TILTH STRUCTURE AND SOIL PHYSICAL CONDITIONS

A thesis
submitted by

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SUMMARY

The following broad areas are reviewed:

(a) genesis, and deformation of soil structure,

(b) measurement of soil structure,

(c) tillage, and soil water and temperature, and

(d) water vapour transport in soil.

Technique

A new method of measuring the internal macro-structure of tilled soil *in situ* was successfully applied in field investigations of the effects of tilth structure and meterological factors on tilth water and temperature. Tilled soils were impregnated with paraffin wax, sections were cut through impregnated tilth block samples, and primary structural data of the distribution of intercepted aggregates and pores at 1 mm intervals were collected from within the top 6 cm of tilled soils. Statistical calculations of the proportions of different sizes of aggregates and pores were performed. Structural parameters including mean (number - mean) aggregate or pore size, tilth structural entropy, and macroporosity were also derived. At least four sets of primary structural data were collected for each tillage treatment. Tillage was done to about 10 cm depth.

Structures produced by tillage

Progressive decreases in structural entropy, and the proportion of aggregates and pores smaller than 8 mm were observed from the lower levels to the upper levels of tilled soils.

The tilth produced by ploughing was more cloddy than that produced by tillage with a rotary cultivator or scarifier. The scarifier produced the least proportion of clods larger than 8 mm.

Maximum production of small aggregates and pores and maximum structural entropy by disc ploughing were attained after the second pass of the implement.

Tillage with a pass of a tined implement after a single pass of a plough caused increased structural entropy and proportion of small aggregates and pores, and reduced mean aggregate size and macroporosity.

Tillage with a pass of a tined implement with wide points alone or after ploughing produced greater structural entropy, and proportion of small aggregates and pores smaller than 8 mm than tillage with a pass of a tined implement with narrow points (width smaller than 70 mm).

Repeated tillage with tined implements up to three consecutive passes caused a progressive increase in the proportion of small aggregates and pores smaller than 8 mm.

Tillage with two passes of a disc plough, or three passes of a tined implement, or a pass of a tined implement after disc ploughing produced comparatively small proportions of aggregates and voids larger than 8 mm.

Factors determining tilth structure

Continuous cropping as opposed to the inclusion of fallow in rotation led to the production of greater proportions of aggregates and pores larger than 8 mm during tillage.

The inclusion of pasture in rotation with wheat and fallow increased the amount of small aggregates and pores smaller than 8 mm when tillage was done. The same attributes applied to plots that came out of pasture compared with plots that came out of fallow or wheat.

Tillage at a water content slightly below Plastic Limit (0.87 of Plastic Limit) or Field Capacity (0.94 of Field Capacity) produced the smallest proportion of clods and voids larger than 8 mm compared with tillage at greater or smaller water contents. The greatest proportion of clods occurred in the tilth produced at the smallest water content.

Rainfall during the cropping season caused a reduction in the proportion of aggregates and pores smaller than 8 mm in the top zone of tilled soils. This effect can be prevented by early crop cover.

Tilth structure, meteorological factors and tilth temperature

Tilth structure had no significant effect on mean tilth temperature. However, tilth macroporosity was positively correlated with daily temperature range and the vertical gradient of tilth temperature. Multiple regression equations of mean tilth temperature on major meteorological factors, and of tilth temperature range and gradient meteorological and tilth structure have been developed.

Tilth temperature was positively correlated with air temperature and windspeed. The effect of tilth water content was small compared with those of meteorological factors. However, increased water content increased the vertical temperature gradient.

Tilth structure, meteorological factors, and tilth water content

Regressions of daily mean tilth water content on tillage treatment effect and on meteorological factors were performed. The void size distribution was the principal soil structural feature that effected differences in tilth water content. The porosity in voids larger than 8 mm gave the greatest negative correlation with mean tilth water content.

The drying of tilled soils was concluded to occur mainly by convective transport of heat and water vapour through voids larger than

8 mm to about 5 cm depth. The meteorological factor mostly causing tilth water loss was air temperature, followed by wind speed.

Transportation and distribution of water in tilled soil

There was a mean increase in gravimetric water content of 1 to 2% at the bottom of tilled soils during the hottest times of day. The magnitudes of tilth water loss during the day which varied between 1 to 8% were almost the same as the magnitudes of gain over night.

In laboratory investigations, it was found that evaporation took place most intensely within 2 cm from the soil surface or source of heat but extended down to 6 cm. Evaporated water condensed mainly within 8 cm from the evaporation zone, while the greatest water content was detected about 4 cm from the evaporation zone.

Soil temperature gradient and its duration of application were positively correlated to the amount of water vapour transferred and how far it was transferred in soils at water contents between wilting point and field capacity. Water contents at different depths in tilled soil were influenced by their relative positions in relation to the direction of temperature gradient.

Implications for agriculture

It is shown that the structure of the tilled layer of soil influences the physical conditions within it. Structure can be modified by using different tillage implements and by tilling under different conditions.

The physical conditions that can be modified by tillage include the daily temperature range and the mean water content. Both of these factors are important for crop growth. Daily temperature range influences the germination of seeds, the viability of seedlings and the mobility of nutrients in the soil.

The study of these effects is of prime importance to the overall performance of crops since the majority of plant roots and the majority of nutrients exist within the tilled layer of soil.

DECLARATION

This thesis contains no material which has been accepted for the award of any other degree of diploma in any University, and to the best of the author's knowledge and belief, the thesis contains no material previously published or written by another person, except where due reference is made in the text of the thesis.

S. Olusola Ojeniyi

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ABBREVIATIONS

$\overline{D}$	=	Mean aggregate size (mm)
$\overline{\delta}$	=	Mean pore size (mm)
PL	=	Plastic Limit (lower)
ψ_m	=	Water potential (cm or mbar)
ψ_{grad}	=	Water potential gradient
k	=	Permeability
K	=	Hydraulic conductivity
ε	=	Air filled porosity
Do	=	Diffusion coefficient of gas in air
D*	=	Diffusion coefficient of gas in soil
w (or W)	=	Gravimetric soil water content (%)
θ	=	Volumetric water content (%)
r.h.	=	Relative humidity
df	=	Degree of freedom
SSD	=	Sum of square deviation
MSD	=	Mean square deviation
F	=	Treatment MSD/Error (Residual) MSD
η_L	=	Macroporosity in tilled soil

CHAPTER 1

INTRODUCTION

1.1 Experimental and Method

Planting of crops is normally initiated by the breaking up (or tillage) of a consolidated soil mass to produce a tilth which forms the seedbed.

The major problem in carrying out reliable investigations on the physical properties and state of tilled soil formerly was the lack of a method of evaluating the *in situ* structure of tilled soil. Structure in this sense refers to the spatial distribution and arrangement of aggregates and voids.

A new sensitive method that measures the undisturbed spatial macro-structure of tilled soil is utilized in this research in the investigation of major structural properties of, and physical processes in the seedbed. In essence, the statistical distributions of intercepted aggregate and pore sizes at least 1 mm in diameter in the top zone of 10 cm thick tilths are evaluated. The top 5 cm of a tilled soil normally constitutes the seedbed. Paraffin impregnated tilth block samples collected from tilled soils were sectioned. Other parameters including mean aggregate or pore size, structural variability or entropy, and macroporosity are used in the characterisation of the structures of tilled soils. By the use of the method, the assessment of the proportion of large voids which is lacking in methods used to measure soil structure (such as wet or dry sieving) is possible. Dry or wet sieving for aggregate size distribution is not sensitive and the result depends on the methods of sampling and sieving and in any case gives no information about void sizes.

Tillage mainly affects soil macro-structure; and macro-structure has been connected (Salter, 1940; Greenland, 1971; Taylor and Ashcroft, 1972) with adequate aeration and water status and favourable root-soil relationships in the seedbed.

With the method of measuring the internal tilth structure established, investigations based on important physical factors and processes of the seedbed were carried out using replicated experiments. The sole aim of this exercise, apart from probing into the subject matter of the physics of the seedbed, is to examine the suitability of the above new method of evaluating the structure of tilled soil in place.

The investigations carried out dealt with the structural state of tilled soil, its creation, and its influence on the major physical factors of the seedbed especially water and temperature. The findings are expected to assist in efficient land preparation for arable use.

The experimental aspect of this research starts with the description of the methods used in evaluating tilth structure. The reporting of investigations then follow in sequence.

Tilth structures produced by tillage systems were measured to relate their differences to basic processes occurring during tillage. The findings are expected to assist in providing basis for choice of implement for specific seedbed type, and for recommendations concerning reduced tillage for seedbed preparation.

The major factors which could determine or influence the soil structure produced by tillage are cropping history, soil water content, and rainfall. The effects of cropping practises and rotations on tilth structure later produced were investigated. The tilth structures that resulted from different initial soil water contents were characterised. Seasonal changes in the structures of tilled soils attributable to rainfall were traced. The observations resulting from these investigations may assist in the management of arable soil to maintain some specific desirable state.

The three principal physical factors affecting seedling performance are the structure of the seedbed, temperature, and water content. Within the seedbed, the soil structure indirectly determines soil water and temperature conditions through its effect on the influence of meteorological factors on these factors. Essentially the soil structure is the independent factor while the soil water and temperature conditions are the dependent factors. A most important reason for measuring tilth structure is to be able to relate it with the dependent factors of water and temperature.

Therefore, different tilth structures were produced by different tillage systems and structural characteristics and parameters were related to absolute temperature, temperature distribution, heat and air transfer into the soil, and water content and its distribution in the soil.

It will be unrealistic to isolate the effect of tilth structure on temperature and its distribution without due reference to the role of meteorological factors that have more directeffect on tilth temperature. A statistical analysis of the dependence of tilth temperature and its gradient on tilth structure, air temperature, relative humidity, wind intensity, and soil water was performed.

The analytical and statistical examination of the dependence of tilth water content and its gradient on structural and meteorological factors was also performed.

With assumption of the intermittent nature of rainfall, for most of the time water movement within the seedbed is in vapour form. A thorough discussion of the dependence of tilth water content on structural and meteorological factors must refer to the phenomenon of water vapour transfer in soil. Thermal transfer of water has long been confirmed by laboratory experiments. Its importance, and the distribution of condensed water vapour in soil have been investigated by Rose (1968) and Gurr *et al.* (1952). However, no known attempt exists to relate findings on thermal water transfer and its significance to observed distribution and variation of water content in the seedbed.

Therefore, a laboratory project was conducted on the relationship between temperature gradient and quantity and distribution of condensed water vapour. The findings were related to observed variation in water content at different times of day and at different depths within the seedbed.

Furthermore, the need for the investigations is based on the fact that while there exists a considerable body of theoretical information on transfer of water, gases, and heat in soil, the practical application of theory to agriculturally important situations is not particularly advanced (Smiles, 1977). As a result, there have been serious criticisms of the direction of research in some areas of soil physics. According to Smiles, the basic point is that major problems in many areas of soil physical research appear to lie in bridging the gap between theoretical expertise and biological practise.

The investigations covered by this research are mainly directed at problem areas related to the physical properties of seedbeds. Findings from previous laboratory and empirical investigations are related as much as possible to results from field experiments covered by this research.

The principles, observations and findings generated could contribute to the control of seedbed physical conditions for the needs of developing crops. The latter aim in essence connotes a principle of crop husbandry.

1.2 Review

The interest in the structure of tilled soil, and its effect on water and temperature necessitated a comprehensive literature review. The available literature is mainly based on work that has been done on untilled soils. However, the principles and observations in this literature are undoubtedly useful for the explanation of observations on tilled soils.

The broad areas of generation and disruption of aggregate and soil structure, soil structure measurement (wet and drying sieving techniques especially can be used for tilled soils), tillage practises, the effect of tillage and soil physical properties on soil water and temperature, and the phenomenon of water vapour transfer in soil are reviewed.

CHAPTER 2

REVIEW OF LITERATURE

2.1 Introduction

Soil structure is defined as the mutual arrangement of soil particles, aggregates, and associated voids in a three-dimensional network. A review of the mechanisms of genesis of constituent soil aggregates is a useful introduction to the study of soil structure.

The soil mass is broken into various sizes of aggregates and clods by tillage. After tillage, the soil is exposed to weather and especially the effect of rainfall and this also changes the structure.

The measurement of soil structure has been a problem. Many of the methods which have been used to measure soil structure are reviewed.

It is concluded that soil tillage, not without its problems, is inevitable in agricultural use of land. The beneficial and adverse effects of tillage are reviewed. Different tillage implements produce different tilth structures. The functions of major tillage implements, and tillage approaches concerning conventional, minimum, and zero tillage are discussed.

The distribution and variation of water and temperature in soil tilths form a major aspect of this research. The results of previous research relating tillage with soil water and temperature are reviewed. Aspects of water evaporation, and the dynamics of water vapour are discussed.

2.2 Factors of Aggregate Formation

2.2.1 Flocculation and aggregation

Soil structural units are products of the bonding of primary particles such as clay and quartz. Ionic clay flocculation (Bradfield, 1950) in an absolutely aqueous and colloidal system has been theorised. However, in field situation, the necessary conditions for flocculation do not commonly exist. Quirk (pers. comm., 1976) said that the process of flocculation does not occur in the subsoil. Flocculation is possible on the soil surface when aggregates are broken by raindrops and the clay fraction is dispersed. Bradfield said that aggregates are more stable when formed from flocculated particles. In the main, aggregates are formed by physical forces generated by the presence of colloids (clay particles and cations) and organic polymers that have many active groups that react with clay particles (Allison, 1968; Greenland, 1971). The colloids and polymers hold the primary particles within an aggregate unit and maintain the stability of the unit.

The main soil components which interact with each other to produce aggregates can be classified as organic matter, primary and secondary clay minerals, cations and oxides and hydroxides of iron and aluminium. The interaction of these components is consolidated by dehydration, pressure, and coagulation which finalise the process of aggregation. Coagulation, dehydration, and pressure are generated in various degrees by wetting and drying, freezing and thawing, root growth and decomposition. Organic polymers which also stabilise the aggregate unit are formed as a result of microbial decomposition of plant residues. Further modification of the structure of the soil mass is caused by the actions of soil macro-fauna. Their activities are usually regarded as beneficial to further development and maturation of the soil structure.

2.2.2 Functions of ions and oxides in the formation and stabilization of soil aggregates

Calcium and hydrogen ions are regarded as being important in basic flocculation and ultimate aggregate formation. The ability of calcium ions to compress the clay electric double layer with minimum water hull and reduce zeta potential has been demonstrated (Emerson, 1959; Fathi *et al.*1971). Calcium-saturated aggregates were found (Emerson, 1954) to be metastable in distilled water. The properties of calcium have been compared with the high degree of hydrolysis and zeta potential that characterise the sodium ion and most of its salts. Calcium, hydrogen, and some other cations act as bridges between clay particles, organic matter, water, and other primary soil particles. The particle-oriented water-cation-oriented water-particle model based on electrokinetic relations was discussed by Russell (1934).

No firm conclusion has been reached on the relation importance of calcium and hydrogen ions in aggregate formation. Some workers (Baver and Hall, 1937; Myers, 1937) have indicated that clays saturated with hydrogen ions are more permeable and H^+ humates are more stable than their Ca^{++} equivalents. It was expressed (McHenry and Russell, 1943) that monovalent ions gave better aggregation of puddled mixtures of sand-clay-silt than did divalent ions which were in turn superior to trivalent ions. Liming has always been suggested in connection with attempts to improve structure and aggregation of impoverished soils (Baver, 1961; Berglund, 1972). But the role of calcium ions (from lime) is looked upon as influencing the decomposition of organic matter (Russell, 1938; Baver *et al.*, 1972). The analysis of physical properties of 4-6 mm diameter aggregates from 147 arable soils and 37 from grasslands in Britain (Williams, 1970) showed that there was no detectable association between the calcium carbonate contents and physical properties of the soils.

It was shown (Baver, 1935) that dehydrated ferric hydroxide is an important ingredient in the production of stable aggregates. However, soil aggregate formation is quite distinct from laterite formation to which iron is indispensable. Mixtures of iron and aluminium oxides added to clay (Sideri, 1939) hindered the aggregation of clay particles. The presence of oxides in large amounts destroyed the orienting properties of clay in respect to humus. It was said that in this case coagulation occurred with confused distribution of particles. There is also evidence (Despande *et al.*, 1964) from the results of permeability, wet-sieving, and mechanical analyses that iron oxides cement soil particles together. Changes in soils' structural and physical characteristics were observed with and without iron extracted.

Forms of phosphorous have been shown to increase soil aggregation and aggregate stability. P_2O_5 and organic carbon were highly correlated (Shankarnarayana and Mehta, 1967) with percentage of aggregates larger than 0.25 mm. The feasibility of using phosphoric acid as a soil anti-crustant was examined (Inman and Ririe, 1969), and the result was encouraging though it was concluded that more research is needed. The indication was given (Prummel, 1975) that a higher phosphate availability was being required on a soil with poor structure than on a soil with better structure.

