that have been maintained across the site for a minimum of 5 yr.

- have a consistent documented variation in crop yields across the range of textures.
- be planted in corn in the 1991 and 1992 growing seasons.

The site that was selected, and which met these criteria, was located on the farm of Mr. Don Lobb, located on concession road 15-16 Goderich Township, Huron County, just north of Clinton, Ontario. The farm is located in the 2900 corn heat units zone. The site was one of the T-2000 sites investigated during the Ontario Land Stewardship program and is one of the longest running field scale side-by-side comparisons of zero and conventional tillage in Ontario. The comparison had been maintained for 11 yr. prior to initiation of the study as a strip (side by side comparison) across soils with a range of properties. A corn-soybeans-wheat rotation had been maintained on the site and the site was planted to corn in 1991 and 1992.

The site was characterized by establishing 36 study locations along a 0.5 km transect in each of two parallel transects located on each tillage treatment. Each transect was 0.5 km in length. The locations included the T-2000 permanent bench mark locations (Aspinall and Kachanoski, 1993). The locations were spaced according to soil type and paired between tillage treatments according to landscape position. The remaining point locations were equally spaced between the permanent benchmarks. Soils at each of the 36 locations on each tillage treatment were sampled by horizon. The depths of the horizons varied along the transects and between tillage treatments and consequently additional sampling was performed by depth (0-20, 20-40 cm). The soil properties at the different locations are summarized by depth and by horizon in Appendix I and II respectively. Additional measurements on each location that relate to specific experimental objectives are provided in subsequent sections.

Preliminary studies related to methodology development were carried out at the Elora Research Station. Details on this site are provided in section 2.2.1.

2. CHARACTERIZING SOIL STRUCTURE

2.1 Introduction

Soil structure can be defined in terms of structural form and structural stability. Structural form relates to the arrangement or "architecture" of solid and void space whereas structural stability refers to the resistance of structural form to deformation when stress is applied. Structural form can progressively change subsequent to a change in soil or crop management practices through changes in the level of stress applied to soil or by changing the population of soil organisms (e.g. earthworms). Structural form will also change if the stress remains constant but the stability changes. Management practices can cause changes in stability by causing a change in the level of stabilizing materials (primarily organic in origin) in soil. Methodologies to assess both structural stability and structural form were assessed in this study.

Parameters that were used to describe structural stability related to the resistance of soil to deformation by two types of stress: moving water and mechanical stress causing fragmentation. Stability parameters related to moving water were assessed at two different scales: that of aggregates > 0.25 mm, and that of clay sized particles (< .002 mm). The resistance to mechanical stress was assessed using tensile strength measurements and aggregate size distributions created by tillage. The sensitivity of the stability parameters to both inherent soil properties and management was assessed.

Parameters which were used to describe structural form included both static and dynamic parameters. The concept of least limiting water range (LLWR) was used to describe the combined effects of structural form on aeration, resistance to penetration and available water and represented measurements under "static" conditions. Structural form was characterized under dynamic conditions using infiltration measurements. Once again the sensitivity of these parameters to inherent soil properties and to management was determined.

2.2 Wet Aggregate Stability and Dispersible Clay

The stability of different sized structural units to moving water can be measured under field or laboratory conditions. Field measurements normally utilize rainfall simulation measurements and the structural stability is inferred indirectly from the amount of runoff and the concentration of sediment in the runoff. Laboratory measurements involve some variation of shaking soil in water and determining the persistence of aggregates (wet aggregate stability) and the amount of clay-sized particles that become suspended (dispersible clay). Field measurements are particularly time consuming and therefore preliminary studies were initiated to determine the relation between laboratory and field measurements of stability. Additional studies were initiated to determine if the stability characteristics of soils, and the sensitivity of these characteristics of soils to tillage could be predicted from the inherent soil characteristics normally included in soil surveys.

2.2.1 Importance of Stability and Hydrologic Robustness Parameters on Runoff and Sediment Load

2.2.1.1 Introduction

The ability of surface soil to retain its structural integrity during rain events determine, at least partially, the amount of runoff, RO, and the sediment load, SL, i.e., the concentration of sediment in the runoff. The structural parameters that have been widely used to describe structural changes are dispersible clay, DC, and wet aggregate stability, WAS. The Water Erosion Prediction Project, WEPP, model, a US-based study has recently developed a process-based numerical model that uses data on DC rather than WAS as one of the input parameters to predict soil loss from cultivated land (Foster and Lane, 1987).

The hydrologic robustness of soil surface has a strong influence on infiltration (White et al., 1989), and therefore would be expected to have an impact on RO and SL. These workers have defined hydrologic robustness in terms of time to incipient ponding. Runoff and sheet erosion cannot occur until the microrelief on soil surface is filled with water and this would occur only when the soil water potential at the surface is zero. The time taken to reach incipient ponding during a rain event is called time to ponding, TP. Intuitively, it is expected that TP should increase with increasing WAS and decreasing DC and this may result in reductions in RO and SL.

A preliminary study was initiated to assess the relative importance of WAS and DC on RO and SL on a medium textured soil under different crop and tillage conditions and to assess the contribution of TP to variation in RO and SL.

2.2.1.2 Materials and Methods Field Experiments

Rainfall simulation studies were carried out during the 1991 and 1992 growing seasons, in a crop rotation-soil structure experiment established in 1988 May at the Elora Research Station. The soil at the experimental site is a Conestogo silt loam (Aquic Eutrochrept) with 17.9% clay, 53.4% silt, and 3.4% organic matter contents. The pH of the soil was 7.17. Prior to 1988, the experimental site was under conventionally-tilled (plowing in the fall followed by secondary tillage in spring) continuous corn (*Zea mays* L.) production for at least 10 yr. Cropping treatments included a conventionally-tilled continuous corn, C_n (the subscript n indicates that corn was previously grown for more than 10 years treatment, and different corn-forage rotations. The forages included in the rotation were alfalfa (*Medicago sativa*. L), and bromegrass (*Bromus inermis*. L). The forage phases in the experiment had three time treatments in which the forages established in 1988 were grown for 2, 4, and 6 yr before the conventionally-tilled corn was re-introduced in those plots. For example, the alfalfa grown for 2 yr is abbreviated C_n AL_2 and bromegrass as C_n BG_2. When corn was re-introduced in the C_n AL_2 plots, following conventional cultivation practices, the treatment is abbreviated C_n AL_2 C_x, where x refers to number of years under corn following forages. Similar abbreviations were followed for the other treatments. Red clover (*Trifolium pratense.* L) was underseeded in the minimally tilled corn, C_n MC_x, treatment about 12 to 14 days after corn was seeded. The red clover stand was very poor during the 1991 season. The experimental design was a randomized complete block with four replications.

Rainfall simulations were carried out twice during each growing season. The first simulation was carried out immediately before planting corn. The second simulation was carried out when the corn was about 5 to 8 leaf stage. A portable rainfall simulator, the Guelph Rainfall Simulator II, (Tossell et al., 1987) was used in this study. The simulator was used to create rain events for 15 minutes at an intensity of 160 mm hr^{-1} (Wall et al., 1991). Simulations were carried out over a 1-m by 1-m plot in each replicate of each treatment. Before each simulation was carried out the surface cover, both live and dead, was determined using a 1-m by 1-m frame with pins at every 10 cm^2. In this study an effective surface cover was defined as one which was about 2 to 3 cm in size and was in contact with a pin. Soil samples for gravimetric soil water content, w, determinations were taken from 0 to 5 cm depth both immediately before and 24 hr after the simulation. Runoff from the 1 m^2 plot was trapped in a collection trough, pumped into collecting bottles and the total volume recorded. The concentration of sediment in RO was determined from 1 L RO subsamples by drying in an oven, at 105ºC, to constant mass. The depth of water applied was monitored in four rain gauges installed at each corner of 1 m^2 plots. A portable wind barrier was used to minimize the variability in water application rates due to wind drift.

Wet Aggregate Stability and Dispersible Clay measurements

Soil cores (7 cm diameter and 7 cm length) were collected from the surface 0-7 cm layer at four randomly selected locations from each replicate about 10 to 15 d before each simulation. The soil cores from each replicate were bulked and approximately one quarter of the bulked moist soil was sieved using a nest of sieves with mesh openings of 10, 2, and 1 mm, respectively, and a shaking time of one minute. Aggregates retained on the 1 mm sieve, i.e., the 1 to 2 mm aggregates, were used for WAS and DC determinations using the procedure described by Pojasok and Kay (1990). The w of 1 to 2 mm aggregates were determined.

Because, rainfall simulation and soil sampling for WAS and DC measurements were not carried out on the same day, the measured values of WAS and DC were adjusted for w that existed just before simulation.

2.2.1.3 Results and Discussion Influence of Cropping and Tillage Systems

Cropping and tillage systems had a significant influence on RO, SL, TP, WAS, DC, surface cover, and time to runoff, TRO, during each simulation in 1991 (Table 2.1). In 1992, the effectiveness of some of the variables was not significant at P = 0.05. However, for the data pooled for 2 yr the influence was significant for all the variables, exclusive of TRO.

Table 2.1. Statistical significance of cropping and tillage system effects on runoff, sediment load, time to ponding, time to runoff, surface cover, dispersible clay, and wet aggregate stability.

	Significant level during				Pooled data
	1991		1992		
	for simulation				
	I	II	I	II	
Runoff	*	**	ns	*	**
Sediment in runoff	**	**	**	na	**
Time to ponding	**	**	**	**	**
Time to runoff	**	**	na	na	*
Surface cover	**	**	**	**	**
Dispersible clay	**	**	*	na	**
Wet aggregate Stability	**	**	*	ns	**

**, *, and na are significant at P = 0.01 and 0.05, and not significant (at P = 0.05), respectively.

The RO from the minimally-tilled corn and that from the forage phases of corn-forage rotations were significantly less than that from the conventionally-tilled continuous corn treatment (Table 2.2). Compared to the RO from the conventionally-tilled continuous corn treatment, that from the minimally-tilled corn and forage phases were 27 and 70% less, respectively. Fifty two percent of the water applied appeared as RO from the conventionally-tilled continuous corn treatment compared to 38% from the minimally-tilled corn and 15% from the forages. The RO from corn following the forages was similar to that observed in the conventionally-tilled continuous corn during both years. This suggested that the residual beneficial effects of forages in reducing RO did not persist during the corn phase of rotation.

The influence of cropping and tillage systems on SL was similar to that observed for RO (Table 2.2). However, the residual beneficial effects of forages on SL during the corn phase seems to have persisted, i.e., the SL from these plots was 25 to 40%, during both years, less compared to the conventionally-tilled continuous corn. Because, the surface cover of corn phase was similar to that of conventionally-tilled continuous corn, the differences in SL between these two treatments is attributed to differences in TP or TRO (Table 2.2). The SL from the minimally- tilled corn was 63% less compared to the conventionally-tilled continuous corn and that from the forage it was 87% less. A comparison of the percent reductions in RO and SL created by minimum till practice indicates the effect was much greater on SL than on RO.

Table 2.2 Mean values of runoff (RO), sediment load (SL) in RO volume, time to ponding (TP), time to runoff (TRO), surface cover (SC), dispersible clay (DC), and wet aggregate stability (WAS).

Cropping treatment	RO (L m^{-3})	SL (g L^{-1})	TP (.min.)	TRO (.min.)	SC (... %..)	DC (..%...)	WAS (..%..)
Simulation 1 1991							
C_n	18.75a	20.67a	0.73c	1.85d	19.8c	4.30a	28.85c
C_n MC_4	12.67b	7.72b	1.01b	2.25b	31.8b	4.90a	30.93c
C_n AL_2 C_2	15.42a	18.72a	0.62bc	1.78d	26.0bc	4.22a	35.50b
C_n BG_2 C_2	18.32a	16.21b	0.65bc	1.84d	24.8bc	4.10a	31.92c
C_n AL_4	4.61c	1.73c	1.02b	2.07c	73.2a	2.67b	43.31a
C_n BG_4	3.12c	2.20c	1.33a	3.60a	89.3a	3.08b	42.42a
Simulation 2, 1991							
C_n	29.84b	40.78a	0.25c	0.72c	17.8c	3.47b	29.31b
C_n MC_4	11.48c	4.48c	0.32b	0.85b	27.8b	3.36b	31.06b
C_n AL_2 C_2	37.21a	28.97b	0.30b	0.80b	15.8c	3.38b	30.91b
C_n BG_2 C_2	40.51a	26.20b	0.31b	0.72c	23.0b	3.29b	33.47b
C_n AL_4	5.99d	2.38d	0.95a	1.08a	89.5a	2.56a	43.44a
C_n BG_4	4.70d	2.28d	1.10a	1.37a	85.5a	2.32a	44.75a
Simulation 1 1992							
C_n	21.53a	26.39a	0.38c	0.53c	13.2c	0.89a	30.96b
C_n MC_4	12.80b	10.50b	0.49bc	1.08b	21.0b	0.93a	26.50c
C_n AL_4 C_1	8.00c	12.19b	0.66b	1.04b	9.5c	0.99a	30.25b
C_n BG_4 C_1	13.45b	13.36b	0.91a	1.65a	11.0c	0.40b	38.63a
C_n AL_5	8.46c	3.39c	0.66b	0.78c	88.0a	1.18a	34.65a
C_n BG_5	5.11c	4.48c	0.63b	1.42a	93.8a	0.38b	36.31a
Simulation 2 1992							
C_n	13.25a	13.06a	0.26c	0.63c	11.0b	3.09a	16.23b
C_n MC_4	14.32a	14.95a	0.28c	0.43c	19.7b	2.78a	19.66b
C_n AL_4 C_1	10.07b	12.14a	0.26c	0.58c	12.0b	2.91a	19.67b
C_n BG_4 C_1	12.27a	12.67a	0.30c	0.66c	13.2b	2.73a	24.45a
C_n AL_5	6.47c	5.93b	1.00a	2.02a	92.0a	2.79a	22.07a
C_n BG_5	8.93c	2.86b	0.69b	0.92b	97.2a	2.49b	23.86a

C_n = corn grown for number of years (> 10 yr) using conventional cultivation practices. The subscripts for other letter abbreviations indicates the number of years under a crop. C_n MC_4 = minimally tilled corn established in Ca plots In 1988 in the 4th year, C_n AL_2 C_2 = alfalfa established in C plots in 1988 grown for 2 yr before and corn re-introduced in 1990, C_n AL_4 = alfalfa established in 1988 Ca plots grown for 4 yr and corn re-introduced in 1992. Similar abbreviations were used for bromegrass (BG). Same letter followed by the mean values in a column indicate the values are not significantly different at P = 0.05.

The surface cover in the minimally-tilled corn and forages was greater than that in the conventionally-tilled corn by 62 and 480%, respectively. The hydrologic robustness and the stability of soil aggregates under the forages were higher than that under conventionally-tilled continuous corn.

Functional Relations

Simple linear correlation analysis indicated that RO was linearly negatively correlated to WAS, surface cover, TP, TRO, and w (Table 2.3). A similar trend was observed for SL, exclusive of that with w. A significant positive correlation existed between RO and SL. These analyses indicate that both RO and SL were correlated to stability and hydrologic robustness parameters and surface cover. A significant positive correlation existed between TP and surface cover or WAS. A similar trend was observed for TRO. However, a comparison of the correlation coefficients obtained for the relation between TP and surface cover or WAS with the corresponding coefficients obtained for TRO indicates that the former correlations was stronger than the latter. This suggests that TP is relatively more sensitive to changes in WAS or surface cover than TRO, and thereby on RO and SL.

Table 2.3. The correlation matrix for the variables, RO , SL, SC, WAS, DC, TP, TRO, and w.

Variable	RO	SL	SC	WAS	DC	TP	TRO	w
RO		0.79**	-0.47**	-0.32*	0.14ns	-0.52**	-0.43**	-0.21*
SL			-0.52**	-0.29*	0.18ns	-0.46**	-0.38**	-0.09ns
SC				0.21*	0.23*	0.48**	0.23*	-0.32**
WAS					-0.23*	0.27*	0.24*	-0.27*
DC						-0.15ns	0.18ns	0.48**
TP							0.69**	0.28**
TRO								0.41**
w								

Correlation coefficients followed by '**' and '*' indicate the relation was significant at P = 0.01 and = 0.05, respectively, and those followed by ns indicate the relation was not significant at P = 0.05.

When TP was regressed, using the stepwise variable selection procedure, with surface cover (SC), DC, WAS, and w at simulation and the interaction terms involving the latter three variables the following equation was obtained:

$$\mathbf{TP = -27.68 - 2.30\,WAS + 0.19\,WAS\,w + 0.93\,SC} \qquad \mathbf{[2.1]}$$

$(R^2 = 0.53,\ P = -0.01)$

Equation [2.1] implies that TP increased with increasing WAS, w, and SC. Surface cover alone accounted for 23% of the variability in TP in Eq. [2.1] and WAS x w and WAS accounted for 20 and 10% of the variability, respectively. An increase in WAS by 5% (from 25 to 30, at SC = 25, w = 20, Fig. 2.1) resulted in 24% increase in TP compared to 14% increase for 5% increase in SC, from 25 to 30%, (at WAS = 25 and w = 20).

In the minimally-tilled corn treatment, where WAS did not change substantially (Table 2.2), the increases in TP was thus due to increases in SC. However, minimum-till practices for long-term may bring about positive changes in WAS, thus having larger effects on TP. The residual beneficial effects of forages on TP, if any, was primarily through WAS, because the SC during the corn phase of forage-corn rotation was similar to that of conventionally-tilled continuous corn (Table 2.2). Thus, the residual beneficial effects on forages on TP was determined by the persistence of WAS under corn.

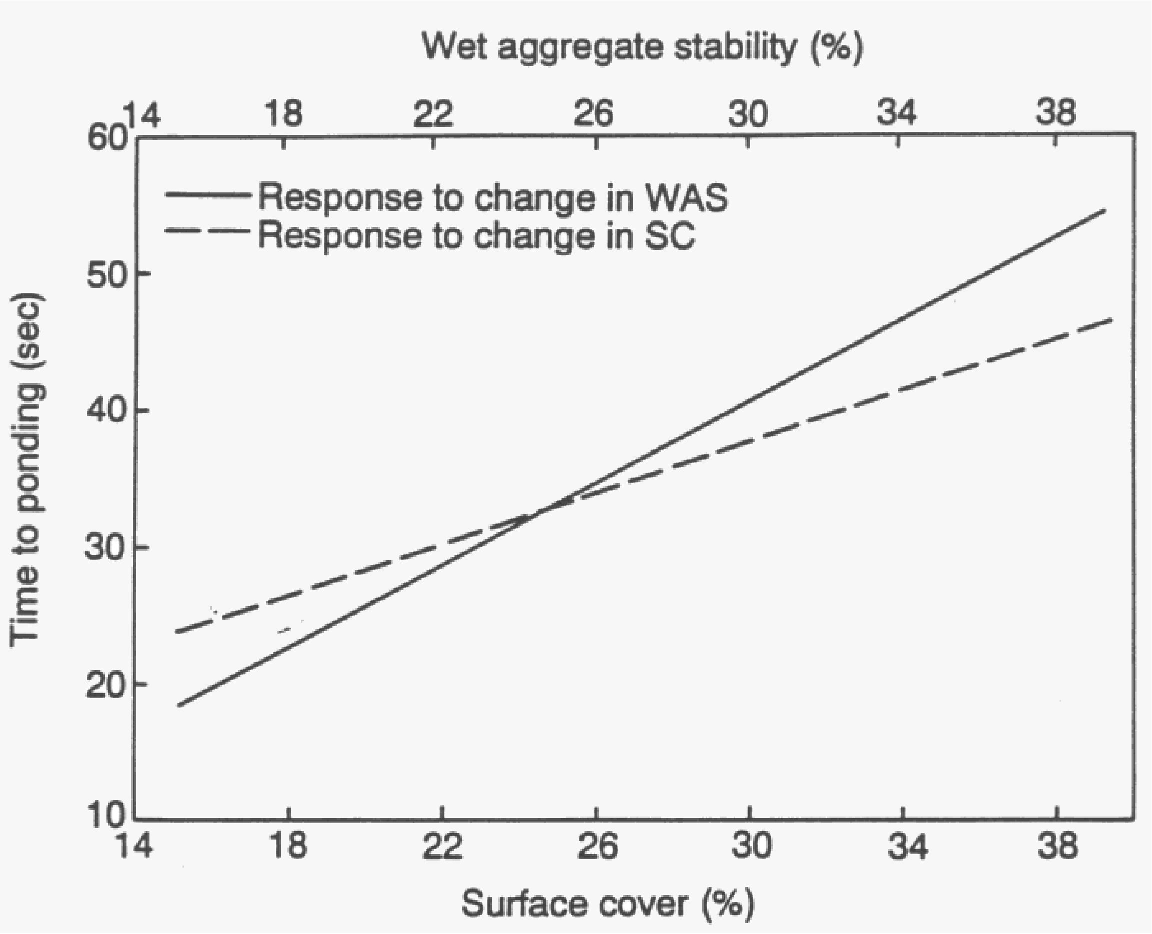

Figure 2.1. The influence of the changes in surface cover, wet aggregate stability, and dispersible clay on time to ponding.

The cumulative effect of TP, TRO, SC, WAS, DC, w, and the interaction terms involving the latter three on RO and SL was explored using the stepwise variable selection procedure and the following equations were obtained:

RO = 38.38 + 2.73 DC - 1.09 w - 0.05 TP - 0.16 SC **[2.2]**

($R^2 = 0.48$, $P = 0.01$)

SL = 32.01 + 1.97 DC - 0.77 w - 0.04 TP - 0.19 SC **[2.3]**

($R^2 = 0.46$, $P = 0.01$)

In Eq.[2.2], TP accounted for 27% of variability in RO compared to 12, 6, and 3% by SC, w, and DC, respectively. The SC accounted for 27% of the variability in SL compared to 8, 7, and 4% by w, TP, and DC, respectively. Equations [2.2] and [2.3] suggest that RO and SL depend on DC and not on WAS, however, the linear correlation analysis indicated that both RO and SL were significantly correlated to WAS but not to DC. There are at least two reasons for this inconsistency. First, both RO and SL are influenced by TP, Eqs.[2.2] and [2.3], which in turn depends on WAS, Eq.[2.1]. Thus, both RO and SL are indirectly influenced by WAS. Second, it seems the influence of DC became important, in determining the amounts of RO and SL, when several variables, particularly TP and SC, were involved.

Equations [2.2] and [2.3] indicate that increases in TP, w, and SC resulted in decreases in both in RO and SL. As TP increased, water intake increased, and therefore RO and SL decreased. At high soil water content, slaking would be minimized and/or the forces of aggregate destabilization would decrease, thereby increasing water intake and reducing RO. As DC increases, surface seal formation and pore clogging will increase, thereby reducing water intake and increasing RO and SL.

Equation [2.2] suggests that 10% increase in SC, from 15 to 25% (at DC = 3, w = 20, and TP = 32), resulted in 10% reduction in RO (Fig. 2.2a). The values of SC and DC used for the above computation are similar to that existed in the minimally tilled corn (Table 2.2). One percent reduction in DC, from 3 to 2% (at SC = 25, w = 20, and TP = 32), lead to 15% decrease in RO (Fig.2.2a). This amount of DC was similar to that existed in the forage treatments. A similar analysis for SL indicated that 10% increase in SC or 1% decrease in DC resulted in 11-12% reduction in SL (Fig. 2.2b). These analyses indicate that DC was as important as SC in determining the amounts of RO and SL from cultivated land. However, the impact of DC on RO and SL was more important particularly under conventionally-tilled row crop production system, more specifically on seed beds, where SC was practically non-existent.

Time to ponding is not a routine measurement unless rainfall simulation studies are being conducted. The cumulative effect of readily measured variables (SC, DC, WAS, w) and the interaction terms involving WAS, DC, and w was explored using the stepwise variable selection Procedure and the following equations were obtained:

RO = 42.60 - 1.42 w + 3.19 DC - 0.21 SC **[2.4]**

($R^2 = 0.38$, $P = 0.01$)

$$\mathbf{SL = 35.27 - 1.03\,w + 2.32\,DC - 0.22\,SC} \qquad \mathbf{[2.5]}$$

$(R^2 = 0.35, P = 0.01)$

The WAS term did not appear in the above equations and, although the DC did appear, the coefficients were the only coefficients in the models that were not significant.

2.2.1.4. Conclusions

The changes in WAS, DC, SC, and TP created by variations in cropping and tillage systems had a significant influence on RO and SL. A switch from conventionally-tilled continuous corn to rotations involving 2 to 4 yr forages resulted in significant reductions in DC and increases in WAS and TP during the forage phases. These changes in stability and hydrologic robustness parameters contributed, at least partially, to decreases in RO and SL. The preliminary study did not, however, provide conclusive evidence that one stability parameter was much more important than another. Both RO and SL increased with an increase in DC and a decrease in TP. TP increased with an increase in WAS. When TP was removed from the stepwise regression, DC remained in the models but the coefficient was not significant. Measurements of both parameters were therefore carried out as part of the more detailed study on the Lobb farm.

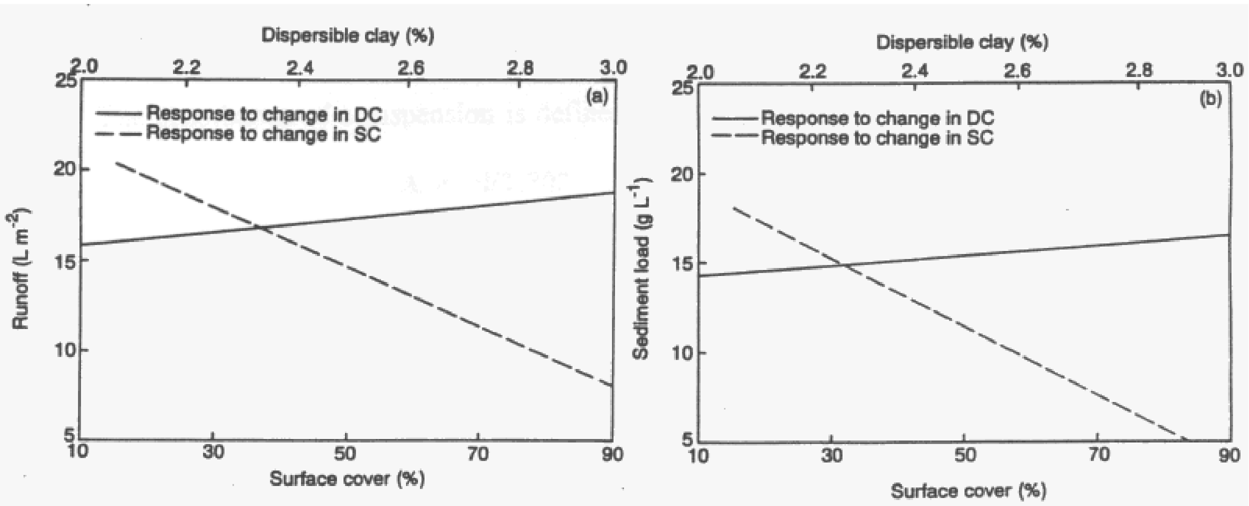

Figure 2.2. The influence of the changes in surface cover and dispersible clay on runoff and sediment load.

2.2.2 Dispersible Clay: Influence Of Soil Properties On Dispersible Clay And On Its Measurement

2.2.2.1 Introduction

The dispersibility of clay is determined by shaking soil in water allowing particles > 0.002 mm to settle out and then determining the amount of clay in the suspension. The amount of dispersed clay can be determined using gravimetric or turbidimetry procedures. The gravimetric method involves taking a known volume of suspension, drying it at 105º C for 24 hours and determining the weight of clay. Turbidimetry measurements, on the other hand, involves measurement of the absorbance of the suspension and determination of the concentration from a calibration curve which relates concentration of the dispersed clay to absorbance. The calibration curve is then used for repeated measurements of dispersible clay.

Measurement of dispersible clay using the gravimetric procedure is time consuming in comparison to turbidimetry technique. A limitation of the turbidimetry procedure, however, is that individual calibration curves may be required for each site especially if there are variation in soil properties such as texture and organic matter content. There is no information on influence of cropping treatments on the calibration curve.

The absorbance of a suspension is defined by the Beer-Lambert Law:

$$\mathbf{A = \tau l / 2.303} \qquad \mathbf{[2.6]}$$

where A is the absorbance, l is the optical path length, τ is the turbidity of the suspension (Ferreiro and Helmy 1974; Bartoli and Phillippy 1987; 1989). The turbidity of a suspension can be related to the characteristics of the suspension by:

$$\mathbf{\tau = K N V^2} \qquad \mathbf{[2.7]}$$

where K, N and V are the optical constant, number of particles per cm^3 of suspension and the volume of the individual particles. Equation [2.7] is based on the optical methods of studying flocculation, and is valid when the radius of the particles under consideration is less than 0.05 λ (Ferreiro and Helmy 1974), where λ is the wavelength of the radiation employed and ranges from 450 to 700 nm. Thus A varies with number of scattering units and the square of the volume of the particle under consideration (Ferreiro and Helmy 1974). Substituting equation [2.7] into equation [2.6] gives,

$$\mathbf{A = (1 / 2.303) K N V^2} \qquad \mathbf{[2.8]}$$

If we assume V is a constant, in equation [2.8], then

$$\mathbf{A = K_1 N} \qquad \mathbf{[2.9]}$$

where, $K_1 = (1/2.303)\ K\ V^2$. However, equation [2.9] is not valid for particles greater than 0.1 λ (Ferreiro and Helmy 1974). The value of λ used by Pojasok and Kay (1990) was 620 nm, and therefore this theory is not applicable to particles larger than 0.062 µ. The Mie theory of light scattering must be used for dispersible clay particles which can vary up to 2 µ in size. The relation developed for a coagulating system is based on Timasheff (1966) who extended earlier work of Oster (1947) as follows:

$$\tau = K \sum_x N_x V_x^{2/3} (V_x^{1/3}/\lambda)^m \qquad \textbf{[2.10]}$$

where $V_x = xV$; V is the volume of the initial aggregating particle, K is a constant independent of λ, N_x is the number of the particles of degree of aggregation x, and m is a constant which varies from a value of 4 for Raleigh scattering to -2.2.

In soil, the degree of clay flocculation (i.e. the *size* distribution of the suspended materials) or dispersion may vary with surface charge on clays (Shanmuganathan and Oades 1982), composition and amount of exchangeable cations (Rengasamy et al. 1986; Ali et al. 1987), clay mineralogy (Levy and van der Watt 1988), nature and amount of cementing materials (Kay and Dexter 1990) and external forces such as tillage and rain drop impact (Emerson 1983). Substituting equation [2.10] into equation [2.6] we obtain

$$A = \frac{1}{2.303} K \sum_x N_x V_x^{2/3} (V_x^{1/3}/\lambda)^m \qquad \textbf{[2.11]}$$

Where N_x is defined as

$$N_x = M_x/\rho_x V_x^{3/3} \qquad \textbf{[2.12]}$$

where M_x and ρ_x are the mass and density of the particles of degree of flocculation x in a cm^3 of suspension. Substituting equation [2.12] into equation [2.11] and rearranging we obtain

$$A = \frac{1}{2.303} K \sum_x \frac{M_x}{\rho_x} V_x^{-(1-m)/3} \lambda^{-m} \qquad \textbf{[2.13]}$$

The = $\sum_x M_x$ is equal to the concentration C of clay in the suspension. Since M_x and V_x in equation [2.13] are variables, the relation between the concentration and M_x can not be obtained and thus an empirical relation, i.e. a calibration curve, must be developed between absorbance and concentration. There is, however, no information on the influence of soil properties on such an empirical relation. Once a calibration curve is determined, the dispersibility of clay can be measured.