Aggregation depends mostly on cations such as calcium and hydrogen. The effects of oxides of iron and aluminium are controversial. The less important role of these oxides is indicated by the statement of Emerson (1970) that clay mineral crystals react with organic polymers of a whole range of composition and molecular weight in the presence of impurities such as iron, aluminium, and silica to form aggregates.

2.2.3 Colloid and particle interactions

Both clay particles and organic polymers are cementing agents for slowly reversible, irreversible, and stable aggregate formation for primary particles. Clay is more effective on smaller particles (Kheyrabi and Monnier, 1968; Fies, 1971), and its amount determines the percentage of soil aggregation. A correlation of 0.428 (0.20) being significant) was found between clay content and the percentage of mechanical separates larger than 0.05 mm that were aggregated into larger particles (Baver *et al.*, 1972). Clay domains are formed by mutual electrostatic attraction (Emerson, 1959) and orientation between clay particles and they may afterward remain separate as micro-aggregates or be adsorbed on a quartz particle to form a stable aggregate. Both clay and quartz are the main constituents of soil aggregates. The orientation of clay particles during dehydration is significant in aggregate formation (Telfair *et al.*, 1957). However, it was hinted (Batey and Davies, 1971) that not all soils with a high clay content are stable to water. For example, instability is a marked feature of clay soils with a high content of silt- and sand-sized particles. It was shown (McHenry and Russell, 1943) that aggregation of clay-sand mixtures increased logarithmically with increased clay content.

Participation of organic colloids in soil aggregation is attributed to the modification of the surface characteristic of clay and it also stabilizes clay-quartz bond formation. Organic polymers are bound to clay particles through cations (Peterson, 1947; Kohl and Taylor, 1961; Kohnke, 1968); hydrogen bonding; van der Waal's forces; and sesquioxides-humus complexes (Escolar and Lopez, 1968). It is postulated that organic matter increases aggregate stability by reduction of swelling and disruptive forces of entrapped air on wetting, reduction in wettability, and strengthening of the aggregate (Kolodny and Neal, 1941; Emerson, 1959).

Many investigations (Browning, 1938; Bertramson and Rhoades, 1939; Elson, 1940; Stauffer *et al.*, 1940; Peerlkamp, 1950; Quirk and Panabokke, 1962; Biswas *et al.*, 1971) have confirmed that organic matter stabilizes the soil framework and improves the physical properties of soil. Mechanized production of sugar beet in Belgium requires an annual manure application (Simon, 1964) to a total of 6,000-7,000 kgha^{-1} organic matter. Water stable aggregates larger than 3 mm diameter amounted to 11.8% of total aggregates following organic manuring as compared with 1.9% after mineral fertilizing (Hurich and Sklodowski, 1962). The fact that undecomposed organic material reduces aggregation because of its diluting effect (McHenry and Russell, 1943) shows that it is the organic product of decomposition that stabilizes soil aggregates.

Organic and clay colloids and cations interact together in various ways in an aqueous medium with soil primary particles such as quartz to form soil aggregates. A possible model of the interactions involved was proposed by Emerson (1959).

2.2.4 Microbial activity

Microbes such as fungi, actinomycetes, and bacteria contribute *en masse* to soil aggregation especially because they ensure the decomposition of organic matter. Their effect depends on the type of microbe, the amount of growth, the substrate, and the metabolic products released (Swaby, 1942b; Black, 1968; Aspiras *et al.*, 1972; Harris, 1972). For example, substrate sugar produces a more rapid growth of fungus mycelia than cellulose because it is more easily decomposed (Pe le and Beale, 1940). Fungi are more effective than actinomycetes and bacteria in the process of aggregation (Martin and Waksman, 1940).

In addition to the mechanical effects of mycelia and other bodies, microorganisms can produce gums, waxes, and other hydrophobic substances. The aggregating effects of the metabolic products of microorganisms were observed to be many times greater than the binding effect of microbial cells (Martin, 1945). The complex organic binding products are the polysaccharides and polyuronides (Kohl and Taylor, 1961; Greenland, 1965; Reddy and Dakshinamurti, 1971; Sarma and Dakshinamurti, 1971), proteins, lignin-like colloidal materials, and humic and fulvic acids (Greenland *et al.*, 1962; Dell'agnola and Ferrari, 1971).

These microbial products adsorbed on soil aggregates range from 0.1-1% by weight of soils rich in organic matter (Greenland *et al.*, 1962). The role of organic matter is incomplete without the degradative effects of soil microbes (McHenry and Russell, 1944; Martin, 1945, 1946; Robinson and Page, 1950), and it is the specific distribution of components of organic matter, especially the carbohydrates in substrates, that is important (Cooke and Williams, 1971).

2.2.5 Summary

The main factors of natural aggregation of soil particles are the cations such as calcium and hydrogen, clay particles, organic polymers, and soil microbes.

2.3 Agents and Processes Creating Soil Macro-Structure

Soil aggregation implies the existence of soil pores. Certain processes such as dehydration, exertion of pressure, and perforation of soil bulk are essential to aggregation and crumb formation. The factors bringing about these processes include roots; soil fauna such as earthworms, termites and ants; alternate wetting and drying; and alternate freezing and thawing. E.W. Russell (1971), delivering his presidential address to the British Society of Soil Science, also enumerated the major mechanisms creating soil structure. They include the shrinkage which takes place when many soils or soil crumbs are dried, for this forms cracks or planar pores through the body of the soil; secondly, the channels left by plant roots after they have dried and begun to decompose; and thirdly, the burrowing and channelling activities of the larger members of the soil fauna; and finally, the pulling of tillage implements through the soil. These factors are reviewed below.

2.3.1 Wetting and drying

Alternate wetting-drying induces fragmentation of compact clods of fine soil materials and it increases subsequent formation of tilth. Drying within a bulk of a soil clod dried will be uneven, and this will lead to formation of fractures. If the same bulk is rehydrated, the rate of water absorption will not be uniform between drier and moist sections, and there will be uneven release of strains and resultant disintegration. In a clay soil, the rate of swelling is more outside than inside a soil bulk, and this causes fracture. During a two-year period (Telfair *et al.*, 1957), platy structure was developed as a result of wetting and drying in an experiment to regenerate the structure of a silt loam. Aggregation was found (McHenry and Russell, 1943) to increase with alternate wetting and drying up to 20 cycles. It seemed probable that each dessication caused further orientation of water dipoles so that water stability of the system was increased. It was further stated that increased water content will afford better opportunities for aggregation, but beyond a certain value which corresponds to where all water dipole linkage bonds are provided, no increase in aggregation will be expected. Soils at field capacity were better aggregated than when air-dried. However, irreversible aggregation is caused (Kubota, 1973) if an allophane soil is dried beyond a critical water level.

Clod fracturation or fragmentation is also attributed to the compression of occluded air when water is taken up by soil capillaries.

The air is forced to escape when the attractive forces for water by cohesive soil exceeds the cohesive force between soil particles. The disruption of a compact soil was shown (Baver *et al.*, 1972) by the equation

$$rC + Ci < 2A,$$

where r is diameter of the longest capillaries in soil, C is the apparent cohesion of soil, Ci is the cohesion of water, and A is the affinity of soil for water. Alcohol, or detergent (Emerson, 1970) may be added to reduce factors Ci and 2A thus eliminating explosive disruption of soil aggregate. Another equation was also proposed (Robinson and Page, 1950) to explain disruption of soil aggregate by the escape of entrapped air. The equation is

$$F = 2\pi r \Upsilon \cos\theta \qquad (1)$$

where F is disruptive force generated, r is radius of capillary pore, Υ is surface tension of entering liquid and θ is the wetting angle of liquid-surface interface. Equation (1) gives the force transmitted to the soil by the water meniscus.

2.3.2 Freezing and thawing

If a wet soil freezes, crystals of ice form and withdraw water from the surrounding soil volume, increase in size and impose pressure on the surrounding soil. This process will induce compaction of small soil particles into larger aggregates and pores that are enlarged will retain their new shapes after thawing. It was found (Richardson, 1976) that the weathering to which a soil is subjected during a normal winter may be sufficient to achieve structural regeneration and that the possibility of the soil having an appreciably reduced stability in the following spring is more likely after a mild winter when frost penetration has been slight.

The effect of frost depends on soil constitution and original aggregate sizes, water content, and rapidity of freezing. Presence of organic matter increases aggregation caused mainly by freezing and thawing. Aggregates smaller than 1 mm appeared (Hinman and Bisal, 1968) to be disrupted by freezing, the process being reversed by subsequent thawing and drying at room temperature. High water content can cause the reverse effect of freezing and thawing on aggregation. It was found (Leo, 1963) that freezing and thawing eight soils at saturation decreased their total porosity. The process decreased the water stability of moist soils (Slater and Hopp, 1949).

However, freezing and thawing have been used to advantage under normal conditions of water content and freezing rate. Joint use of freezing-thawing and wetting-drying cycle three times (Richardson, 1976) improved water stable aggregation in a dispersed soil to the level greater than that of untreated field soil. Experiments were also conducted to determine the effect of freezing and thawing on the formation of aggregates and the permeability in dispersed soils (Gardner, 1945). It was concluded that freezing and thawing might be used to good advantage in cold climates as aids in restoring structure and permeability in the process of reclaiming soils that have been injured by sodium salts.

2.3.3 Root growth and soil structure

The long-term effects of the ramification of soil by roots are established as the fragmentation of the soil into crumbs and the stabilization of these crumbs. Bradfield (1950) visualized the roots of grass penetrating a soil every millimeter or so, completely ramifying it in every direction and blocking it off into discrete units which become completely separated when the soil is ploughed.

A number of mechanisms have been suggested through which the roots exert their influence on soil aggregation. Briefly the mechanisms are (a) the pressure exerted by the tips of penetrating roots and the resultant increase in contact among soil particles (Kvaratsteheha, 1951; Batey and Davies, 1971); (b) secretion of substances that cement soil particles (Reddy and Dakshinamurti, 1971); (c) soil dehydration along the roots due to uptake of soil water which leads to shrinkage and fracturation (Kolodnyl and Neal, 1941; Bradfield, 1950; Low, 1976); and (d) the binding action of products of microbiological decomposition of plant roots and secretions and the residues of the growing roots (Telfair *et al.*, 1957; Sarma and Dakshinamurti, 1971).

The planting of sod, grass-legume mixture, and the use of 'periodic grass break' have often been suggested as ways of regenerating soil structure (Page and Willard, 1946; Editorial Trop. Agriculturist, 1948; Joachim and Pandittisekera, 1948; Greenland, 1971). Improvement of soil's physical properties has been attributed to root growth and its effect on soil structure. The accumulation of fine roots in top soil increased hydraulic conductivity and decreased bulk density (Kennedy and Russell, 1958; Low, 1976). Increased porosity was attributed (Reddy and Dakshinamurti, 1971; Low, 1976) to root growth.

However, it was shown (Barley, 1953, 1954; Sedgley and Barley, 1958; Barley and Sedgley, 1959) that root growth did not increase soil macroporosity, but compressed adjacent soil and altered the pore size distribution. The commonly observed difference in porosity between cropped and pasture plots could have been due to decline in porosity of the cropped plots rather than an increase in porosity under grass. Also definite increase in porosity under grass could be attributed to the transport of soil to the surface by earthworms and other soil animals which are most active and abundant on undisturbed grassland.

The physical improvement of the soil by grass growth has been found to be a very slow process (Low *et al.*, 1963) taking at least about four years. Greenland (pers. comm., 1976) said that a soil under pasture for a year or two will show no significant improvement in structural aggregate stability. Results were presented (Siddoway, 1963) to show that at least two physical properties (dry aggregation and wind erodibility) were adversely affected by the use of grasses and legumes in rotation.

Fragmentation into and stability of soil aggregates are ensured by long periods under grass. However, it is not likely that soil macroporosity will be increased by root growth.

2.3.4 Soil fauna and soil structure

The major soil animals contributing to the development of soil structure are the earthworms, termites, and ants. Physical processes are not enough to produce stable aggregates, but earthworms and other soil animals are essential for reworking the soil, to reassemble the domains into micro-aggregates and arranging these into aggregates with a more porous structure than previously existed (Greenland, 1971).

2.3.4.1 Earthworms and soil structure

Earthworms, especially the casting species, are the most important soil fauna modifying soil structure. They feed on soil, and ingested food is casted on the surface or just below the surface. A deposition rate of 0.2 mm Yr^{-1} equivalent to mixing and inversion of the top 30 cm of the profile in about 1,500 years was measured at the Waite Institute (Barley, 1959).

One of the principal effects of earthworm activity is on the aggregate structure of soil. The size of the aggregates is reduced but their stability in water is increased by earthworms. The mean particle diameter is decreased by communition in the passage of particles through worm intestine. The mechanical composition of worm casts collected in Western Nigeria (Nye, 1955) showed that casts contained virtually no particles larger than 0.5 mm, and a low portion between 0.2 and 0.5 mm. Worm casts have been found to contain more water stable aggregates than non-cast soil (Gurianova, 1940; Joachim and Pandittisekera, 1948; Swaby, 1950). The percent water-stable aggregates of non-cast soil was 7-19% of worm cast soil (Murillo, 1966). However, the ways in which the aggregates in worm casts become stabilized are not confirmed. Increased stability of ingested particles has been attributed to mechanical reinforcement of ingested plant materials, and the stabilizing materials such as arising from worm's secretions, intestine microfloral, calcium humate synthesised in the worm's intestine, and calcite excreted by calciferous glands (Satchell, 1958).

Macroporosity and water infiltration rate of soil have been found to increase due to the presence of earthworms' burrows. Earthworm tunnels which vary between 0.7 and 5 $cm^3 cm^{-2}$ (Barley, 1959) and 2 to 11 mm diameter (Ehlers, 1975) are too wide to conduct water by capillarity and they therefore form part of the aeration porosity in the soil above the water table. The rate of water infiltration into clay subsoil was found (Hopp and Slatter, 1948) to be three or four times larger when worms were present. The time for water to pass through containers of sandy loam was reduced by a factor due to earthworm action (Guild, 1955). Earthworm tunnels open at the surface of loess soil were capable of taking in tension-free irrigation water to a maximum depth of 180 cm (Ehlers, 1975). Roots can grow along earthworm tunnels (Edward and Lofty, 1972).

Over a long period of time, it may be possible for worms' activity to affect profile differentiation. In a two-year-old pasture, the amount of coarse sand relative to silt and clay was found to increase appreciably with depth as a result of long continued activity of earthworms (Evans, 1948). Earthworms also incorporate organic matter (Edward *et al.*, 1972).

The influence of earthworms on soil structure is not always beneficial. An incidence of a garden where earthworm activity destroyed a well-aggregated structure and turned it into a sticky plastic mess was reported (Thorp, 1949). Some hill tops were turned into a cloddy, amorphous state (Agarwal *et al.*, 1958). The formation of worm burrows may lead to reduction in total and non-capillary porosity. Due to increase in the activity of earthworms after rain or irrigation, an enlargement of a limited number of non-capillary pores may cause a reduction in the size of surrounding pores to the extent that they enter the capillary pore size range. An 85% reduction in non-capillary porosity to capillary porosity was reported (Greacen and Perkman, 1953) in a sod plot.

Evidence shows that aeration porosity is increased by earthworms' activity and that soil textural composition becomes more coarse due to transport of soil particles by earthworms over a long period of time (Nye, 1955; Ehlers, 1975).

2.3.4.2 Termites and soil structure

The benefit or otherwise of termite activity on soil physical state is still not confirmed after an enormous amount of research. The subterranean galleries of termites increase infiltration rate of water (Pomeroy, 1976), but the cleared pans around some mounds have the opposite effect. It seemed likely (Joachim and Pandittisekera,1948) that termites have a beneficial effect on the structure of heavy textured soils.

It was shown (Pomeroy, 1976) that two species of termites (*M. bellicosus* and *M. subhyalinus*) tend to produce a stone-free topsoil after rainfall has eroded and levelled the mounds. The resultant soil has physical properties closer to a loam than the average subsoil. The mechanical analysis of the soil brought to the surface by termites in Uganda showed that particles rarely exceeded 1 mm in diameter because they had to be small enough to be carried by the termite workers (Ruelle, 1964b, cited by Pomeroy). The origin of the material composing the termite mound was traced (Nye, 1955) to a depth of 30-75 cm in Western Nigeria. In Uganda, it was concluded (Pomeroy, 1976) that it seemed termites only slightly affected the physical properties of soils even where the mounds were abundant.

2.3.4.3 Ants and soil structure

Experience with ants in England (Green and Askew, 1965) was that alluvial soils were found to contain abundant interconnection of pores, holes, and cavities. These macropores had a great influence on infiltration rate.

In Western Nigeria, black ants of all sizes are active in depositing loose sandy loam on the surface. As a rule the ants operate from a central hole around which they deposit a shallow pile of loose earth up to 15 cm across and 2.5 cm high (Nye, 1955). The mechanical composition of a brown earth deposited revealed fractions mainly between 2-0.002 mm diameter. It was shown that the deposit could have been derived from the upper 30 cm of soil.

The activity of soil ants may increase the rate of water infiltration but does not affect the soil aggregation considerably.

2.3.5 Summary

The natural factors of soil structure formation are the processes and agents such as wetting and drying, root growth and decomposition, and soil fauna especially the earthworms. The effect of soil fauna on soil structure depends on their population. Other soil animals such as termites and ants will only change soil physical properties such as texture and water movement on a local scale. Freezing and thawing will increase soil aggregation in cold regions, but there is also the possibility of its causing poor soil fragmentation depending on soil water content, rate of freezing, and organic matter content.

2.4 Soil Structure Deformation

Rainfall causes the collapse of the surface and subsurface structure of soil. The resultant surface crusting and other effects will be discussed. The use of farm machinery causes mechanical compaction of soil in various degrees, and with constant use of tractors and heavy implements a dense subsurface layer (or 'plough pan') is formed. This review of mechanical compaction includes soil factors that come into play, distribution of compactive effect, effects of compaction on soil and crop, and measures against soil compaction. The compactive effect of animal treading is considered.

2.4.1 Rainfall and soil structure

2.4.1.1 Soil surface crusting

A falling drop of water contains kinetic energy, the exact magnitude of which depends on the drop size and its velocity of fall as it strikes the soil. Under continuous rainfall, a crust or seal develops at the surface of soil as a result of slaking of soil aggregates. Dispersed soil particles are washed slightly into the soil or are precipitated at the surface of the soil after the rain and these processes ultimately result in the formation of a thin tight seal at the surface and a thicker less-tight in-washed layer below the surface (Duley, 1939; McIntyre, 1958a, 1958b). Crust formation has been associated (Ahmad and Rublin, 1971) with soil organic matter contents of less than 1.5% and free iron oxide contents of less than 8%.

The size of the soil aggregates influences the effect of falling raindrops on the surface. It was found (Rose, 1961) that the relative aggregate breakdown increases as the size of the aggregates decreases for any given rainfall intensity. Detachment of soil from naturally-occurring soil aggregates when exposed to simulated rainfall increased from 76 mg per cm^3 water as the diameters of aggregates decreased from 9,250-4,760 μm to 2,360-1,680 μm (Mazurak and Mosher, 1970).

The major adverse effect of surface crusting is to decrease water infiltration rate. In laboratory work (Ojeniyi, 1973) it was shown that the hydraulic conductivity of a crust was 30 to 40 times smaller than that of uncrusted soil. In the field, the equilibrium infiltration capacity values for artificially crusted soils were about one-third of the values recorded for undisturbed and ploughed soils. McIntyre (1958) had found that the permeability of a surface crust was $5x10^{-7}$ $cm.sec^{-2}$ compared with $10^{-3}cm.sec^{-1}$ recorded for an uncrusted soil. The smaller infiltration rate due to the presence of crust will lead to increased surface run-off and soil loss (Oades, 1976; Ehlers, 1977). However, the effect of the presence of crusts on water intake depends on soil type, slope, water content, and profile characteristic (Duley, 1939).

Crusting has been found (McIntyre, 1955; Hanks, 1960) to decrease seed germination percentage. A surface crust developed from a sandy loam which had a modulus of rupture of 103-273 mbar was found (Richard, 1953) to decrease significantly the emergence of bean seedlings. The mechanical impedance of crusts was found to increase with sodium concentration and rainfall intensity. For crusts formed under rainfall intensities of 1.3, 2.5, and 5.1 $cm.hr^{-1}$, the maximum impedances were respectively 1,766, 2,226 and 1,851 g force. Crust mechanical impedance increases with drying and reduced cracking (Holder and Brown, 1974).

Crust formation may be delayed by appropriate tillage to create a rough surface topography, by protection of soil surface from raindrop impact, and by increasing the strength of intra-aggregate bonds (Oades, 1976). Oades found that surface soil could be stabilized against crusting by spraying with poly (vinyl) alcohol , PVA.

2.4.1.2 Rainfall and the structure of tilled soil

The collapse in the framework of soil structure that occurs when soil is clean cultivated presents a widespread problem in conserving the production of arable land. The problem becomes acute primarily in loam and clay soils, but it also occurs to a noticeable extent in some of the lighter soils (Hester and Shelton, 1937; Kolodny and Neal, 1941). Studies (Baver, 1948 cited by Hopp and Slater, 1949) have demonstrated that when soil is subjected to clean cultivation, it tends to become more compact while the volume of large pores decreases. Dexter (1977) observed that the effect of rainfall was to reduce the surface roughness of tilled soil to a given proportion in a time which was independent of the initial roughness of the surface and the tillage implement used. It has been indicated (Bulfin and Gleeson, 1967) that rainfall influences porosity in the top 37 to 57 mm of arable soil although the effect is more pronounced in the top 2 mm of a fresh tilth. It was observed (Hopp and Slater, 1949) that the collapse of soil structure was more marked on wheat plots in Maryland, U.S.A., during the winter than any other season.

It was shown (Dexter, 1976) that during winter there was a decrease in the incidence of small aggregates at the top of a tilled soil, and this was partly attributed probably to washing-in of these aggregates to the base of the tilth.

2.4.2 Mechanical compaction of soil

2.4.2.1 Introduction

There is considerable risk of soil deformation when tractor wheels and heavy tillage implements run over land during seedbed preparation as the soil is often wet and readily compacted. Soil compaction has been defined (Gill and Vanden Berg, 1967) as a dynamic soil behaviour in which the bulk density is increased. This definition suggests that every soil is in a degree of compaction except when just tilled. The area of coverage by tractor wheels will depend on the number of separate agricultural operations performed. The practise of fertilizer distribution, twice harrowing, sowing and rolling gives about 90% coverage with medium-sized tractors (Soane, 1970). Approximately 20% of a cereal field will be covered with tractor and combine wheels during harvest (Soane and Pidgeon, 1975). The effect of individual implements has not been studied extensively. The type, weight and shape of implement are important in considering the effect of individual implements (Alexander and Middleton, 1952). Deformation of soil under agricultural machinery can be resolved into compression and shear components (Dexter, 1973).

Soil compaction brings about adjustments in the relative dispositions of aggregates, followed by a process of coalescence of them as the air spaces between them are squeezed out. Further applications of pressures causes tighter close packing until a maximum limiting density is attained (Czeratzki, 1966; Dexter and Tanner, 1973; Reece, 1973). The flattening of soil aggregates especially at the points of contact increases the area on which applied shearing stress acts and when the stress falls below the increasing shearing strength of soil (Day and Holmgren, 1952) deformation ceases. However total plastic deformation during compression is unlikely (McMurdie and Day, 1958) because the soil will still be able to expand (but not to its original volume) after the release of applied load. Since the contraction during compression exceeds the expansion during unloading, continuous compression of soil will cause continuous decrease in its volume until a point of maximum compaction is reached. In the field situation, the point of maximum compaction will not permanently occur due to the swelling and shrinkage of soil in response to trends in water content and weather conditions (2.3.1). It has been suggested (McMurdie and Day, 1958) that the contraction and expansion of soil in response to applied loads are probably influenced by water movement which causes differential swelling and shrinkage of compressed soil bulk, and the minor effect of air movement in and out of compressed soil.

2.4.2.2 Soil factors determining mechanical compaction

The major soil factors influencing the degree of soil compaction are isolated, and the influence of each of them is briefly discussed. The degree of soil compaction depends on water content, organic matter, soil texture (Free *et al.*, 1947; Anderson *et al.*, 1958; Harris *et al.*, 1966; Bender, 1971; Soane, 1973), the type of primary tillage employed, and the state of compaction before tillage (Soane, 1970; Soane and Pidgeon, 1975).

Soil water acts as a lubricant between particles (Bulfin and Gleeson, 1967). Peak compaction occurs at water contents near plastic limit which is about the optimum condition for tillage (Baver *et al.*, 1972).

Soils with a wide range of particle size (such as loams) compact more readily than other soil types and have a higher resultant bulk density (Hubberty, 1944).

The greater the organic matter content of soil, the smaller the ultimate compaction and the greater the water content necessary to achieve a specific compaction level (Soane, 1970). Soil organic matter increases soil plasticity and thus its resilience to compaction. Core soil samples were given maximum compaction to densities of 1.48, 1.71 and 1.81 $g.cm^{-3}$ (Free *et al.*, 1947). The initial organic matter contents of the samples were respectively 4.4, 2.4 and 1.3%. Swanson (1954) investigated the effect of additions of farmyard manure on the reductio of macropores under wheel tracks for heavy and light tractors. For a light tractor (1,300 kg) there was marked resistance to deformation in the presence of farmyard manure but with a heavy tractor (1,830 kg) the extra organic matter made no difference to the change in pore-size distribution.

Changes in bulk density caused by the passage of combined harvester wheels were related to the types of primary tillage employed (Soane and Pidgeon, 1975). Deep ploughed soil showed an increase in bulk density throughout the tilled layer whereas there was little or no change where the top soil was ploughed for six years.

2.4.2.3 Distribution of compactive effect and pressure

The maximum effect of compaction is not immediately below the wheel or the implement or at their edges. For a wheel and most materials, maximum compactive effect, increased density, and reduced porosity are found at a depth equivalent to one-half the diameter of the wheel or contact surface of the material (Soane, 1970). Many soils develop a compacted layer or plough pan at the base of the ploughing layer if the implement is used at high water contents. In addition to plough pans, subsoiled pans, disc harrow pans, and traffic pans have also been observed (Baver *et al.*, 1972).

The soil body has the ability to vector into an applied force in arch form. This is due to the friction between soils, interlocking of soil particles, and cohesion of water films (Nichols, 1929). Pressure distribution under wheels, tyres, and tracks depends on the amount of load, the surface area contact, and the distribution of pressure within the contact area (Alexander and Middleton, 1952; Sohne, 1958; Soane, 1970; Baver *et al.*, 1972).

Soil compaction may be a result of horizontal forces produced by thrust or vertical forces due to load. The general though inconclusive view about speed and compaction is that increase in forward speed reduces compaction (Sitkei, 1971; Dexter and Tanner, 1974). Wheel ship is also more effective than increase in load in causing compaction (Davies *et al.*, 1973; Soane, 1973). While there is need to avoid compaction, particular attention should be given to providing sufficient wheel loading and the possibility of moving faster to take up more power at lower slip (Davies *et al.*, 1973). In order to generate draught all farm tractors develop some wheel slip. But the greater the load on the driving wheels for a given draught, the lower will be the slip.

2.4.2.4 Effects of mechanical compaction on soil and crop

The proportion of macropores in the zone of maximum compaction in continuously-tilled soil decreases asymptotically, with increasing numbers of implement passes towards a minimum limiting value. When there is no significant change in the proportion of macropores, the limiting maximum compaction is then reached. The reduction in the size of large pores due to compaction can lead to reductions in porosity value to below 10% (Soane, 1970) which has been indicated (Vomocil and Flocker, 1961) to be the minimum required for adequate air diffusion into the soil.

Because of the reduction in the size and proportion of macropores (especially pores at least 1 mm in diameter) due to compaction of the soil just below the tilled layer, water infiltration rate and hydraulic conductivity are drastically reduced under conditions of intense rainfall. This reduction in water infiltration rate is often adduced to increased soil density as a result of the compaction (Parker and Jenny, 1945; Trouse and Baver, 1956; Hawkins and Brown, 1963; Kruger, 1970; Primavesi and Primavesi, 1970; Cooke and Williams, 1971). The saturated hydraulic conductivity of the traffic pan in a silt loam soil in Germany was determined as 8×10^{-4} cm.sec^{-1} (Sting, cited by Ehlers, 1975), whereas the uncompacted tilled soil had 5×10^{-3} cm.sec^{-1}.

A lot of research (Betrand and Kohnke, 1957; Flocker *et al.*, 1958; Adams *et al.*, 1960; Mazurak and Chesnin, 1964; Baeumer, 1970) has shown that compaction resulting from agricultural traffic reduces the yields of crops. However, it is difficult to isolate which of the modifications in the soil physical properties were mainly responsible for the yield reductions because the soil properties concerned interact in their effects. It has been shown (Bertrand and Kohnke, 1957; De Roo, 1957, 1960; Pizer, 1962; Greacen *et al.*, 1963; Rosenberg, 1964; Barley *et al.*, 1965) that increased resistance to root growth by compacted soil decreases the rate of root elongation. Significant reductions in potassium and phosphorus uptake by crops grown in compacted soils have been reported (Blake and Aldrich, 1955; Mukhortov, 1964; Bouma and Hole, 1971). However, the resistance of soil to root penetration decreases with greater water content and the consequent less-negative matric potential (Greacen and Oh, 1972). Available soil water will be reduced by compaction of wet soil because water will be held at more negative potentials. It was shown (Rosenberg, 1964) that water in compacted soils with 2:1 montmorillonite clay was held by forces greater than 28.2 bar. The presence of compacted layers makes subsequent tillage more difficult and less efficient (Cooke and Williams, 1971; Low and Piper, 1973).

A limited amount of compaction such as is produced by rolling, increases the rate of seed germination especially when the soil is not adequately wet. This has been shown by a number of investigations (Stranak, 1968; Kruger, 1970). In a field study conducted in Minnesota (Voorhees *et al.*, 1976), it was found that under conditions of less than normal growing season precipitation, wheel traffic increased yields of soyabean by up to 20%. This observation was attributed in part to improved soil water conditions.

The analysis of the effect of soil compaction on root growth is not simple. The analysis should be performed with the thought that roots exert considerable growth pressures which vary between 8 bar (Barley *et al.*, 1965) and 25 bar (Gill, 1961). Secondly, roots have a special characteristic to avoid mechanical resistance by its growth pattern (Greacen *et al.*, 1963; Dexter, 1978). Thirdly, different root sizes may require different pore sizes for their growth.

2.4.2.5 Measures against soil compaction

Reconditioning of compacted soils is a difficult and expensive operation (Lutz, 1968), but the use of subsoilers to break up the dense mass is mandatory (Baver *et al.*, 1972).

Apart from remedial tillage, weathering may reverse the compacted soil condition. The Agricultural Advisory Council (England) found no instance where recovery of soil from compaction had not taken place given time and suitable weather (Batey and Davies, 1971).

Reduced weight per unit power of farm tractors is a way of reducing soil compaction. Some of the ways of directly using tractors of greater power to weight ratio are (Patterson, 1973): by operating draught implements at higher forward speeds than hitherto so that greater power can be used at minimum pull and wheel slip; by applying power through the power takeoff (p.t.o.) to rotating or vibrating tools; and by linkage of tillage and drilling equipment to reduce the number of traffic passes over seedbeds.

Decisions as to whether soil compaction and unfavourable physical state can be ameliorated by such practises as crop rotation, land resting, and addition of amendments or stabilizing agents must be made on the basis of a comparison of cost of amelioration against possible expenses of living with the problem of soil compaction (Vomocil and Flocker, 1961).

2.4.3 Animal or human compaction

Considerable soil compaction has been adduced to animal stocking and grazing. Cattle were observed (Lull, 1959) to impose a mean stress of about 1.6 bar compared with 9 and 4.5 bar for woman and man respectively. Stocking of cattle at 8.9 haA^{-1} (Rhoades *et al.*, 1964) reduced infiltration rate by half. The same stocking rate gave an increase in bulk density of 50-100 Kgm^{-3} for depths varying between 0 to 25 cm. Treading of dairy cows in one season was also found (O'Connor, 1956) to increase bulk density by 20%. An overall assessment of sheep trampling effects (Lagocki, 1976) showed that top soil failure occurred when the soil was saturated. The dry bulk density of the top soil was related to sheep stocking rate (Langland and Bennett, 1973) by the equation

$$P = 1118 + 8.7z, \ kgm^{-3} \qquad (2)$$

where z is the stocking rate in sheep per ha.

The compacting effect of workers tending or harvesting a crop has been considered. The dynamic compactive pressure which is difficult to measure may be twice the static compactive pressure. Most of the compaction below the 5 cm depth of soil was adduced (Bulfin and Gleeson, 1967; Bulfin, 1967) to the workers. It was concluded (Bulfin and Gleeson, 1967) that the soil compaction due to workers is not a hazard to future soil stability and structure in Ireland.