Factors that influence clay dispersion in the field are total clay content (Oades 1993; Rasiah et al. 1992), soil pH (Gillman 1974; Bartoli and Phillippy 1987; 1989), soil moisture content (Pojasok and Kay 1990; Rasiah et al. 1992) and organic matter (Gillman 1974; Bartoli and Phillippy 1987; 1989).

The shrink-swell properties of clay have a strong influence in the amount of clay dispersed from soil (Oades 1993). Dispersibility of soils low in organic matter depends primarily on soil mineralogy. Rasiah et al. (1992) indicated that soils with high clay content will experience greater swelling pressure on wetting and this may lead to greater dispersible clay. They indicated that organic matter decreases clay dispersibility by constraining the swelling pressure as the soil is wetted. In addition, higher concentrations of polyvalent cations such as Ca^{2+} in the soil matrix may help to stabilize soil aggregates, thereby reducing swelling pressure (Pojasok and Kay 1990; Rasiah et al. 1992). However, due to reduced swelling pressure under dry conditions, inorganic binding agents will play important role in clay stabilization (Rasiah et al. 1992).

Gillman (1974) indicated that sorption of organic materials changes the point zero charge (PZC) of clay particles, thereby reducing clay dispersion. Oades (1984) showed that when the PZC coincided with the pH of soil through addition of polyvalent cations such as Fe, clays flocculation increases. Bartoli and Phillippy (1989) indicated that clay flocculation is mainly controlled by Ca^{2+} and Al^{3+} at pH less than PZC. On the other hand, at pH values greater than PZC clay dispersion was determined by negative pH-dependent organic matter charge (Bartoli and Phillippy 1987). Tama and El Swaify (1978) and El Swaify (1980) ascertained that changes in soil pH may cause clay deflocculation and aggregate breakdown. In addition, solubility of materials containing Ca^{2+} and Al^{3+} has been shown to be pH-dependent and, therefore the stability of soils can be changed by changing the soil pH (Yeoh and Oades 1981). The stability of soils with higher organic matter content are more strongly correlated with pH than those with lower organic matter. Correlations with organic matter have been attributed to lower PZC on the clay particles (Bartoli and Phillippy 1989).

Organic acids and polysaccharides constitute part of soil organic matter (Shanmuganathan and Oades 1982). Organic anions of citric, oxalic, tartaric, (Stevenson 1967), succinic and lactic (Matsumoto et al. 1979) acids enhanced clay dispersion by blocking positively charged sites on clay/colloid surfaces and complexing polyvalent cations in solution (Bloomfield, 1963; Gillman, 1974). The ability of organic anions to disperse clay increased in the presence of phosphate and fulvate ions while lactate and acetate had a negative effect on clay dispersion (Shanmuganathan and Oades 1983; Oades 1984). The influence of organic anions on clay dispersion has been shown to be reduced by mucilage of plant and microbial origin. These mucilages acted as glues, thereby binding soil aggregates and reducing clay dispersion (Shanmuganathan and Oades 1983; Oades 1984).

Kay and Dexter (1990) indicated that initial soil moisture content can also influence the amount of dispersed clay. Pojasok and Kay (1990) showed that the amount of clay which was mechanically dispersed (in the absence of slaking) increased with the initial water content of the sample.

The literature is inconclusive as to the influencing of tillage practices on dispersible clay.

The primary objective of this study was to determine how tillage and soil properties influence the dispersibility of clay. Secondary objectives were to determine if calibration curves for turbidimetric measurement of dispersible clay vary with soil properties and, if so, to determine the nature and the cause of this variation. Progress on the secondary objectives had to be achieved before the primary objective was addressed.

2.2.2.2 Materials And Methods

Field Experiment

Soil samples were collected in 1992 and 1993 from six locations under each tillage treatment on the Lobb farm. The sites were selected to give a range of inherent soil properties (Tables 2.5, 2.6).

Calibration curve determination

Soil cores (7 cm diameter and 7 cm length) were collected from the surface 0-7 cm layer at six points selected at random around each of the twelve locations. The soil cores were bulked for each site and brought to the lab for further analysis. The soil were sieved using a nest of sieves with mesh openings of 10, 2, and 1 mm, and a shaking time of one minute. Aggregates retained on the 1 mm sieve, i.e., the 1 to 2 mm sized aggregates, were used to obtain stock suspensions and to determine dispersible clay using the Pojasok and Kay (1990) method. In brief, four 5 g subsamples of the field-moist 1 to 2 mm aggregates were prewetted on a wetting table at 1 cm suction head for 90 min. Using 40 ml of distilled water, the prewetted sample was transferred into a 50 ml test tube.

Table 2.5: Soil characteristics at selected locations along the transect for con-till sites.

Location #	% Clay	% OM	pH	% Silt
1	16.3	7.5	7.1	27.7
4	11.7	5.6	6.7	21.6
8	7.5	2.6	7.1	24.4
19	19.7	2.5	7.2	35.6
21	24.5	2.4	7.2	47.4
36	37.4	3.7	7.3	47.1

Table 2.6: Soil characteristics at selected locations along the transect for no-till sites.

Location #	% Clay	% OM	pH	% Silt
1	24.7	11.6	6.5	41.7
2	20.0	9.8	6.8	34.7
3	16.4	9.5	6.8	28.6
8	7.5	2.7	7.1	25.9
10	11.7	6.6	7.1	40.7
36	37.4	3.5	7.1	49.8

The suspension was shaken in a mechanical shaker for 10 min, and then transferred to a 250 ml conical flask using another 80 ml of distilled water. After 180 min settling time, the stock suspension was siphoned off from the surface up to a depth of three cm. According to Stokes' Law the sample should contain particles with an effective diameter ≤ 2 µm. Fifteen ml of the stock suspension was then used to determine the concentration (mg/ml) of clay particles using the gravimetric technique. Two ml of the stock suspension was diluted 2, 3, 4, 5, 6, 7, 9, 11, 17, and 21 times and the absorbance of each dilution determined at $\lambda = 620$ nm.

Characterization of particle size distribution in dispersible clay fraction

From the remaining stock suspension, 200 ml of suspension was transferred into a 250 ml centrifuge bottle which was shaken and centrifuged at 1000 RPM (IEC Model K Centrifuge) for the time required to sediment particles (using Stoke's law) coarser that 2.0, 1.5, 1.0 and 0.5 *µm* to a depth of 10 cm. The upper 10 cm of suspension was then siphoned off and 15 ml of the suspension was then used to determine the concentration (mg/ml) of clay particles using gravimetric procedure. The mass of dispersed clay in a size range fraction was computed by taking differences in mass between two consecutive size fractions. The mass of clay in a size range was then multiplied by the mean size of the particles in this size range and these values were than cumulated, from the smallest to < 2µm size in order to obtain MWD of the clay particles < 2µm.

Statistical Analysis

The statistical analysis of the data was carried out using Statgraphics computer software packages (SAS Institute, 1985). The linear, quadratic, exponential and stepwise variable selection best-fit procedures were used for analysis of the data.

2.2.2.3 Results And Discussion

The relationship between concentration and absorbance for the 12 soils is shown in Fig 2.3. The relationship between absorbance and concentration of the stock suspension for each soil was explored using linear, exponential, multiplicative, and quadratic best-fit procedures. The R^2 values for each of the 12 soils indicated that the linear and quadratic fits were better than the exponential or multiplicative fits. Furthermore, the R^2 values for the linear and quadratic fits were similar indicating that the linear model was sufficiently accurate to relate concentration of stock suspension to absorbance.

Table 2.7. Statistical significance of the influence of soil on slope (S) and intercept (I) of the standard curve, mid-concentration (MC) and mean weight diameter (MWD) of the < 2µm dispersed clay.

Variable	S	I	MC	MWD
Significant level	**	**	**	**

*, ** significant at p = 0.05 and 0.01, respectively

An analysis of variance indicated a significant variation among the soils in mid-concentrations (MC) of the calibration curve (concentration of maximum minus minimum diluted stock suspension divided by two for each site), slopes (S) and intercepts (I) of the standard curves of dispersible clay, and the MWD of the < 2 µm of the dispersed clay particles (Table 2.7). The multiple range test indicated that S and I of the standard curves could be grouped into five significantly different categories, MC into six and MWD into three (Table 2.8).

The influence of clay, OM, pH, moisture, tillage and the interaction between clay and OM on S, I, MC and MWD was investigated using the stepwise variable selection regression procedure (Table 2.9). The equations obtained for S, I, MC and MWD with the interaction terms had similar R^2 values as that of those with simple terms. Therefore, the simple term models were selected.

Table 2.8. The summary of the results of multiple range test on the influence of soil along the transect on S, I, MC and MWD.

Parameters	Location #											
	4	10	8	8	1	3	21	1	19	2	36	36
	Tillage System											
	CT	NT	CT	NT	CT	NT	CT	NT	CT	NT	CT	NT
S	a	bc	ab	bc	abc	abc	e	c	d	be	e	e
I	a	a	a	a	a	a	d	ab	c	a	e	f
MC	a	b	a	ab	ab	a	c	a	b	a	d	e
MWD	a	a	a	a	a	ab	c	ab	ab	ab	be	c

Note: Common Letters within a row indicate no significance

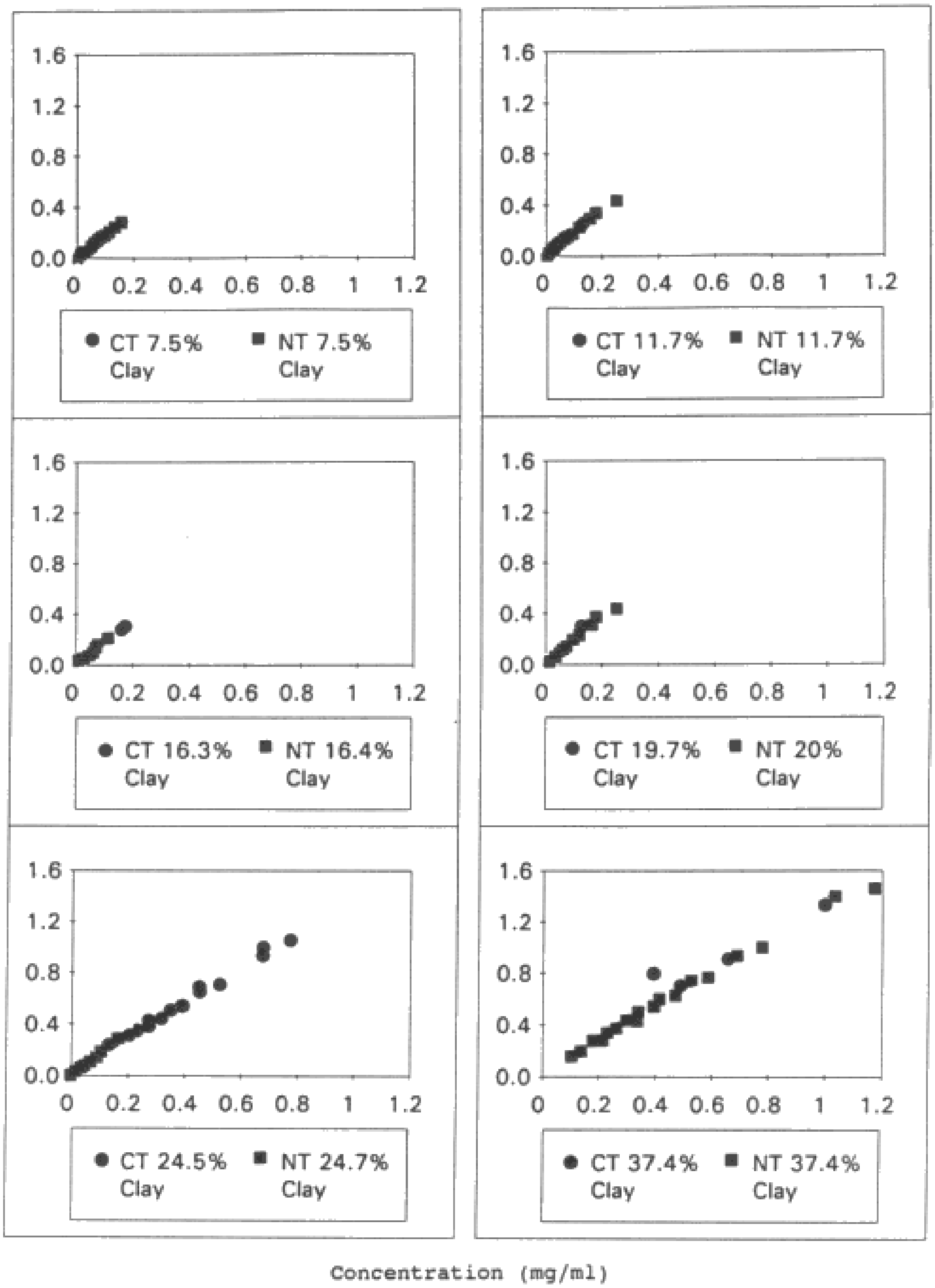

Fig. 2.3. The relationship between absorbance and concentration used in the determination of dispersible clay through the standard curve.

Table 2.9. The summary of the results of stepwise variable analyses for S, I, MC and MWD as a function of soil properties. The models are significant at $P < 0.01$.

Variable						
Dependent	Independent	Partial r	R_x ‡	Coefficient	P > F	Model R^2
S	Clay	0.83	0.68	-0.022	0.01	0.91
	OM	0.49	0.91	0.040	0.01	
	Constant			1.974	0.01	
I	Clay	0.87	0.76	0.001	0.01	0.94
	OM	0.44	0.94	-0.002	0.01	
	Constant			-0.001	NS	
MC	Clay	0.86	0.74	0.014	0.01	0.96
	OM	0.49	0.96	-0.023	0.01	
	Constant			0.027	NS	
MWD	Clay	0.66	0.44	-0.004	0.01	0.51
	OM	0.27	0.51	0.005	0.05	
	Constant			1.094	0.01	

R_x ‡ indicates progressive improvements in R^2 values when the independent variables entered the models in the order determined by the F values obtained at each step in the regression procedure.

Clay accounted for 68%, 76%, 74% and 44% of the variability in S, I, MC and MWD respectively. The organic matter content accounted for 23%, 18%, 22% and 7% additional variability in S, I, MC and MWD respectively. The linear relations between I and S, S and MC, I and MC, S and MWD, I and MWD, and MWD and MC were investigated (Table 2.10). The relation between I and S indicate that both parameters are highly correlated (Table 2.10). In addition, MC was also highly correlated to S and I (Table 2.10). Since the values of S, I and MC are dependent on the same soil properties (Table 2.9), they are significantly correlated to each other. However, the intercept of the I versus MC relation was not significant indicating that at very low concentrations of stock suspension, the calibration curve will have an intercept of zero (Table 2.10). The correlations between MWD and S and I were not as high as the correlation with MC (Table 2.10). There was a negative correlation between MC and MWD (Table 2.10).

Table 2.10. The linear relations between S and I, S and MC, I and MC, S and MWD, I and MWD, and MWD and MC.

Variable				
Dependent	Independent	Coefficient	P > F	Correlation Coefficient
I	S Constant	-0.057 0.115	0.01 0.01	0.94
S	MC Constant	-1.644 2.029	0.01 0.01	0.96
I	MC Constant	0.101 -0.002	0.01 NS	0.94
S	MWD Constant	3.086 -1.453	0.01 0.02	0.70
I	MWD Constant	-0.183 0.206	0.01 0.01	0.68
MWD	MC Constant	-0.267 1.085	0.01 0.01	0.69

Influence of soil properties on suspension characteristics

The model sensitivity analysis, using the models presented in Table 2.9, indicated that changing the clay and OM of the soil influenced the suspension parameters. Increasing the clay content (OM constant) resulted in an increase in MC and a decrease in MWD (Table 2.9).

Increases in OM (constant clay) would cause the swelling forces to decrease and thus diminish the dispersibility of clay. The result would be a decrease in the concentration of clay in the suspension and thus a decrease in MC (Table 2.9).

Influence of soil properties on coefficients of the calibration curve

Increasing the clay content (constant OM) resulted in a increase in I and a decrease in S (Table 2.9). The significant correlation between MC and S or I suggests that higher clay contents lead to increases in the concentration of stock suspension, MC and a decrease in MWD.

Increases in OM at constant clay, resulted in the values of S to increase and the values of I to decrease (Table 2.9). The increasing S with increasing OM suggest that the concentration of the stock suspension is decreased due to reduced dispersibility and thus a decrease in MC. A decrease in MC results in an increase in MWD (Table 2.10), i.e. a decrease in the number of particles in suspension. Since S and I are negatively correlated (Table 2.10), this increases in MWD results in an decrease in I.

Using the relations for S and I with soil properties, the concentration for a given absorbance at any location along the transect can be determined. Since the relationship between absorbance and concentration is

$$\mathbf{A = I + SC} \qquad \mathbf{[2.14]}$$

where A, I, S and C are the absorbance, intercept, slope and concentration, respectively. Furthermore, the relation of S and I to inherent soil properties (Table 2.9) are given by

$$\mathbf{S = 1.974 - 0.22(Clay) + 0.40(OM)} \qquad \mathbf{[2.15]}$$

$$\mathbf{I = -0.01 + 0.01(Clay) - 0.02(OM)} \qquad \mathbf{[2.16]}$$

Using equation [2.15] to predict slope as a function of soil properties for soils across Ontario (Table 2.11) gave a 1:1 relationship indicating equation [2.15] can be used to predict slopes of the calibration curve for a range of soils accurately (Fig 2.4). The model R^2 was 0.73 ($P < 0.01$).

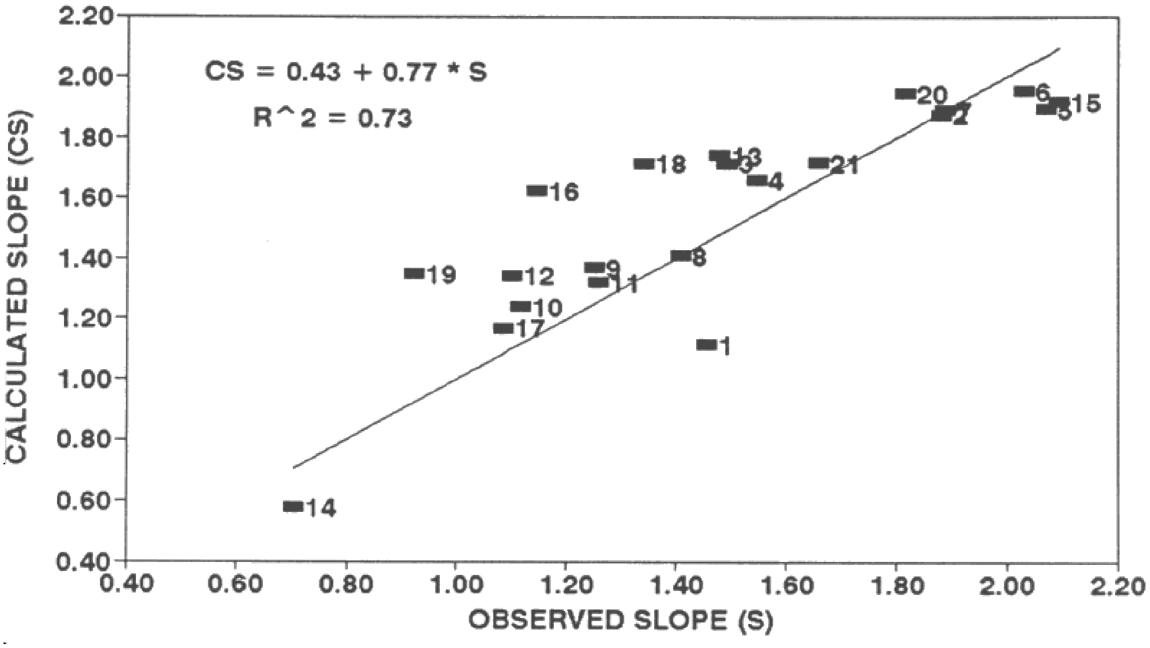

Fig. 2.4. The 1:1 relationship between measured and predicted slopes for soil across Ontario using equation [2.15].

Table 2.11. Soil characteristics at selected locations across Ontario.

Locations	Soil #	% Clay	% OM	References
Clinton	1	42.3	2.2	present study (29/CT)[‡]
Clinton	2	13.5	5.1	present study (11/CT)[‡]
Elora	3	17.9	3.6	unpublished data
Elora	4	20.6	3.7	unpublished data
Clinton	5	9.6	3.4	present study (15/CT)[‡]
Clinton	6	9.6	4.9	present study (12/NT)[‡]
Clinton	7	13.5	5.4	present study (11/NT)[‡]
Inwood	8	34	5.0	D. Dagesse unpublished data
Inwood	9	37	5.6	D. Dagesse unpublished data
Inwood	10	42	5.2	D. Dagesse unpublished data
Inwood	11	37	4.4	D. Dagesse unpublished data
Harrow	12	34	3.3	J. Caron unpublished data
Elora	13	17.7	4.1	T. Pojasok thesis 1988
Alfrid	14	71.1	4.9	Rasiah et al. 1992
Ayr	15	6.4	2.2	Rasiah et al. 1992
Chatham	16	21.1	3.1	Rasiah et al. 1992
Kemptville	17	42.5	3.7	Rasiah et al. 1992
Kerwood	18	18.5	3.9	Rasiah et al. 1992
Maidstone	19	33.8	3.3	Rasiah et al. 1992
Rodney	20	6.4	2.9	Rasiah et al. 1992
Elora	21	18.3	3.8	Rasiah et al. 1992

[‡] CT, NT and numbers refer to Con-till and No-till and location number respectively.

Substituting equation [2.15] and [2.16] into equation [2.14] gives

$$\mathbf{A = \{-0.01 + 0.01(Clay) - 0.002(OM)) + \{1.974 - 0.22(Clay) + 0.040(OM)\}C} \qquad \textbf{[2.17]}$$

Rearranging equation [2.17] to solve for C for any location along the transect is given by

$$\mathbf{C = \frac{A - \{-0.001 + 0.01(Clay) - 0.02(OM)\}}{\{1.974 - 0.22(Clay) + 0.040(OM)\}}} \qquad \textbf{[2.18]}$$

Using equation [2.18] the DC along the transect can be determined for the tillage systems and row position. Using the stepwise variable selection regression procedure the influence of inherent soil properties and moisture (w) on DC was determined (Table 2.12). Tillage and row position were included in the analysis as qualitative (class) variables.

Table 2.12. The summary of the results of stepwise variable selection analyses for no-till and con-till row and inter-row position. The model R^2 was 0.91 ($P < 0.01$). The regression coefficients for the model is DC = a + b*Clay + c*OM + d*w.

Treatment, position	Regression Coefficient			
	a	b	c	d
No-Till, row	-0.118	0.152	-0.349	0.035
No-Till, inter-row	-0.118	0.152	-0.349	0.035
Con-Till, row	-1.548	0.180	-0.349	0.081
Con-Till, inter-row	-1.548	0.180	-0.349	0.081

Note: If tillage and/or row position was significant the coefficient was added to the parameters that had the influence of tillage and/or row position.

The 'b' and 'd' coefficients in Table 2.11 indicate that DC had a positive relation with clay and w. However, con-till has larger coefficients, indicating clay and w have a greater influence on DC in con-till system. Kay and Dexter (1990) indicated that the amount of dispersible clay could depend on the energy applied and/or the surface area of the aggregates exposed. Furthermore, Rasiah et al. (1992) indicated that increasing clay and w resulted in an increase in DC. Since tillage results in increase surface area and smaller aggregates size, the influence of clay and w in con-till system would be greater. The 'c' coefficient, on the other hand, was negatively correlated to DC indicating that organic matter is acting as a stabilizing material. Rasiah et al. (1992) also reported an increase in stabilization of DC clay with increasing organic matter. However, the no-till system has significantly higher OM indicating that OM will play a more important role in clay stabilization in the no-till system. The intercept of the con-till was more negative indicating at low and medium clay content soil, there is some inconsistencies on the influence of tillage on DC. However, as the clay content of soil further increases the influence of tillage is more pronounced, and the DC is higher on the con-till treatment.

2.2.2.4 Conclusions

The slope (S) and intercept (I) of the relation between absorbance and concentration of dispersible clay (DC) in suspension were significantly influenced by clay and organic matter (OM) contents of soils. This indicated that different calibration curves are required to predict DC if there is a variation in soil properties. Empirical equations were developed to predict S and I as a function of soil properties. Ninety one and ninety four percent of the variability in S and I was accounted for by soil properties. Calibration curves for locations in the field which had contrasting soil properties were estimated, thereby eliminating the need for the establishment of calibration curves in the laboratory. A 1:1 relationship was observed in predicting the slope of the calibration curve for a number of Ontario soil using the estimated regression equation for slope.

Values of S increased with increasing OM and decreasing clay contents. Values of I, on the other hand, increased with increasing clay and decreasing OM content. The mean weight diameter, MWD, of particles in the suspension used to develop of calibration curves had positive and significant relations with S. Values of MWD increased with increasing OM and decreasing clay content. Thus, it seems when the clay content increased, the MWD of the clay particles in the suspension decreased, and the absorbance was lower than would have been predicted at lower concentrations.

The amount of dispersible clay produced along the transect was influenced by inherent soil properties and moisture (w). Clay and w had positive relation on DC while the influence of OM was negative.

2.2.3 Wet Aggregate Stability

2.2.3.1 Materials and Methods

Soil cores were taken from the 0-18 cm depth in the row and inter-row positions at all 36 locations along both tillage transects (i.e. n = 144). Sampling took place on 19 June 1991, at the silking stage of plant development. The wet-aggregate stability, WAS, of the 1-2 mm fraction was measured using the method of Pojasok and Kay (1990). The water content at time of sampling, w_s was measured gravimetrically.

2.2.3.2 Results and Discussion

Multiple regression analysis was performed with WAS, the dependent variable, as a function of w_s clay content (cl) and organic matter content (om). Tillage and position were included in the analysis as independent qualitative (class) variables. The model R^2 was 0.65 ($p < 0.001$). Table 2.13 presents the resulting regression coefficients.

Table 2.13. Regression coefficients for the model WAS = a + b*cl + c*om + d*w_s.

Treatment, position	Regression coefficient			
	a	b	c	d
No-till, row	19.17	0.65	2.44	-0.84
No-till, inter-row	19.17	0.65	2.44	-0.96
Conventional-till, row	13.74	0.65	2.44	-0.84
Conventional-till, inter-row	13.74	0.65	2.44	-0.96

The different intercept terms (i.e. 'a' in Table 2.13) for the two tillage treatments indicate the WAS was higher under no-till than under conventional-till. Hermawan and Cameron (1993) also reported an increase in aggregate stability under no-till compared to conventional-till. They attributed this increase to the greater organic matter content of long-term no-till soils. However, the increase shown in Table 2.13 is independent of any differences in clay, organic matter or water contents between tillage treatments. In this case, the increase in WAS under no-till may be related to the greater bulk density of aggregates from this tillage treatment.

The 'b' and 'c' coefficients in Table 2.13 indicate the WAS increased with increasing clay and organic matter contents. Both relationships were independent of treatment and position effects. The 'd' coefficients indicate a linear decrease in WAS with increasing water content at sampling time. This decrease was less pronounced in the row position of both tillage treatments. The root length density at silking was shown to be significantly higher in the row position than in the inter-row position. Thus, the reduced sensitivity of WAS to water content in the row position may be related to the enmeshment and stabilization of aggregates by the increased presence of plant roots.

2.2.4 Summary

Wet aggregate stability and dispersible clay, measured under laboratory conditions are correlated with both the runoff and sediment load in the runoff. Both WAS and DC are strongly influenced by soil properties such as clay, organic matter and soil water contents. DC appeared to be more sensitive to tillage than WAS, although the influence of tillage on DC was manifested consistently at all water contents only at high clay contents.

2.3 Fragmentation Characteristics 2.3.1 Introduction

Analysis of the strength of air-dry aggregates is important for predicting soil response to tillage (Wolf and Hadas, 1987), and wind erosion (Hagen et al., 1992). Air-dry aggregates usually fail as brittle materials while moist aggregates show plastic characteristics. The change from plastic to brittle behaviour is manifested in the stress-strain curve. An aggregate is considered brittle if this curve shows little or no plastic deformation, and a distinct failure at low strain (Lee and Ingles, 1968; Dexter, 1975).

Brittle fracture of air-dry aggregates is usually characterized in terms of the tensile stress at failure, T. However, the T is difficult to measure directly (Gill, 1959). Consequently, most investigators use indirect (compressive) methods to estimate T (Dexter, 1975; Rogowski and Kirkham, 1976). Using this approach the T for an equivalent spherical aggregate is given by:

$$\mathbf{T = k4F_r / \pi x^2} \qquad \mathbf{[2.19]}$$

where k is a coefficient representing the ratio of tensile strength to compressive strength, F_r is the compressive force at rupture, and x is a measure of aggregate diameter. According to Griffith's (1924) theoretical study of brittle fracture, the value of k in Eq. [2.19] should be 0.125. However, measured values of k for soil aggregates range from 0.711 (Hadas and Lennard, 1988) to 1.461 (Dexter, 1988). An added complication in using Eq. [2.19] is the problem of defining x for irregular shaped aggregates (Dexter and Kroesbergen, 1978).

Assuming failure in tillage occurs mainly by tensile loading, the resulting dry aggregate size distribution (DASD) should be related to the T of the bulk soil. Understanding the relationship between T and DASD may enhance our ability to predict the physical condition of the seed bed following tillage.

The DASD is obtained by separating the fragmented soil into different size classes using flat or rotary sieves. The percentage by weight in each size class is then determined. To be useful for statistical analyses these data must be summarized in one or two parameters that are sensitive to soil properties and management practices. The simplest approach is to select a single size class for comparative purposes. However, much information is lost by this approach and the results depend upon the size class selected (Schaller and Stockinger, 1953). A more comprehensive approach is to parameterize the DASD by fitting a mathematical function to the data for all size classes. The parameter estimates are then used instead of the individual fractions. This approach is preferable since it utilizes all of the information available. Furthermore, the function employed can provide physical insight with respect to the fragmentation process (Perfect et al., 1993a).

Perfect et al. (1993a) compared different size distribution functions for parameterizing the DASD in terms of their physical implications for fragmentation, goodness of fit, and parameter sensitivity to soil properties and management practices. They concluded that the fractal function (Mandelbrot, 1982) was the most robust. Assuming scale-invariant aggregate density and shape, the fractal function is given by:

$$\sum_{\bar{x}_*=1}^{\bar{x}_*} P(\bar{x}_*)/\bar{x}_*^{3} = k_c/\bar{x}_*^{D} \qquad \textbf{[2.20]}$$

where $P(\bar{x}_*)$ is the percentage of aggregates by weight between successive sieves, $\bar{x}_*$ is the arithmetic mean size of successive sieves normalized with respect to the largest fraction, and k_c and D are constants. The k_c is equal to the number of aggregates in the largest fraction, multiplied by their bulk density. For $x^* << 1$, the D is equal to the fractal dimension, as defined by Mandelbrot (1982). Theoretically, the fractal dimension is limited to the range $0 < D < 3$. However, values of $D > 3$ are possible under conditions of multifractal fragmentation (Perfect et al., 1993b). The larger the value of D, the greater the amount of fragmentation.