2.4.4 Summary

Continuous rainfall alters the surface and immediate subsurface structure of soil. Surface crusting as a result of rainfall causes drastic reduction in macroporosity and water infiltration rate, and when it dries the crust reduces germination percentage of some seed types. Crusting which results from the collapse of soil aggregate structure and sedimentation of dispersed clay particles may be reduced by earlier crop cover and stabilization of soil aggregates. Decreases in macroporosity and incidence of small aggregates within the top 10 cm of tilled soil have been adduced to seasonal rainfall.

Continuous mechanical tillage, animal stocking, and human activities connected with crop tending and harvesting cause the formation of compacted dense subsurface layers of soil. However, compaction due to the movement of farm workers may not be important. The presence of compacted soil layers that resulted from mechanical tillage will reduce macroporosity and water infiltration and will adversely affect other soil physical properties. The effects of soil compaction will lead to reduction in crop yield and performance. But minimum surface compaction after seeding is advocated in dry climates to increase seed germination. The major effect of animal compaction is to decrease soil macroporosity and water infiltration.

Maximum soil compaction may be prevented by devices that increase tractor power output per unit weight. Subsoiling and weathering have been suggested as means of eliminating a compacted layer.

The degree of soil compaction depends on soil, implement, and tractor properties. The soil properties are mainly water content, organic matter, texture, and previous tillage history.

2.5 Measurement of Soil Structure

2.5.1 Introduction

Soil structure is here defined as the spatial arrangement of soil aggregates and pores. Assessment of soil structure has been based largely on interpretation of results from measurements of physical parameters which are its manifestations. Soil physical properties such as water stability, infiltration rate, water permeability, and bulk density are useful for characterising specific soil behaviour. For example, permeability is a useful measure of potential rate of gas exchange between soil and the atmosphere, while infiltration and intrinsic permeability are useful for assessing change in stability, drainage, and erosivity. The attempts to evaluate soil structure using physical measurements are apparently not desirable and are illegitimate. The importance and difficulty of the continuous search for methods of expressing undisturbed spatial structure of soil have often been stressed (Bolt *et al.*, 1948; Bradfield, 1950; Low, 1954; De Boodt, 1960).

Broadly, the shortcomings of using soil physical properties to indicate soil structure are stated below.

(a) The soil physical properties do not express the natural, undisturbed structure of soil. In most of the physical determinations, the soil is considerably disturbed or soil samples are taken.

(b) They are cumbersome and slow. Considering the high cost of laboratory determinations and the time necessarily involved and the actual need for efficient and quick answers concerning possible soil structure changes by different treatments in mechanical, chemical, or physical way, quick field methods for measuring undisturbed soil structure ought to be developed (De Boodt, 1960).

(c) They are insensitive. When measuring such quantities as infiltration, bulk density, or resistance to penetration under field conditions, the variability of replicated treatments makes it laborious to evaluate significant differences between treatment means (Richards *et al.*, 1960).

(d) They are not standardized. Survey of the methods of soil structure measurement (De Boodt, 1960) revealed that the structure evaluation on one and the same soil gave different results in various laboratories. The standardization of techniques of soil structure measurement up to sampling, transporation, and storage of soil for aggregate stability and pore size distribution was advocated.

In the search for methods of assessing the undisturbed field structure of soil, soil has been impregnated with materials that could fix its structure. In the great majority of the efforts thus made, the process of structure measurement after the impregnation was visual and non-quantitative. In an exceptional case, the scanning of isolated fraction of the film of a section of a small soil block was performed, and the distribution or interception in number of aggregates or pores was obtained from scanning equipment. Core soil samples were collected in the field. This technique is discussed in greater detail in section 2.5.5.

Therefore, there is a need for a method of soil structure measurement that will be able to evaluate the actual undisturbed macro-structure of soil. The structural elements more important for crop establishment start from about 1 mm in diameter (Katchinski, 1956; Edwards, 1957; Russell, 1961, 1973; Cornforth, 1968). A large sample of soil should be able to be measured at once in addition to the use of replicates so that representative structure measurements are possible. Other desirable properties of the prospective method are low-cost, rapidity, and simplicity.

The above requirements are met in the method of Dexter (1976) used for structural evaluation in this research. The new method was used in this investigation of basic physical problems connected with seedbed structure. The method and some others based on it are discussed in Chapter 3.

Soil structure and associated factors change with time in response to climate, tillage, management practises, and cropping sequence. Therefore to characterise the structure of a soil, continual assessments have to be made. Soil structure is actually time-dependent.

Low (1954) has performed a review of most of the methods used in assessing soil structure. This review of the methods that have been used to measure soil structure is briefly performed under the following headings:

(a) Measurements of physical properties that are functions of pore size distribution.

(b) Measurements of soil stability and aggregate size distribution.

(c) Descriptive and microscopic assessment of impregnated soil structure.

(d) Measurement of soil structure by scanning of photographic film of small section of soil.

It is necessary to mention that methods such as nitrogen adsorption and mercury injection (Sills *et al.*, 1971) have been used to give information about micro-pore volume in soil. The pores dealt with which are usually less than 1 μm are not important in terms of tillage, air and water movement, water availability, temperature, and other physical properties of seedbed

2.5.2 Soil Physical Properties that Indicate Pore Distribution

2.5.2.1 Water characteristic curve

The distribution of different pore sizes in a soil sample could be assessed from the water characteristic curve of the soil which is a plot of water content (usually on volume basis) against applied water potential. The pore size equivalent to an applied potential (expressed as a height) can be got using the Kelvin equation

$$h = \frac{2\gamma \cos\emptyset}{\rho g r}, \quad (3)$$

where h is the applied potential (m), γ is surface tension of water (73 mNm^{-1}), ρ is density of water (1,000 kgm^{-3}), g is gravity force (9.81 ms^{-2}), Ø is the angle of contact between water and the soil particles (usually assumed to be zero), and r is radius of capillary pore (m) which indicates the largest pore size that retains water at the applied potential. There is a direct relationship between the volumetric water content as a function of h, and the pore size distribution. Therefore the water characteristic curve could be used to compare different soils. Because of hysteresis (Childs, 1969), drying water characteristic curve is normally used for assessing size distribution of pores and core soil samples are therefore saturated for at least 48 hours before placement on pressure tables or in sintered glass funnels for less negative potentials.

However, estimation of pore size distribution from the water characteristic is not a suitable method for soils that shrink and swell (Marshall, 1962; Childs, 1969). The shrinking and swelling in response to water content alters the natural pore size distribution of soil.

Certain low tensions (50-100 cm water) are associated with the presence of large pores in soil. The proportion of pores (smaller than 0.3 mm in diameter) in soil is often determined by calculation using the amount of water drained at 50-60 cm suction (Low, 1954). The equation for the calculation is

$$Sn = \frac{100(Wi - Wet)}{Ms} \qquad (4)$$

where Sn is % of soil volume drained under an applied suction (cm) of water, Wi is saturated weight of soil sample, Wet is net weight of sample after drainage by suction for at least 24 hr, and Ms is the dry weight of the sample after drying in oven for 24 hr at 105°C.

In general, porosity determination by application of suction is only applicable for assessing pores smaller than 0.3 mm (Dexter, 1976). Childs (1940) argued that the technique has a great advantage because very little violence is inflicted on the soil sample and that the method is supportive to wet sieving aggregate size distribution in the study of the ability of the soil to withstand natural disintegrating forces. However, the standardization of the techniques used for water characteristic curve determination was called for by De Boodt (1960).

2.5.2.2 Drainage

The ease by which water drains out of a saturated core soil sample is sometimes used to indicate the distribution of large pores. Core soil samples are saturated with water, or prewetted at low suction of about 5 cm. The sample is later drained using a low suction of about 60 cm. The volume of water lost by suction drainage corresponds to the distribution of large pores, and soils can be compared on this basis. However, undisturbed core samples may be difficult to collect using the hammer type core (Lutz, 1947).

2.5.2.3 Permeability and infiltration capacity

Childs *et al.* (1957) argued that permeability (the rate of liquid movement through a soil column) could be used as an objective measure of soil structure. They designed a method of measuring the permeability of soil beneath the water table especially for the study of drainage systems. It was said that in the absence of cracks and fissures, aggregate and pore size distribution and water permeability are directly related. Marshall (1958) derived an equation relating permeability (k) and pore size distribution. It was shown that permeability depends on the mean radius of the pores in equal fractions of total pore space in soils.

Hydraulic conductivity, K, is defined by Darcy's (1856) equation:

$$Fx = -K\frac{d\psi}{dx} , \qquad (5)$$

where Fx is the volume of water flowing in the x direction through unit area in unit time ($m^3 sec^{-1}$), $\frac{d\psi}{dx}$ is hydraulic potential gradient through a soil column, and K is the hydraulic conductivity. The use of Darcy's equation is based (Childs, 1969) on the assumption that the porous body must be large compared with its microstructure (pore and aggregate size), and that the velocity of flow must be small.

Equilibrium hydraulic conductivity is usually determined using core soil sample or a packed but large volume of soil. Apparently, results from the core sample will be more realistic. A constant head of water is maintained on the soil and the rate at which water drains through the test soil column is recorded.

The flux is

$$F = \frac{Q}{At} , \qquad (6)$$

where Q is quantity of water (m^3) collected in a time interval t and A is the cross-section area of soil (m^2).

$$\frac{d\psi}{dx} = \frac{H_2 - H_1}{\ell_2 - \ell_1} , \qquad (7)$$

where H_2 and H_1 are the hydraulic heads (m) at the top and bottom of the soil column, and ℓ_2 and ℓ_1 are the heights (m) of the top and bottom of the soil column.

The surface of the test soil is normally protected from crusting with a light material such as cotton wool or tissue paper.

Equilibrium infiltration rate of water is often determined in the field to indicate surface condition of soil or its subsurface structure. However, the surface condition more limits infiltration rate than the subsurface condition. In the determination of infiltration rate, a calibrated infiltrometer is sunk into the soil and the equilibrium rate is normally used. The soil surface is protected except when infiltration of surface crust is of interest. A constant water head has to be maintained always.

Both hydraulic conductivity (K) and permeability (k) are used to indicate the frequency of macropores in soil. The relationship between the two parameters are

$$K = \nu k, \qquad (8)$$

where ν is the dynamic viscosity of the fluid. Permeability is independent of liquid viscosity, while hydraulic conductivity is not independent of viscosity.

Among the major criticisms against the use of permeability and infiltration rate is that they are not suitable for use when cracks and fissures are present in the soil. Cracks and fissures will exaggerate results. Secondly, the methods are not suitable for soils that swell. Thirdly, the methods are not standardized. However, they are useful for comparing soils when used consistently by one worker. Fourthly, it may not be adequate to use infiltration or permeability to compare the structures of disturbed and undisturbed soils. While the porosity of the former may be higher than that of the latter, it may have a lower permeability and infiltration. It was discovered (Ojeniyi, 1973) that the equilibrium infiltration rates on undisturbed soil surfaces were greater than those on ploughed surfaces on a site in Western Nigeria. Related observations had been made by Childs *et al.* (1953), and Collis-George and Young (1958). This phenomenon was adduced (Childs and Collis-George, 1950; Wilson and Luthin, 1963) to breakage in the continuity of capillary channels through which water could move freely into the soil and through which air could move out of the soil by tillage. Entrapment of soil air by the wetting front produces a back-pressure effect which will decrease infiltration and permeability.

2.5.2.4 Aeration porosity

The use of an air pycnometer affords a technique for assessing aeration porosity (Kummer and Cooper, 1945), and it is based on Boyle's law. In an air pycnometer equipment, a quantity of air from soil placed in a smaller compression chamber diffuses into a large chamber. There are different forms of pycnometer.

Baver *et al.* (1972) described a typical pycnometer. A dry soil is placed in one of two containers of a pycnometer and soil air is allowed to diffuse into the other larger vessel by opening a connecting valve. The pressure-volume changes in both containers are numerically equated as

$$P_iV_i + P_2V_2 = P_3V_i + P_3V_2 \qquad (9)$$

The left hand represents the initial values of pressure (P) and volume (V) at both arms of pycnometer, and the right hand represents the new pressures and volumes after the two sides of the pycnometer are connected. The volume of soil air can be got by calculation using P_3 which could be read from a mercury manometer place in the larger chamber.

A type of pycnometer was designed (Russell, 1949) in which the volume change due to air contained in soil enclosed in an airtight container will reflect in pressure increase recorded by a mercury manometer. The pressure change was also calibrated against air volume.

The pycnometer avoids many of the criticisms of the usual method of evaluating soil porosity (Baver *et al.*, 1972). But it gives erroneous results on soils near or below air dryness unless proper calibration has been made (Page, 1947; Jamison, 1953).

2.5.2.5 Available water

The use of available water to express soil porosity is based on the concept that the available soil water is held in soil pores and capillaries. The available water is defined as the difference in water contents at field capacity and permanent wilting point of soil.

The field capacity is determined by applying a water potential of 100 cm to a saturated soil for at least 24 hr. In some cases, a saturated soil is allowed to drain freely for 2-3 days. The water content at permanent wilting point is determined by applying a higher suction of 15 bar on an initially-saturated soil for as long as one week. In some cases especially on swelling soils, it is determined by finding the soil water content at which sunflowers become permanently wilted (Briggs and Shantz, 1912).

The available water is a direct consequence of the distribution of sizes of pores in soil.

2.5.2.6 Bulk density

The methods of determining soil bulk density or soil mass/volume ratio are now reviewed. The relationship between bulk density and porosity is given.

2.5.2.6.1 Core samples

The commonly used method for bulk density determination is to find the mass (of dry soil) - volume (of wet soil) ratio of oven-dried (at 105^{o}C for 24 hr) core soil samples. There have been various modifications in the shape and size of the round core sampler (Veihmeyer, 1929; Bradfield, 1936; Berndt *et al.*, 1976) to avoid as much as possible the disturbance of soil and to collect samples at deeper depths. However, the core method is unsuitable for stoney and gravelly soils because it will be impossible to collect undisturbed samples. Also it may not be suitable for heavy soils that could easily be compacted.

However, Berndt *et al.* (1976) has designed a core device about 11 cm in diameter with a rigid liner. This has been used to obtain core samples to 60 cm depth in a cracking-clay soil. Evidence presented indicates that the soil in the core suffers a minimum of compaction.

2.5.2.6.2 Clod sample

To be able to determine the bulk density of stoney and gravelly soils, clod density is sometimes determined (Sekera, 1931; Campbell, 1973). A soil clod is coated with oil and the amount of water displaced by the coated clod which is equal to its volume is determined. The oil is removed by a solvent (such as xylene), the soil is oven-dried to expel water, and the net weight of the clod is determined. Clod wet bulk density is independent of clod size (Campbell, 1973).

2.5.2.6.3 Hole filling method

Attempts have been made to determine soil bulk density by boring holes into the soil and pouring a solution into the hole to determine the volume of soil removed (Baver, 1961). The seepage of the solution is prevented by coating the walls of the hole by an hydrophobic material. The weight of the soil dug out is determined in the laboratory after expulsion of water. The processes involved in the use of this method show that it has low accuracy.

2.5.2.6.4 Gamma ray absorption

Forms of equipment for determining soil bulk density using gamma ray absorption have been developed (Vomocil, 1954; van Bavel, 1958; Soane, 1968; Soane *et al.*, 1971). The absorption of gamma rays follows Beer's law (Baver *et al.*, 1972).

$$\frac{I}{Io} = e^{-\mu x} \qquad (10)$$

where Io is the initial intensity of gamma rays at source and μ is a factor proportional to bulk density. Studies have shown that the relationship between a gamma ray count on transmission and bulk density is linear and it is largely independent of water content and soil type for Cs-137 radiation (Soane, 1970). Gamma ray count is calibrated against soil bulk density.

A two-pronged gamma ray probe is normally used vertically. But a special control for automatic two-dimensional scanning with gamma ray probe has been developed at the Scottish Institute of Agricultural Engineering (Soane, 1970). This permits density measurements to be made on a 1x1 cm grid over a cross-section of 140 cm x 140 cm. Transmission data, coordinates, and water content printed on a magnetic tape are fed into the computer and dry bulk density values are automatically printed on regular coordinates. Using this method, contours for density distribution or isodens can be drawn for tillage and crop husbandry research purposes.

2.5.2.6.5 Epoxy resin impregnation

A method was recently proposed (Becher and Wilke, 1976) for bulk density determination that is applicable to soils rich in rock fragments or thin soil sections. The soil is impregnated with epoxy resin. Bulk density (Db) is determined after hardening of epoxy resin according to the equation

$$Db = \left(\frac{D(\text{soil + epoxy resin}) - D\ \text{epoxy resin}}{Db - D\ \text{epoxy resin}}\right) \qquad (11)$$

Bulk densities determined by the method were found to agree well with those obtained by the core sample method.

2.5.2.7 Particle density

Particle density (Dp) is usually used with bulk density (Db) in the estimation of total porosity (ε) of soil. The equation relating the three parameters is

$$\varepsilon = 1 - \frac{Db}{Dp}\,(100),\ \% \qquad (12)$$

However, porosity so determined empirically has low accuracy.

Particle density is determined by finding the volume of kerosene oil (or similar liquid) displaced by soil aggregates in a density bottle under vacuum. The result from this method becomes more accurate if an oil or liquid that can be absorbed at all by soil is used, and if a good vacuum can be maintained.

2.5.3 Aggregate Size Distribution and Stability

2.5.3.1 Aggregate size distribution by dry sieving

Sorting of dry aggregates of soil samples collected from tilled soils into different classes by sieving is useful in assessing the structures of the soils. A soil of known weight is sieved through a nest of sieves manually or mechanically. A rotary sieve was designed

(Chepil, 1952) to separate dry soil in one operation into any number of fractions up to 14. The results from mechanical sieving are independent of personal judgement. A plot of the percentage of aggregates in each fraction can be made or the percentage of soil aggregates larger than a particular size can be got. Dry sieving has been used (Keen, 1933; Cole, 1939) to investigate susceptibility of soils to wind erosion, and it was used (Yoder, 1937) to trace seasonal changes in the structure of tilled soil. The minimum aggregate size considered in the latter was about 2 mm.

The dry sieving technique needs to be standardized in a number of its aspects such as method of sieving and soil sampling. It is not commonly used because it does not indicate stability to water which usually forms the basis of comparison of soils. Soil aggregates are also broken down during sieving (Chapman, 1927), however this factor could be used to assess the relative mechanical stabilities of soils. When the technique is used, the depth and method of sampling needs to be specified.

Other possible ways of expressing aggregate size distribution after dry sieving are discussed below.

2.5.3.2 Aggregate size distribution and stability in wet sieving

2.5.3.2.1 Methodology

Wet sieving is one of the commonly used methods for assessing the stability of tilled and untilled soils. The size distributions of aggregates before and after sieving are compared. Although the technique of wet sieving varies depending on the facility and interest, most of the techniques being used follow those described by Yoder (1936) who developed the wet sieving technique introduced by Tiulin (1933).

Sieves which hold different sizes of aggregates are fixed into a mechanical siever. The sieves containing soil aggregates are permanently under water during the wet sieving and are alternately lifted and lowered by the machine with speed of about 3 cm per min. for thirty minutes.

2.5.3.2.2 Pretreatment of aggregates

Treatments of aggregates before wet sieving aim at equilibrating the aggregates under uniform conditions of humidity and temperature, and prevention of considerable slaking of the aggregates due to escape of entrapped air during wet sieving.

Apart from equilibrating the aggregates under uniform conditions of humidity and temperature, it was advocated (Russell and Tamhane, 1940) that gas vapour could be passed over the aggregates to achieve the same end.

Precautions against disruption of aggregates due to forceful air escape include evacuation, prewetting at about 5 cm suction, or water-spraying (Low, 1954), and treatment with non-polar liquids (Henin *et al.*, 1955). However, Low (1954) hinted that the presence of entrapped air in aggregates may not be the major factor in the disintegration of air dry aggregates on wetting.

2.5.3.2.3 Results from wet sieving

Aggregates that are left on each sieve after wet sieving are oven dried to expel water and weighed. The weight of each size fraction over the initial weight of the aggregates before wet sieving can be got, and a plot of % stability and size can be obtained. Usually the % aggregate stability of all aggregates larger than a particular size (mm) such as 0.10 (Baver and Rhoades, 1932), 0.25 (Tiulin, 1933), and 0.05 (Quirk, 1950) are presented relative to the initial weight of soil.

Statistical expression of aggregate size distributions after wet or dry sieving in form of Mean weight diameter (MWD) and Geometric mean diameter (GMD) used to be common. The proportion of weight of a given size fraction relative to total weight of soil is multiplied by the average diameter of that fraction. The MWD is the sum of the products for all size fractions of the soil (Van Bavel, 1949). For the GMD, the weight of aggregates in a given size fraction is multiplied by the logarithm of the mean diameter of that fraction. The sum of these products for all size fractions is divided by the total weight of soil sample (Mazurak, 1950).

2.5.3.2.4 <u>Factors affecting results from wet sieving</u>

A number of works (Quirk, 1950; Panabokke and Quirk, 1957; Russell, 1971) have indicated the problems with the use of wet sieving technique especially as related to the fact that it is not standardized.

Results from wet sieving stability determination depend on the initial water content of aggregates or suction, initial aggregate size, the aggregate size on which stability assessment is based, method of sieving, sieving time length, pretreatment and method of prewetting.

Some examples are now given. Evans (1954) found that prewetting and storing of aggregates increased their water stability compared to when storing was not done. This was thought to be due to closing of planes of weakness in the aggregates that were given the former treatments. It was suggested that a prewetting treatment be chosen which reinstates the soil to a structural condition that most likely exists under the natural conditions being investigated. Low (1954) recorded an instance in which the choice of aggregate size > 0.25 mm rather than > 3 mm could have obliterated stability difference due to difference in organic matter contents of soils. Panabokke and Quirk (1957) found that aggregation (0.05 mm) was greatest when wet sieving was performed on aggregates at initial suction of between 0.1 - 0.3 bar.

Apart from the fact that the result from wet sieving depends on the worker and facility, another criticism is that it is not useful on compacted soil (Burke *et al.*, 1964; Gradwell and Arlidge, 1971; Gradwell, 1973). A good water stability could be shown either by porous aggregates from good arable soils or by compact, impermeable aggregates from agronomically condemned soils. In the Netherlands, deterioration of heavy clay soils was caused by mechanical compaction rather than dispersion action of water, therefore it was concluded (Boekel and Peerlkamp, 1956) that wet sieving tests for water stability were not satisfactory for the soils. The presence of compacted zones between 7-20 cm depth in soils of certain vegetable gardens in New Zealand was not related to the water stability of the soils aggregates (Gradwell and Arlidge, 1971). Thirdly, the wet sieving method has been found to be insensitive when high replications were used. Pereira (1955) who worked on tropical soils wrote that the ordinary wet sieving tests proved inadequate to distinguish between the physical conditions of soils which showed contrasting field behaviours. He said that although the technique might differentiate between some soil conditions, it was insufficiently sensitive at high replications to be able to measure the smaller but important changes due to normal agricultural practises.

2.5.3.3 Permeability as stability index

The decrease in permeability of soil due to leaching with dilute salt solution has been used (Dettman and Emerson, 1959) as an index of collapse of soil structure. Soil aggregates are wetted under low suction with 0.05N sodium chloride solution and the permeability (K1) to the same solution is then determined. Leaching of the test soil with the salt solution follows, after which another permeability (K2) run is made. A salt solution of 0.05N was found to be high enough to promote flocculation and low enough to cause deflocculation when used for soil leaching. The index of stability of the soil is equal to K2/Kl.

Emerson (1954a, 1954b, 1955) originated the technique of using salt solution permeability to trace changes in stability of soil. He used higher concentration of salt solution (0.5N) for initial flocculation and increasingly diluted solutions (100 mN, 20 mN, 2 mN) and distilled water were used for leaching until the permeability of the soil was zero. The least concentration then used was called 'critical concentration'. A highly stable soil had the least critical concentration or had to be permeated with distilled water. Quirk and Schofield (1955) found that below a certain concentration which is specific for each ion, decreases in the permeability of soils occurred. The threshold concentration for sodium chloride was 0.25 M.

2.5.3.4 Emerson dispersion test

Soil aggregates have been divided into eight classes (Emerson, 1967) by observing the coherence of the clay fraction in distilled water. The aggregates that slake as a result of disruption by entrapped air or swelling are placed in classes 1 to 6. Those that swell but are still coherent are in class 7, whereas those that remain unchanged by immersion in water are in class 8 and they are the most stable. When immersed in water, those aggregates that are completely dispersed are in class 1, and those that are partially dispersed are in class 2. Those aggregates that are not dispersed are remoulded to field capacity and immersed in water. If dispersed as a result, the respective aggregates will fall into class 3. Aggregates that are not dispersed after remoulding but contain calcite or gypsum are in class 4. Those aggregates that are dispersed between field capacity and suspension are in class 5. If a suspension of aggregates completely flocculates at 5 min. standing, those aggregates will fall into class 6.

The Emerson dispersion test has been modified by Loveday and Pyle (1973). Aggregates are immersed in water and the degree of their dispersion is scored at 2 and 20 hr after. The non-dispersed, slightly dispersed, moderately dispersed, and highly dispersed are scored 0, 1, 2, 3, 4 respectively. The dispersion index (DI) for air-dried aggregates which are not dispersed is got by adding the 2 and 20 hr scores after remoulding at 100 cm suction, and the maximum DI value is therefore 8. For those aggregates that are dispersed, the 2 and 20 hr scores are added to 8 so that the range of possible DI values is 9-16.

The Emerson dispersion index is a useful indicator of soil stability but its accuracy depends on the skill of the user.

2.5.3.5 Dispersion of silt and clay fraction

The degree of dispersion of silt and clay when aggregates are shaken in water has been used as index of aggregation and aggregate stability (Low, 1954; Williamson *et al.*, 1956; Pringle, 1972). The method involves soaking of soil aggregates smaller than 8 mm in water for 24 hr followed by shaking by inversion of the cylinder containing the water and aggregates 30 times. The total silt and clay in the original soil aggregates is determined by a separate mechanical analysis. The result from this mechanical analysis and the amount of silt and clay in the dispersed aggregates (also determined by mechanical analysis) are related.

The dispersion ratio (D) of the soil concerned is calculated as

$$D = \frac{\text{Silt + Clay dispersed by shaking}}{\text{Total silt + clay by mechanical analysis}} \qquad (12)$$

2.5.3.6 Water drop test

To assess the stability of soil under rainfall, the ease by which its aggregates are disrupted under simulated raindrops can be determined. The numbers of water drops or the energies of water drops to disrupt different aggregates can be compared.

Smith and Cermuda (1971) modified the water drop test of McCalla (1942, 1944) especially to cover its application in the tropical regions. Prewetting of 6-12 mm diameter aggregates after evacuation was suggested against air-escape disruption and because the water drop alone is not strong enough for the aggregates of some tropical soils to be disrupted. However, a direct water drop test has been used for temperate soils (Low, 1954) usually with the average size of drops of 4 mm diameter, terminal velocity of 7 $m.sec^{-1}$, and drop fall of 1 metre. Smith and Cermuda (1971) in Puerto Rico suggested the use of 1 drop per sec., 0.1 g per drop, and a drop fall of 60 cm on 6-12 mm aggregates. It was considered that an aggregate is destroyed when it falls apart and all its parts fall through a 5 mm sieve.

Instead of counting the number of drops required to disrupt an aggregate as in most other works, McCalla (1942) calculated the kinetic energy (K.E.) of water drops that caused the disruption of aggregates. He compared the K.E. values needed to disrupt the moist aggregates of soils that were given different treatments. Drops of water approximately 4 mm in diameter, falling 0.5 m from a burette at the same rate, and aggregates 4 mm in diameter placed on 1 mm screen were used.

Grierson and Oades (1977) have constructed a rainfall simulator that could be used in the field for water drop tests. The simulator is mounted on a two-wheeled trailer towed either by car or tractor. Simulated rainfall with intensity, drop size, and drop velocities within the range of natural rainfall can be produced over 1 m^2 of surface.

The water drop test is quite a useful method for stability determination on dry and carefully wetted aggregates. But aggregates should have strictly uniform sizes since the result depends on aggregate size. Secondly, replications and rainfall simulation that will cover a large number of aggregates are needed. The water drop method usually suffers the need to select an extremely small sample of crumbs (Pereira, 1955).

2.5.4 Soil Impregnation

Impregnating soil pore spaces with different materials for visual and descriptive analysis of soil structure had been performed. A method of impregnation whereby thin sections could be examined later under microscope was suggested by Pigulevsky (1930). A mixture of three parts paraffin and one of napthelene was forced into soil spaces. A section of the impregnated soil was cut and polished for examination. Other works (Kubiena, 1938; Altemuller, 1956; Brewer, 1964) later resulted in improved methods, wider applications, and better use of the method of impregnation. Polyester resin (Rogaar, 1974) was used for impregnation. However, all the efforts on the use of impregnated thin sections for soil structure study were descriptive and non-quantitative, and much depends on the visual judgement of the worker concerned.

2.5.5 Soil Impregnation and Film Scanning

A recent advancement in the measurement of soil structure after impregnation was by Wilkins *et al.* (1977). A laboratory technique was developed to measure soil pore size, aggregate size, and orientation of soil pores and aggregates. The technique consisted of fixing soil samples with a fluorescent polyester resin, sectioning the soil samples, and taking a photograph of a section of each impregnated soil sample under ultra-violet light. The photographs were scanned with a flying spot particle analyser (FSPA). From the FSPA scanning information, means, and covariances of soil aggregate size, pore size, and apparent soil porosity were calculated.

The FSPA is an instrument that scans, using a small light beam, an 18x18 mm area of 35 mm film approximately 900 times. In lineal analysis mode of operation, information was obtained on pore spaces and intercept lengths. Information from the FSPA on intercept length is in the form of numbers of intercepts greater than a designated size. The maximum range of intercepts detected with the FSPA was 20 to 20,480 μm. However, the technique can evaluate pores of any size if micrographs are used.

This technique with some modification (Murphy *et al.*, 1977a) has been applied in soil survey studies (Murphy *et al.*, 1977b). The structural information after scanning is passed through computer which produces a paper printout.

The accuracy of results depends on the contrasting between pores and aggregates by the scanning instrument.

The sample collected for structure measurement may not represent the structure of the soil. The structure of a very small fraction of soil could only be considered using a core sampler smaller than 8 mm in diameter, while only an area of 324 mm^2 (Wilkins *et al.*, 1977) is used for scanning at a time.

To prevent soil disturbance during core sampling is a very difficult problem. Because of this, there is a limitation on the type of soil from which the sample may be collected.

The method is costly and cumbersome. The use of replicates is hindered when many soils given different treatments have to be compared in terms of their structures. Quick field assessment of macro-soil structure which considers a larger area of soil at a time is needed.

2.5.6 Summary

Most of the methods used to evaluate aspects of soil structure have been reviewed. The general problems concerning their use have been mentioned, and each method has been briefly and critically discussed.

The methods discussed included those assessing physical properties that are functions of soil structural state such as porosity, pore size distribution, permeability, available water, and bulk and particle density. Those methods discussed that indicate the stability of soil structure included dry and wet sieving for aggregate distribution and stability, determination of permeability change in response to salt leaching, determination of dispersion index, and measurement of stability under water drops.

Impressions have been created that the methods of indirect measurement of soil structure are not dependable for use on some tropical soils. It was found (Pereira, 1955) that free draining pore space and percolation rates tended to reflect the level of insect activity in some East African soils rather than soil stability. And wet sieving techniques, percolation rates, and free draining pore space were not efficient indications of structural conditions of lateritic soils.

Efforts made to impregnate soil with different materials for further descriptive and visual analysis were mentioned. A development of this technique was the scanning of the photographic film of impregnated small soil section for the distribution in number of sizes of large aggregates and pores.

There is need for other techniques apart from those discussed that could be used to evaluate the actual undisturbed soil macro-structure on a fairly large scale. The techniques have to be rapid, inexpensive, and easy to use.

2.6 Tillage Modification of Soil

2.6.1 Introduction

Tillage is any mechanical modification of soil in the process of crop production. Tillage connotes change in the structure of soil, and it is a mechanical aid in the formation and arrangements of separate soil aggregates. A tilth is defined as a soil condition produced by tillage.

Survey of the literature on the necessity for tillage revealed that it serves two major purposes. They are weed control (Cole, 1939; Russell and Keen, 1941; Russell *et al.*, 1942; Cook *et al.*, 1953; Olson and Schoebert, 1970; Ouwerkerk and Boone, 1970), and tilth formation (Slipher, 1932; Baver, 1961; Arakeri *et al.*, 1962; Cannell, 1973).

The fragmented soil in a tilth is made up of separate aggregates and their associated voids; the aggregates and voids are essential for good establishment of a crop seedling. Tilth connotes a prepared seedbed which is characterised by reduced soil density, and resistance to root penetration, increased infiltration and retention of water, and optimum aeration. Therefore, it seems that some tillage is inevitable to economic and continuous production of crops.