2.3.2 Tensile Strength

Sampling for the tensile strength measurements took place on 12 May 1992, immediately after cultivation in the conventional-till treatment. The mean gravimetric water content at cultivation, w_c was 18.31% (CV = 26.86%). The dispersible clay and wet-aggregate stability at cultivation, DC_c and WAS_c, were predicted using the regression equations for the conventional-till, inter-row position in Tables 2.12 and 2.13, respectively. Soil was obtained from the seed bed at all 36 transect locations using a flat spade (Kemper and Rosenau, 1986). The samples were brought into the laboratory and spread out on trays to dry. The mean gravimetric water content after air drying was 1.77% (CV = 21.14%). Large aggregates (x_i = 23.75 mm, where xi is the arithmetic mean of the upper and lower sieve apertures) were separated from the air-dried soil by sieving.

Individual aggregates were weighed, placed on a flat plate in their most stable orientation, and crushed with an upper parallel flat plate (Dexter and Kroesbergen, 1985). The crushing was done using an ELE Digital Tritest 50, instrumented with load cells for measurements of the compressive force at fracture, F_r, in the range 0 - 334 (± 0.03) N. All tests were performed at a constant rate of compression of 1.67x10 m/s. The tensile strength, s, was computed from F_r using Eq. 2.19 with k = 1.461 and $x = (M/\bar{M}i)^{1/3}x_i$, where M is the individual aggregate mass, and $\bar{M}_i$ is the mean aggregate mass for the x_i size class (Dexter and Kroesbergen, 1985; Dexter, 1988). An average of 14 aggregates were crushed for each transect location, and the mean s was determined from the individual measurements.

The variation in mean s with distance along the transect is shown in Fig. 2.5. The mean s was positively correlated with DC_c, (r = 0.84), clay content (r=0.82), WAS_c (r = 0.72) and air-dry water content (r=0.34), and negatively correlated with organic matter content (r = -47). All of the correlations were significant at $p < 0.05$. The s usually decreases with increasing aggregate water content (Guerif, 1988). In the present study, however, a positive correlation was obtained, probably because of significant co-linearity with clay content (r = 0.43 for clay content versus air-dry water content). When a multiple regression analysis was performed, dispersible clay was the only variable selected as a significant predictor of s.

This relationship is given below:

$$\mathbf{s = 23.13 + 38.10DC_c\ (R^2 = 0.70;\ p < 0.05)} \qquad \mathbf{[2.21]}$$

Chan (1989) and Chan and Heenan (1991) report similar relationships between tensile strength and dispersible clay for Australian soils.

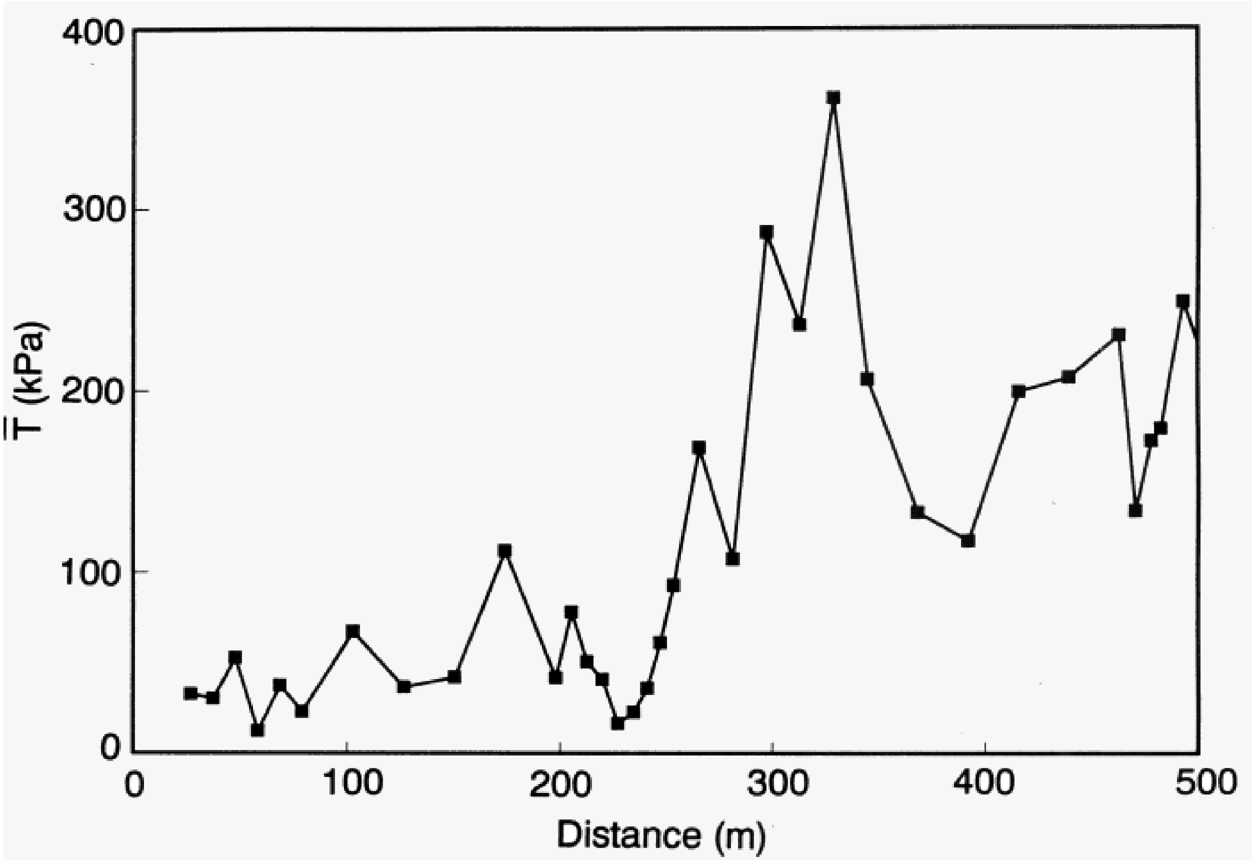

Figure 2.5. Variation in mean tensile strength of air-dry aggregates from the 16-31.5 mm fraction as a function of distance along the conventional-till transect.

2.3.3 Aggregate Size Distribution

Sampling for the dry aggregate size distribution (DASD) took place on 12 May 1992, immediately after cultivation. The soil properties at cultivation are described in Section 2.3.2. Three 0.5 kg dry weight sub-samples were obtained from the seed bed at all 36 locations along the conventional-till transect using a flat spade (Kemper and Rosenau, 1986). These were brought into the laboratory and spread out on trays to dry. After air drying to a mean water content of 1.77% (CV = 21.14%), the soil was passed through a 31.5-mm sieve. The material < 31.5 mm was placed on a nest of sieves (sized 16, 8, 4, 2, 1 and 0.5 mm) and shaken for 6 s on a Tyler portable sieve shaker (Model RX 24). The mass of aggregates in each size fraction was recorded.

Equation [2.20] was fitted to the data (averaged for each location) by non-linear regression using the multivariate secant method (SAS Institute, 1985). Material passing the 0.5 sieve was not included in the fitting because of the confounding presence of primary particles in this size fraction. All of the fits were significant at $p < 0.05$, with the mean $R^2 > 0.999$.

The influence of clay content (Clay), organic matter content (OM), wet-aggregate stability at cultivation (WAS_c), gravimetric water content at cultivation (w_c), and dispersible clay at cultivation (DC_c) on the parameter estimates from eq. [2.20] was examined using correlation and multiple regression analyses. The results of the correlation analyses are summarized in Table 2.14.

Table 2.14. Correlation matrix for model parameters (kc and D) and soil properties.

Variable	Correlation Coefficient				
	Clay	OM	WAS_c	w_c	DC_c
k_c	0.806	-0.441	0.718	NS	0.818
D	-0.880	0.362	-0.749	NS	-0.891

NS: Not significant at $p < 0.05$.

With the exception of correlations involving w_c, all of the analyses were significant at $p < 0.05$ (Table 2.14). The kc parameter was positively correlated with clay content, DC_c and WAS_c, and negatively correlated with organic matter content (Table 2.14). Dispersible clay was the only significant predictor of kc when all five independent variables were included in a multiple regression analysis. The resulting model is given below:

$$k_c = -45.74 + 86.67DC_c \qquad (R^2 = 0.68;\ p < 0.05) \qquad [2.22]$$

Equation [2.22] indicates increasing numbers of aggregates in the largest size fraction with increasing dispersible clay at cultivation. The increase in cloddiness with increasing DC_c, is due to the ability of dispersed clay particles to adhere to each other, as well as to sand and silt particles as the soil drys (Chepil, 1953 a,b; Alberts and Wendt, 1985).

The D parameter was negatively correlated with clay content, DC_c and WAS_c, and positively correlated with organic matter content (Table 2.14). When a multiple regression analysis was performed, with all five soil properties included as independent variables, dispersible clay was selected as the only significant predictor of D. The resulting regression equation is given below:

$$\mathbf{D = 4.01 - 0.45DCc \quad (R^2 = 0.79;\ p < 0.05)} \qquad \mathbf{[2.23]}$$

Equation [2.23] indicates that aggregate fragmentation increases with decreasing dispersible clay at cultivation. This relation is consistent with the observations of Chepil (1953 a,b) and Alberts and Wendt (1985).

Eq. 2.20 indicates that two parameters, k_c and D, are needed to fully characterize the dry aggregate size distribution of tilled soil. However, the D parameter was negatively correlated with the K_c parameter (r=-0.82). This relationship indicates a greater spread of aggregates over the whole range of size classes with decreasing numbers of aggregates in the largest fraction. Table 2.14 suggests that D is more sensitive to soil properties than k_c. This observation, coupled with the strong correlation between D and k_c, suggests that the fractal dimension, D, can be used as a single descriptor of seed bed conditions across a range of soils.

2.3.4 Relationship Between Fragmentation Characteristics

Because both the D and T varied as a function of soil properties, a relationship between these fragmentation characteristics is to be expected. This possibility was explored using linear regression analysis. A highly significant negative relationship was found between D and the logarithm of T (Fig. 2.6). This relationship explained 81% of the total variation in D. The coefficients of the resulting regression equation (see Fig. 2.6) indicated increasing fragmentation with decreasing tensile strength of the largest aggregates. Rogowski et al. (1968) also found a strong relationship between dry strength and the aggregate size distribution: cloddiness increased with increasing strength, which is consistent with our results for k_c versus T (r = 0.793).

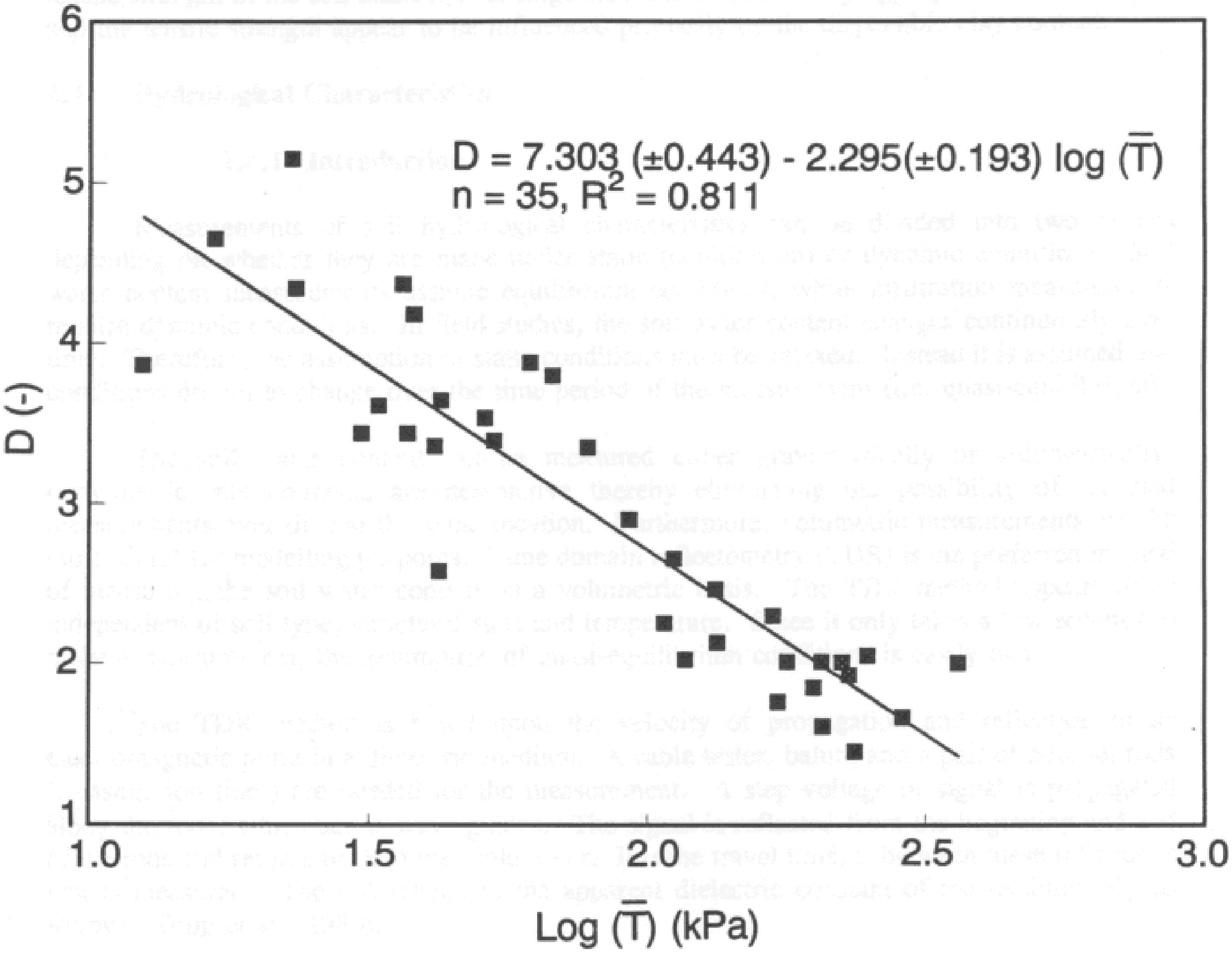

Figure 2.6. Relationship between the fractal dimension, D, of the aggregate size distribution and the mean tensile strength, T, of air-dry aggregates from the 16-31.5 mm fraction.

2.3.5 Summary

The quality of a seedbed subsequent to tillage can be characterized by the dry aggregate size distribution. The distributions across a range of textures appear to be described best by fractal parameters. The coarseness of a seedbed appears to be positively correlated with the tensile strength of the soil matrix (or of large clods) and both the dry aggregate size distribution and the tensile strength appear to be influenced primarily by the dispersible clay content.

2.4 Hydrological Characteristics

2.4.1 Introduction

Measurements of soil hydrological characteristics can be divided into two groups depending on whether they are made under static (equilibrium) or dynamic conditions. Soil water content measurements assume equilibrium conditions, while infiltration measurements require dynamic conditions. In field studies, the soil water content changes continuously over time. Therefore, the assumption of static conditions must be relaxed. Instead it is assumed that conditions do not to change over the time period of the measurement (i.e. quasi-equilibrium).

The soil water content can be measured either gravimetrically or volumetrically. Gravimetric measurements are destructive thereby eliminating the possibility of repeated measurements over time at the same location. Furthermore, volumetric measurements are the most useful for modelling purposes. Time domain reflectometry TDR) is the preferred method of measuring the soil water content on a volumetric basis. The TDR method appears to be independent of soil type, structural state and temperature. Since it only takes a few seconds to make a measurement, the assumption of quasi-equilibrium conditions is easily met.

The TDR method is based upon the velocity of propagation and reflection of an electromagnetic pulse in a dielectric medium. A cable tester, balun, and a pair of parallel rods (transmission lines) are needed for the measurement. A step voltage or signal is propagated along the rods, which act as wave guides. The signal is reflected from the beginning and end of the rods and returns back to the cable tester. It is the travel time, t, between these reflections that is measured. The t is related to the apparent dielectric constant of the medium, K_a as follows (Topp et al., 1980):

$$\mathbf{K_a = (ct/L)^2} \qquad \textbf{[2.24]}$$

where c is the speed of light (3×10^8 m/s), and L is the length of the transmission line.

Liquid water has a dielectric constant > 80, compared to values < 6 for air and the soil matrix. Thus, measurements of K, will be governed by the water content of the soil. The following empirical equation describes the relationship between K, and the volumetric soil water content, θ (Topp et al., 1980):

$$\theta = -5.3\ \mathrm{x}10\text{-}^{2} + 2.92\ \mathrm{x}10^{-2}\ K_a - 5.5\ \mathrm{x}10^{-4}\ K_a^{2} + 4.3\ \mathrm{x}10^{1}\ K_a^{3} \qquad [2.25]$$

To avoid extrapolation, eq. [2.25] is restricted to the range $\theta > 0.07$.

Infiltration measurements are made under dynamic conditions. Two types of infiltration characteristic are recognized depending on whether the measurement is made under transient dynamic conditions or (quasi-) steady state dynamic conditions. The sorptivity is a transient parameter, while the field saturated hydraulic conductivity and macroscopic capillary length parameters assume (quasi-) steady state conditions.

Philip (1957) proposed the following physically-based equation for transient infiltration into a homogeneous soil with a uniform initial water content, θ :

$$I = S(\theta)_h t^{1/2} + At \qquad [2.26]$$

where θ is relative saturation (-), I is cumulative infiltration (m), t is time (s), $S(\theta)_h$ is sorptivity ($\mathrm{m}\bullet\mathrm{s}^{-1/2}$) at ponded head h, and A is transmissivity ($\mathrm{m.s}^{-1}$). Physically, $S(\theta)_h$ can be interpreted as that component of infiltration due to unsaturated flow, while A is that component due to saturated flow.

In the early stages of infiltration, the second term in eq. [2.26] is negligible relative to the first term. Talsma (1969) found that $S(\theta)_h$ dominated over A from 0.25 to 600 s depending on the soil type. Thus, for early time infiltration eq. [2.26] is re-written as (Elrick and Reynolds, 1990; van Es et al., 1991):

$$I = S(\theta)_h t^{1/2} \qquad [2.27]$$

Gardner (1958) proposed the following empirical equation relating hydraulic conductivity, K (m. s'), to the soil water pressure head, (m) under (quasi-) steady state conditions:

$$K(\psi) = K_{fs}\, e^{\alpha\psi}; \qquad \leq 0 \qquad [2.28]$$

where K_{fs} is field saturated hydraulic conductivity ($\mathrm{m.s}^{-1}$) and α is the slope of ln{K} versus ψ (m^{-1}). The reciprocal of a in Eq. [2.28] is known as the macroscopic capillary length, λ_c (m) (White and Sully, 1987).

The λ_c represents a measure of pore size weighted for flow rate. Values differ between soils of different texture, and are sensitive to structural changes due to biological activity on the same soil (White and Perroux, 1987). Thus, λ_c offers promise as an infiltration characteristic that is sensitive to soil quality. The λ_c parameter can also be used in erosion studies to predict variables such as time to ponding.

2.4.2 Infiltration

Information on the infiltration characteristics at Lobb farm were collected using the Guelph pressure infiltrometer (Reynolds and Elrick, 1990). The two-ponding depth protocol was followed, with heads of 0.05 and 0.15 m, respectively. Early time data were also collected at the 0.05 m head; cumulative infiltration was measured every 20 s for the first 3 min, and every 30 s thereafter until steady-state was attained. Measurements were made in the non-trafficked inter-rows of all 36 locations along the two 500 m tillage transects at two times during the 1991 growing season (June 26-July 11 and Oct 18 - Nov 14).

The early time data were used to compute sorptivity values for each location. Equation [2.27] was fitted to the early time data by linearly regressing cumulative infiltration against the square root of time. Since h = 0.05 m, $S(\theta)_h$ was defined as $S(\theta)_{0.05}$. The coefficients of determination (R^2) ranged from 0.89 to > 0.99, and estimates of $S(\theta)_{0.05}$ ranged from 8.83 x10^{-5} to 9.82 x10^{2} m.s$^{-1/2}$. Several studies have shown that $S(\theta)_h$ is a log-normally distributed parameter (Cassel et al., 1990; Starr, 1990). Therefore, all statistical analyses were performed on the log-transformed values of $S(\theta)_{0.05}$.

Measured times to reach steady-state ranged from 3.0 x10^{2} to 6.6 x10^{2} s for the first ponding height. Elrick et al. (1990) predicted increasing equilibration time with increasing clay content for unstructured soils. In the present study no relation was observed between equilibration time and texture, suggesting soil structure was more important than texture in determining the steady state infiltration characteristics.

The steady-state data were used to compute the field saturated hydraulic conductivity and macroscopic capillary length parameters. We obtained estimates of K_{fs} and α in eq. [2.28] using the two-ponding depth, shape factor independent of ponding, computational procedure of Reynolds and Elrick (1990). The macroscopic capillary length, λ_c (m), was then calculated as $1/\alpha$ (White and Sully, 1987).

The occurrence of negative estimates of K_{fs} and λ_c is a source of concern with the Guelph pressure infiltrometer method (Reynolds and Elrick, 1990). Altogether, 11.8% of the K_{fs} estimates, and 27.1 % of the k estimates were negative; these values were rejected. The remaining K_{fs} estimates ranged from 3.16 x10^{-7} to 2.49 x10 m.s^{-1}, while the λ_c estimates ranged from 6.43 x10^{-3} to 1.56 x10^{0} m. It is well known that steady-state infiltration characteristics are log-normally distributed (Nielsen et al., 1973; Reynolds and Elrick, 1985). Thus, all statistical analyses were performed on the log-transformed values of K_{fs} and λ_c.

Correlations between the infiltration characteristics are given in Table 2.15. There was a significant positive correlation between $\ln\{S(\theta)_{0.05}\}$ and $\ln\{K_{fs}\}$. There are theoretical reasons to expect a relationship between sorptivity and field saturated hydraulic conductivity (Chong et al., 1982; White and Perroux, 1987). Table 2.15 also indicates $\ln\{\lambda_c\}$ was negatively correlated with $\ln\{K_{fs}\}$. This correlation implies the slope of $\ln\{K\}$ versus ψ in eq. [2.28] decreases with decreasing K_{fs}.

Table 2.15. Correlation matrix for the infiltration characteristics

Infiltration Characteristic	Infiltration Characteristic		
	$\ln\{S(\theta)_{0.05}\}$	$\ln\{K_{fs}\}$	$\ln\{\lambda_c\}$
$\ln\{S(\theta)_{0.05}\}$	-	0.703 (126)[1]	NS[2]
$\ln\{K_{fs}\}$	-	-	-0.451 (105)
$\ln\{\lambda_c\}$	-	-	-

[1] Pearson correlation coefficient and number of observations in parentheses

[2] NS not significant at $p < 0.05$

Values of $\ln\{S(\theta)_{0.05}\}$ and $\ln\{K_{fs}\}$ are plotted as a function of distance along each tillage transect for both sampling periods in Figs. 2.7 and 2.8, respectively. The means of each transect are compared for the different tillage / sampling permutations in Table 2.16. The mean $\ln\{S(\theta)_{0.05}\}$ and $\ln\{K_{fs}\}$ were significantly higher under no-till than under conventional-till, regardless of sampling period. This may be due to structural effects or to differences in the clay content and θ between tillage treatments.

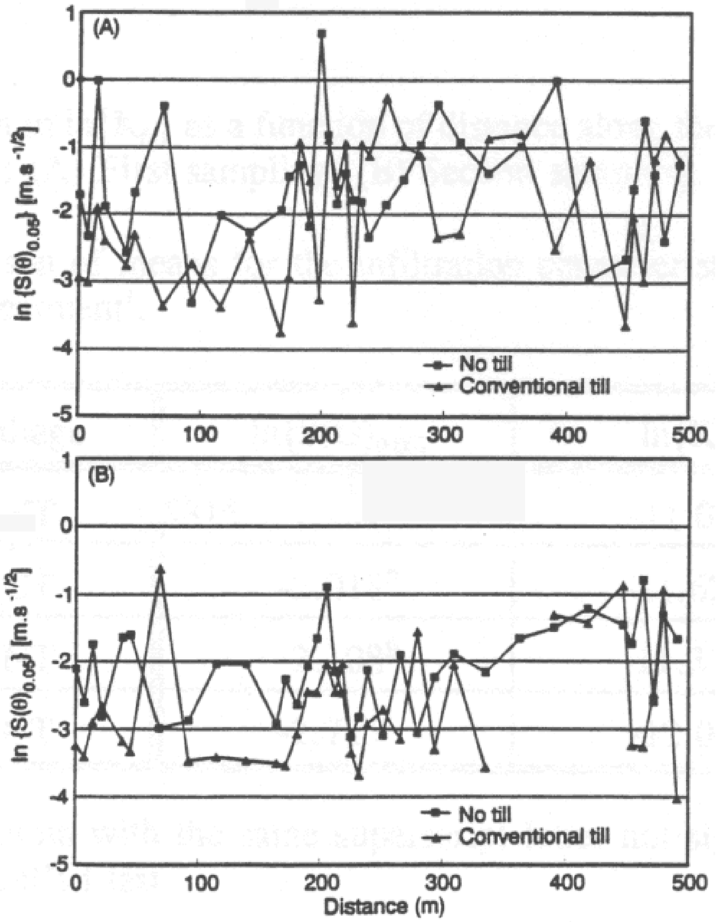

Figure 2.7. Variation in $\ln\{S(\theta)_{0.05}\}$ as a function of distance along the conventional-till and no-till transects: (A) First sampling, (B) Second sampling.

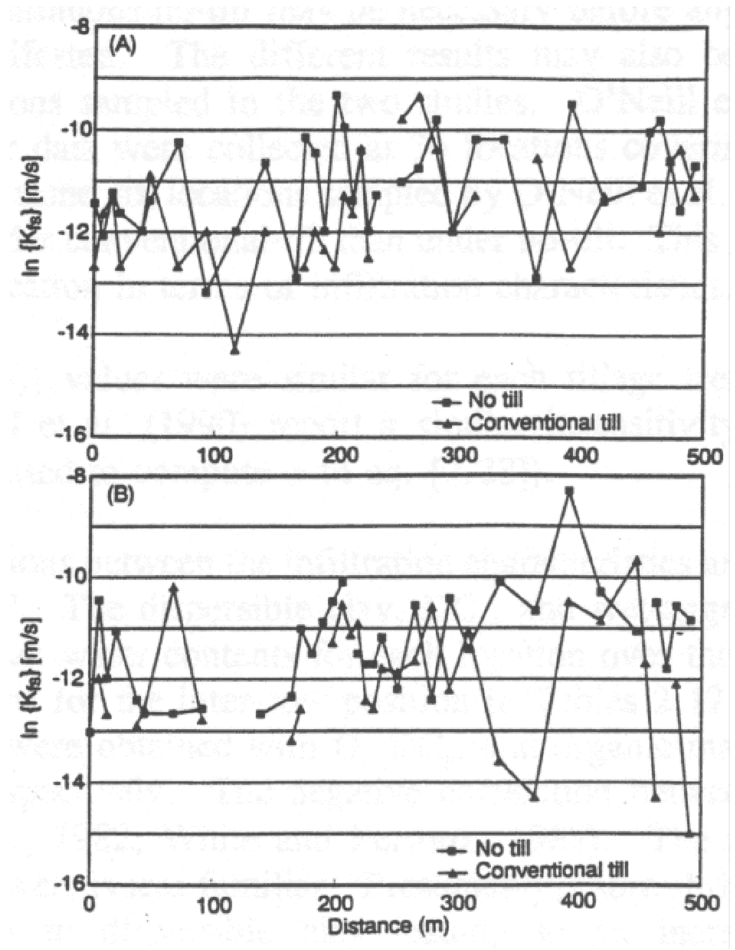

Figure 2.8. Variation in ln{K_{fs}} as a function of distance along the conventional-till and no-till transects: (A) First sampling, (B) Second sampling.

Table 2.16. Comparison of means for the infiltration characteristics by sampling period and tillage treatment[1].

Sampling	Tillage	ln{$S(\theta)_{0.05}$}	ln{K_{fs}}	ln{λ_c}
1	NT	-1.531 ^{A}	-11.054 ^{A}	-2.383 ^{A}
	CT	-2.018 ^{B}	-11.624^{BC}	-2.438 ^{A}
2	NT	-2.108 ^{B}	-11.301^{AB}	-2.663 ^{A}
	CT	-2.715 ^{C}	-12.018 ^{C}	-2.285 ^{A}

[1] Means in the same column with the same superscript letter not significantly different at $p < 0.05$ according to Student's t-test

O'Neill et al. (1990) found the geometric mean K_{fs} was significantly higher under conventional- till and than under no-till at the same site using similar methodology. However, their study was carried out 3 years earlier. The contrasting results of these two studies suggest that many years of continuous no-till may be necessary before any improvement in infiltration characteristics is manifested. The different results may also be explained in terms of the different spatial locations sampled in the two studies. O'Neill et al. (1990) only sampled 6 locations, whereas our data were collected at 36 locations covering a wide range of textures. When restricted to the same six locations sampled by O'Neill et al. (1990) our data also showed ln $\{K_{fs}\}$ was higher under conventional-till than under no-till. This result suggests an interaction between tillage and location in terms of infiltration characteristics.

The mean ln$\{K_{fs}\}$ values were similar for each tillage treatment and sampling period (Table 2.16). O'Neill et al. (1990) report a similar insensitivity to tillage and time for the matric flux potential (used to compute a in eq. [2.28]).

Simple correlations between the infiltration characteristics and selected soil properties are reported in Table 2.17. The dispersible clay, DC_p, and wet-aggregate stability, WAS_P, were predicted from the mean water contents for each location over the 1991 growing season using the regression equations for the inter-row position in Tables 2.12 and 2.13, respectively. The strongest correlations were obtained with θ, DC_p, and organic matter content for ln$\{S(\theta)_{0.05}\}$, ln$\{K_{fs}\}$ and ln$\{\lambda_c\}$, respectively. The negative correlation between sorptivity and θ is to be expected (Chong et al., 1982; White and Perroux, 1987). The positive correlation between ln$\{K_{fs}\}$ and DC_p, however, is less familiar. Presumably, more shrinkage cracks develop during drying for soils high in dispersible clay leading to an increase in saturated hydraulic conductivity. We are currently unable to suggest any physical reasons for the correlation between ln$\{\lambda_c\}$ and organic matter content in Table 2.17.

Table 2.17. Correlations between infiltration characteristics and soil properties.

Soil Property	Infiltration Characteristic		
	ln$\{S(\theta)_{0.05}\}$	ln$\{K_{fs}\}$	ln$\{\lambda_c\}$
θ	-0.345 (137)[1]	-0.240 (121)	NS[2]
clay	0.162 (143)	NS	NS
OM	NS	-0.229 (127)	0.312 (105)
DC_p	0.251 (143)	0.277 (127)	NS
WAS_P	0.171 (143)	NS	0.283 (105)

[1] Pearson correlation coefficient and number of observations in parentheses

[2] NS not significant at $p < 0.05$

Multiple regression analyses (stepwise selection procedure) were conducted to determine the relative importance of tillage, relative saturation and soil properties as predictors of infiltration characteristics. The final models selected were:

$$\mathbf{\ln\{S(\theta)_{0.05}\} = -1.09 + 0.15DC_p - 0.45Till - 1.430} \qquad \mathbf{[2.29]}$$

$$\mathbf{\ln\{K_{fs}\} = -10.66 + 0.19DC_p - 0.47Till - 1.570} \qquad \mathbf{[2.30]}$$

where Till is an indicator variable for tillage (0 = no-till, 1 = conventional-till). In each case DC_p was selected over clay and organic matter content as the best soil predictor of infiltration characteristics. Multiple regression analysis involving $\ln\{\lambda_c\}$ failed to improve on the simple correlation with organic matter content (Table 2.17).

The model R^2 values associated with Eqs. [2.20] and [2.30] were 0.255 and 0.250, respectively. In the multiple regression analyses reported by van Es et al. (1991), the model R^2 values never exceeded 0.31. These authors concluded that "sorptivity measurements were too variable to be used for predictive modelling purposes." Our analyses tend to support this statement for all three parameters. Stochastic modelling of infiltration parameters should be explored as an alternative to the use of deterministic predictions based upon regression analysis (Hopmans, 1989).

Eq. [2.29] indicates the sorptivity increased with increasing dispersible clay and decreased with increasing relative saturation. The negative sign in front of the coefficient for tillage indicates $\ln\{S(\theta)_{0.05}\}$ was higher under no-till than under conventional-till. Obviously, conventional tillage will increase sorptivity early in the growing season. However, this increase is transient and the sorptivity decreases rapidly over time due to weathering-induced changes in the pore size distribution (Mapa et al., 1986). The magnitude of this decrease is such that the sorptivity under no-till is higher than that under conventional-till over most of the growing season (Starr, 1990).

Eq. [2.30] indicates the saturated hydraulic conductivity increased with increasing dispersible clay and decreased with increasing relative saturation. The positive relationship between DC_p and Kfs may reflect the increasing structural development (i.e. cracking) on finer textured and more dispersible soils. The negative coefficient for tillage indicates $\ln\{K_{fs}\}$ was reduced under conventional-till compared to no-till. Thus, any increase in K_{fs} due to tillage must have been short lived. Mapa et al. (1986) showed the K_{fs} of freshly-tilled soil decreases rapidly in response to wetting and drying cycles. Wu et al. (1992) report higher geometric mean Kfs values under no-till compared to conventional-till. In the present study, soil bulk density was significantly higher under no-till than under conventional-till. Thus, the higher Kfs under no-till must be due to the presence of more continuous macropores in this treatment. Both Logsdon et al. (1990) and Wu et al. (1992) found increased macropore continuity under no-till compared to conventional-till.

Time stability was evaluated using the Spearman rank correlation coefficient method (Starr, 1990; van Es et al., 1991). No significant temporal persistence was found in the spatial structure of $\ln\{S(\theta)_{0.05}\}$, $\ln\{K_{fs}\}$ or $\ln\{\lambda_c\}$ in either tillage treatment. This is somewhat surprising as one would have expected the spatial structure to be determined in part by the textural variation across the site which was stable over time. Differences in water content between sampling periods may have been sufficient to mask any carry over of the spatial structure. Van Es et al. (1991) found the spatial structure for sorptivity was preserved only when the soil water conditions were similar.

2.4.3 Water content

2.4.3.1 Introduction

Tillage has an impact on the water content by modifying the soil structure as well as the amount of plant residue left on the soil surface. Several studies have shown that the average soil water content under conventional-till (moldboard plow followed by secondary tillage) is lower than under no-till (Negi et al., 1981; Lindstrom et al., 1984; Denton and Wagger, 1992). This difference is usually explained in terms of reduced evaporation and/or greater water storage in soils under no-till.

The variation in soil water contents under row crops is not random. Van Wesenbeeck and Kachanoski (1988) demonstrated a systematic trend in soil water contents in a corn field under conventional tillage, with higher water contents in the interrow compared with the row position.

Zhai et al. (1990) observed, for a single soil, systematic spatial differences in soil water content within and between tillage treatments, i.e. fall moldboard, 1 year no-till and long term (> 15 yr) no-till. They concluded that the temporal dependence of the spatial variability of soil water and the spatial dependence of the temporal variability were affected by the tillage treatments.

Studies were initiated to evaluate the temporal and spatial variability of the soil water content with inherent soil properties under two tillage systems, no-till and conventional.

2.4.3.2 Methodology

Volumetric soil water contents, 8, were measured over two ranges of depths (0-20 and 0-40 cm) in the row and inter-row positions at each location in each of the two transects. This gave a total of 288 measurement locations. The measurement periods were as follows:

1991 - 45 days (daily) between the silking and grain-filling stages (July, 25 - September, 6)

1992 - 48 days (every two or three days) between 10 leaf stage and harvest (June 23 - Oct. 10)

In both years the measurements were made, as noted above, using time domain reflectometry (TDR). Water contents for the 20-40 cm depth, were obtained using the following relationship:

$$\theta_{20\text{-}40} = 2 * \theta_{0\text{-}40} - \theta_{0\text{-}20}$$

where $\theta_{0\text{-}20}$ and $\theta_{20\text{-}40}$ are the water contents measured over 0-20 cm and 0-40 cm, respectively.

The temporal variation in θ was summarized for each location in terms of the mean (θ_{avg}) and coefficient of variation (θ_{cv}) calculated by depth and year. Multiple regression analysis was used to assess the influence of tillage (indicator variable), position (indicator variable), inherent soil properties (clay and organic matter contents) and bulk density on the θ_{avg} and θ_{cv}. The inherent soil properties (Appendix I) were assumed to be the same in the row and interrow positions.

2.4.3.3 Results

The regression outputs are presented in Tables 2.18 to 2.25.

1991

The regression model for θ_{avg} at 0-20 cm explained 64% of the spatial variation (Table 2.18). The θ_{avg} increased with increasing clay and organic matter contents. The negative coefficient for tillage indicates that the conventional-till was drier on average than the no-till as observed previously by Negi et al., 1981; Lindstrom et al., 1984; Denton and Wagger, 1992. The positive effect of position implies that the interrow was wetter on average than the row position. This result agrees with that obtained by Van Wesenbeeck and Kachanoski (1988).

Table 2.18. Results for θ_{avg} ($cm^3\ cm^{-3}$), 0-20 cm, 1991

Variable	Parameter	Standard error	t	Prob > ; | t |
intercept	0.1156	0.0117	9.867	0.0001
clay	0.0049	0.0003	15.280	0.0001
OM	0.0095	0.0017	5.507	0.0001
tillage	-0.0236	0.0066	-3.550	0.0005
position	0.0174	0.0065	2.659	0.0087

F = 62.57, Prob > F = 0.0001, r^2 = 0.64, N = 144

The θ_{cv}, at 0-20 cm was also significantly related with clay, tillage and position (Table 2.19). However, the regression model explained less of the spatial variation (only 41%) than that for the mean water contents (Table 2.18). The θ_{cv}, decreased as the clay content increased. Water contents under the conventional-till treatment were more variable over time than those in the no-till treatment. The interrow position showed less temporal variability than the row position. This difference can be accounted for by differences in root length density, and thus plant water extraction, between the row and interrow positions.

Table 2.19. Results for θ_{cv} (%), 0-20 cm, 1991

Variable	Parameter	Standard error	t	Prob > |t|
intercept	0.3475	0.0114	30.500	0.0001
clay	-0.0039	0.0004	-8.678	0.0001
tillage	0.0238	0.0093	2.563	0.0114
position	-0.0419	0.0092	-4.579	0.0001

F = 32.56, Prob > F = 0.0001, r^2 = 0.41, N = 144

At the second depth, 20-40 cm, the variation in θ_{avg} was related with clay and bulk density (Table 2.20). The tillage and position effects were not significant. Overall, the regression model explained less of the spatial variation (53%) than was explained by the model for the 0-20 cm depth (Table 2.18). The difference in intercepts between these two models indicates that the θ_{avg} at 20-40 depth was higher than the θ_{avg} at 0-20 depth.

Table 2.20. Results for θ_{avg} ($cm^3\ cm^{-3}$), 20-40 cm, 1991

Variable	Parameter	Standard error	t	Prob > | t |
intercept	0.0062	0.0525	0.117	0.9068
clay	0.0045	0.0004	12.342	0.0001
BD	0.1122	0.0337	3.331	0.0011

F = 78.24, Prob > F = 0.0001, r^2 = 0.53, N = 144

The regression analysis was only able to explain 5% of the spatial variation in θ_{cv} at the second depth (Table 2.21). The analysis indicated a small but significant negative relationship with bulk density. The difference in intercepts between Tables 2.19 and Table 2.21 indicates the temporal variation in water contents was less at 20-40 cm than at 0-20 cm.

Table 2.21. Results for θ_{cv} (%), 20-40 cm, 1991

Variable	Parameter	Standard error	t	Prob > | t |
intercept	0.2980	0.0468	6.372	0.0001
BD	-0.0804	0.0306	-2.627	0.0096

F = 6.90, Prob > F = 0.0096, r^2 = 0.05, N = 144

1992

The results obtained for θ_{avg} at the 0-20 cm depth were similar to those obtained in 1991 (compare Tables 2.18 and 2.22). However, the different intercepts for the two models indicates the θ_{avg} was significantly higher in 1992 compared to 1991. This is because 1992 was a much wetter year. The increase in mean water content resulted in a reduction in the response to clay and organic matter. The negative coefficient for bulk density indicates decreasing O with increasing bulk density. The appearance of tillage as a significant effect in 1991 (Table 2.18), but not in 1992 (Table 2.22) suggests the increase in θ_{avg} under no-till compared to conventional-till is less pronounced in wet years than in drier ones.

Table 2.22. Results for θ_{avg} (cm^3 cm^{-3}), 0-20 cm, 1992

Variable	Parameter	Standard error	t	Prob > I t |
intercept	0.4617	0.0796	5.798	0.0001
clay	0.0034	0.0003	11.044	0.0001
OM	0.0069	0.0032	2.171	0.0316
BD	-0.1732	0.0537	-3.227	0.0016
position	0.0204	0.0073	2.786	0.0061

F = 46.47, Prob > F = 0.0001, r^2 = 0.57, N = 144

Because 1992 was a wetter year than 1991, the θ_{cv} at 0-20 cm depth was significantly reduced (compare the intercepts in Tables 2.19 and 2.23). The regression model for 1992 was only able to explain 21% of the spatial variation in θ_{cv}. Furthermore, the effect of tillage was no longer significant. The temporal variation in the row position was still greater than that in the interrow position. The other main difference was the trend towards decreased variability with increasing organic matter instead of clay content.

Table 2.23. Results for θ_{cv} (%), 0-20 cm, 1992

Variable	Parameter	Standard error	t	Prob > I t
intercept	0.1289	0.0070	18.546	0.0001
OM	-0.0044	0.0014	-3.115	0.0022
position	-0.0288	0.0055	-5.202	0.0001

F = 18.38, Prob > F = 0.0001, r^2 = 0.21, N = 144

The regression model for θ_{avg} at 20-40 cm depth explained 49% of the spatial variation (Table 2.24). Despite the wetter conditions in 1992, the intercept was not significantly different from the intercept in 1991 (Table 2.20). The mean water content for the second depth increased with increasing clay content, as in 1991. Surprisingly, the effect of position was significant at the second depth in 1992: the θ_{avg} at 20-40 cm was higher in the interrow than in the row (Table 2.24). In 1991, the θ_{avg} at 20-40 cm increased with increasing bulk density (Table 2.20). The apparent substitution of position for bulk density may indicate an effect of position on bulk density at the 20-40 cm depth.

Table 2.24. Results for θ_{avg} ($cm^3\ cm^{-3}$), 20-40 cm, 1992

Variable	Parameter	Standard error	t	Prob > | t |
intercept	0.0935	0.0395	2.367	0.0193
clay	0.0030	0.0003	10.901	0.0001
position	0.1279	0.0254	5.046	0.0001

F = 67.09, Prob > F = 0.0001, r^2 = 0.49, N = 144

The results for θ_{cv} at 20-40 cm (Table 2.25) indicate reduced temporal variability at this depth compared to 1991 (Table 2.21). Once again the model R^2 was low, and variability decreased with increasing bulk density. In 1992 however, clay content was also significant; the coefficient showed decreasing variability with increasing clay content.

Table 2.25. Results for θ_{cv} (%), 20-40 cm, 1992

Variable	Parameter	Standard error	t	Prob > I t |
intercept	0.1787	0.0298	5.996	0.0001
clay	-0.0011	0.0002	-5.235	0.0001
BD	-0.0489	0.0191	-2.557	0.0116

F = 15.73, Prob > F = 0.0001, r^2 = 0.18, N = 144

2.4.4 Summary

The infiltration characteristics, $S(\theta)_{0.05}$, K_{fs} and λ_c, were log-normally distributed. All 3 log-transformed characteristics were highly variable. The In{K_{fs}} was the most predictable characteristic (multiple regression analysis explained 27% of the total variation), while the In{$\lambda_c k$} was the least predictable (multiple regression analysis explained only 10% of the total variation). The In{K_{fs}} increased with increasing clay content, and decreased with increasing organic matter content and water content at the time of sampling. The In{K_{fs}} was higher under no-till than under conventional-till, regardless of sampling date. The infiltration characteristics were too variable to be accurately predicted using deterministic approaches based on regression analysis. Stochastic approaches should be explored in future studies.

The temporal variation in θ at each site was expressed in terms of a mean (θ_{avg}) and coefficient of variation (θ_{cv}). Soil properties, tillage and position explained between 49 and 64% of the spatial variation in θ_{avg} depending on the depth and year. The θ_{avg} was higher in 1992 than in 1991. The θ_{avg} was higher in the 20-40 cm depth than in the 0-20 cm depth. The θ_{avg} increased with increasing clay and organic matter contents. The θ_{avg} was higher under no-till than under conventional-till. The θ_{avg} was higher in the interrow than in the row. The θ_{cv}, was less predictable than the θ_{avg}. Depending on the year and depth it was possible to explain between 5 and 41 % of the spatial variation in θ_{cv} in terms of soil properties, tillage and position. In general, the θ_{cv} decreased with increasing clay or organic matter content. The θ_{cv} was higher under conventional-till than under no-till. The θ_{cv} was higher in the row than in the interrow. The use of θ_{avg} and θ_{cv} to summarize the water content data ignores the possibility of trends over time. Further research using water balance models is required to predict such trends.

2.5 Porosity

The total porosity of soils influences a number of processes that are important to plant growth. Bulk density is commonly employed as a measure of porosity, on the assumption that variations in particle density have minimal influence on porosity.

2.5.1 Bulk density

2.5.1.1 Introduction

Bulk density variation in the field can be associated with inherent soil properties such as soil texture (Rawls, 1983) and organic matter (Huntington et al., 1989). Cassel (1982) pointed out the importance of also taking into account position when evaluating bulk density in the field because bulk density varies with distance normal to the direction of machinery travel.

The objective of this research was to assess the relative importance of tillage, position, texture and organic matter on the variation in bulk density in the field.

2.5.1.2 Methodology

Throughout the 1991 and 1992 growing seasons bulk density was measured periodically at the 5-7.5 cm depth. The earliest measurement in each year was at least one month after seeding. Each of the 36 locations in each tillage treatment was sampled 8 times, i.e., 4 samples in the row and interrow positions respectively (Table 2.26). This gave a total of 576 measurements, i.e.: 72 locations x 2 positions x 4 measurements. In the laboratory 6 cores were considered inappropriate for further use. These cores were discarded. The bulk density of each of the 4 measurements was averaged to give 144 values of the mean (bd_{mean}) and standard deviation (bd_{std}) for each location and position.

Table 2.26. Number of samples taken at each location for bulk density measurements according to year and position.

Crop stage	1991		1992	
	Row	Interrow	Row	Interrow
6 leaf	1		1	1
silking	1	1	1	1
harvest		1		

2.5.1.3 Results

Table 2.27 shows the statistical moments for the averaged data, bd_{mean}. The minimum and maximum values indicate a wide range of bulk densities under field conditions. The Shapiro-Wilk statistic (W) indicated the bulk density data were normally distributed.

Table 2.27. Statistical moments for the natural bulk density (bd_{mean}), the compacted bulk density (bd_{ref}), and the relative bulk density (bd_{rel}).

Statistic	bd_{mean}	bd_{ref}	bd_{rel}
N	144	72	144
Mean	1.31	1.54	0.85
Std Dev	0.12	0.13	0.05
Minimum	0.95	1.11	0.72
Maximum	1.52	1.74	0.97
CV	9.31	8.15	5.75
W:Normal	0.94	0.92	0.97

Multiple regression analysis was carried out to assess the influence of tillage, position, clay and organic matter (om) contents on bd_{mean} and bd_{std}. The regression outputs are given in Tables 2.28 and 2.29. Organic matter had the strongest (i.e. the highest t value) effect (negative) on bd mean. The negative effect of tillage indicates a higher bulk density in the no-till treatment. The positive effect of position demonstrates a higher bulk density in the interrow position. Clay content was related with bd_{mean}. both as a main effect (negative), and as well as an interaction with organic matter content. Altogether it was possible to explain 83 % of the spatial variation in bd mean.

Table 2.28. Multiple regression analysis for bd_{mean}.

Variable	Parameter	Standard error	t	Prob > | t |
intercept	1.5746	0.0267	58.971	0.0001
tillage	-0.0655	0.0124	-5.283	0.0001
position	0.0372	0.0122	3.041	0.0028
till*position	0.0695	0.0173	4.017	0.0001
OM	-0.0732	0.0067	-10.851	0.0001
clay	-0.0032	0.0013	-2.534	0.0124
om*clay	0.0012	0.0004	3.372	0.0010

F = 108.88, Prob > F = 0.0001, R^2 = 0.83, N = 144

Multiple regression analysis was only able to explain 22 % of the spatial variation in bd_{std} (Table 2.29). The bd_{std} was positively related with clay content, indicating increasing variability with increasing clay content.

Table 2.29. Multiple regression analysis for bd $_{std}$.

Variable	Parameter	Standard error	t	Prob > | t |
intercept	0.0687	0.0076	9.034	0.0001
clay	0.0021	0.0003	6.305	0.0001

F = 39.76, Prob > F = 0.0001, r^2 = 0.22, N = 144

2.5.2 Relative Bulk Density

2.5.2.1 Introduction

Bulk density has been used to characterize the state of soil compaction. However, bulk density varies with texture and organic matter content (see section 2.5.1), and therefore it has limited value as a measure of compaction when different soils are compared.

In order to diminish this limitation, Erikson (1974) and Carter (1990) have used the relative bulk density, bd rel, calculated as the natural bulk density divided by the bulk density of that soil under some standard compaction treatment (bd $_{ref}$). The maximum bulk density obtained by the Proctor test has been used as the reference bulk density (Carter, 1990). However, the Proctor test was developed for geotechnical purposes. An alternative way to obtain the bd_{ref} for agricultural purposes was proposed by Hakansson (1988).

The objectives of this research were to quantify the bd_{ref}, using Hakansson's approach (1988), and to relate both the reference bulk density and the relative bulk density to soil properties.

2.5.2.2 Methodology

Disturbed samples (approximately 3 kg) were taken from the soil surface of each plot. After sampling, the soils were stored in plastic bags in a refrigerator at 4ºC to inhibit moisture loss and biological activity.

The soil samples were sieved using a 25 mm sieve, primarily to remove large stones and very large aggregates. The soils were wetted to saturation prior to compaction. Once saturated, the soils were placed in a 15 cm diameter Rowe cell. The cell was lined with a porous sheet of plastic around the perimeter to allow for radial drainage. A porous plate was placed in the bottom of the

Rowe cell prior to the addition of the soil, and another porous plate was placed on top to allow for vertical drainage. A steel plate was situated above the top porous plate to help provide an even distribution of the applied pressure. The soil sample was then subjected to a pressure of 200 kPa for a period of 1 hour (drainage had ceased by this time). The volume of the soil was determined by taking equidistant height measurements around the perimeter of the cell and averaging these values. The soil was then removed from the Rowe cell, and sampled to determine the water content and the dry bulk density (bd ref). The relative bulk density, bd_{ref}, was computed as bd_{mean}/ bd_{ref}. The bd_{ref} was assumed to be independent of position.

2.5.2.3 Results

Table 2.27 shows the statistical moments for bd_{ref} and bd_{rel}. The mean bd_{ref} was higher than the bd. due to the compaction treatment. However, their coefficients of variation were similar. In contrast, the coefficient of variation for bd_{rel} was much lower than those for bd mean and bd_{ref}, indicating a reduction in spatial variability for this parameter. Like bulk density in the field, the data for bd_{ref} and bd_{rel} were normally distributed.

Multiple regression analysis was carried out to assess the influence of tillage, clay and organic matter contents on bd_{ref} (Table 2.30). Organic matter had the strongest (the highest t) effect (negative) on bd_{ref}. The positive effect of tillage indicates a higher bulk density under standard compaction in the conventional-till treatment. Clay content was related with bd_{mean} as a main effect as well as interacting with organic matter.

Table 2.30. Multiple regression analysis for bd_{ref}.

Variable	Parameter	Standard error	t	Prob > I t |
intercept	1.8098	0.0353	51.231	0.0001
clay	-0.0041	0.0017	-2.403	0.0190
OM	-0.0749	0.0092	-8.169	0.0001
tillage	0.0664	0.0121	5.502	0.0001
clay*OM	0.0011	0.0005	2.234	0.0288

F = 95.74, Prob > F = 0.0001, r^2 = 0.85, N = 72

In order to assess the effects of normalization on bulk density, the same multiple regression model that was developed for bd. was fitted to the data for bd_{rel}. The results of this analysis are presented in Table 2.31. Comparing Table 2.31 with Table 2.28, it is clear that normalizing with respect to bd ref effectively eliminated the influence of clay, organic matter and their interaction on bulk density. In contrast, the use of bd $_{r}$el enhanced the significance of tillage, position and their interaction in the model. The R^2 for bd_{rel} was 0.62, compared to an R^2 of 0.83 for $bd_{mean..}$ This represents a relatively small loss in predictability considering the very strong influence of organic matter on bd_{mean}, and the lack of significance for this variable in Table 2.31. We conclude that bd_{rel} is a powerful parameter for discriminating management effects across a range of soil properties.

Table 2.31. Multiple regression analysis for bd_{rel}.

Variable	Parameter	Standard error	t	Prob > | t |
intercept	0.8704	0.0158	55.250	0.0001
tillage	-0.0777	0.0073	-10.621	0.0001
position	0.0253	0.0072	3.501	0.0006
till*position	0.0422	0.0102	4.134	0.0001
OM	-0.0056	0.0040	-1.404	0.1624
clay	0.0002	0.0007	-0.288	0.7740
om*clay	0.0002	0.0002	0.876	0.3826

F = 37.828, Prob > F = 0.0001, R^2 = 0.62, N = 144

2.5.3 Summary

The range in natural bulk densities under field conditions was 0.95 to 1.52. Organic matter content explained most of the spatial variation in natural bulk density. Normalizing the natural bulk density with respect to the bulk density after compaction to 200 kPa, reduced the significance of inherent properties and improved the significance of management. The normalized bulk density, bd_{rel}, was higher under no-till than under conventional-till. The bd_{rel} was higher in the interrow than in row, and this difference was more pronounced under conventional-till than under no-till. The bd_{rel} can be used to discriminate management effects across a wide range of soil properties.

2.6 Least Limiting Water Range

2.6.1 Introduction

Soil and crop management practices can have detrimental impacts on the sustainable productivity of soils. An evaluation of any such practice should, therefore, include an assessment of its impact on those characteristics of soils which may impose subsequent limitations on plant growth. Non-thermal physical properties of soils which may influence productivity relate to supplies of oxygen and water and the degree to which the soil matrix inhibits the proliferation of roots. The relative importance of these limitations will vary between climatic zones and may also vary with crop species. The supplies of oxygen and water and the mechanical impedance of soil are determined by soil structural form and soil water content, both of which can be altered by soil and crop management practices.

A multitude of characteristics have been used to characterize structural form. Growing concern regarding detrimental impacts of soil and crop management practices on the sustainable productivity of soils are highlighting the need for a minimum number of parameters which can be used to characterize the influence of cropping practices on the supplies of oxygen, water and the mechanical impedance of soils. The concept of a range in water contents which incorporates limitations of water content on plant growth related to aeration, soil strength and available water was introduced by Letey (1985). The limits to the range were considered water contents at which plant growth would cease or be dramatically reduced. The range in water content, was referred to by Letey, as the non-limiting water range. This choice of terms is somewhat misleading since there is abundant evidence (e.g., Hillel, 1980, p. 193; Dexter 1987; Allmaras and Logsdon, 1990) that growth varies in a continuous fashion with potential, strength or aeration rather than following a step function. The response of plants to variation in water content must be considered one of degree - inside the range defined by Letey growth is least limited whereas outside of the range growth is most limited. Consequently we will use the term least-limiting water range (LLWR) rather than non-limiting water range to describe the concept introduced by Letey. The concept of least-limiting water range integrates three factors associated with plant growth into a single variable and may, therefore, be useful as an index of structural quality of soil for crop production. If so, it could be employed as a parameter to characterize the impact of management practices on the sustainable productivity of soils.

2.6.2 Influence of Inherent Soil Properties on Functions Employed

2.6.2.1 Introduction

The concept of LLWR has not been thoroughly evaluated under field conditions. Such an evaluation requires that the concept of LLWR first be converted to a quantifiable parameter based on experimentally measurable variables. For a given soil with a given structural form, the water release curve must be determined as well as the functional relation between mechanical impedance and water content (soil resistance function). Limiting values of water potential, mechanical impedance and aeration must be defined and the water contents then determined at the limiting values. The smallest range between these limiting water contents is defined as the LLWR.

The water release curve as well as the soil resistance function are time consuming measurements. The LLWR determination can be sped up utilizing pedotransfer functions developed to predict both the water release curve and the soil resistance function from easily measured soil properties such as texture and organic matter. The objective of this section is to develop such functions.

2.6.2.2 Methodology

Three hundred and sixty (360) undisturbed cores (5 cm x by 2.5 cm) were collected from the plots during the growing season in 1991 and employed to determine the water release and resistance to penetration characteristics and bulk density. Tables 2.32 and 2.33 show the ranges in soil properties from which the water release curve and soil resistance models were established, respectively.

Water Release Curve

The samples were saturated with water and equilibrated on pressure plates at seven water potentials: 0.002; 0.004; 0.006; 0.01; 0.033; 0.01 MPa. The water content at 1.5 MPa was obtained from disturbed cores.

Table 2.32. Range of the variables employed on the water release model.

Variable	Minimum	Maximum
Potential (MPa)	0.002	1.5
Volumetric water content (%)	0.0160	0.6116
Clay (%)	1.2	54
Organic matter content (%)	0.5	11.6
Bulk density (g cm^{-3})	0.92	1.79

Soil Resistance to Penetration

After the water release measurements were completed the samples were split into six groups, saturated and equilibrated at five water potentials: 0.002; 0.05; 0.1; 0.5 and 1.5 MPa. An additional drying treatment consisted of allowing the samples to air dry for several days. After equilibration the samples were stored at 4ºC for a week to eliminate any gradient in water content inside the samples.

The soil resistance to penetration was measured using an ELE Digital Tritest 50, instrumented with load cells for measurements of compressive force. Instrument control and data acquisition were achieved with a Sciemetric System 200 (consisting of a 293 bench-top chassis, a 231 A/D converter module, a 206A 8-Channel Bridge conditioning module and 251NQ analog multiplexing module) interfaced to a Compaq 286 computer through an 802 interface card.

Soil resistance was measured on each sample at a constant rate of penetration (2 mm/mm using a penetrometer with a 30º cone and a 4 mm basal diameter. One penetration was performed on each core. A reading was obtained every 0.09 mm throughout the 0.4 to 2 cm distance (177 measurements) in the centre of each core. The readings for each core were averaged. The samples were then oven dried and the water content and bulk density determined.

Table 2.33. Range of the variables employed on the soil resistance model.

Variable	Minimum	Maximum
Potential (MPa)	0.112	8.641
Volumetric water content (%)	0.0101	0.5278
Clay (%)	1.2	54
Organic matter content (%)	0.5	11.6
Bulk density (g cm^{-3})	0.92	1.79

Statistical analysis

The water release data were fitted to a function employed by Ross et al. (1991) ,i.e.,:

$$\theta = a\ \psi^{b} \qquad [2.31]$$

or alternatively

$$\ln \theta = a + b \ln \psi \qquad [2.32]$$

where θ is the volumetric water content ($cm^3\ cm^{-3}$), is the water potential (MPa) and a, b are constants. The approach suggested by Williams et al. (1989) was used to obtain the influence of texture (clay), organic matter (o.m.), bulk density (b.d.) and tillage on a and b. Tillage was included as indicator variable. The function was expressed as:

$$\begin{aligned} \ln \theta = {} & a_0 + a_1p1 + a_2p2 + ...a_ipi + \\ & (b_0 + b_1p1 + b_2p2 + ...b_ipi)\ \ln \psi \qquad [2.33] \end{aligned}$$

where p_i are soil properties and a_i and b_i are constants. Non linear effects were estimated using transformations. Multiple linear regression (SAS, 1985) was carried out and the procedure suggested by Peixoto (1987) was implemented to select the significant terms ($p > 0.05$).

Soil resistance data were regressed against water content and bulk density using the model proposed by Busscher (1990),i.e.,:

$$SR = d\theta^{c}\ bd^{f} \qquad [2.34]$$

or alternatively

$$\ln SR = d + e \ln \theta + f \ln bd \qquad [2.35]$$

where d, e and f are constants and SR is the soil resistance (MPa). The influence of texture, o.m. and tillage on d, e and f in Eq. [5] was assessed using the same approach as used for the water release curve, i.e.:

$$\begin{aligned} \ln SR = {} & d_0 + d_1 p1 + d_2\, p2 \ldots + di\; pi \\ & (e_0 + e_1 p1 + e_2 p2 + \ldots e_i\; pi) \ln \theta + \\ & (f_0 + f_1 p1 + f_2 p2 + \ldots f_i\; pi) \ln bd \end{aligned} \qquad [2.36]$$

where d_i, e_i, and f_i are constants.

2.6.2.3 Results

Water release curve

Table 2.34 presents the output of the water release curve model. All the main effects as well as the two-way interaction were highly significant (Prob > | T | > 0.0001). The R^2 (0.89) is very close to William's (1989) results using the same approach to model the water release curve. The D statistics (SAS, 1985) is related to the residuals analysis and the value obtained demonstrated that the residuals have a normal distribution which is essential to assess the model's adequacy (Neter, 1989).