With the advent of herbicides in the 1960's, and with increased costs and undesirable soil compaction and increased erosion that are associated with conventional tillage (ploughing plus multiple harrowing), two other tillage systems are presently being used in addition to conventional tillage. One of them is zero tillage which originated due to possible elimination of tillage practise for weed control. A school of thought (Boone and Kuipers, 1970; Kuipers, 1970; Poesse and Perdok, 1970; Stibbe and Ariel, 1970; Moffatt, 1971; Gard and McKibben, 1973; Young, 1973) believed that the more important function of tillage was weed control, and if this could be done by the use of herbicide, then tillage practise should be a 'luxury'. And because of high costs of conventional multiple tillage in terms of money, time, and soil structure, and the inevitability of some degree of tillage, minimum tillage practises became widely practised. Another school of thought (Baeumer and Bakerman, 1973; Cannell, 1973) believed that tilth formation was the more important function of soil tillage.

Therefore, selections of tillage systems all over the world have been based on three main systems which are zero tillage, minimum tillage, and conventional tillage.

In the following, the merits and demerits of the tillage systems are discussed, and a conclusion on choice of tillage system is proposed. There have been many research experiments carried out on the comparison of tillage systems especially in temperate countries, opinions and findings are naturally diverse but not equally divided. Only a small proportion of the research that has been done into tillage systems can possibly by referred to.

2.6.2 Zero Tillage

There is no fixed definition for the practise of zero tillage. Usually, zero tillage is synonymous with conservation tillage and is based on the zonal tillage concept whereby land is divided into a seedling management zone and soil management zone (Larson and Gill, 1973). The tilled seedling environment zone provides for good emergence, proper stand and satisfactory yield (Lal, 1976). The above definition of zero tillage is somehow synonymous with the definition of minimum tillage, and where zero tillage is practised in this sense it has given crop yields as high as that of conventional tillage (Gard and McKibben, 1973; Lal, 1976; Van Doren *et al.*, 1976).

A more direct definition of zero tillage refers to the situation where no tillage of the soil including the seed row is performed. The perfect example of zero tillage is the 'sowing' of pastures by dropping seed from aeroplanes in Australia. In this case, a seed management zone cannot be distinct from a soil management zone. When zero tillage was practised in this sense, poor germination and seedling emergence (Bowers and Bateman, 1960; Cannell and Finney, 1973; Reeves and Ellington, 1974) and low crop yield (Cannell, 1973; Wedd, 1975) were recorded. However, some improvements in certain soil properties have been attributed to the practise of zero tillage. These include increased structural stability (Dell'agnola and Ferrari, 1971), reduced wind and water erosion when vegetative materials are present on the soil surface (Shanholtz and Lillard, 1968; Gard and McKibben, 1973; Young, 1973; Lal, 1976), increased organic matter content (Bakerman and de Wit, 1970; Free, 1970; Moschler *et al.*, 1972; Tomlinson, 1974) and increased earthworm activity (Graff, 1969; Stonebridge, 1975).

Adverse changes in most of soil physical properties can also be caused by zero tillage. It has been shown that in some cases continuous zero tillage results in increased soil density and resistance to seedling root growth, reduced water infiltration and increased soil erosion, and reduced pore size and porosity (Anderson *et al.*, 1958; Bulfin and Glaeson, 1967; Ouwerkerk and Boone, 1970; Cannell, 1973; Cannell and Finney, 1973). Less favourable soil physical state as a result of zero tillage was found to produce a very low dry matter yield (Wedd, 1975). However, it is emphasised that there is no direct relationship established between soil structural properties and yield of crop. Change in crop yield could not be evidently associated with change in soil structure alone since a number of other chemical and biological factors all interact to determine crop yield.

Conclusions have been arrived at on the ultimate effect of zero tillage on the yield of crops. There appear to be no strong scientific backing for the practise of zero tillage. However, one work (Cannell and Finney, 1973) concluded that zero tillage adversely affected soil structure and seedling establishment but these effects might not reduce final yield considerably. But Culpin (1971) recorded that in England direct drilling was unsatisfactory at all farms where it was experimentally practised. Experiments confirmed a belief that 'reduced tillage' as opposed to 'zero tillage' is a sensible objective. Although zero tillage which saves time is gaining popularity with growers, the soil scientist has remained dubious and unimpressed about its long term effects on the structure and physical properties of soil. Experience gained so far (Baeumer, 1970) does not justify the recommendation to use direct drilling in general practise and especially for more demanding crops and less well drained soils (Soane and Pidgeon, 1975).

2.6.3 Conventional tillage and deep tillage

It is generally accepted by agronomists and soil scientists that conventional types of soil preparation comprising multiple passes of different implements should be discouraged. The main reasons are because it causes the formation of a compacted plough pan, it increases soil water erosion, and it is uneconomical in terms of time, labour, and money (Green and McCullough, 1974; Stonebridge, 1975). In addition, continuous tillage has been associated with reduction in the level of soil organic matter (Page and Willard, 1946; Rovira and Greacen, 1957), and reduction in aggregate stability (Miller, 1919; Dorman, 1933; Jenny, 1933; Retzer and Russell, 1941; Law and Evans, 1949; Cook *et al.*, 1953; Spencer and Stirling, 1962).

Since about twenty years ago, investigators have come up with ideas supporting deep (up to 60 cm depth) tillage or deep ploughing. In the long run, continuous deep tillage will cause those problems that have been associated with conventional tillage. Therefore, its practise could only be advocated for remedial purposes against the presence of compacted subsurface layers.

Nevertheless, improved soil physical properties and crop yield have been attributed to a deep tillage. The improved physical properties included decreasing density and increased permeability up to 30-45 cm depth (Mallick and Nagarajarao, 1972; Gidnavar *et al.*, 1973), and increased water capacity by 8-12% (Kunze, 1963). Variable weather conditions in different agricultural districts of Hungary (Egerszegi, 1963) especially frequent drought, justified attempts to raise water storage considerably by deep tillage. Chiselling and other deep ploughing operations significantly increased the yield of maize, wheat, rice, oats, rye and most cereals on rainfed soils (Satinski, 1959; Toshio *et al.*, 1959; Drezgic and Jevtic, 1963; Mukhortov, 1964; Moolani and Hukkheri, 1965; Simeonov, 1966). The yield increases were attributed to favourable physical properties (Burov *et al.*, 1973) and increased root growth (Singh *et al.*, 1971). However, lack of yield response to deep tillage was recorded on soils already in good physical state (Anderson *et al.*, 1958; Khan, 1958). Improved soil physical properties and yields due to deep tillage were observed to last several years (Buornett and Tackett, 1958; Galeva and Dilkova, 1968).

Ploughing should be discouraged on clay and heavy soils because subsurface soils that will be brought to the surface will not break easily into small fragments important for seedling performance even with secondary tillage. Cooke and Williams (1971) at Rothamsted reported their experiences with Saxmundham soil on which deep furrow slices brought to the surface by deep ploughing to 25 cm could not be broken down into small clods and aggregates by weathering during cold winters.

Minimum surface tillage has always been the rule. In semi-arid South Australia, farmers till only to about 7 cm depth. Even for initial breaking up of land they use scarifier-type implements (Webber *et al.*, 1976) in tillage for weed control, and development of a good seedbed is usually carried out with a scarifier or even a combine drill.

Exception to the rule of minimum surface tillage in form of deep tillage or ploughing has always been advocated for soils in which the subsurface compacted layers restrict root growth and also for soils which are susceptible to flooding. In the latter case, more water will be conserved. Burnett and Hauser (1967) who reviewed the phenomenon of deep tillage in relation to soil, plant and water relationships suggested that physical changes in the soil profile created by deep tillage will only be long-lasting if the soil is fine textured throughout the profile and if the dense or fine textured zone in the profile is genetic.

2.6.4 The need for minimum tillage

Seedbed preparation is inevitable in the process of crop establishment, therefore minor tillage will always be part of crop husbandry. Seed broadcasting has been found (Russell and Mehta, 1938; Hunt *et al.*, 1963; Watkins and Vickery, 1965) to be inferior to hand sowing. There are many other sources of information available (Stonebridge, 1975) to show that the performance of seedlings established in prepared beds is better than the performance of seedlings established in untilled soil. The problems involved in sowing, harvesting, and crop management have (Poesse and Perdok, 1970) made it less likely that tillage would be abandoned.

In ordinary situations, conventional and multiple tillage has been discouraged in the light of scientific findings about the need to use minimum or reduced tillage practises in crop establishment. Depending on climate, resources, type of crop, and soil type, there are different forms of reduced tillage. It varies from the simplest row seedling in which the seed management zone is only prepared, to others such as shallow scarifier tillage, one-pass tillage, tillage-spray drilling and strip processing. The major points in favour of reduced tillage are stated below.

It is indicated (Brown, 1975; Hutchings and Hinks, 1975; Stonebridge, 1975) that the increasing cost of fuel and labour will induce movement towards fewer and milder tillage. In terms of fuel and cost, reduced tillage was found to be more efficient than other systems of tillage. Operations in conventional ploughing would cost 2.26 $GJha^{-1}$ in Australia, and for direct drilling, harrowing, and spraying the cost would be 1.02 $GJha^{-1}$, though the assessment was critical (Green and McCullouch, 1974). If herbicides are to be an integral part of crop establishment practise in reduced tillage systems, the cost of herbicides will be a vital factor in the degree of acceptance of the systems (Stonebridge, 1975). Therefore (Wells and Reeves, 1975), in the context of energy and cost, reduced tillage without herbicides may become a new conventional standard.

With reduced tillage, the farmer will have more control over the timing of operations, and there will be more time for leisure and other activities. This point should have been better argued for zero tillage, but for soil problems associated with its practise. However, exceptions may be found where the soils are higher in organic matter and lighter in texture (Jones *et al.*, 1969; Shear and Moschler, 1969; McCalla *et al.*, 1962).

With minimum tillage, there will be less damaging effect on the soil, soil water storage will be increased, the degree of soil erosion will be reduced, and soil preparation under wet conditions will be encouraged. These improved soil properties have been attributed to larger aggregate size (Page *et al.*, 1946) and decreased compaction (Free, 1960). As shown by aggregation data (Swanson and Jacobson, 1957), soil structure was deteriorated least where some weeds were allowed to grow, or with one tillage operation rather than three. Due to increased infiltration (Meyer and Mannering, 1961), ponding of water will be reduced by mild tillage (van Duin, 1955). Tillage tools can be used to create various surface microreliefs to aid in the management of water (Larson, 1963, 1964). The potential amount of water that can be temporarily stored in the surface micro-depressions of tilled soil is termed 'depression storage'. Increased porosity, due to loosening of a soil by tillage, acts as a reservoir for temporary storage of water during intense rain. According to Larson, reduced tillage methods, if on the contour, probably have a potential storage for a 5.0 to 7.5 cm rain in the micro-depressions. A smooth soil surface such as is prepared by conventional tillage practise can store less than 2.5 cm of water. Farm activities such as seeding, fertilizer application, thinning, harvesting, major tillage and tillage for special purposes are usually destructive of the porosity already created. The researcher needs to seek ways of omitting unnecessary tillage (Moens, 1963) and of combining operations so as to reduce the number of trips over a field (Blake, 1963).

Argument is stronger in favour of optimum release of mineralized nitrogen under mild tillage than under either zero of conventional tillage (Wells, 1975).

Minor surface tillage coupled with some herbicide treatment if necessary will counter staggered germination pattern and preservation of weed seed more than the use of herbicides alone (Stonebridge, 1975). The opportunities which herbicides provide for modifying tillage systems are being rapidly exploited. It was estimated (Cannell and Finney, 1973) that in the United Kingdom there were about 400,000 ha of cereals grown following some form of modified or reduced tillage. Direct drilling as such, was used only for a small area of crops in the United Kingdom but increased to 55,000 ha, of which about one-third was cereals. Minimum tillage requires less skill than zero or conventional tillage (Hutchings and Hinks, 1975) and its yields are usually the highest (Blake and Aldrich, 1955; Wedd, 1975). Minimum tillage was accepted readily by farmers in Japan but more slowly in tropical Asian rice-growing countries despite excellent technical results obtained in field trials (Brown and Quantrill, 1973).

Research reports mostly favour the practise of minimum tillage rather than zero or conventional tillage when all the systems were examined on the basis of soil, and crop properties. However, there will be exceptional needs for the use of zero tillage and conventional tillage. For example, grass- and weed-killing chemicals are often useful in areas of rolling topography where the preparation of a seedbed by ploughing the land could result in serious loss of soil during heavy rains before the crop canopy has become established (Bear, 1965). Some tuberous and tap-rooted crops will need deep-tilled soil for better performance and yield.

2.6.5 Summary

Most research studies into tillage practises were carried out under temperate conditions. Tillage is inevitable especially in seasonal crop production. Minimum or reduced forms of tillage are ideal for soil management and crop establishment and increased yield. Major points against zero tillage are its adverse effects on soil structure and physical properties and seedling performance. The major criticisms of the conventional multiple tillage are based on soil compaction, high cost and soil erosion hazard.

In most of the tropics, the conclusion is on the use of medial technology. The major factors of cost, high rainfall, rugged topography, small farm holdings, and unemployment are against the use of big farm machines and implements. Presently, the move is towards the design of small, light and powered farm tools in Nigeria, for example. The products of this effort will certainly improve the efficiency and output of farmers each of whom usually has farm holdings less than 3 ha in one location. Experience at the International Institute of Tropical

Agriculture (I.I.T.A.) in Nigeria (Lal, 1976) has shown that tillage which causes minimal soil exposure and leave crop residue on the soil surface will maintain required high level of infiltration by preventing rainfall soil slaking which characterises conventional tillage involving soil inversion.

However, there are various forms of reduced tillage from row tillage and strip processing to single pass scarifier tillage and some use of herbicide. The form of reduced tillage will depend on climate especially as determined by rainfall, topography, soil type, type of crop, economic feasibility, and farm size. Any method that provides a good seedbed in the row and promotes germination will produce yields equal to those of conventional planting. One can only conclude in principle on the need for minimum tillage rather than the mode of operation.

2.7 Tillage Implements

Common tillage implements are the mouldboard and disc ploughs, rotary implements, and tine cultivators.

The designs of tillage implements or tools were mainly evolved by trial and error on the part of the manufacturers and developers. Researchers have been attempting only to explain the functions and purposes of designs. This is because the explanation of the working of farm tools is complicated and unresolved. Nichols and Kummer (1932), Nichols and Doner (1934) and Nichols and Reed (1934) gave compressed analyses of mouldboard design and the dynamic soil mechanical properties. The operations of mouldboard plough, rotary implements, and oscillating tools were discussed by Soane (1973), while O'Callaghan and Farrelly (1964) discussed the mechanics of simple tines.

2.7.1 Tine cultivators

Shallow tine cultivators (5-10 cm) provide sufficient loose soil for the use of standard drills for cereals and if the subsoil is freely drained no further tillage (for land preparation) is required (Moffatt, 1970; Elliot and Pollard, 1974).

Complicated analyses of tillage implements could be approached through a study of tools such as a simple narrow tine. It was hypothesised (O'Callaghan and Farrelly, 1964) that the cleavage mechanism of a soil acted upon by a flat line is a combination of two types of plane strain which are vertical plane shearing, or upheaval, and horizontal plane shearing or soil being pushed aside.

Figure 1 shows succession of shearing planes in front of a moving tine. Shearing occurs when the shearing stress imposed by the moving tine equals the shearing strength of the soil between the tine and the surface. A shearing plane will occur along the surface where minimum draught force for tine movement occurs. The shape of the detached soil block (Figure 2) is crescent-like, although there will be some secondary shearing planes within the detached soil. The detached block is simultaneously raised and pushed forward by the moving tine. In the process, it is fragmented into small pieces, sorting of crumbs occurs in its front, and their mixing occurs at the rear. The tine is known for its property to sort small soil crumbs to the bottom of the tilled layer and large crumbs to the top of the tilled soil. The distance between successive shear planes depends on the compressibility of soil and thus its texture and water content. According to Dexter (1973), in a soil of low compressibility the shear planes would be closely together, whereas in a soil of high compressibility, considerable tine movement can occur before a shear failure condition is attained, and the shear planes would be correspondingly further apart. The angle of the shear plane is given by

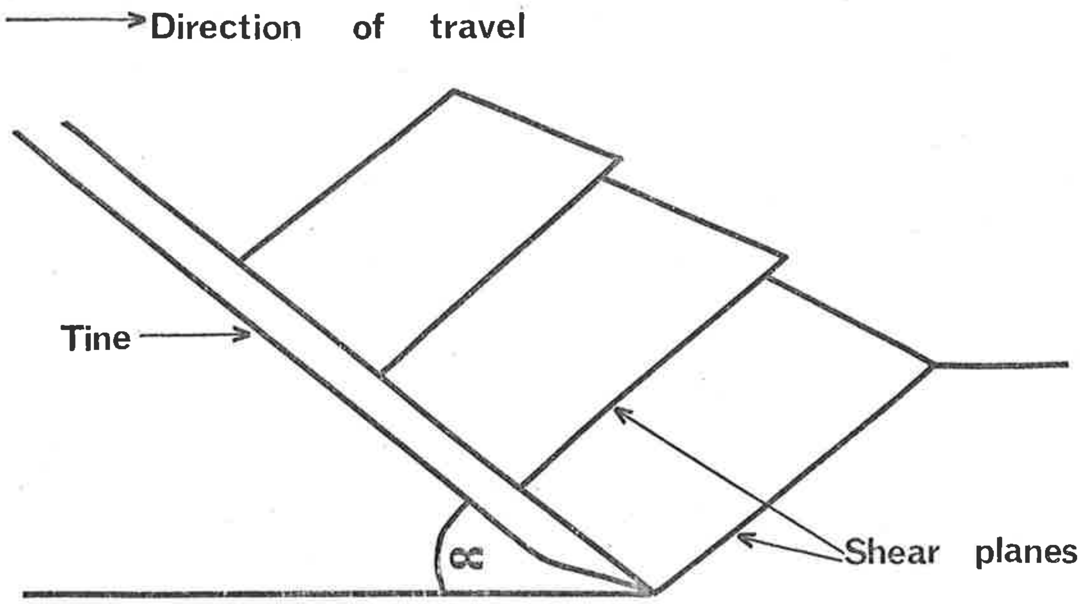


Fig. 1. Succession of shear planes during tine tillage.