The model for the two tillage systems, expressed as Eq. [2.33], becomes:

no-till:

$$\begin{aligned} \ln \theta = {} & -4.3841 + 0.6658 \ln clay + 0.3832 \ln om + 0.5951 \ln bd \\ & + (-0.6028 + 0.1174 \ln clay + 0.0402 \ln om + 0.1524 \ln bd) \ln \psi \end{aligned} \qquad [2.37]$$

conventional-till:

$$\begin{aligned} \ln \theta = {} & -4.4591 + 0.6658 \ln clay + 0.3832 \ln om + 0.5951 \ln bd \\ & + (-0.6208 + 0.1174 \ln clay + 0.0402 \ln om + 0.1524 \ln bd) \ln \psi \end{aligned} \qquad [2.38]$$

The non-linear effect of clay, organic matter and bulk density on Eq.[2.33] was also observed by Williams and (1989). The interactions show that the influence of clay, organic matter and bulk density on θ depends on the ψ value. From the interactions between θ and ln clay, ln om and ln bd it can be seen how the slope (the b parameter) of the water release varies with clay, organic matter and bulk density. The higher the clay content, the less negative is the slope and consequently the less water is released from the soil. The same explanation applies to the organic matter. These relations also imply that the inherent properties of the soil would have a higher impact at drier conditions (low water potential).

Soil resistance to penetration

Table 2.34 presents the output of the soil resistance model. All the main effects as well as the two-way interaction were highly significant (Prob > |T| > 0.01). The W statistics (SAS, 1985) demonstrated that the residuals have a normal distribution. Clay and organic matter contents influence soil resistance directly through the intercept (c parameter) and indirectly through the d an e coefficients of the Eq.[2.35]. Consequently, the effect of 6 and bd on the soil resistance depends on the clay and organic matter contents.

Table 2.34. Multiple linear regression analyses using form of Eqn. [2.36].

Variable	DF	Parameter Estimate	Standard Error	T for HO:	Prob > | t |
				Parameter = 0	
intercept	1	-3.4326	0.2959	-11.599	0.0001
in θ	1	-0.4334	0.0980	- 4.425	0.0001
In bd	1	4.5270	0.6486	6.979	0.0001
clay	1	-0.0822	0.0131	- 6.259	0.0001
In om	1	1.4976	0.1614	9.278	0.0001
In θ clay	1	-0.0791	0.0083	- 9.511	0.0001
In θ In om	1	0.3986	0.0946	4.216	0.0001
In bd clay	1	0.0643	0.0219	2.936	0.0036
In bd In om	1	-1.1603	0.3330	- 3.484	0.0006
tillage	1	-0.5635	0.1660	- 3.395	0.0008
tillage In θ	1	-0.3042	0.1181	- 2.576	0.0104

F value = 85 Prob > F = 0.0001, R^2 = 0.71
MSE = 0.22205, N = 350, W:Normal = 0.98, Prob.W ,.038

The soil resistance model for both tillage systems were:

no-till:

$$\begin{aligned}\ln SR = \ & -3.4326 - 0.0822\ clay + 1.4976 \ln om \\ & (-0.4334 - 0.0791\ clay + 0.3986 \ln om) \ln \theta \\ & (4.5270 + 0.0643\ clay - 1.1603\ in\ om) \ln bd\end{aligned} \tag{2.39}$$

conventional-till:

$$\begin{aligned}\ln SR = \ & -3.9961 - 0.0822\ clay + 1.4976 \ln om \\ & (-0.7376 - 0.0791\ clay + 0.3986\ in\ om) \ln \theta \\ & (4.5270 + 0.0643\ clay - 1.1603 \ln om) \ln bd\end{aligned} \tag{2.40}$$

2.6.3 Variation in LLWR With Inherent Soil Properties and Tillage

The relationship between LLWR and soil properties, specifically, clay, organic matter and bulk density are shown for both tillage treatments in Figures 2.9, 2.10 and 2.11 respectively. For each plot LLWR was calculated using the models described in section 2.6.2 to predict the water release and soil resistance functions. The clay and organic matter contents for each plot were input to the models to obtain the upper and lower limits of LLWR. The average bulk density for each plot was estimated from the model presented in section 2.5.1. The data plotted in Figures 2.9 presents the LLWR variation with clay content at each plot with organic matter and bulk density associated with each plot. The same explanation applies to Figures 2.10 and 2.11. Variation in LLWR reflects the variation in all three variables. For instance, at a given clay content (Fig. 2.9) the variation in LLWR reflects, in part, variations due to organic matter content and bulk density.

The LLWR decrease linearly increasing clay content, increase exponentially increasing organic matter and decrease exponentially increasing bulk density.

2.6.4 Plant Response to Variation in Soil Water Content and LLWR

Two approaches were used in the evaluation of plant response to LLWR. First, the variation of yield and plant population with LLWR was assessed. Second, the θ data were used to calculate the frequency (days) in which θ was outside the LLWR (t_{out}) and the frequency and related to yield.

The relationship between LLWR and plant population and yield are shown for 1991 and 1992 in Figures 2.12 to 2.17. The data suggests that plant response to LLWR is stronger with respect to the plant population than to yield; population increases with increasing LLWR.

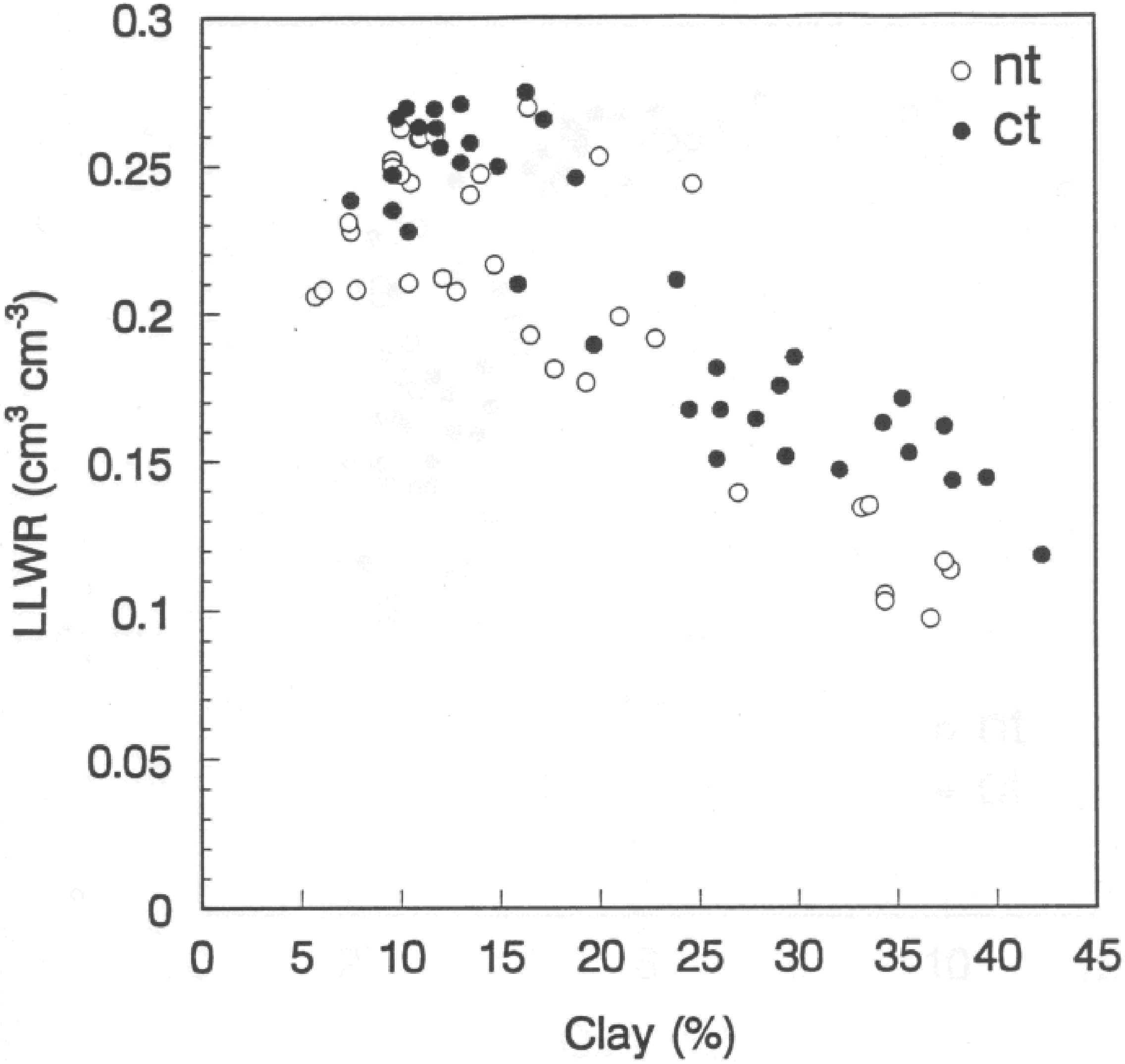

Fig. 2.9. LLWR Variation in LLWR with clay content for no-till (nt) and conventional-till (ct) treatments.

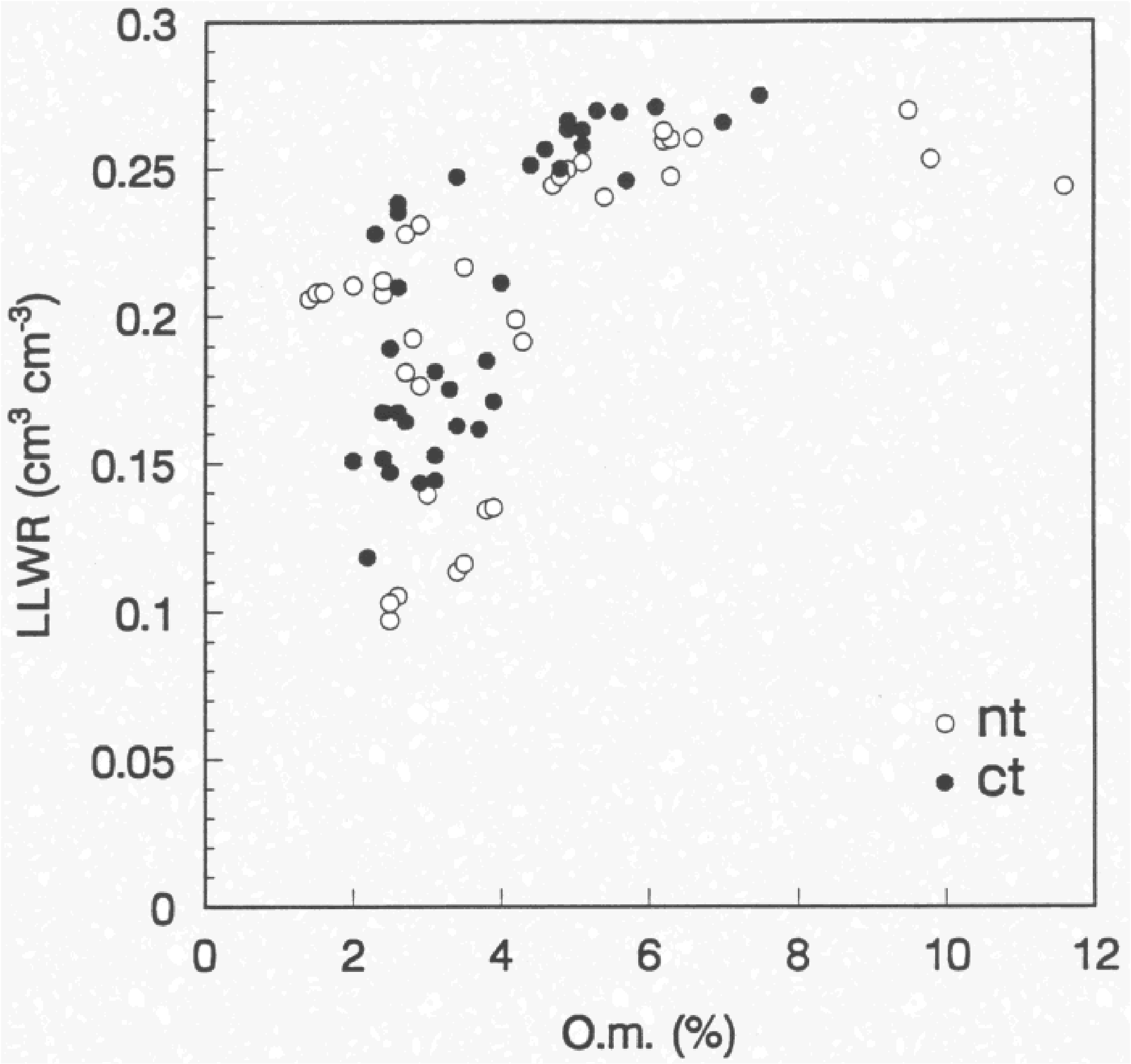

Fig. 2.10. Variation in LLWR with organic matter content for no-till (nt) and conventional-till (ct) treatments.

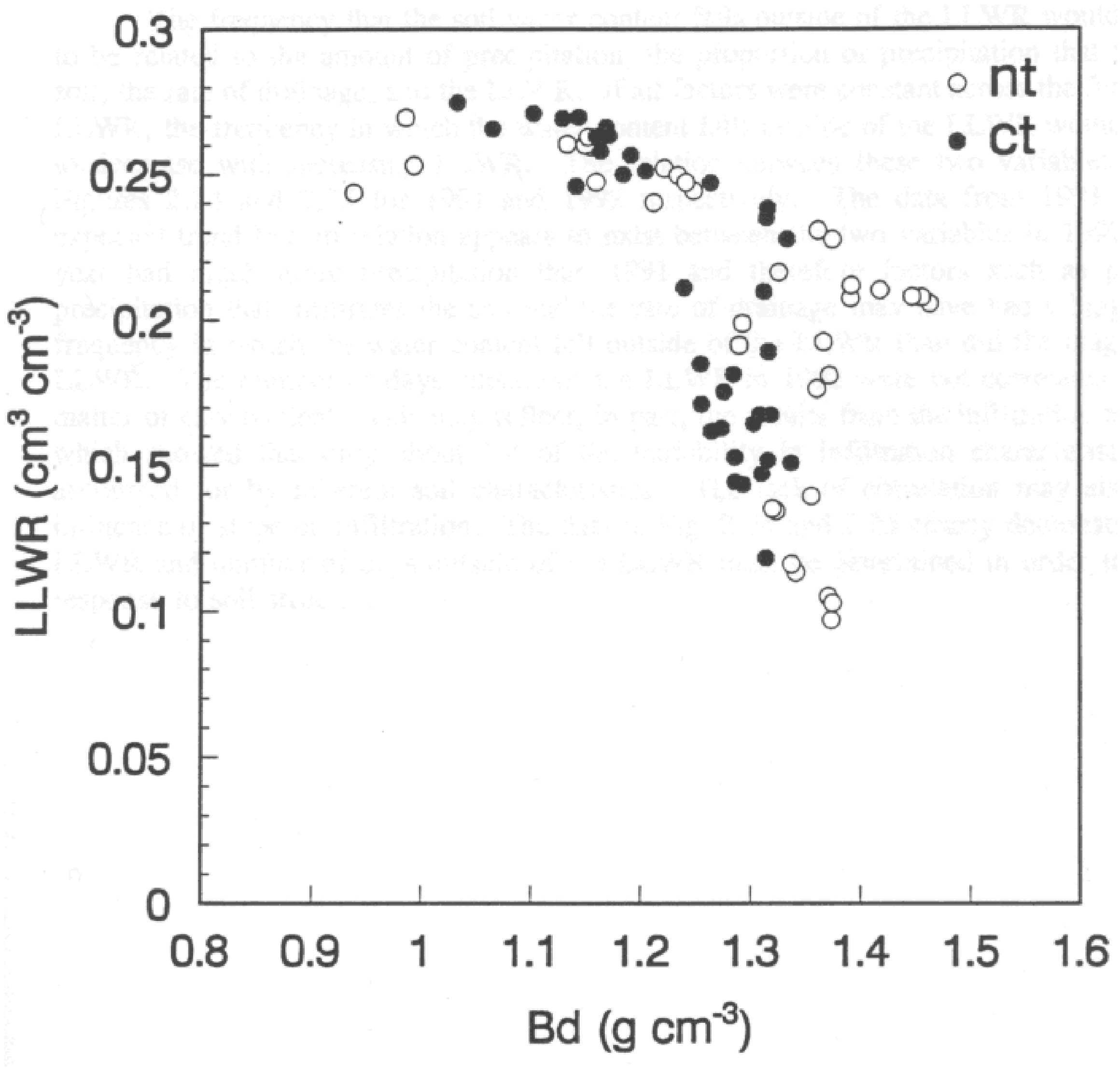

Fig. 2.11. Variation in LLWR with bulk density content for no-till (nt) and conventional-till (ct) treatments.

The relationship between t_{out} versus plant population and yield are shown for 1991 and 1992 in Figures 2.18 to 2.23 (data on plant populations are included to permit a visual assessment of the relation between population and yield, there is little reason to expect that plant population is influenced by the number of days outside of the LLWR considering the growth stage during which this parameter was measured). Despite the data variability it can be seen that t_{out} has a stronger effect on yield than LLWR; yield decreases with the number of days outside of the LLWR.

2.6.5 Factors Influencing the Frequency that the Water Content Lies Outside of LLWR

The frequency that the soil water content falls outside of the LLWR would be expected to be related to the amount of precipitation, the proportion of precipitation that infiltrates the soil, the rate of drainage, and the LLWR. If all factors were constant across the field site except LLWR, the frequency in which the water content falls outside of the LLWR would be expected to decrease with increasing LLWR. The relation between these two variables is shown in Figures 2.24 and 2.25 for 1991 and 1992 respectively. The data from 1991 illustrate the expected trend but no relation appears to exist between the two variables in 1992. The 1992 year had much more precipitation than 1991 and therefore factors such as proportion of precipitation that infiltrates the soil and the rate of drainage may have had a bigger effect the frequency in which the water content fell outside of the LLWR than did the magnitude of the LLWR. The number of days outside of the LLWR in 1992 were not correlated with organic matter or clay content. This may reflect, in part, the results from the infiltration measurements which showed that only about 1/4 of the variability in infiltration characteristics could be accounted for by inherent soil characteristics. The lack of correlation may also reflect the influence of slope on infiltration. The data in Fig. 2.24 and 2.25 clearly demonstrate that both LLWR and number of days outside of the LLWR must be determined in order to relate plant response to soil structure.

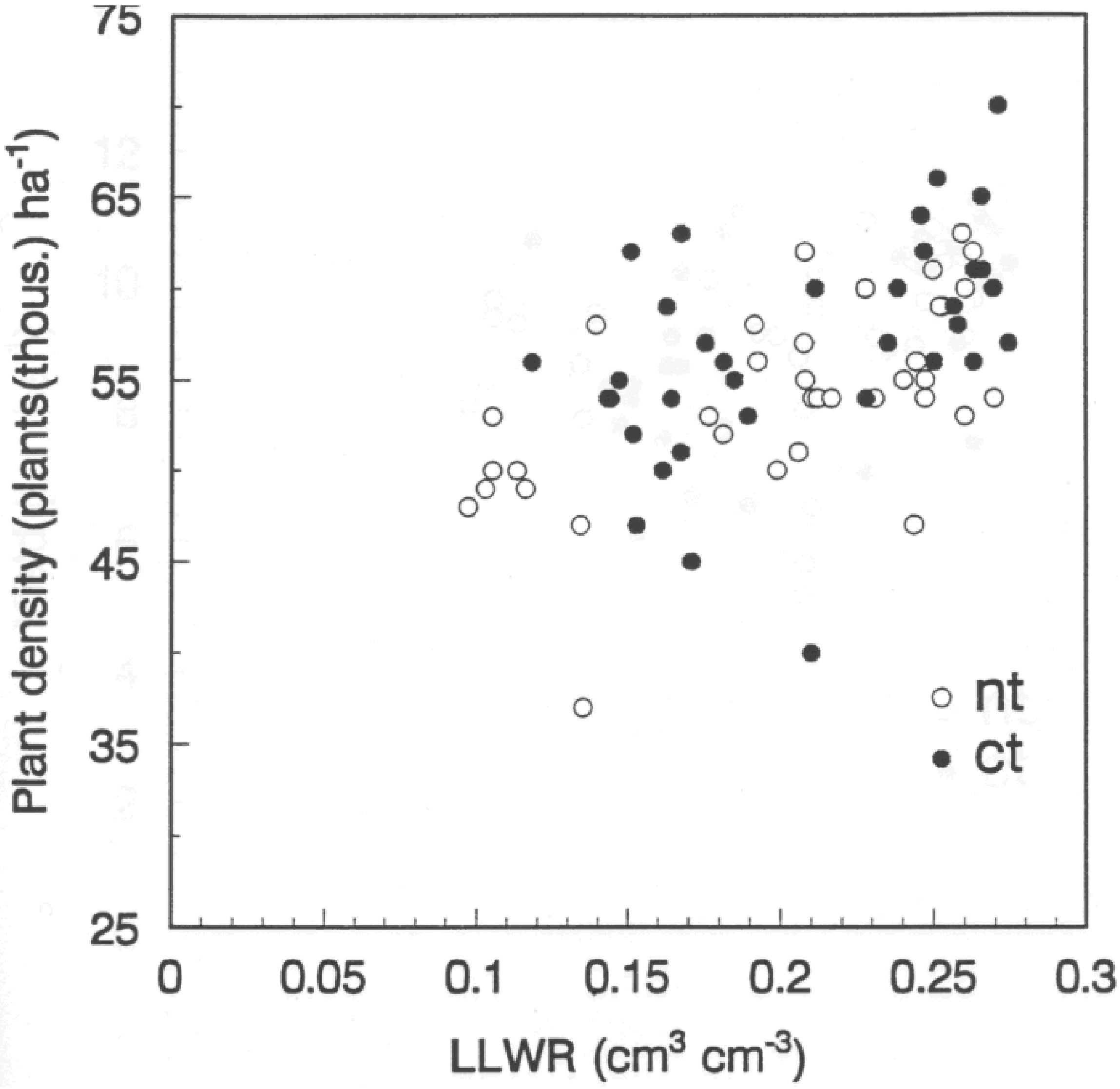

Fig. 2.12. Plant density variation with LLWR for no-till (nt) and conventional-till (ct) treatments. 1991.

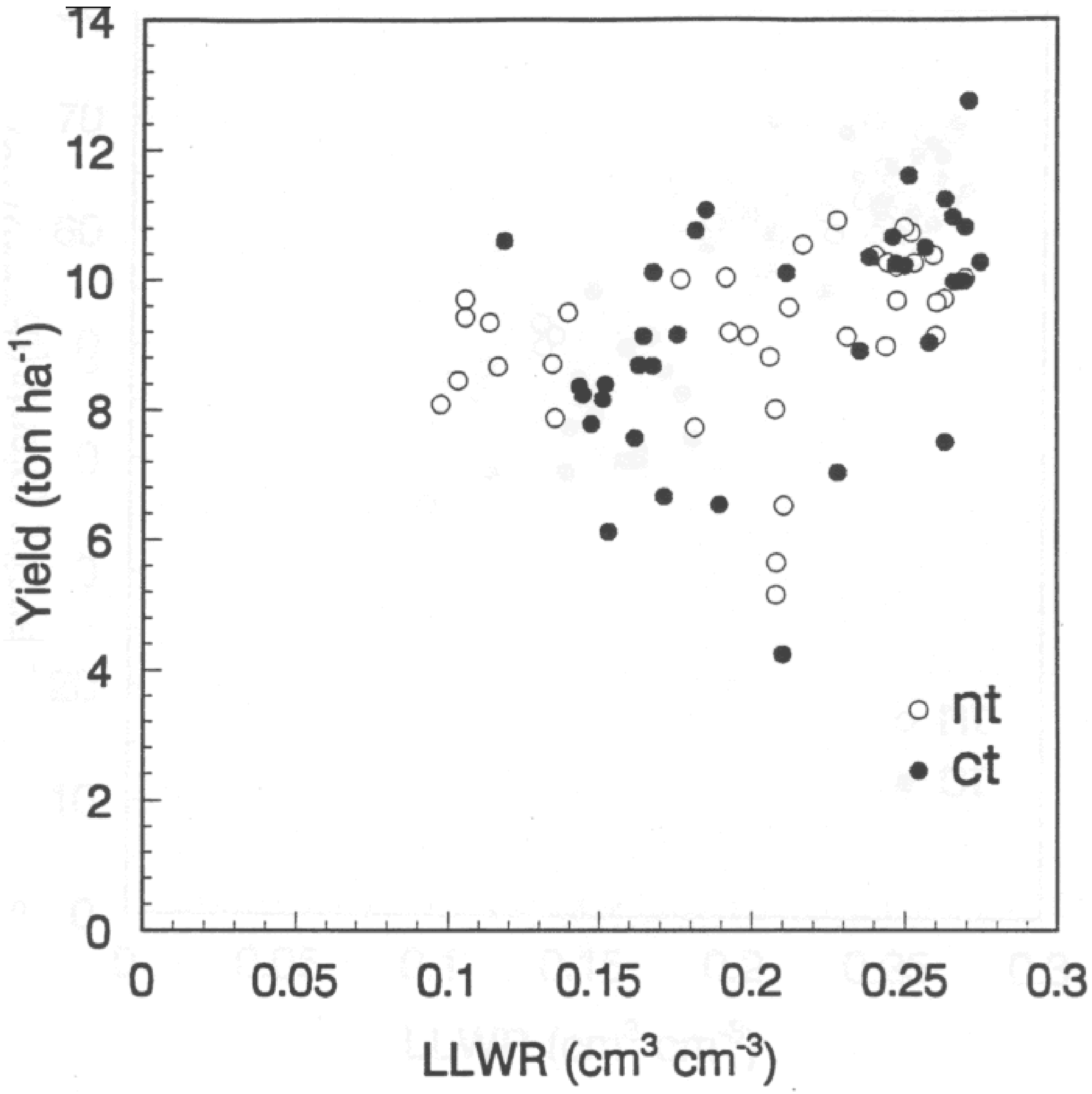

Fig. 2.13. Yield variation with LLWR for no-till (nt) and conventional-till (ct) treatments. 1991.

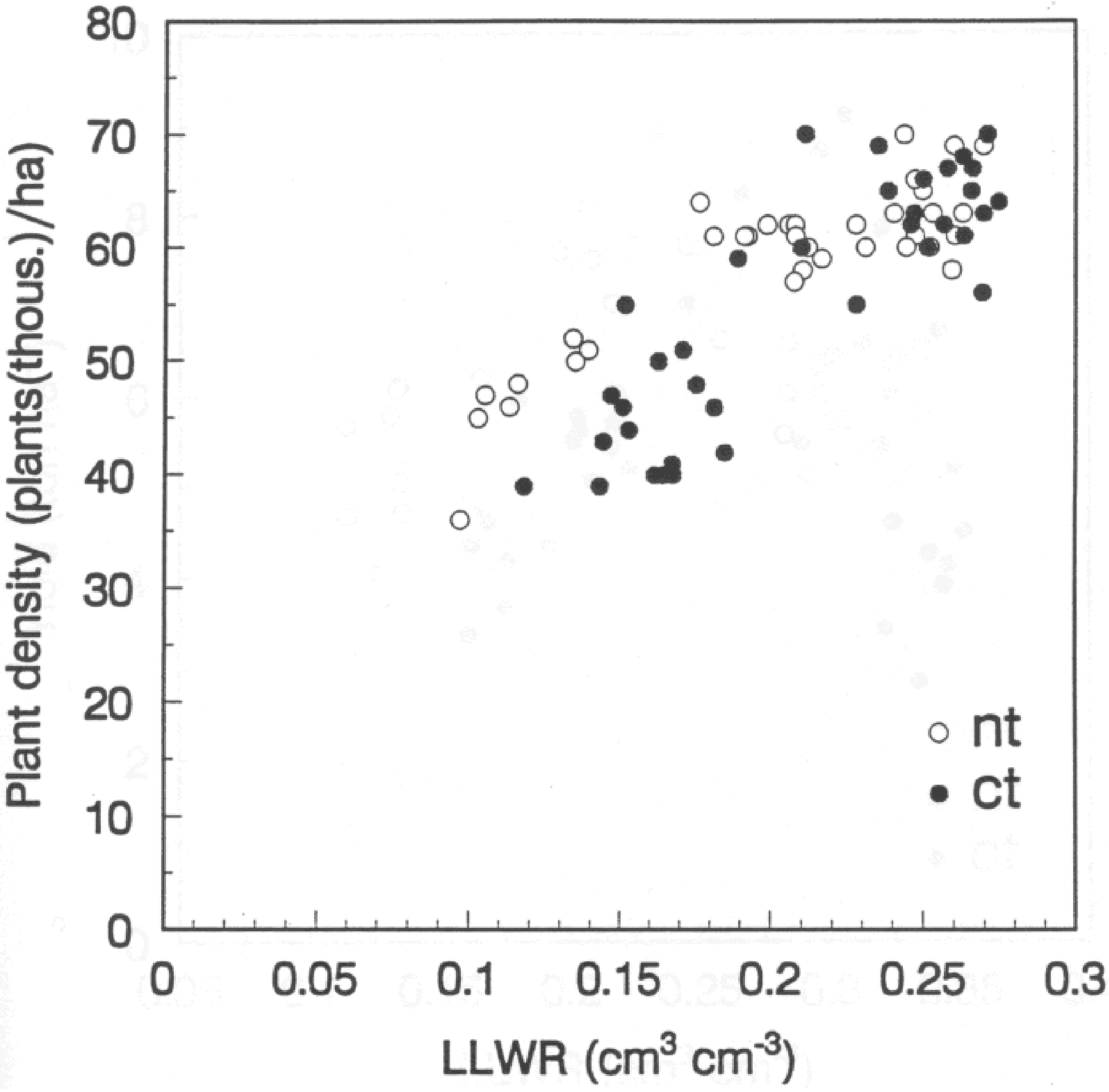

Fig. 2.14. Plant density variation with LLWR for no-till (nt) and conventional-till (ct) treatments. 1992, uncontrolled population.

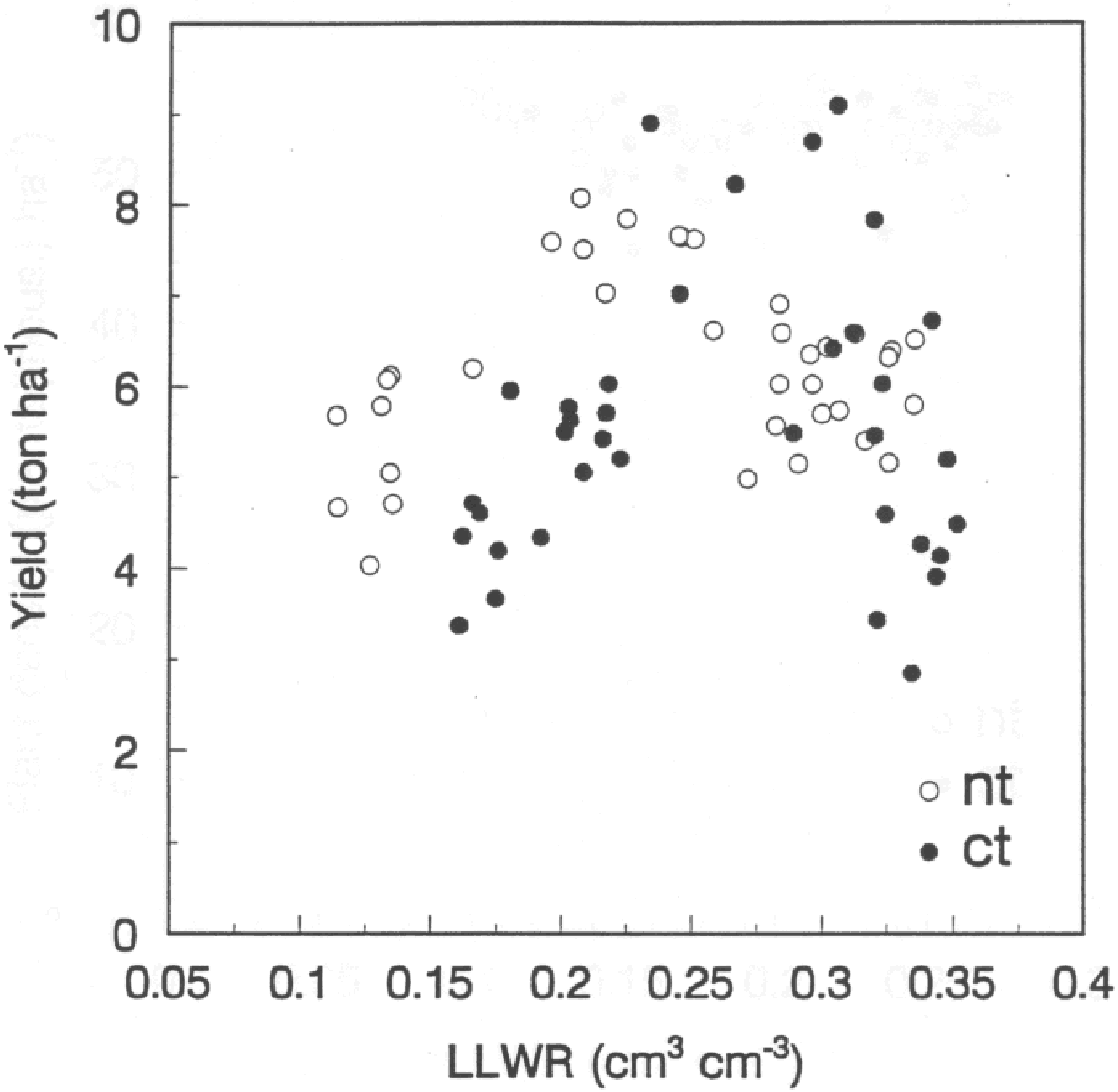

Fig. 2.15. Yield variation with LLWR for no-till (nt) and conventional-till (ct) treatments. 1992, uncontrolled population.

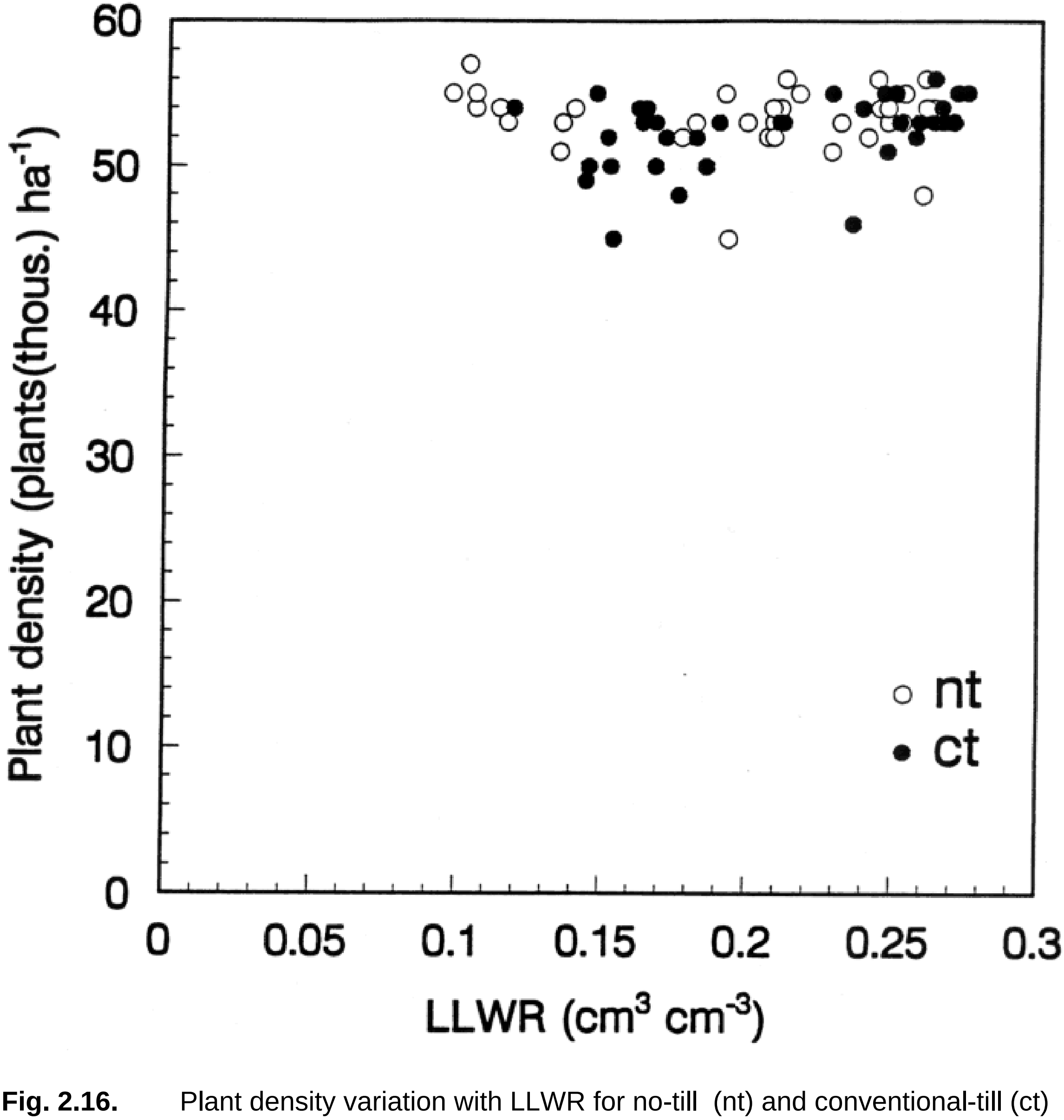

Fig. 2.16. Plant density variation with LLWR for no-till (nt) and conventional-till (ct) treatments. 1992, controlled population.

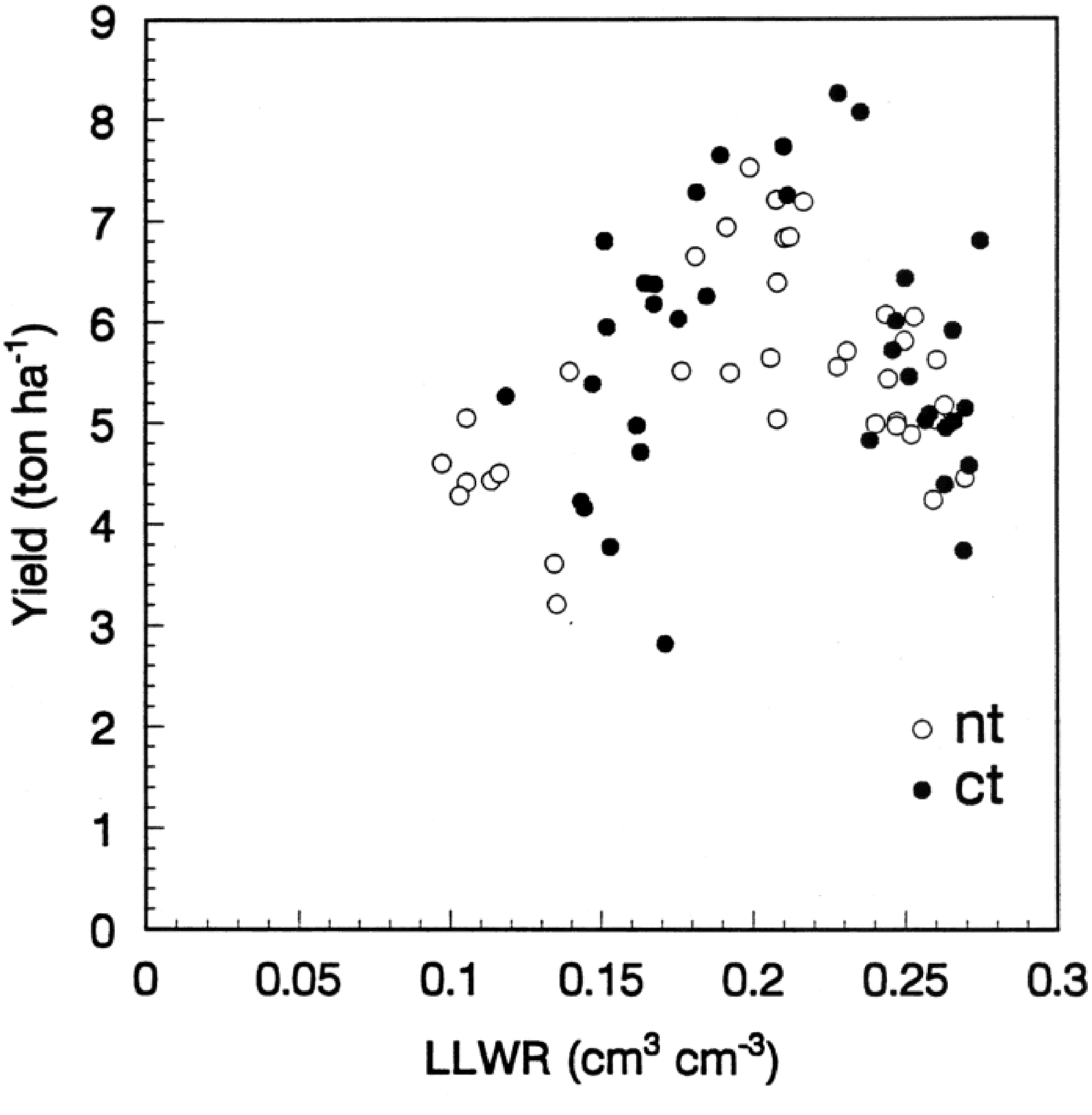

Fig. 2.17. Yield variation with LLWR for no-till (nt) and conventional-till (ct) treatments. 1992, controlled population.

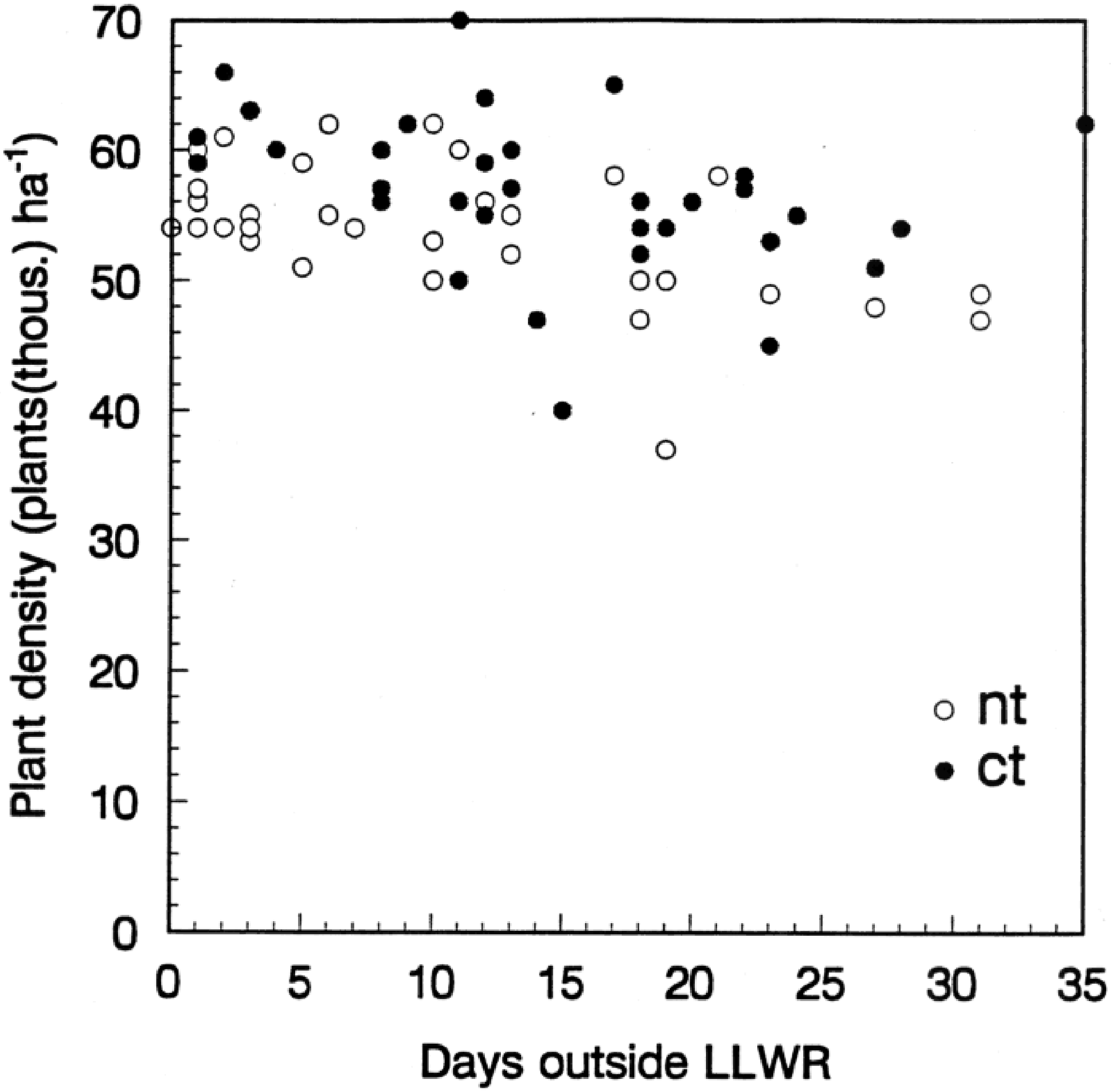

Fig. 2.18. Plant density variation with θ_{out} 1991.

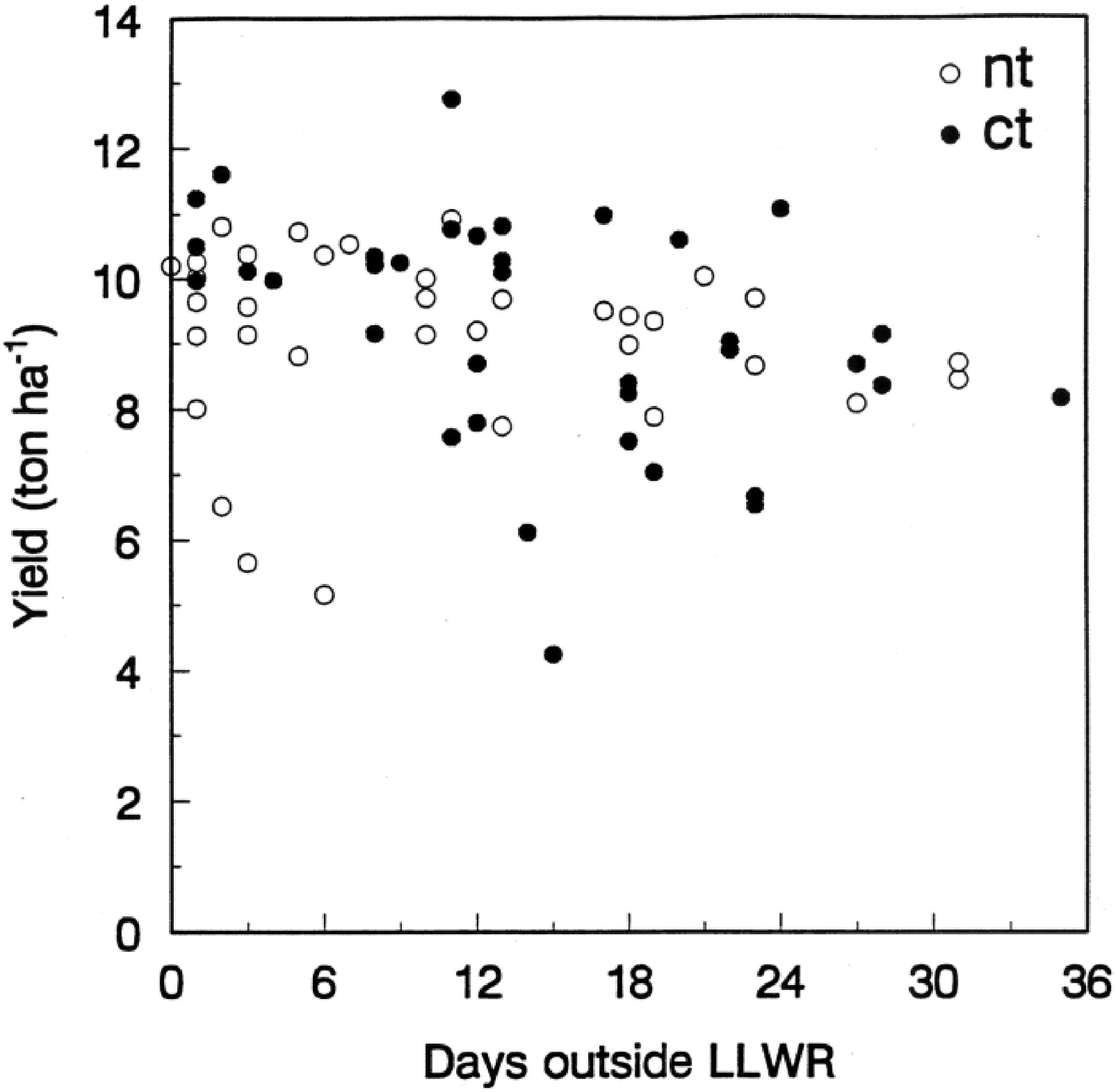

Fig. 2.19. Yield variation with θ_{out}. 1991.

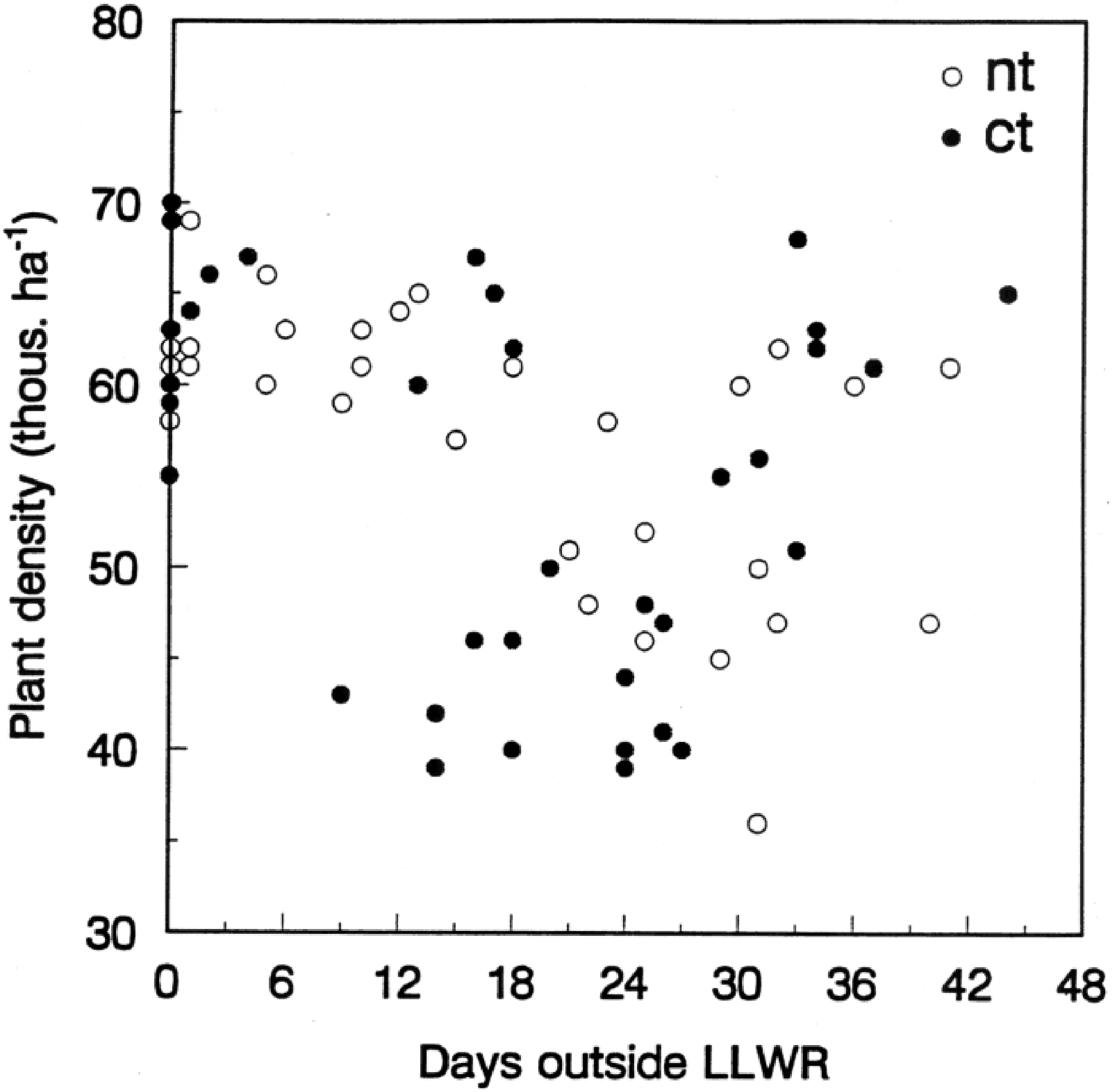

Fig. 2.20. Plant density variation with θ_{out}, 1992, uncontrolled population.

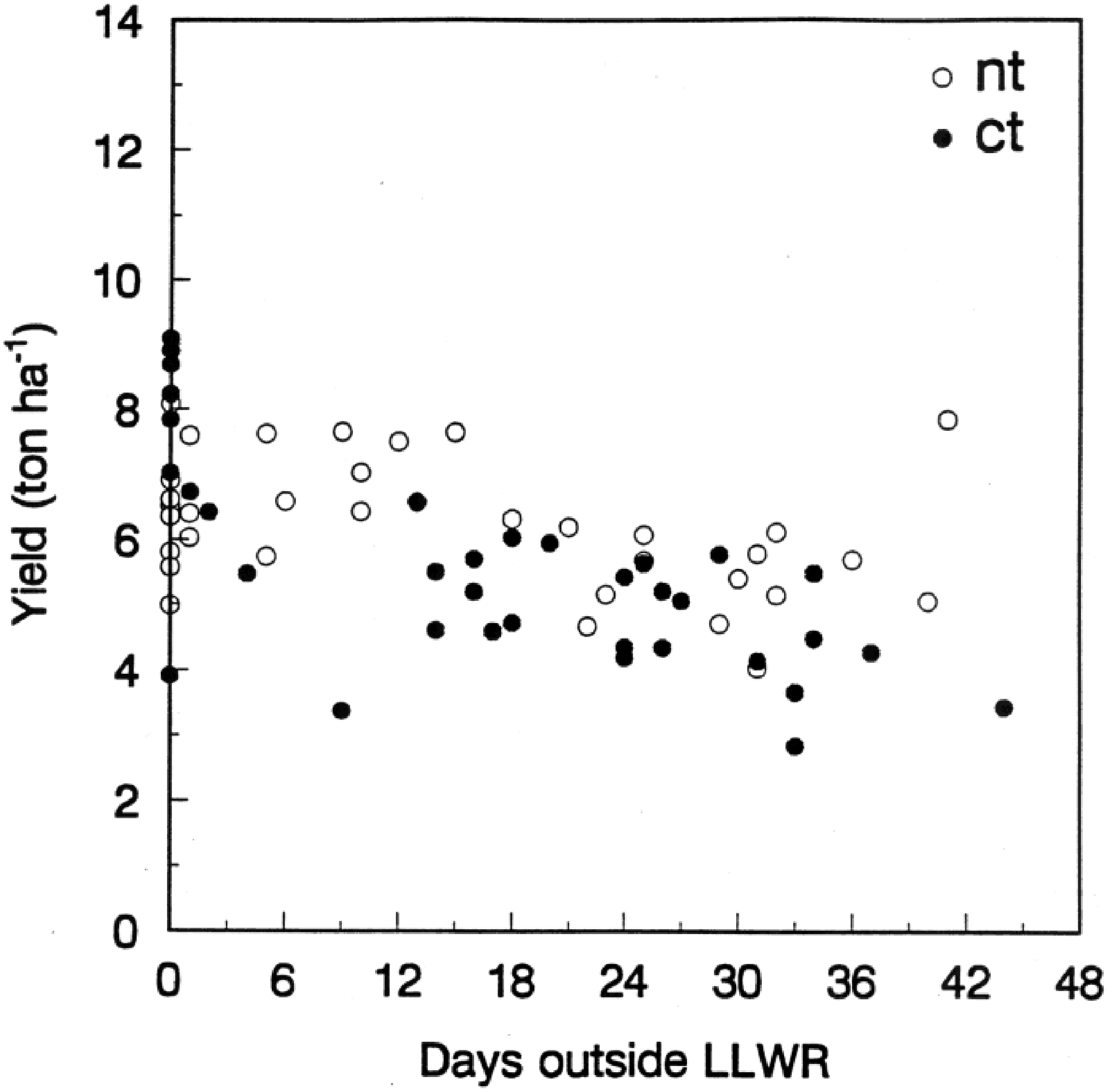

Fig. 2.21. Yield variation with θ_{out}. 1992, uncontrolled population.

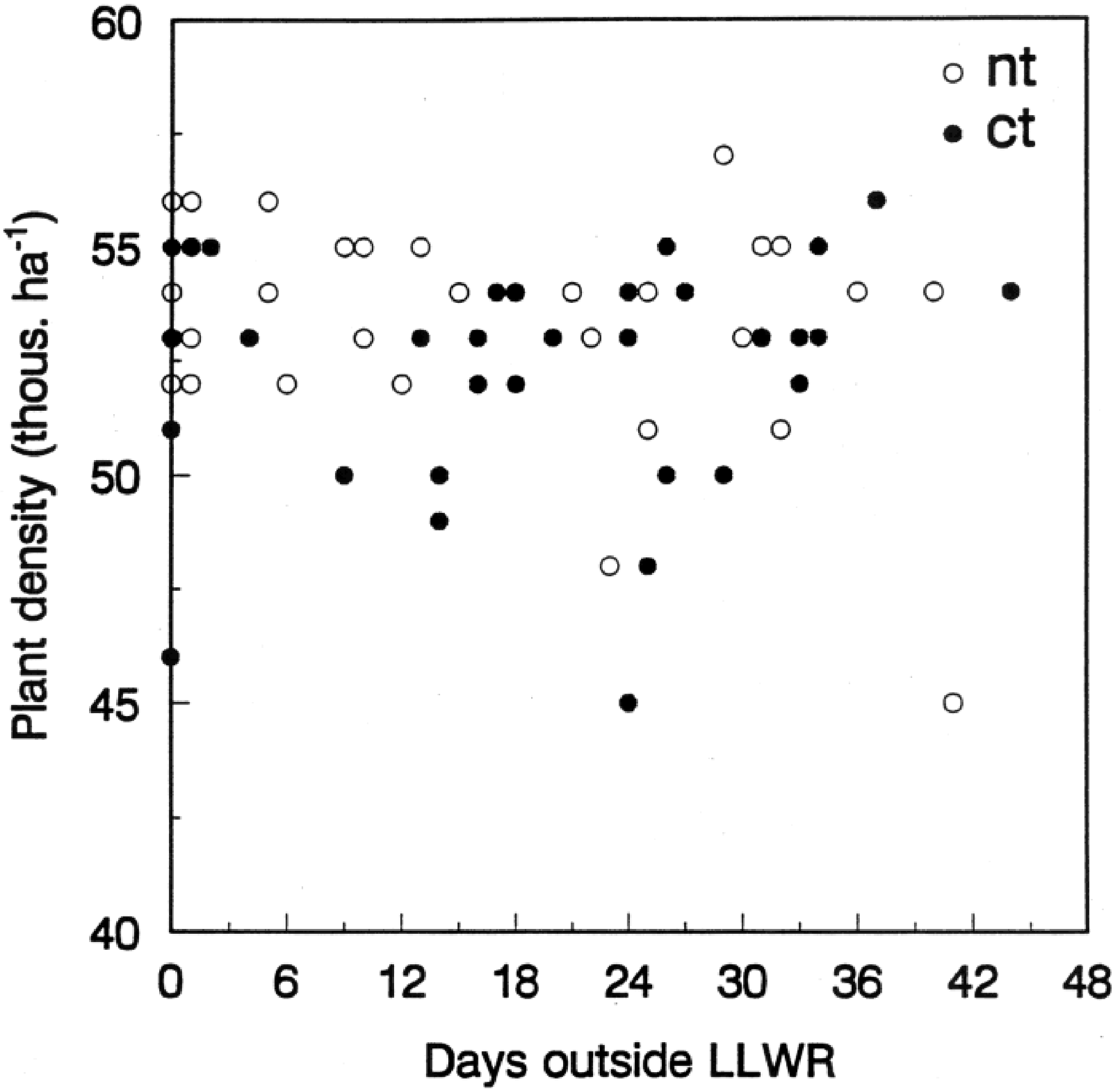

Fig. 2.22. Plant density variation with θ_{out}, 1992, controlled population.