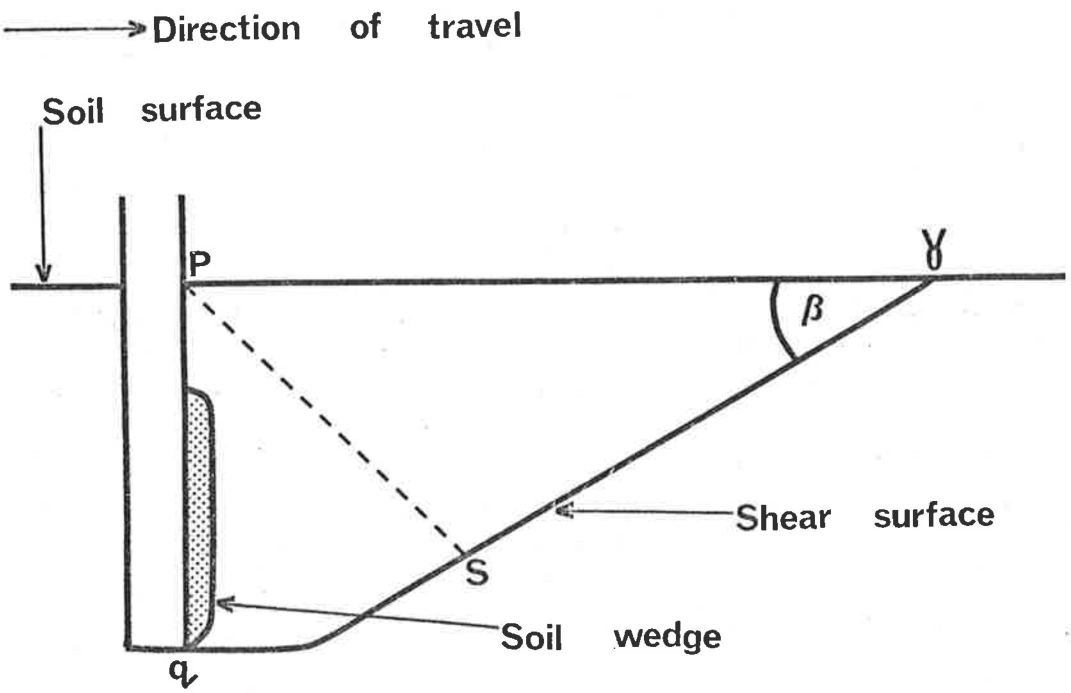


Fig. 2. Soil shearing by a tine.

$$\beta = (\frac{\pi}{4} - \frac{\phi}{2}) \qquad (14)$$

where ϕ is the angle of soil internal friction.

The angle between the furrow floor and the rear of the tine (Figure 2) which is the rake angle (α) was related to the forces acting on the tine and the shapes of the failure surfaces produced by Payne and Tanner (1959). They found that there is no net vertical force acting when $\alpha = \frac{\pi}{4}$, and that tines develop a net downwards force for $\alpha < \frac{\pi}{4}$ and a net upwards force for $\alpha > \frac{\pi}{4}$. If α is decreased at a constant working depth ℓ, the length of the crescent soil shape in the direction of motion is increased, whereas increasing α shortened it.

Vertical upheaval is descriptive of the mechanism extending from soil surface to a depth where the ratio of tool depth to tool width equals 0.6. Below this depth, a transition zone exists and the cleavage mechanism is not well defined until the ratio approaches 1.0 and then the tool becomes deep working. At this point a soil wedge (Figure 1) is formed on the surface of the tool point which moves upward to the surface and is replenished from the furrow bottom. A soil core laminates the start of the wedge and the soil furrow. A soil bin investigation (Collins and Lalor, 1973) of a deep working tillage tool was performed. For a simple wide tine, the force (p) acting on the face before a shear plane develops is

$$P = 2\mathrm{Cpk}\tan(\frac{\pi}{4} + \frac{\phi}{2}) + \rho g z \tan^2(\frac{\pi}{4} + \frac{\phi}{2}) \qquad (15)$$

where Cpk is peak soil cohesion, ρ is soil density, g is acceleration of gravity, z is depth of operation, and ϕ is the angle of internal soil friction.

Various forms of tine include the tail chisel plough, and the scarifier. The largest width of a tine may vary from 65 mm for a narrow tine to 200 mm for a wide tine, and the length may vary from

95 mm to 200 mm for all types of tine.

2.7.2 Plough implements

Most of the investigations that have been done on ploughs to investigate their operation were on the mouldboard plough. The mechanical functions of the plough consist of cutting loose, granulation, and inversion of the furrow slice. The loosening of the soil surface is achieved by the breaking loose and inversion of furrow slice. The cutting loose of a furrow slice takes place at the edge and shin of the plough share, granulation occurs throughout the centre of the mouldboard although a considerable part of the granulating action may take place at the front portion of the plough surface. Lifting and inversion of the slice take place throughout the length of the mouldboard.

The traditional mouldboard shapes are not successful at high speeds because of the high draught and the poor furrow slice inversion. Therefore, research has been stimulated (Soane, 1973) to modify the plough for use at high speeds. By so doing, labour cost will be reduced due to reduction in required man-hours and it will be possible to plough a greater farm size at optimum soil water conditions.

The shape of the mouldboard tool varies from helicoid to semi-helical (White, 1918) and the plough bodies in current use function satisfactorily (Soane, 1973) up to 1.9-2.2 $m.sec^{-1}$. Another advantage of ploughing at higher speeds is that the tractive efficiency of wheel tractors is increased, leading to reduction in the severity of soil compaction. A rolling disc coulter is often used with a mouldboard to prevent trash from collecting ahead of it.

White (1918) performed a study of the forms of mouldboard bottoms, analysed the motion of the soil particles as they pass over its surface, and performed a mathematical analysis of the most important historical plough bottoms which were designed to be geometrically exact.

The disc plough is used to advantage for soils that will not scour properly on mouldboards or for fine textured soils when being ploughed in a very dry state.

2.7.3 Rotary implements

Direct application of power to cause rotation of cutting blades for soil tillage has been used since 1856 (Soane, 1973).

The commonly used rotary cultivator consists of a multiple and segmented helix of truncated cone shape turning on a horizontal axis. The rotary implement is powered from the tractor power take-off. The rotary cultivator is useful for shallow primary tillage.

Rotary cultivators are known to cause a higher degree of soil fragmentation and more fine looking tilth than other implements. Melikov *et al.* (1967) in Russia found that for their rotary cultivator, unlike the conventional plough, the degree of crumbling did not decrease with increasing forward speed and that the finer material was concentrated at the bottom of the tilled layer.

The draught requirement for operating a rotary cultivator is lower by 17-33% compared with that for operating a plough implement. However, the total power requirement for a rotary cultivator has been shown to be 20% higher than that of the conventional plough.

The rotary cultivator is increasingly being used especially in Japan for primary tillage. This is due to the need to eliminate large clods with minimum passes of implements. However, it is known that the rotary cultivator has lower forward speed, higher purchasing price, and higher maintaining cost than most other implements.

The width of most cultivators is smaller than the outside width of tractor tyres (Soane, 1973). However, with increasing tractor horsepower wider cultivators are being used especially in Japan and Britain. To utilise the forward tractive force generated by forward rotating blades, Soane indicated the possibility of fixing permanent tines at the front or back of the rotary cultivator to break up any compacted layer.

2.8 Soil Structures Produced by Tillage Implements

Information is rare concerning the structures produced by tillage with different implements. The soil structure produced by a tillage implement depends on the soil texture and water content. Another problem is the method of evaluating the soil structure produced by an implement. Until recently, the tilled soil was disturbed for its structure to be assessed.

The use of a mouldboard plough has always been associated with the production of large soil clods. A mouldboard was found to produce more large clods and non-erodable crumbs (> 0.84 mm) than a disc plough (Gill and McCreey, 1960; Siddoway, 1963) or a subsurface sweep (Lyles and Woodruff, 1962). The soil fraction under the disc plough was observed (Bhushan and Ghildyal, 1972) to contain smaller clods than that under the mouldboard plough, and this was attributed to the abrupt curvature of the mouldboards compared with the gradual curvature of the plough discs.

The radius of curvature of a tillage tool and its size have been related with clod size distribution. In field experiments on a lateritic sandy loam soil at three water contents from 5.6 to 9.2%, seven ploughs were tested with radii of curvature of their mouldboards from 10.14 to 15.7 cm. The mean clod size was larger and the bulk density was less after ploughing with the larger mouldboard radii (Bhushan and Ghilyal, 1971, 1972). It was also observed (Gill and McCreey, 1960) that clod mean weight diameter increased as the size of plough was increased.

It has often been stated that rotary cultivators produced more soil comminution than other tillage implements (Russell and Mehta, 1938; Page and Willard, 1946; Gill and McCreey, 1960; Boose and Kunze, 1971; Soane and Pidgeon, 1975). However, there is no evidence that the rotary cultivator produces more small aggregates than all other tillage implements, although it produces a more fine looking tilth with lower proportion of large clods. A roto-tiller was also found (Feverlein, 1958) more suitable than a plough when a good mixing of organic matter with soil was intended.

It will be expected that the possible depths of tillage will vary between tillage implements. Reddy and Dakshinamurti (1971) assigned depths of 10, 10, 25, and 45 cm for Indian desi plough, disc plough, mouldboard plough, and deep chisel plough, respectively.

Difference in soil structure produced by different tillage implements was connected (Moffätt, 1971) with difference in crop yields on the soils tilled with different implements.

Differences in the size and shape of tillage tools produce differences in structures of tilled soils. Evidence points to a greater predominance of large aggregates in tilth produced by a mouldboard plough compared with tilths produced by other tillage tools.

2.9 Soil Structure and Water and Meteorological Factors

A discussion on soil water is hardly possible without reference to evaporation as the main avenue for water loss in bare soil. Soil structure when related to water content will focus mainly on aggregate or pore size distribution and its interaction with major meteorological factors in the determination of water evaporation. A brief discussion of measurement of evaporation was found necessary.

2.9.1 Soil structure and evaporation

Evaporation of soil water after wetting has been categorised into three stages (Lemon, 1956; Deacon *et al.*, 1958; Willis, 1960; Amemiya, 1965; Hadas and Hillel, 1972; Hillel and Hadas, 1972; Arias and Millar, 1973; Hanks and Gardner, 1965; Hadas, 1975). The first stage is controlled by meteorological conditions and lasts as long as the soil profile supplies water to the evaporating surface at a rate satisfying the evaporative potential. As the profile dries out, water cannot be supplied any longer at the potential evaporation rate and the second stage commences during which evaporation falls rapidly. When evaporation reaches a low and fairly constant rate, a third stage can be distinguished. In the last two stages, evaporation is controlled by soil's hydraulic properties as determined by soil structure. Evaporation must be recognized as a water transport process that can be significantly affected by the structure of the tilled layer, the associated stratification, and the transport process of the substratum (Allmaras, 1967).

In tilled and untilled soils there is a top dry layer for evaporation retardation (Call and Sewell, 1917; Veihmeyer, 1927; Shaw, 1929; Kolesnic, 1948; Burov, 1962; Allmaras, 1967; Kuipers, 1970; Heinonen, 1971; Hadas, 1975). The rate of approach to steady state evaporation by drying and establishment of the top dry zone on the soil surface is strongly influenced by soil tilth (Holmes *et al.*, 1960). If the soil is coarse textured as for a tilled soil, the rate of evaporation is increased, and the surface mulch (dry layer) is more rapidly created than if the surface soil is fine textured. Cumulative evaporation will diminish as the depth of the top layer increases (Hanks and Gardner, 1965). However, it is evident (Hanks and Woodruff, 1958) that the influence of depth of dry soil surface barrier on water vapour movement increases greatly for the first 2.5 cm, and then diminishes in effect.

Tillage-produced mulches reduce evaporation loss provided tillage is performed prior to the introduction of water into the soil by rain or irrigation (Hadas, 1975). In Northern Nigeria (I.A.R., 1976) disc ploughing at the end of the rains was recorded to be more effective than herbicide treatment in the conservation of profile water.

The efficiency of surface mulches has long been of interest to researchers. The amount of water retained in a soil with surface mulch rarely exceeds 3-30% of the rainfall in the previous fallow period (Evans and Lemon, 1957; French, 1966; Schultz, 1971). The possibility of values as low as -20% was indicated (Fawcett, 1976). However, experience from the wheat land of the Great Plains (Matthews and Army, 1960) indicated that the amount of water stored during the fallow period is related to the initial amount of water content and the precipitation during the fallow.

The depth of water table has been considered to be very important in determining the efficiency of surface mulches on an untilled soil. When the soil mulch was effective, the water table was relatively close to the surface; while in cases where it was ineffective, the ground water was far below the soil surface (Shaw, 1929). It was concluded (Hilgard, 1906; Shaw and Smith, 1927; Shaw, 1929) that the maximum capillary rise for loams and soils with greatest water lifting power was not over 300 cm. This implies that if the water table goes beyond 300 cm in the soil, the surface mulch will be inefficient.

The efficacies of self mulching and mulching by soil tillage in the conservation of soil water can be differentiated. Self mulching connotes the natural drying of soil surface layer to a friable state with fractures and cracks. The efficacy of mulching due to surface tillage lies in its obstruction to the upward capillary movement of water from the subsoil. Whereas for the untilled soil in the last phase of evaporation, the fact that the upward movement of soil water could not satisfy the evaporation potential accounts for the presence of dry surface mulch, in which case the soil water table should have fallen drastically. The factor of depth of water table indicated by Shaw will not be significant in determining the efficiency of an artificial mulch. It was suggested by Penman (1941) that dry soil surface due to summer sunshine will have little effect on water conservation.

The quality of tillage as it affects the degree of pulverisation, the clod size, and the porosity of the tilled layer determines water loss from a tilled soil. Coarse tillage leaves large cavities into which air could penetrate to increase vapour flow (Farrell *et al.*, 1966; Hillel, 1972; Ritchie and Adams, 1974). Fine tillage may result eventually in a compact surface that will defeat the aim of reducing water diffusivity (Jacks *et al.*, 1955; Willis, 1960).

For the untilled soil, the presence of a fine textured soil overlying a coarse textured soil increases evaporative loss (Hadas and Hillel, 1972) for a given water table less than 28 cm (Willis, 1960). If the sequence of layers is coarse textured soil overlying a fine tectured one, the evaporative loss will be markedly reduced.

An optimum aggregate size for water conservation, which will possibly lead to tillage recommendation against excess evaporation, has been proposed. But field work needs to be carried out for soil types and rainfall patterns. Suggested optimum aggregate size ranges from 0.25 to 5 mm (Burov, 1954, 1962; Heinonen, 1971; Hillel and Hadas, 1972; Hadas, 1975). Results from a wind tunnel experiment (Holmes *et al.*, 1960) suggested optimum aggregate size of 2.5 mm for soil water conservation against evaporation.

2.9.2 Measurement of soil water evaporation

2.9.2.1 Meteorological approach

Penman (1948) did pioneering work on the empirical use of meteorological data for measuring evaporation. Equations were used to symbolise the fact that evaporation is determined by wind movement and solar energy when water is not limiting as in a moistened bare surface, and exposed water surface. Combining the effect of both wind and solar energy balance, a composite equation was obtained as

$$E_o \text{ (mm)} = (H\Delta + \gamma E_a)/(\Delta + \gamma), \text{ m day}^{-1} \qquad (16)$$

where Δ is de_a and e_a is the saturated water vapour pressure at air temperature, Ta. H is the net energy available at the soil surface and γ is the wet and dry buld hydrometer constant (0.66 mbar K^{-1}).