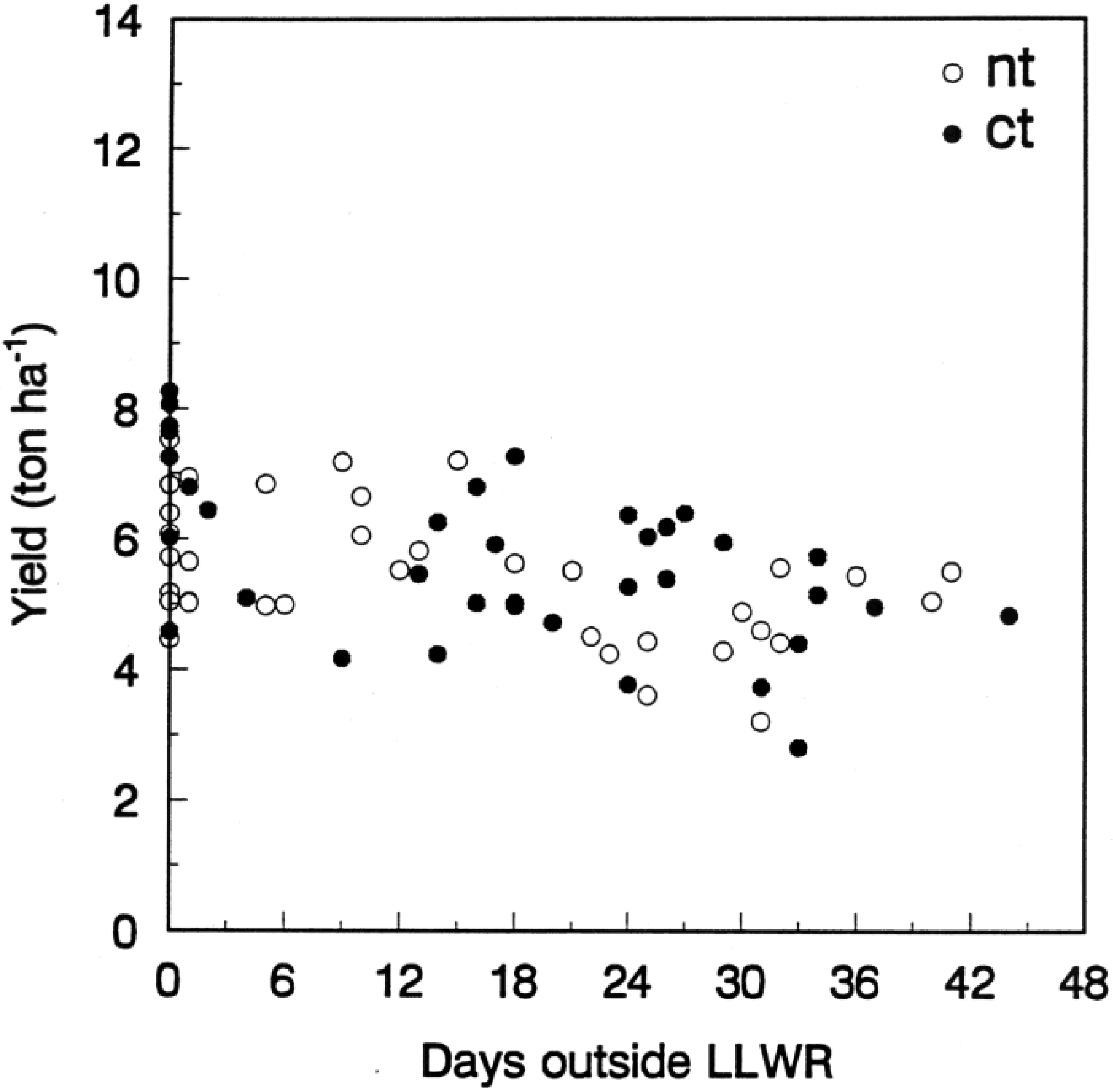

Fig. 2.23. Yield variation with θ_{out}, 1992, controlled population.

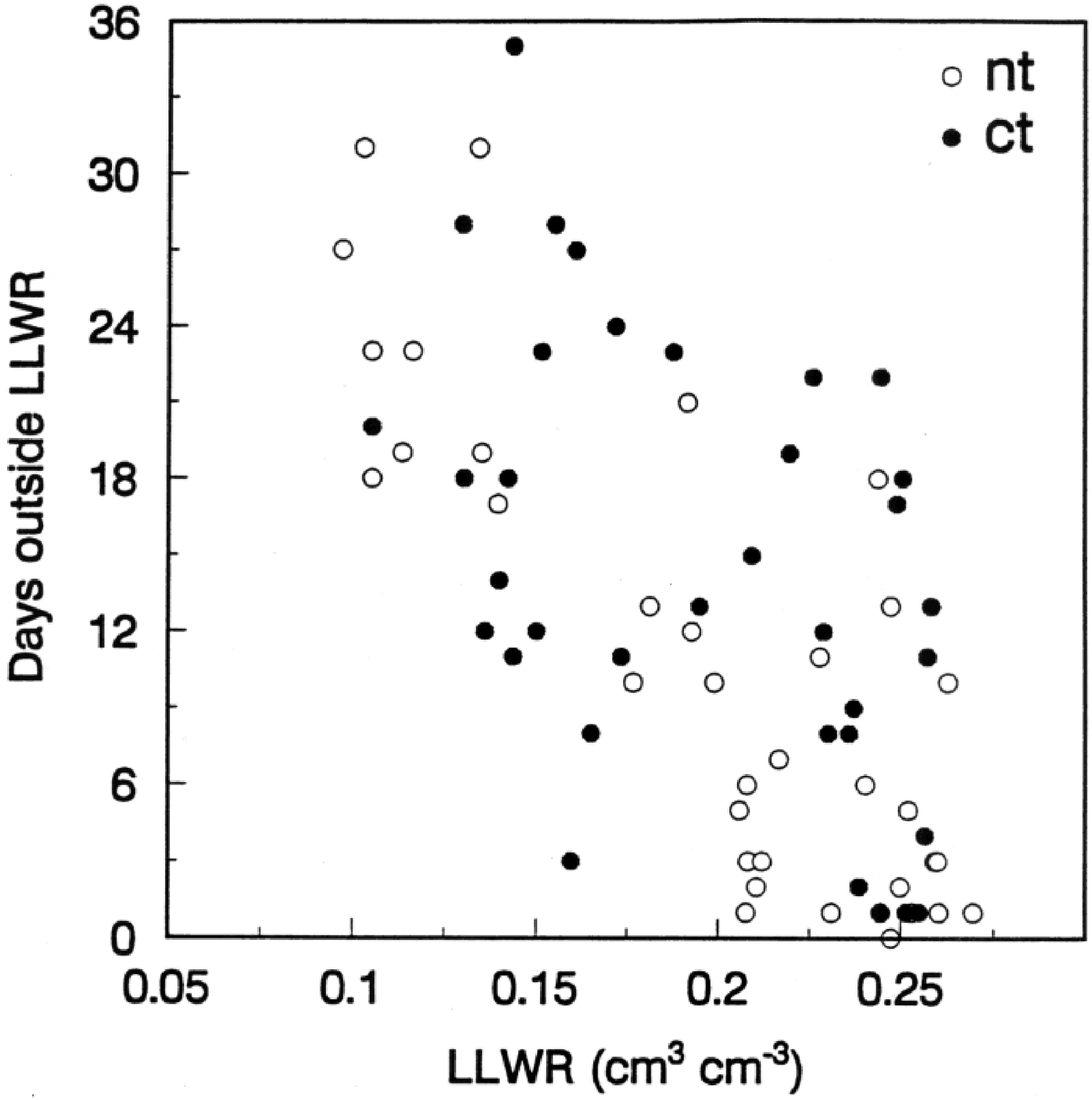

Fig. 2.24. θ_{out} variation with LLWR. 1991.

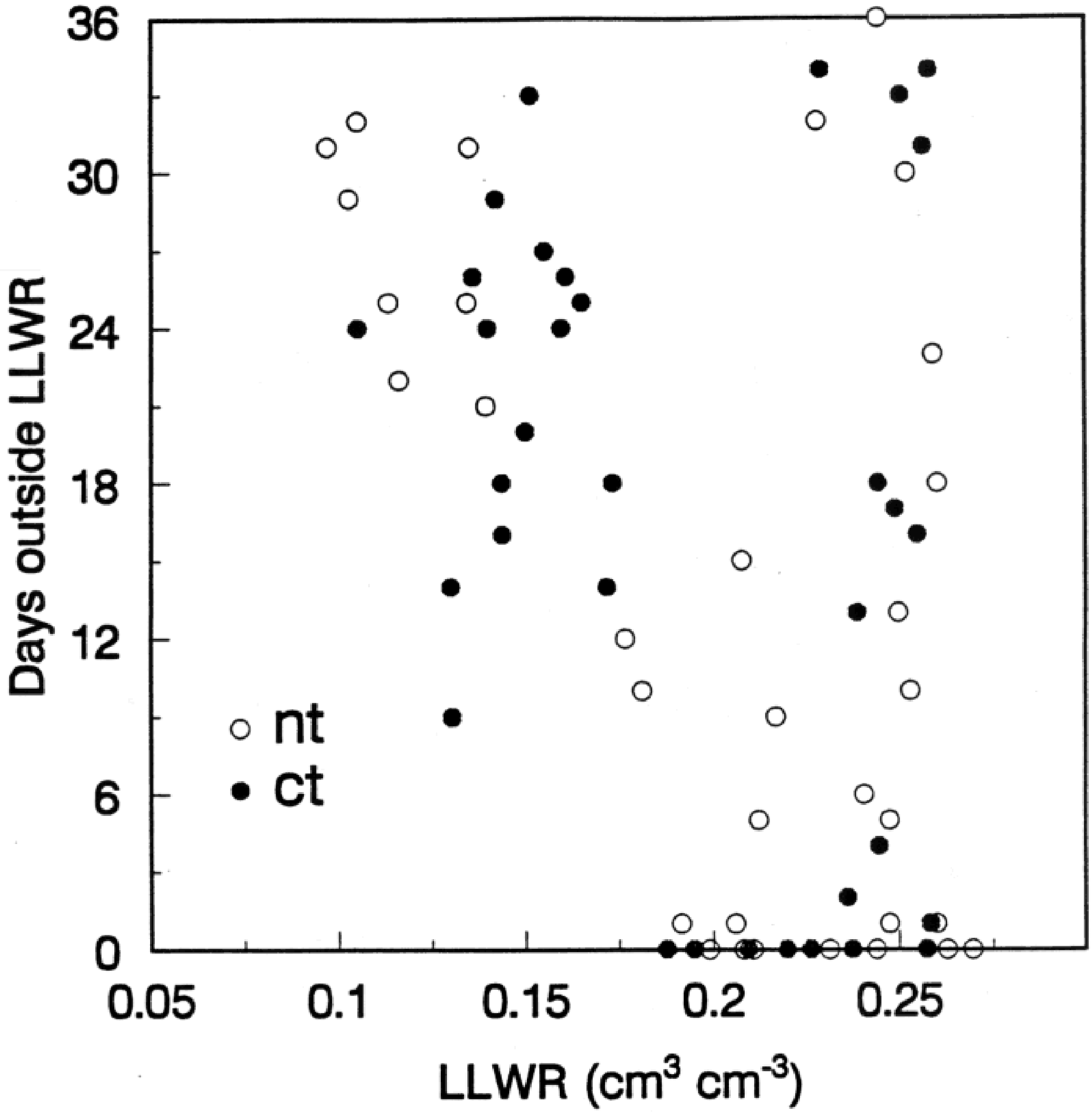

Fig. 2.25 θ_{out} variation with LLWR. 1992.

2.6.6 Summary

The LLWR is strongly related with clay and organic matter contents and bulk density. LLWR at a specific site is dependent on the combination of these soil properties. In the experimental site LLWR decreases with increasing clay content and bulk density and increases with increasing organic matter. Plant population was more affected by LLWR than yield. Days outside LLWR has a higher impact on yield than LLWR itself. The frequency that the soil water content falls outside of the LLWR is negatively related with LLWR in 1991. No trend is observed in 1992, a very wet year. In order to relate plant response to LLWR both LLWR and number of days outside LLWR must be determined.

2.7 Coefficient of Linear Extensibility

The coefficient of linear extensibility, COLE, was measured at the Lobb site to assess the shrink-swell capacity of soils along the transect. Such an assessment is important for the bulk density, soil water retention and infiltration measurements, all of which have been interpreted in the preceding sections assuming a rigid soil matrix. Significant shrinking and swelling could also influence the water content measurements by creating an air annulus around the TDR rods.

The COLE is defined as:

$$\mathbf{COLE = (BD_d / BD_m)^{1/3} - 1} \qquad \textbf{[2.41]}$$

where BD_d is bulk density in the dry state, and BD_m is bulk density in the moist state. The COLE was measured on samples collected from the conventional-till treatment using the method of Schafer and Singer (1976). This method uses the change in linear dimension of a cylindrical soil paste extruded from a syringe to estimate the change in (undisturbed) bulk density. It is difficult to use this method on coarse-textured soils (Schafer and Singer, 1976). In practice, we were able to obtain useful data for 14 out of the 36 locations, ranging in clay content from 15.9 to 42.3% clay content. Three subsamples were measured at each location.

The mean gravimetric water content of the moist samples was 27.87(± 1.77) %. The COLE was determined on both air-dried and oven-dried samples. The mean gravimetric water content of the air-dried samples was 2.88(± 0.61)%. The regression equation of Schafer and Singer (1976) was then used to standardize both estimates. A significant 1:1 relationship was found between the standardized COLE for the air dried samples, $COLE_a$ and that for the oven-dried samples, $COLE_o$:

$$\mathbf{COLE_a = -0.002 + 1.030\ COLE_o; \quad n = 38, \quad R^2 = 0.792} \qquad \textbf{[2.42]}$$

The 1:1 relationship between the two estimates in Eq. [2.42] indicates Schafer and Singer's (1976) equations can be applied to the Lobb site without loss of accuracy.

Because of the 1:1 relationship between the two measures, only the data for COLE. will be discussed in detail. The COLE. ranged from 0.028 to 0.059, with a mean value of 0.045. The COLE. was positively correlated with clay content (r = 0.626) and organic matter content (r = 0.606). The relationship between COLE. and initial water content (in the moist state) was not significant. When all three variables were included in a stepwise multiple regression analysis, the following model was selected:

$$\mathbf{COLE_o = -0.009 + 0.001clay + 0.008OM; \quad n = 14, R^2 = 0.766 \qquad [2.43]}$$

where OM is organic matter content (%). According to Buol et al. (1980) significant shrink-swell activity can be expected if COLE exceeds 0.09. None of the data for the Lobb site approached this value, indicating the assumption of a rigid soil matrix is reasonable for the whole site. Substituting 0.09 into eq. [2.43] along with the mean value for organic matter content, results in the prediction that shrink-swell activity only becomes significant at clay contents of 75% or more. An alternative approach is to use eq. [2.43] to predict the clay content where shrink-swell activity exceeds the accuracy, say 10%, with which bulk density can be determined. According to eq. [2.41], the COLE associated with a 10% accuracy in bulk density is 0.032. Using this value in eq. [2.43] along with the mean value for organic matter content leads to the prediction that volume changes due to shrink-swell activity will go undetected at clay contents of 11% or less.

The wet-aggregate stability (WAS) and dispersible clay (DC) contents of the moist pastes were predicted using the regression equations in Tables 2.13 and 2.12, respectively. The $COLE_o$ was positively correlated with the predicted WAS (r = 0.728**) and DC (r = 0.534) values. When WAS and DC were included in a multiple regression analysis along with clay, organic matter and initial water content, the WAS was selected over clay content as a significant predictor of $COLE_o$. The full equation is given below:

$$\mathbf{COLE_o = -0.001 + 0.007om + 0.002\ WAS; \quad n = 14, R^2 = 0.788 \qquad [2.44]}$$

3. MODELLING CROP RESPONSE TO CHANGES IN SOIL STRUCTURE

3.1 Introduction

The preceding analyses have conclusively illustrated that the response of crops to soil structure is strongly dependent on climate. It is impractical to expect that studies can be extended over a sufficient number of years to adequately describe an empirical relation that relates crop response to soil structure under different climatic conditions. Simulation models, however, may provide the framework for developing such a relation.

Studies were initiated with the objective of evaluating existing crop productivity models in terms of their suitability for predicting crop response to changes in soil quality under different climatic conditions.

3.2 Model Evaluation and Selection

Computer models used to simulate plant development and yield can serve many different purposes. Applications can range from research to policy issues and users can vary from farm operators to land use planners. Crop growth models can be empirical or mechanistic in their approach. Empirical models are advantageous in that their data input requirements are small and they tend to be simpler and easier to understand. There are two major disadvantages to using empirical models however. One is that they are restricted to being used at the site for which they were developed, precluding the opportunity of extrapolating the model to other areas with contrasting environments and growth conditions. The second limitation is the lack of causality among variables. Empirical models describe the relationships between variables without referring to the processes connecting those variables (Acock and Acock, 1991). Mechanistic models, on the other hand, are process based and are concerned with the interactions between all factors.

The modelling objectives for this study relate to selecting an appropriate crop simulation model which is amenable to being modified. The modifications concern the model components that describe root growth and involve factors which are controlled mainly by soil structural parameters.

The criteria used in selecting a model include scale, timestep, level of organization or detail, input data requirements and documentation. The scale at which the model will be run varies from the plot to the field scale with the option of extrapolating to smaller scales such as regional or county levels. The level of organization relates to the hierarchical level, ranging from molecular to biome, at which the model runs and at which the model outputs are interpreted. The availability and quality of input data limits the level of detail at which the model can function and the scale to which the results may be applied. For the purposes of this research, a daily time step is the most appropriate. Considering that one of the long term objectives is to use the modified model at other locations, input data will come from a variety of sources including soil survey reports. Thus, the scale of application of the model output, the level of organization and the availability of input data all influence the choice for the time step of the model.

The corn simulation model CERES-Maize (Crop Environment Resource Synthesis) was selected as best meeting the criteria for model selection for this study. The model simulates the effects of genotype, weather, soil properties and soil and nitrogen dynamics on crop response (Ritchie, 1986). A daily time step is used and the data input requirements are such that the model could be run from a minimum data set made up of soil survey type information and parameter values estimated or derived from pedotransfer functions (van Lanen and Bouma, 1988). There is a published users guide, (Ritchie et al., 1992) as well as a text explaining the equations and functions used for the various soil-plant-atmosphere processes (Jones and Kiniry, 1986).

Also of concern but not directly related to this study, is the facility with which the model results can be extrapolated from point estimates to soil polygons or landscape units. To this end, models have been incorporated into pcARC/INFO, a Geographic Information System (GIS), to facilitate the spatial nature of climate and soil variables and for extrapolation to areas where there is adequate information available for model input requirements (Hoogenboom and Gresham, 1993; Lal et al., 1993).

3.3 Parameters Used in Models 3.3.1 Meteorological variables

A weather station was established at the field site which automatically recorded solar radiation, precipitation, maximum and minimum temperatures, and wind speed. A Lycor pyranometer was used to measure solar radiation in KJ/m^2. This information was recorded as an hourly sum which was later aggregated into a daily value. A tipping bucket rain gauge measured rainfall in 0.1 mm increments which were summed to give both an hourly and a daily amount of precipitation in millimetres.

The 1992 growing season was wetter and cooler than the previous year. Prior to planting (May 9) 117 mm of rain had fallen compared to 81 mm in 1991. Through May and June there was slightly more rain than 1991. In July of 1992, however, more than three times the amount of rain fell as compared to July 1991 (77 mm to 20.4 mm). September 1992 also received more rain than September 1991. Neither OMAF or Environment Canada collects precipitation data close enough to the field site to be able to compare the 1991 and 1992 values with the 30 year normals.

Maximum daily air temperatures were generally higher in 1991 than 1992. For example, the average monthly difference between 1991 and 1992 for the months April through September was 2.8 degrees C. For the months June, July and August, 1992 was consistently 2 to 3 degrees cooler than the 30 year normals recorded at Brucefield while the 1991 temperatures were very close to the normals.

3.3.2 Plant Population

3.3.3 Root Development

Root information was collected each year to document the distribution and depth of root development over time. Soil cores were taken to a depth of 20 cm at selected benchmarks. The row position was sampled twice during the 1991 growing season, at the six leaf stage and at silking, and once during the 1992 growing season at silking. The interrow position was sampled once during each year at silking. The samples were washed to separate the roots from the soil. The root samples were then preserved in a 1:1:18 solution of glacial acetic acid, formaldehyde and ethanol. Total root length density (Lv) was estimated using the line intersect method (Tennant, 1972).

In 1991, for the first sampling date, the mean Lv at 0-20 cm for the row position in the cultivated treatment was significantly greater ($P < 0.05$) than the row position in the no-till treatment. For the second sampling in 1991, conventional till showed a significantly higher Lv ($P < 0.01$) than no-till for the row position, but no significant difference ($P > 0.10$) between tillage treatments at the inter-row position. Comparisons of the mean values of Lv between the row and the inter-row positions revealed a significant difference ($P < 0.01$) in the conventional till treatment and no significant difference ($P > 0.10$) for the no-till.

In 1992, the average Lv values were greater in the row position than in the inter-row position for both no-till and conventional till measured at silking ($P < 0.01$). There was no significant difference ($P > 0.10$) in the row position between no-till and conventional till, however, there was a significantly greater Lv ($P < 0.01$) between tillage treatments at the interrow position.

Comparing mean Lv between 1991 and 1992 shows a consistently greater Lv in 1991 than 1992. The Lv for the row and inter-row positions for both no-till and conventional till were significantly greater in 1991 than in 1992. This is due in all probability, to the cold wet growing season experienced in 1992.

3.4. Modelling Activities in Progress

3.4.1 Rationale

The agronomic implications of incorporating an assessment of soil structural parameters into a crop simulation model will be to improve the sensitivity of predicted crop response to variations in soil physical properties. The adjusted CERES-Maize model will act as a useful tool for predicting the effects of soil structure on soil productivity and in estimating the spatial variability in yields under known ranges of soil properties. This will be useful for the eventual simulation of crop rotations in sustainable land management systems and links directly into the proposed Integrated Farming Systems (IFS) research program initiated by Miller et al. (1993) as well as the soil specific crop management approach.

At present, CERES-Maize does not model the effects of soil structure on the movement and partitioning of water or on the growth and distribution of roots throughout the soil profile. This limitation may result in an incorrect estimate of root water uptake through either an overestimation of the root distribution or an overestimation of the soil water available for uptake. These limitations, and model refinements to account for the impact of soil structure on root growth, moisture uptake and movement are currently being investigated, as part of the workplan, of Mr. Ken Denholm, Agriculture Canada. Mr. Denholm was a participant in this study and the modelling phase of the study has been incorporated into the Ph.D. thesis of Mr. Denholm. All of the data collected in the study will be available to Mr. Denholm for evaluation of models. Details on the models, including an outline of limitations that must be removed, before evaluation proceeds are outlined in the following sections. Work on model development and assessment is expected to continue over the next 4 years.

3.4.2 CERES-Maize - Limitations

Root distribution is determined in CERES-Maize by a weighting factor which estimates the daily root growth in each soil layer. Root growth and water uptake estimates are used to update the volumetric soil water. There is no method for adjusting the estimated root distribution in the various layers of the soil profile for the influences of soil structure such as reduced aeration or increased penetration resistance.

Soil evaporation is calculated in a two stage process for the surface soil layer and the volumetric soil water content is adjusted daily for the amount of estimated evaporation. Transpiration is a function of estimated root growth and is controlled by plant available soil water content in the active rooting zone. Transpiration is also calculated daily and used to determine the total soil water content. In CERES-Maize, soil water contents are determined by the subroutine - WATBAL - which calculates the redistribution of water due to irrigation, precipitation and drainage and to calculate potential evapotranspiration, soil evaporation and transpiration (Jones et al., 1986). It also calculates leaching of nitrate by horizon and uses equations to simulate saturated and unsaturated flow between soil layers. The soil moisture calculated by the WATBAL subroutine is based on the drained upper limit of volumetric soil water (DUL), lower limit of plant-extractable water (LL) and the layer thickness. The model estimates DUL and LL and porosity (PO) with an algorithm using sand, silt and clay contents, bulk density, and organic carbon for each layer. The greatest limitation of the WATBAL subprogram centres on the estimation of water content, flow between layers, and the flux between saturated and unsaturated zones. This is limiting in that soil water dynamics are influenced by soil structure which is absent in the present model.

Landscape variability and slope position effects on infiltration, runoff or plant available water in the soil profile are not accounted for by the CERES-Maize model. Management impacts on soil structure varies with landscape and slope position. The effects of soil structure on plant response will then also vary with landscape. The model presently uses a runoff curve number, developed by the Soil Conservation Service, which is based on surface texture and solum depth (Ritchie et al., 1986) to estimate the amount of precipitation which runs off and the amount that enters the soil.

3.4.3 CERFS-Maize - Improvements

Although the CERES-Maize model has been tested with relatively good success at numerous sites globally (Entenmann and Allison, 1992: Saka et al., 1992), the above discussion points out several areas of the model which need to be improved. Adjusting the soil water flow/storage subprogram would allow a better estimation of the influence of soil structure on soil aeration, soil resistance and soil water dynamics during the growing season. This will be achieved by applying certain aspects of the SWATRE (Soil Water Actual Transpiration Extended) type models (discussed below) into the WATBAL subprogram of CERES-Maize.

Root growth and distribution functions in CERES-Maize also need to be improved to better assess the influence of soil structural parameters (aeration and soil resistance) on plant growth and yield. A root simulation model, described by Jones et al. (1991), will be integrated as a component of CERES-Maize. This will improve estimates of root growth and distribution by taking into account the effects of soil structural properties at the site. It would also permit the transfer of these effects into the simulation of plant growth and yields and will more realistically update the volumetric soil water content.

The effect of landscape on yield variability at the field scale, through its influence on the soil moisture regime, will be evaluated separately from the modelling part of the project. This does not mean landscape is not important in assessing the spatial variability of productivity, simply that it is beyond the scope of this project.

3.4.4 Root Simulation

Root growth and root water extraction from the various soil layers is modelled in a simplistic manner in the CERES-Maize model. A root growth simulation model, Jones et al. (1991), will be included into CERES-Maize in conjunction with the improved soil water simulation component (ie. SWATRE). Jones et al. (1991) use a series of stress factors, determined from soil profile information, to limit estimated root growth. Aeration and soil strength are included as stress factors in this approach but these will be improved upon. Also, there is a need to improve the representation of soil structure in this model before it is included into the CERES-Maize/SWATRE combined model. These improvements relate to the role of soil structure on the advancement of the rooting front, which is controlled in the present version, by soil resistance.

3.4.5 SWATRE

Including the SWATRE type models within the CERES-Maize simulation model would allow an improved estimation of the soil water regime as it fluctuates over the growing season. It would also allow for an increase in the model's capability to simulate the effects of soil physical parameters on water extraction and root growth. The SWATRE model would enhance or replace the current soil moisture subprogram, WATBAL, within CERES-Maize and would be linked to the functions and algorithms used to determine soil evaporation, transpiration, root extraction of soil water and phenological stages.

The Soil Water Actual Transpiration Extended (SWATRE) model (Feddes et al., 1988b; Belmans et al., 1983) and the ONZAT model (van Lanen et al., 1992) simulate transient, one-dimensional soil moisture flow by numerically integrating saturated and unsaturated flow using an implicit finite-difference technique. In this approach, dynamic simulation of water flow and evapotranspiration determine moisture deficit and aeration. Van Lanen and Bouma (1988), use land characteristics (eg. horizon thickness and rooting depth) as direct model inputs, or convert them into land properties (eg. moisture retention and hydraulic conductivity data) by pedofunctions to run the model. In the SWATRE type models, the soil system is divided into a number of compartments of equal height and compartments may be joined to create layers in the profile representing different physical properties (Belmans et al., 1983). The finite difference method uses a two-dimensional grid with the flow and time domains divided into equal intervals (Feddes et al., 1988b). The advantages of this approach are its relative simplicity and efficiency in solving one-dimensional unsaturated flow problems. The model does not calculate yields, however, and simply defines root water extraction as a sink term. SWATRE also ignores the influence of landscape and slope on soil water dynamics.

4. GENERAL CONCLUSIONS

The following conclusions have arisen from research directed to the identification of method(s) for measuring changes in soil structure arising from management across a range of soil conditions.

- Dispersible clay appears to be the stability parameter that is best correlated with a number of soil properties. Strongest correlation exists with fragmentation characteristics (tensile strength and dry aggregate size distribution created by tillage) and with runoff and sediment load in runoff. Dispersible clay is influenced by soil properties (clay and organic matter contents), tillage and soil water content. The influence of water content is greatest on fine textured soils. If dispersible clay is measured on fine textured soils to characterize the influence of management practices, a number of measurements at different water contents will be required to characterize the dispersible clay - water content relation. Comparisons across different textures at a site will require either data to allow for an assessment of the variable influence of water content, measurements at similar water contents (e.g. saturation), or demonstration that the spatial variation in dispersible clay exhibits temporal stability (therefore justifying comparisons made on the basis of a single sampling)

- Infiltration characteristics were found to be very variable. While tillage and soil properties (water content and dispersible clay) were significantly correlated with infiltration characteristics, these variables accounted for only about 25% of the variability in sorptivity and saturated hydraulic conductivity. Further developments in the methodology that will permit either a more rapid measurement (and therefore a larger number of measurements) or a larger sampling area are required before it would appear reasonable to use infiltration measurements on a routine basis to characterize the influence of management on soil properties.

- Soil water content measured regularly over the growing season is a reflection of infiltration, storage, drainage and evapotranspiration characteristics and appears to be a more predictable hydrologic characteristic than infiltration characteristics. Mean water contents over the growing season in the 0-20 cm depth are influenced by clay and organic matter contents, tillage and row/interrow position ($R^2 = 0.64$ in 1991, $R^2 = 0.57$ in 1992). The variation in water content over a growing season at the 0-20 cm depth also varies with soil properties and row position. Non-destructive measurements of water content through the growing season using time domain reflectometry provide data that appear to be particularly sensitive to both inherent soil properties and to management.

- Total porosity, as reflected in measurements of bulk density, is strongly influenced by soil properties and by management. The influence of management on bulk density is emphasized when a relative bulk density (observed bulk density divided by the bulk density under a standard compaction treatment) is calculated. Relative bulk densities are independent of clay and organic matter content and were found to be 0.08 higher under the no-till treatment than the conventional till treatment.

- The least limiting water range is a new parameter that incorporates structural effects on available water, aeration and soil strength. A methodology was developed to characterize this parameter. The least limiting water range was found to vary with clay and organic matter contents as well as bulk density. Soil water content data used in conjunction with least limiting water range data showed that the frequency that the soil water content fell outside the least limiting water range (a measure of cumulative stress) was negatively correlated with yield in 1991. No trend was observed in 1992, a very wet year. The parameter offers considerable potential as an index of the quality of soils for crop production. Additional research on crops other than corn and carried out under a range of climatic conditions is very strongly recommended.

- The majority of the soil structural parameters evaluated in this study are only applicable to a consolidated soil matrix. However, a fragmented matrix (seedbed) is a reality for many soils that are tilled regularly. Although fragmented conditions may only last for a few weeks or even days, they are critical to the germination and establishment of most crop species. The dry aggregate size distribution is a simple and sensitive parameter for characterizing fragmented conditions in the seed bed. Because of the lack of suitable measurement techniques, little is known about the bulk density, relative bulk density and least limiting water range of seedbeds. Further research is needed on the development of methods for measuring these parameters in seedbeds, and relating them to the dry aggregate size distribution.

Research related to evaluation of crop productivity models has been directed primarily to the collection of crop and soil data for use in the evaluation. Model evaluation has been incorporated into the work plans of an Agriculture Canada employee and will continue over the next 5 years. The model evaluation will be based, in part, on data collected in this study during the 1991 and 1992 field seasons.

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Appendix I

Summary of soil properties by depth

Table I.1 Soil characteristics for the no till treatment

Location N	Distance	Elevation	Clay[1]	Clay[2]	Silt[1]	Silt[2]	Sand[1]	Sand[2]	Organic Matter[1]	Organic Matter[2]	pH[1]	pH[2]	CaCO3 [1,3]	CaCO3 [2,3]
	(m)	(m)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)			(%)	(%)
1	0	0	24.70	4.50	41.90	21.70	33.39	73.80	11.60	1.30	6.50	7.50	0	28
2	12	0	20.00	2.90	34.70	16.80	45.30	80.30	9.80	0.80	6.80	7.40	0	49
3	20	0	16.40	4.10	28.60	25.80	54.98	70.10	9.50	0.60	6.80	7.40	0	45
4	28	0	10.90	2.90	20.90	14.30	68.21	82.90	6.20	0.60	6.90	7.50	0	39
5	37	0	11.00	2.50	21.20	19.70	67.83	77.90	6.30	0.50	7.00	7.40	3	41
6	44	0	10.00	5.30	20.00	10.60	70.03	84.10	6.20	0.80	6.90	7.30	0	13
7	73	1	9.60	4.60	21.30	21.60	69.16	73.80	5.10	1.40	6.90	7.40	0	34
8	101	1	7.50	9.70	25.90	22.00	66.59	68.20	2.70	4.90	7.10	7.00	13	1
9	128	1	14.00	4.50	29.20	17.90	56.81	77.60	6.30	0.90	7.10	7.40	11	31
10	156	2	11.70	2.90	40.70	20.10	47.57	77.10	6.60	0.50	7.10	7.40	10	43
11	181	2	13.50	6.10	30.70	20.50	55.79	73.40	5.40	0.90	7.10	7.40	5	36
12	197	2	9.60	4.50	30.40	25.70	60.02	69.80	4.90	1.30	6.70	7.50	0	32
13	211	2	10.50	4.50	24.30	13.80	65.30	91.70	4.70	1.30	6.90	7.40	0	7
14	225	3	10.00	4.80	18.80	8.50	71.17	86.70	4.80	1.10	6.90	7.20	0	6
15	239	3	7.40	5.00	12.40	16.90	80.14	78.10	2.90	3.90	6.90	7.10	0	1
16	252	3	5.70	2.80	10.70	11.00	83.60	86.20	1.40	1.60	7.00	7.10	12	1
17	259	4	6.10	1.20	12.30	6.00	81.61	92.70	1.50	0.50	7.00	7.20	13	45
18	265	4	7.80	15.70	13.90	8.80	78.33	75.50	1.60	1.10	7.10	7.30	16	11
19	272	5	10.40	6.20	20.70	24.40	68.90	69.60	2.00	1.40	7.10	7.20	9	1
20	278	5	12.80	6.90	26.80	24.80	60.44	68.30	2.40	1.30	7.20	7.10	6	1

21	285	5	12.10	9.40	22.60	30.30	65.30	60.20	2.40	1.60	7.10	7.10	7	1
22	293	5	19.30	33.00	36.90	57.80	43.80	9.20	2.90	1.30	7.10	6.60	5	1
23	301	5	16.50	19.70	34.20	58.70	49.26	21.60	2.80	1.20	7.10	6.60	3	1
24	310	4	17.70	9.40	30.70	24.50	51.63	66.10	2.70	0.80	7.00	6.70	1	1
25	319	4	14.70	8.00	27.30	36.30	57.94	55.70	3.50	2.70	6.20	6.50	0	1
26	326	3	22.80	18.40	30.80	27.40	46.43	54.20	4.30	4.10	6.50	6.60	0	1
27	351	4	21.00	22.40	33.40	24.10	45.62	53.50	4.20	3.40	6.90	6.90	0	1
28	376	4	27.00	20.90	52.40	52.50	20.64	26.60	3.00	1.80	6.90	6.90	0	1
29	399	5	34.40	19.50	57.20	49.10	8.46	1.50	2.60	1.30	7.10	7.20	3	1
30	423	5	37.70	45.10	53.80	52.30	8.47	2.60	3.40	1.60	7.10	7.00	2	2
31	446	7	34.40	37.40	46.70	61.20	18.88	1.50	2.60	1.40	7.10	7.50	5	40
32	452	7	36.70	38.20	48.80	45.90	14.41	15.90	2.50	3.40	7.30	7.10	3	1
33	469	6	34.40	28.90	47.20	69.70	18.41	1.40	2.50	1.30	7.30	7.60	5	44
34	477	6	33.20	51.50	47.70	45.80	19.15	2.80	3.80	1.40	7.10	7.30	1	3
35	483	6	33.60	44.90	50.00	46.50	16.35	8.60	3.90	1.10	7.10	7.20	3	3
36	490	7	37.40	37.30	49.80	62.10	12.81	0.60	3.50	2.40	7.10	7.50	3	34

1 = 0-20 cm
2 = 20-40 cm
3 = Soils with a pH value less than 7.0 were not analyzed for $CaCO_3$ and were assigned a value of 0.

Table I.2. Soil characteristics for the conventional till treatment

Location #	Distance	Elevation	Clay[1]	Clay[2]	Silt[1]	Silt[2]	Sand[1]	Sand[2]	Organic Matter[1]	Organic Matter[2]	pH[1]	pH[2]	CaCO3 [1,3]	CaCO3 [2,3]
	(m)	(m)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)			(%)	(%)
1	0	0	16.30	7.80	27.70	23.30	56.04	68.90	7.50	1.40	7.10	7.40	4	15
2	12	0	17.20	3.70	26.30	14.90	56.45	81.40	7.00	1.90	7.00	7.40	4	20
3	20	0	13.00	3.30	24.20	21.70	62.84	75.00	6.10	0.80	6.90	7.50	0	40
4	28	0	11.70	3.30	21.60	16.40	66.71	80.30	5.60	1.10	6.70	7.40	0	39
5	37	0	9.80	3.70	20.10	20.20	70.04	76.10	4.90	0.80	6.90	7.40	0	29
6	44	0	10.30	5.90	22.30	19.60	67.36	74.50	5.30	2.80	6.90	7.10	0	1
7	73	1	11.80	2.50	29.10	18.80	59.13	78.80	5.10	0.80	7.10	7.40	8	32
8	101	1	7.50	2.90	24.40	15.20	68.11	81.90	2.60	0.80	7.10	7.40	29	29
9	128	1	10.90	3.30	32.20	18.50	59.64	78.20	4.90	1.30	7.10	7.40	10	44
10	156	2	18.80	12.80	25.50	31.10	45.63	56.10	5.70	2.00	7.10	7.20	6	3
11	181	2	13.50	11.60	24.50	23.30	62.05	65.10	5.10	1.80	7.20	7.30	6	6
12	197	2	14.90	13.30	24.70	28.70	60.41	57.90	4.80	4.80	7.10	7.30	8	3
13	211	2	12.00	6.20	27.40	16.10	60.61	77.70	4.60	2.00	7.10	7.00	4	17
14	225	2	13.00	5.30	24.40	11.40	62.55	83.30	4.40	2.40	7.10	7.00	2	1
15	239	3	9.60	7.90	18.40	14.10	72.01	78.00	3.40	4.60	7.00	7.00	1	1
16	252	3	9.60	5.00	17.90	14.50	72.57	80.50	2.60	2.30	7.00	7.00	2	2
17	259	4	10.40	5.00	20.90	14.50	68.68	85.00	2.30	2.30	7.00	7.00	4	1
18	265	4	15.90	5.30	32.30	9.40	51.80	85.30	2.60	1.30	7.10	7.20	3	43
19	272	4	19.70	5.30	35.60	26.70	44.72	68.00	2.50	1.00	7.20	6.80	3	1
20	278	5	25.90	11.90	39.70	37.80	34.39	50.20	2.00	1.50	7.10	6.80	3	2

21	285	5	24.50	14.50	47.40	33.50	28.07	52.10	2.40	1.10	7.20	7.30	8	27
22	293	5	26.10	34.50	48.90	39.90	25.07	25.60	2.60	1.30	7.20	7.10	3	2
23	301	5	29.10	39.50	54.90	53.40	15.93	7.10	3.30	2.10	7.10	7.10	3	2
24	310	4	27.90	21.60	54.90	18.00	17.26	60.40	2.70	1.20	7.20	6.90	4	1
25	319	4	25.90	19.10	51.70	41.90	22.44	38.00	3.10	3.20	7.00	6.60	1	1
26	326	4	29.40	23.70	46.20	34.10	24.35	42.10	2.40	2.90	7.10	6.90	2	2
27	351	4	23.90	27.40	39.40	31.10	36.77	41.50	4.00	4.90	7.20	7.10	4	3
28	376	4	29.80	28.90	49.90	55.80	20.29	15.30	3.80	3.90	7.30	7.20	5	3
29	399	5	42.30	26.10	49.70	13.90	7.96	60.00	2.20	0.90	7.30	7.00	5	1
30	423	5	39.50	48.30	51.20	50.40	9.33	1.30	3.10	1.70	7.00	7.30	3	5
31	446	7	37.80	40.20	48.00	57.80	14.24	2.00	2.90	1.80	7.30	7.70	4	36
32	452	7	32.10	54.00	45.40	43.10	22.44	2.90	2.50	1.30	7.40	7.30	7	10
33	469	7	35.60	37.70	47.10	61.00	17.32	1.30	3.10	1.60	7.40	7.50	3	42
34	477	6	34.30	46.40	46.40	49.30	19.26	4.30	3.40	1.20	7.30	7.30	2	8
35	483	6	35.30	37.70	44.40	47.60	20.27	14.70	3.90	2.90	7.40	7.40	2	6
36	490	7	37.40	41.30	47.10	56.70	15.43	2.10	3.70	1.60	7.30	7.70	2	21

1 = 0-20 cm
2 = 20-40 cm
3 = Soils with a pH value less than 7.0 were not analyzed for $CaCO_3$ and were assigned a value of 0.

Appendix II

Summary of soil properties by horizon

TABLE II.1 Soil profile characteristics for the no till treatment

LOCATION #	HORZ	UP	LOW	SAND	SILT	CLAY	TEXTUR	PH	CACO3	OM
1	Ap	0	20	56	28	16	FSL	6.9	0.0	7.1
1	Bm	20	35	68	23	9	FSL	7.2	6.8	0.8
1	Bm2	35	45	71	24	5	FSL	7.3	36.6	0.8
1	Ck	45	55	77	20	3	LFS	7.5	42.3	0.0
2	Ap	0	20	60	25	15	FSL	7.0	4.6	7.2
2	Bm	20	25	69	28	3	FSL	7.3	48.1	0.6
2	Ckgj	25	60	78	19	3	LFS	7.7	49.1	0.0
3	Ap	0	20	63	23	13	FSL	7.1	3.2	6.7
3	Bm	20	33	75	18	7	FSL	7.1	10.2	0.9
3	Ckgj	33	55	80	16	4	LFS	7.5	46.6	0.0
4	Ap	0	20	66	22	12	FSL	7.0	3.0	6.5
4	Bm	20	30	85	10	4	LFS	7.2	5.1	0.4
4	Ckgj	30	63	81	16	3	LFS	7.5	41.6	0.0
5	Ap	0	20	68	21	11	FSL	7.1	4.5	6.5
5	Bm	20	36	85	12	3	LFS	7.4	17.1	0.6
5	Ckgj1	36	50	79	17	3	LFS	7.6	46.4	0.0
5	Ckgj2	50	68	73	24	3	FSL	7.8	50.9	0.0
6	Ap	0	25	67	22	11	FSL	7.1	5.7	5.2
6	Ckgj	25	50	78	19	3	LS	7.4	47.5	0.0
6	(IICk	50	90	27	62	11	SIL	7.6	49.1	0.0
6	(IICk	50	90	65	32	4	FSL	7.7	52.2	0.0

7	Ap	0	20	65	24	11	FSL	7.1	5.7	5.1
7	Ckg1	20	40	79	18	4	LFS	7.3	32.9	0.0
7	Ckg2	40	62	83	15	2	LFS	7.7	46.5	0.0
8	Ap	0	23	66	26	8	FSL	7.2	13.0	4.1
8	Smgj	23	30	75	20	5	VFSL	7.2	24.0	2.0
8	Ckgj	30	44	76	20	4	LFS	7.4	29.7	0.0
8	Ckg2	44	110	68	28	4	VFSL	7.7	47.6	0.0
9	Ap	0	20	61	33	6	FSL	7.3	13.8	4.6
9	Ckgj	20	40	78	19	2	LS	7.4	49.4	0.0
9	Ckg	40	83	84	13	3	LVFS	7.6	44.4	0.0
10	Ap	0	22	49	39	13	L	7.2	8.5	5.6
10	Sm	22	34	59	28	13	FSL	7.2	2.0	1.4
10	Ckgj1	34	68	67	29	4	FSL	7.4	36.0	0.0
10	Ckgj2	68	78	57	38	5	VFSL	7.7	46.9	0.0
11	Ap	0	20	62	28	10	FSL	7.2	7.4	4.1
11	Bm1	20	34	67	24	9	FSL	7.2	3.0	2.1
11	Sm2	34	47	74	18	7	FSL	7.3	13.7	0.6
11	Ck	47	52	68	28	4	GSL	7.7	54.9	0.0
12	Ap	0	25	58	30	12	FSL	7.3	6.1	5.3
12	Apb	25	35	60	32	9	FSL	0.0	0.0	9.9
12	Smgj	35	61	73	23	4	FSL	7.5	28.7	0.7
12	Ckgj	61	95	82	16	1	LFS	7.7	44.1	0.0
13	Ap1	0	20	61	29	10	FSL	7.4	3.9	4.9
13	Ap2	20	30	65	29	6	FSL	7.4	3.5	5.2

13	Bmgj	30	57	68	22	10	FSL	7.4	7.7	1.0
13	2Ckgj	57	69	15	66	18	SIL	7.8	43.9	0.0
13	3Ckg	69	100	82	16	2	LFS	7.8	42.4	0.0
14	Ap1	0	26	68	21	10	SL	7.3	3.9	4.1
14	Ap2	26	32	73	23	4	FSL	7.3	0.0	10.3
14	Bm	32	50	84	12	4	LS	7.5	11.4	1.0
14	Ckg	50	88	88	10	2	FS	7.7	41.3	0.0
14	2Ckg	88	100	19	66	15	SIL	7.9	49.7	0.0
15	Ap	0	25	77	15	8	FSL	7.4	2.5	3.5
15	Bmgj1	25	47	84	9	7	LS	7.5	2.6	1.0
15	Smgj2	47	74	84	13	3	LS	7.5	23.7	0.6
15	Ckg	74	0	90	9	1	FS	7.7	42.9	0.0
16	Ap	0	23	78	15	7	LS	7.4	5.2	2.5
16	Bm	23	35	86	10	4	LS	7.5	5.1	1.1
16	Bmgj1	35	70	82	14	3	LS	7.6	25.1	0.7
16	Bmgj2	70	89	83	15	3	LS	7.5	28.4	0.7
16	Ckg	89	103	85	12	3	LS	7.7	39.8	0.0
17	Ap	0	24	76	16	8	FSL	7.3	7.2	2.3
17	Bm	24	88	88	8	4	S	7.4	1.4	0.8
17	Smgj	88	93	85	13	2	LS	7.5	33.1	0.5
17	Ckgj	93	103	89	10	1	S	7.6	41.0	0.0
18	Ap	0	27	72	19	9	FSL	7.4	7.3	2.3
18	Ckgj	27	48	93	5	2	S	7.6	42.9	0.0
18	Ckg	48	110	96	3	1	S	7.8	46.0	0.0

19	Ap	0	20	59	27	13	FSL	7.5	3.8	2.6
19	Sm	20	68	67	12	21	SCL	7.5	5.3	1.0
19	Ckgj	68	97	92	5	4	S	7.6	45.7	0.0
20	Ap	0	22	47	36	17	L	7.6	7.8	2.6
20	Sm	22	38	71	12	17	VFSL	7.5	28.1	0.8
20	Ckgj	38	65	87	11	3	FS	7.8	50.5	0.0
20	2Ckgj	65	75	8	61	31	SICL	7.8	49.6	0.0
20	3Ckgj	75	105	86	13	1	FS	7.9	51.8	0.0
21	Ap	0	22	30	49	21	L	7.5	4.4	2.6
21	Bm1	22	72	35	43	21	L	7.5	10.7	1.2
21	Bm2	72	90	81	16	4	LFS	7.6	40.3	0.5
21	Ckgj1	90	102	14	65	21	SIL	7.8	44.7	0.0
21	Ckgj2	102	110	43	54	3	SIL	7.7	52.5	0.0
22	Ap	0	12	26	49	25	L	7.5	4.4	2.6
22	Smgj	12	41	2	66	32	SICL	7.7	28.1	0.9
22	Ckgj	41	50	1	72	27	SICL	7.8	45.8	0.0
22	Ckgj2	50	90	24	63	13	SIL	7.8	43.8	0.0
23	Ap	0	20	18	55	27	SIL	7.5	3.0	3.1
23	Sm	20	95	26	38	36	CL	7.5	3.5	0.8
24	Ap	0	21	21	53	27	SIL	7.3	4.1	2.9
24	Bm1	21	40	62	16	22	SCL	7.3	6.3	1.0
24	Sm2	40	55	82	14	4	LVFS	7.6	43.5	0.4
24	Ckgj	55	90	49	46	4	VFSL	7.7	49.9	0.0
24	Ckgj	70	80	15	59	26	SIL	7.7	50.1	0.0

25	Ap1	0	25	27	51	22	SIL	7.3	1.4	3.3
25	Ap2	25	45	37	45	18	L	7.0	1.1	2.9
25	Bm1	45	60	39	38	23	L	7.1	1.0	1.2
25	Bm2	60	90	69	11	21	SCL	7.1	1.4	0.8
25	Bm3	90	110	74	8	18	FSL	7.1	1.4	0.8
26	Ap1	0	25	29	46	25	L	7.3	1.6	3.2
26	Ap2	25	34	39	40	21	L	7.4	2.3	2.7
26	AB	34	55	47	33	20	L	7.5	4.0	2.5
26	Bmgj1	55	68	59	24	17	FSL	7.3	1.1	1.0
26	Bmgj2	68	86	71	16	13	FSL	7.5	28.2	0.8
26	Ckgj	86	108	87	7	6	LS	7.6	44.1	0.0
27	Ap1	0	25	48	35	16	L	7.5	20.6	3.6
27	Ap2	25	41	43	39	18	L	7.4	18.6	3.3
27	Ck	41	55	46	38	16	L	7.4	28.5	0.0
27	Ckgj	55	100	86	9	6	LFS	7.7	47.9	0.0
28	Ap	0	25	16	54	30	SICL	7.4	3.3	3.5
28	Bg	25	50	9	55	36	SICL	7.5	6.2	1.5
28	Ckg	50	80	37	51	12	SIL	7.7	43.9	0.0
28	2Ckg	80	100	4	53	44	SIC	7.8	44.7	0.0
29	Ap	0	20	22	47	31	CL	7.5	5.4	2.8
29	Bm	20	40	47	31	21	L	7.4	1.2	0.7
29	Btj	40	58	4	51	45	SIC	7.6	6.9	0.8
29	Ckgj	58	80	2	59	38	SICL	7.7	36.4	0.0
29	Ckg	80	96	1	79	20	SIL	7.7	43.0	0.0

30	Ap	0	25	10	53	37	SICL	7.5	3.4	3.0
30	Bmgj	25	56	1	45	54	SIC	7.6	4.6	1.2
30	Ckg	56	102	1	64	35	SICL	7.7	27.5	0.0
31	Ap	0	20	20	47	33	CL	7.6	5.7	2.5
31	Bmgj	20	30	6	41	53	SIC	7.5	4.6	0.9
31	Ckgj	30	58	1	57	41	SIC	7.7	38.9	0.0
31	Ckg	58	70	2	71	27	SIL	7.6	47.5	0.0
32	Ap	0	20	21	47	32	CL	7.5	5.8	2.6
32	Bmgj	20	30	2	43	55	SIC	7.5	6.9	1.2
32	Ckg	30	70	1	60	38	SICL	7.7	39.6	0.0
33	Ap	0	20	18	48	34	SICL	7.6	4.1	2.7
33	Ckg1	20	40	1	58	41	SIC	7.6	41.1	0.0
33	Ckg2	40	80	1	64	35	SICL	7.7	50.4	0.0
34	Ap	0	20	22	47	31	CL	7.4	2.7	3.3
34	Bmgj	20	40	1	42	56	SIC	7.4	4.6	0.8
34	Ckg1	40	65	1	61	38	SICL	7.6	39.4	0.0
34	Ckg2	65	90	1	63	36	SICL	7.7	42.9	0.0
35	Ap	0	20	16	49	34	SICL	7.4	2.7	3.5
35	Bmgj	20	60	5	43	53	SIC	7.5	1.4	1.0
35	Ckg	60	80	4	55	41	SIC	7.6	41.7	0.0
36	Ap	0	20	14	50	35	SICL	7.5	4.3	3.5
36	Bmgj	20	35	7	49	44	SIC	7.4	2.7	1.2
36	Ckg	35	85	1	62	37	SICL	7.7	45.5	0.0

TABLE II.2 Soil profile characteristics for the conventional till treatment

LOCATION I	HORIZON	UP	LOW	SAND	SILT	CLAY	TEXTURE	PH	CACO3	OM
1	Ap	0	20	56	28	16	FSL	6.9	0.0	7.1
1	Bm	20	35	68	23	9	FSL	7.2	6.8	0.8
1	Bm2	35	45	71	24	5	FSL	7.3	36.6	0.8
1	Ck	45	55	77	20	3	LFS	7.5	42.3	0.0
2	Ap	0	20	60	25	15	FSL	7.0	4.6	7.2
2	Bm	20	25	69	28	3	FSL	7.3	48.1	0.6
2	Ckgj	25	60	78	19	3	LFS	7.7	49.1	0.0
3	Ap	0	20	63	23	13	FSL	7.1	3.2	6.7
3	Bm	20	33	75	18	7	FSL	7.1	10.2	0.9
3	Ckgj	33	55	80	16	4	LFS	7.5	46.6	0.0
4	Ap	0	20	66	22	12	FSL	7.0	3.0	6.5
4	Bm	20	30	85	10	4	LFS	7.2	5.1	0.4
4	Ckgj	30	63	81	16	3	LFS	7.5	41.6	0.0
5	Ap	0	20	68	21	11	FSL	7.1	4.5	6.5
5	Sm	20	36	85	12	3	LFS	7.4	17.1	0.6
5	Ckgj1	36	50	79	17	3	LFS	7.6	46.4	0.0
5	Ckgj2	50	68	73	24	3	FSL	7.8	50.9	0.0
6	Ap	0	25	67	22	11	FSL	7.1	5.7	5.2
6	Ckgj	25	50	78	19	3	LS	7.4	47.5	0.0
6	(IICk	50	90	27	62	11	SIL	7.6	49.1	0.0
6	(IICk	50	90	65	32	4	FSL	7.7	52.2	0.0
7	Ap	0	20	65	24	11	FSL	7.1	5.7	5.1

7	Ckg1	20	40	79	18	4	LFS	7.3	32.9	0.0
7	Ckg2	40	62	83	15	2	LFS	7.7	46.5	0.0
8	Ap	0	23	66	26	8	FSL	7.2	13.0	4.1
8	Bmgj	23	30	75	20	5	VFSL	7.2	24.0	2.0
8	Ckgj	30	44	76	20	4	LFS	7.4	29.7	0.0
8	Ckg2	44	110	68	28	4	VFSL	7.7	47.6	0.0
9	Ap	0	20	61	33	6	FSL	7.3	13.8	4.6
9	Ckgj	20	40	78	19	2	LS	7.4	49.4	0.0
9	Ckg	40	83	84	13	3	LVFS	7.6	44.4	0.0
10	Ap	0	22	49	39	13	L	7.2	8.5	5.6
I0	Sm	22	34	59	28	13	FSL	7.2	2.0	1.4
10	Ckgj1	34	68	67	29	4	FSL	7.4	36.0	0.0
10	Ckgj2	68	78	57	38	5	VFSL	7.7	46.9	0.0
11	Ap	0	20	62	28	10	FSL	7.2	7.4	4.1
11	Bm1	20	34	67	24	9	FSL	7.2	3.0	2.1
11	Bm2	34	47	74	18	7	FSL	7.3	13.7	0.6
11	Ck	47	52	68	28	4	GSL	7.7	54.9	0.0
12	Ap	0	25	58	30	12	FSL	7.3	6.1	5.3
12	Apb	25	35	60	32	9	FSL	0.0	0.0	9.9
12	Smgj	35	61	73	23	4	FSL	7.5	28.7	0.7
12	Ckgj	61	95	82	16	1	LFS	7.7	44.1	0.0
13	Ap1	0	20	61	29	10	FSL	7.4	3.9	4.9
13	Ap2	20	30	65	29	6	FSL	7.4	3.5	5.2
13	Bmgj	30	57	68	22	10	FSL	7.4	7.7	1.0

13	2Ckgj	57	69	15	66	18	SIL	7.8	43.9	0.0
13	3Ckg	69	100	82	16	2	LFS	7.8	42.4	0.0
14	Api	0	26	68	21	10	SL	7.3	3.9	4.1
14	Ap2	26	32	73	23	4	FSL	7.3	0.0	10.3
14	Bm	32	50	84	12	4	LS	7.5	11.4	1.0
14	Ckg	50	88	88	10	2	FS	7.7	41.3	0.0
14	2Ckg	88	100	19	66	15	SIL	7.9	49.7	0.0
15	Ap	0	25	77	15	8	FSL	7.4	2.5	3.5
15	Bmgj1	25	47	84	9	7	LS	7.5	2.6	1.0
15	Bmgj2	47	74	84	13	3	LS	7.5	23.7	0.6
15	Ckg	74	0	90	9	1	FS	7.7	42.9	0.0
16	Ap	0	23	78	15	7	LS	7.4	5.2	2.5
16	Bm	23	35	86	10	4	LS	7.5	5.1	1.1
16	Bmgj1	35	70	82	14	3	IS	7.6	25.1	0.7
16	Bmgj2	70	89	83	15	3	LS	7.5	28.4	0.7
16	Ckg	89	103	85	12	3	LS	7.7	39.8	0.0
17	Ap	0	24	76	16	8	FSL	7.3	7.2	2.3
17	Bm	24	88	88	8	4	S	7.4	1.4	0.8
17	Bmgj	88	93	85	13	2	LS	7.5	33.1	0.5
17	Ckgj	93	103	89	10	1	S	7.6	41.0	0.0
18	Ap	0	27	72	19	9	FSL	7.4	7.3	2.3
18	Ckgj	27	48	93	5	2	S	7.6	42.9	0.0
18	Ckg	48	110	96	3	1	S	7.8	46.0	0.0
19	Ap	0	20	59	27	13	FSL	7.5	3.8	2.6

19	Bm	20	68	67	12	21	SCL	7.5	5.3	1.0
19	Ckgj	68	97	92	5	4	S	7.6	45.7	0.0
20	Ap	0	22	47	36	17	L	7.6	7.8	2.6
20	Bm	22	38	71	12	17	VFSL	7.5	28.1	0.8
20	Ckgj	38	65	87	11	3	FS	7.8	50.5	0.0
20	2Ckgj	65	75	8	61	31	SICL	7.8	49.6	0.0
20	3Ckgj	75	105	86	13	1	FS	7.9	51.8	0.0
21	Ap	0	22	30	49	21	L	7.5	4.4	2.6
21	Bm1	22	72	35	43	21	L	7.5	10.7	1.2
21	Bm2	72	90	81	16	4	LFS	7.6	40.3	0.5
21	Ckgj1	90	102	14	65	21	SIL	7.8	44.7	0.0
21	Ckgj2	102	110	43	54	3	SIL	7.7	52.5	0.0
22	Ap	0	12	26	49	25	L	7.5	4.4	2.6
22	Bmgj	12	41	2	66	32	SICL	7.7	28.1	0.9
22	Ckgj	41	50	1	72	27	SICL	7.8	45.8	0.0
22	Ckgj2	50	90	24	63	13	SIL	7.8	43.8	0.0
23	Ap	0	20	18	55	27	SIL	7.5	3.0	3.1
23	Bm	20	95	26	38	36	CL	7.5	3.5	0.8
24	Ap	0	21	21	53	27	SIL	7.3	4.1	2.9
24	Bm1	21	40	62	16	22	SCL	7.3	6.3	1.0
24	Bm2	40	55	82	14	4	LVFS	7.6	43.5	0.4
24	Ckgj	55	90	49	46	4	VFSL	7.7	49.9	0.0
24	Ckgj	70	80	15	59	26	SIL	7.7	50.1	0.0
25	Ap1	0	25	27	51	22	SIL	7.3	1.4	3.3

25	Ap2	25	45	37	45	18	L	7.0	1.1	2.9
25	Bm1	45	60	39	38	23	L	7.1	1.0	1.2
25	Bm2	60	90	69	11	21	SCL	7.1	1.4	0.8
25	Bm3	90	110	74	8	18	FSL	7.1	1.4	0.8
26	Ap1	0	25	29	46	25	L	7.3	1.6	3.2
26	Ap2	25	34	39	40	21	L	7.4	2.3	2.7
26	AB	34	55	47	33	20	L	7.5	4.0	2.5
26	Bmgj1	55	68	59	24	17	FSL	7.3	1.1	1.0
26	Bmgj2	68	86	71	16	13	FSL	7.5	28.2	0.8
26	Ckgj	86	108	87	7	6	LS	7.6	44.1	0.0
27	Ap1	0	25	48	35	16	L	7.5	20.6	3.6
27	Ap2	25	41	43	39	18	L	7.4	18.6	3.3
27	Ck	41	55	46	38	16	L	7.4	28.5	0.0
27	Ckgj	55	100	86	9	6	LFS	7.7	47.9	0.0
28	Ap	0	25	16	54	30	SICL	7.4	3.3	3.5
28	Bg	25	50	9	55	36	SICL	7.5	6.2	1.5
28	Ckg	50	80	37	51	12	SIL	7.7	43.9	0.0
28	2Ckg	80	100	4	53	44	SIC	7.8	44.7	0.0
29	Ap	0	20	22	47	31	CL	7.5	5.4	2.8
29	Bm	20	40	47	31	21	L	7.4	1.2	0.7
29	Btj	40	58	4	51	45	SIC	7.6	6.9	0.8
29	Ckgj	58	80	2	59	38	SICL	7.7	36.4	0.0
29	Ckg	80	96	1	79	20	SIL	7.7	43.0	0.0
30	Ap	0	25	10	53	37	SICL	7.5	3.4	3.0

30	Bmgj	25	56	1	45	54	SIC	7.6	4.6	1.2
30	Ckg	56	102	1	64	35	SICL	7.7	27.5	0.0
31	Ap	0	20	20	47	33	CL	7.6	5.7	2.5
31	Bmgj	20	30	6	41	53	SIC	7.5	4.6	0.9
31	Ckgj	30	58	1	57	41	SIC	7.7	38.9	0.0
31	Ckg	58	70	2	71	27	SIL	7.6	47.5	0.0
32	Ap	0	20	21	47	32	CL	7.5	5.8	2.6
32	Bmgj	20	30	2	43	55	SIC	7.5	6.9	1.2
32	Ckg	30	70	1	60	38	SICL	7.7	39.6	0.0
33	Ap	0	20	18	48	34	SICL	7.6	4.1	2.7
33	Ckg1	20	40	1	58	41	SIC	7.6	41.1	0.0
33	Ckg2	40	80	1	64	35	SICL	7.7	50.4	0.0
34	Ap	0	20	22	47	31	CL	7.4	2.7	3.3
34	Bmgj	20	40	1	42	56	SIC	7.4	4.6	0.8
34	Ckg1	40	65	1	61	38	SICL	7.6	39.4	0.0
34	Ckg2	65	90	1	63	36	SICL	7.7	42.9	0.0
35	Ap	0	20	16	49	34	SICL	7.4	2.7	3.5
35	Bmgj	20	60	5	43	53	SIC	7.5	1.4	1.0
35	Ckg	60	80	4	55	41	SIC	7.6	41.7	0.0
36	Ap	0	20	14	50	35	SICL	7.5	4.3	3.5
36	Bmgj	20	35	7	49	44	SIC	7.4	2.7	1.2
36	Ckg	35	85	1	62	37	SICL	7.7	45.5	0.0