Apart from the limitation in the area of use of this empirical approach, there are still considerable difficulties in measuring some of the terms, although Penman (1956) reported that progress has been made in the use of meteorological data.

Further breakdown of Penman's approach is sometimes employed to evaluate evaporation using meteorological data. Thornwaite (cited by Baver, 1961) suggested the equation

$$E = -A\left(\frac{dq}{dz}\right) \qquad (17)$$

where E is the evaporation (mm), $\frac{dq}{dz}$ is the gradient of water concentration (relative humidity) between the surface of evaporation and the air, and A is the coefficient of wind conductivity. This equation is based on the fact that any meteorological effect that tends to increase the vapour pressure gradient (as the wind) from the soil will increase evaporation. Since temperature (due to solar radiation) is fundamental to evaporation, evaporation is related to the heat index (I) by

$$e = 1.6(10t/I)^a, \qquad (18)$$

where e is monthly evaporation, t is mean monthly temperature (^{o}C), and I is obtained from summation of monthly values of i when

$$i = \left(\frac{t}{5}\right)^{1.514} , \qquad (19)$$

2.9.2.2 Conservation of water mass

A theory enabling evaporation from the soil to be calculated from measured water content and temperature profiles provided physical properties are also obtained was proposed by Rose (1968). The approach of Penman for the prediction of evaporation from open water surfaces using meteorological data is inapplicable when evaporation is limited by water transport in the soil (Stanhill, 1965).

A volume of soil delimited at top by soil surface and at the base by a horizontal surface at depth z were considered. It was assumed that the gradient in the total potential ψ of soil water in the direction z is positive at every point in the soil. The application of principle of mass conservation of water to this volume of soil over a period of time from ti to t2 (sec) yields

$$\langle E\rangle(t2-ti) = -(\Delta M)oz + (1/\rho)\int_{ti}^{t2} (q\ell+qv)dt \text{ (cm)} \qquad (20)$$

$\langle E\rangle$ (cmsec^{-1}) is mean evaporation rate from soil over time interval (t2-ti) sec, $(\Delta M)oz$ is increase in water storage for depth interval o to z over the time interval, ρ is density of water (gcm^{-3}), $q\ell$ is liquid flux density, qv is flux density of water vapour at depth z (upwards positive) (gm^{-2}sec^{-1}).

Rose discussed the further breakdown of the above equation. It is an empirical approach based on change in soil water content brought about by liquid water and water vapour movement.

2.9.2.3 Change in soil water content

The change in soil water content within a time interval is the easiest and commonly used method for assessing water evaporation. It involves determination of soil water content on depth basis. Water content on depth basis (Wd) is

$$Wd = \frac{\theta d}{100}, \qquad (21)$$

where Wd is expressed in an equivalent depth (mm) of water that is equal to the amount of water in a soil of thickness d (mm). The volumetric water content, θ, is given by

$$\theta = \frac{wDb}{\rho}, \qquad (22)$$

where w is gravimetric water content, Db is soil bulk density, and ρ is density of water.

The necessity to determine bulk density will make the method of tracing soil water content change unsuitable for a freshly tilled soil. In some cases, volumetric water content change alone is used for estimating evaporation from untilled soil.

2.9.2.4 Evaporation pan

Potential evaporation over an area is often determined by the measurement of volumetric water loss from an evaporation pan usually situated in a meteorological station. When it rains, the amount of rain water is subtracted from the net evaporation for a time period. The water in the evaporation pan is brought back to a particular level at specific times, and the volume changes are recorded for the start of another interval of measurement.

The limitation of this practical method is that it only measures water loss from a free water surface. However, it could be used to assess water loss from soil if a correction factor could be found for an area.

2.9.3 Relative importance of meteorological factors in evaporation

In an attempt to develop means of controlling soil water evaporation, researchers have been concerned with what meteorological factor mostly determines evaporation rate. The two major factors of evaporation are insolation (sometimes represented by air temperature), and wind intensity. There is divergence of opinions on the relative importance of these two meteorological factors of evaporation.

Soil water content profiles measured as a function of time (Hanks *et al.*, 1967) showed that cumulative evaporation was greater for a wind treatment than for artificially radiated treatment for a silt loam, and the reverse was the case for a loamy sand.

The shelter effects of a windbreak when radiation was larger or small was compared in relation to wind condition (Skidmore and Hagen, 1973). When radiation dominated, a windbreak influenced evaporation only slightly. Earlier, it was indicated (Skidmore *et al.*, 1959) that the relative importance of radiation-dominant or wind-dominant evaporation varied daily.

A graph was presented (Hadas, 1975) to compare the effects of wind, and isothermal and intermittent radiation in evaporation. Throughout a 30-day period, cumulative evaporation was continuously higher in the wind treatments than others.

The comparison of the cumulative drying under an ambient pressure with drying under aluminium foil (Cary, 1967) suggested that controlling the water vapour diffusion coefficient was more effective in reducing evaporation than controlling the exchange of radiation energy with the soil's surface when the soil was warm and the air above was dry. On the other hand, when the vapour pressure in the air above the soil had some fixed minimum value, there was a transition point where screening of the soil was a more important factor in controlling evaporation than reduction in the vapour diffusion coefficient of the soil.

The relative importance of insolation and wind intensity in evaporation varies from time to time and appears to depend on ambient vapour pressure. It is believed that the effects of these factors cannot be easily separated because they are dependent on each other to a great extent. For example, the wind carries some heat energy (Rosenberg, 1969). However, wind-dominant and energy-dominant evaporation could be distinguished.

2.9.4 Summary

Evaporation is divided into three phases depending on the rate of water loss. The last two phases when the rate of water loss falls below evaporation potential are influenced by soil structure as it affects soil hydraulic properties.

Soil surface mulches created by tillage conserve soil water especially if tillage is done before the rains. However, the efficiency of the surface mulch depends on the initial soil water content and the amount of rainfall.

Coarse structured mulches increase loss of soil water by evaporation. The optimum aggregate size for soil water conservation varies between 0.25 to 5 mm.

The original Penman's empirical approach for estimating evaporation from a moist surface is generally accepted to be cumbersome. Another empirical method of assessing evaporation from depths within soil was developed by Rose (1968). There are other oversimplified empirical approaches based on wind and temperature intensities.

A practical way of measuring evaporation from soil is to trace changes in volumetric water content at a depth of soil. Volumetric water loss from an evaporation pan is often used to measure potential evaporation.

The effects of insolation and wind intensity in evaporation cannot be separated, but energy-dominant and wind-dominant evaporation conditions do occur.

2.10 Movement of Water Vapour in Soil

It is relevant to discuss the process of water vapour movement in soil since evaporation from soil has been considered. This will afford a closer look on how soil, temperature, and wind factors specifically influence water loss from soil. Scientists have been concerned with investigating how water vapour movement in the soil is initiated, the mechanisms of water vapour movement in soil, and the soil physical factors determining the rate of vapour diffusion. The major points generated by some of the previous investigations are put into discussion below.

2.10.1 Factors responsible for water vapour diffusion in soil

Soil water vapour moves along its concentration gradient. The existence of the concentration gradient may be caused by gradients in soil temperature, water content, and suction; the last of these may also be due to salt concentration gradients.

All other causes of water vapour diffusion in soil are less important compared with the temperature gradient (Jones and Kohnke, 1952). For example, from saturation to wilting point (ψ = -15 bar) relative vapour pressure (P/po) only very slightly drops (Baver, 1943; Kuzmak and Sereda, 1957; Rose, 1963b) from 1 to 0.98 (Marshall, 1959). Whereas vapour pressure (p) is more than tripled when temperature changes from 10 to 30°C (Marshall, 1959).

The usually high rate of water vapour diffusion was incorrectly based on diffusion along concentration gradient and through soil aeration pores alone. The vapour flux equation is based on these premises. However, the flux equation has often failed to predict soil water vapour movement (Gurr *et al.*, 1952; Taylor and Cavazza, 1954) because other mechanisms influence the movement of water vapour, none of which is recognized by Fick's flux equation. Secondly, under field conditions, wind gusts and soil air mixing as a result of sinusoidal atmospheric pressure waves on the soil surfaces (Farrell *et al.*, 1966) form a factor that mostly determines the rate of water vapour diffusion out of soil (Hanks and Woodruff, 1958).

Many other workers have pointed out the gross inaccuracy of predicting water vapour movement on the basis of diffusion and aeration porosity. Observed rates of diffusion were several times greater than calculated rates. Measured to calculated ratio of soil vapour diffusion rose from 1.04 for a sandy loam to 1.38 for a silty loam (Rose, 1963b). Data compiled by Philip and De Vries (1957) showed that the ratio of observed vapour transfer to the predicted varied between 3.6-18.0, Woodside and Kuzmak (1958) got 10, and 0.8-8 was got by Hadas (1968). The simple theory of water vapour diffusion in porous media under temperature gradients neglected the interaction of vapour, liquid, and solid phases, and the difference between average temperature gradient in the air-filled pores and that in the soil as a whole (Philip and De Vries, 1957).

2.10.2 The mechanisms of water vapour movement in soil

Apart from mass diffusion, other mechanisms have been suggested for the movement of water vapour in soil. These are mainly vapour transfer, thermo-capillary movement, and liquid-assisted vapour transfer.

2.10.2.1 Vapour transfer

Rapid transfer of water when water vapour condenses on one side and evaporates again on the other side of small liquid bodies in a porous medium has been indicated (Philip and De Vries, 1957). It was indicated that isolated rings of water could receive vapour and transfer it at the same rate as received to the next pore. The water transferred on this basis (Marshall, 1959) could be greater than by simple diffusion alone.

Vapour movement 4 or 5 times the predicted value was also adduced (Rollins *et al.*, 1954) to this process.

2.10.2.2 Thermo-capillary movement

Large movement of water at low water contents could be due to the effect of temperature on the surface tension of water, the latter which decreases slightly with increasing temperature. The resultant suction gradient as a result of local increase in temperature could be capable of moving water through the colder parts of soil (Marshall, 1959). It was also suggested (Smith, 1943) that the mechanism of vapour transfer in soil appeared to be capillary movement triggered by vapour condensation which caused increase in ambient temperature.

Thermo-capillary vapour movement is likely to be induced if the size of the vapour filled capillaries is small, and if there are numerous capillaries in soil of the order of magnitude that this phenomenon may be important (Taylor and Cavazza, 1954). Vapour flow through carbolac was used as an evidence for viscous movement of capillary condensate in a plug with a mean pore radius of 20°A (Carman, 1952).

2.10.2.3 Liquid assisted vapour transfer

The process of thermo-capillary transfer of vapour may not be totally separated from liquid assisted vapour transfer described by Rose (1963b).

Before mass vapour transfer could occur in soil, vapour adsorption by dry soil aggregates must occur. A complete mono-layer is adsorbed on soil at P/po = 0.20 (Quirk, 1955), and transfer under a potential gradient may then occur up to P/po = 0.60 which is an arbitrary transition point between adsorption and capillary condensation (Rose, 1963b). It was earlier shown (Brunauer *et al.*, 1938) that adsorption occurred from P/po = 0.05-0.35 of the adsorbate, and it was generalized (Orchiston, 1953) that adsorption occurs at comparatively low relative pressures.

When vapour adsorption is complete, the second stage is of unimpeded vapour transfer when the water vapour behaves like an inert gas. Its molecules glide over the adsorbed molecular layers.

In the third stage, the necks of the pores will contain liquid water, with or without a thin film of significant thickness on the wall of each pore.

If the former stage has any physical reality, the system is permeable to water only by a process of distillation in which the necks of water act as short circuits for vapour movement. In a thin uniform tube of soil, the effect of introducing a quantity of water could be to decrease the path-length of vapour transfer by a fraction equivalent to the increase in water content and to increase transport constant (Rose, 1963).

2.10.2.4 Tertiary mechanisms of vapour movement

Observed high rate of water vapour movement was also explained in terms of couple diffusion (Henry, 1939; Whitaker *et al.*, 1969). Couple diffusion of water vapour and heat resulted in a higher diffusion rate of water vapour and lower diffusion of heat (Henry, 1939). The coupling between heat and water flux which was considerable between potentials of -0.1 and -15 bar, increased with temperature (Joshua and De Jong, 1973).

A hard line cannot be drawn between the mechanisms of surface migration and molecular hopping suggested by de Boer (1953) as processes by which water vapour is transferred.

2.10.3 Empirical analysis of water vapour flow

2.10.3.1 Diffusion and soil geometry

Diffusion is the molecular transfer of gases by means of their random thermal motion alone through porous media. Water vapour transfer is essentially non-isothermal in soils, firstly because varying temperature gradients always exist, and secondly because water vapour transfer in general involves change of state at points in the process (Smiles, 1977).

The flux of water vapour in soil, $\overline{V}$ vap (cm.sec^{-1}) is conventionally defined as that for gases in terms of the equation

$$\overline{V}\ \text{vap} = \frac{-D^{*}\ \text{grad}\ p}{\rho}, \qquad (23)$$

where ρ is the density of liquid water (g.cm^{-3}), p is water vapour pressure in the soil air, and D* is the diffusion coefficient of water vapour in the soil (cm^{2}sec^{-1}). D* depends on the diffusion coefficient of water vapour in air, the air-filled porosity of the soil and soil general geometry; with the additional complication that enhanced vapour transfer appears to occur as a result of spatially intermittent liquid phase transfer across isolated regions of liquid water (Ross, 1963b).

A study of diffusion rates through different media (Blake and Page, 1958) showed that

$$\frac{D^{*}}{Do} = 0.66S \qquad (24)$$

where Do is the diffusion coefficient of gas in air, and S is the porosity or available cross-section area. A good approximation of $\frac{D^{*}}{Do}$ was suggested (Penman, 1940) as 0.7.

2.10.3.2 Soil physical factors and vapour diffusion

It is confirmed that porosity and pore tortuosity determine water vapour diffusion in soil significantly. The earliest indication seemed to have been given by Hannen (1892) that the sum of the cross-section area of the effective pore volume was mostly affecting diffusion in soils. It was proposed by Marshall (1959) that porosity was more influential than tortuosity and that the greater the porosity the greater will be the chances of pore continuity. This was expressed by

$$\frac{D^{*}}{Do} = \varepsilon^{3/2} \qquad (25)$$

Another view (Willie and Gardner (1948) cited by Marshall, 1959) was that pore interconnections were more important than the sinuous path in determining flow and that tortuosity might be replaced by impedance.

However, tortuosity and porosity were jointly considered important by Millington (1958), thus

$$\frac{D^*}{Do} = \varepsilon^{4/3} \qquad (25)$$

As to the structure of the soil, it was generalized (De Vries, 1950) that a soil with aggregates of spherical appearance will at the same value of porosity show a greater diffusion rate than the same soil with primary particles uniformly distributed. The dependence of gaseous diffusion on the shape of soil aggregates is given (Currie, 1976) by

$$\frac{D^*}{Do} = \varepsilon^{m} \qquad (27)$$

where ε is porosity, and m is a parameter representing granule shape or 'complexity factor' which is 1.5 for a sphere or > 1.5 for all other shapes approximately either prolate or oblate spheroids.

The ratio of diffusion coefficient of gases within soil aggregates (Dc) to diffusion in air, Dc/Do, was estimated at 0.025-0.156 for soils with intra-aggregate porosities in the range 0.25-0.41 (Currie, 1965). The measurement of diffusion in packed soil aggregates showed that inter-aggregate pores contributed more per unit of their volume to diffusion through the packing than do intra-aggregate pores (Currie, 1961a). In field soils, the inter-aggregate pores generally contain less water and more air per unit of their volume than intra-aggregate pores (Currie, 1976).

The water-filled porosity of soil reduces effective porosity and path of vapour diffusion. When a liquid is included in a porous solid, the effective area for diffusive flow of a sparingly soluble gas is determined by the number of pores drained (Smiles, 1977). Then

$$\frac{D^*}{Do} = \frac{n^2(\varepsilon^{4/3})}{m^2} \qquad (28)$$

where ε is air-filled porosity, and m is number of equal volume pore size groups that make up the porosity when n of them are drained.

In general, the diffusion of vapour through soils as expressed by $\frac{D^*}{Do}$ is dependent upon five variables which are the inter-aggregate porosity, the individual shape factor of aggregate, intra-aggregate porosity, drained porosity, and diffusion coefficient of water vapour in air. This dependency is often written (Smiles, 1977) as

$$\frac{D^*}{Do} = Do\alpha e \qquad (29)$$

For many situations, α=0.66, and Do (diffusion coefficient of gas in air) is 1.89 x 10^{-1}, α is porosity factor allowing for the extra path length, and e is aeration porosity of soil.

2.10.3.3 Analogous equation

Equations based on that of liquid water flux were proposed (Smiles, 1977) to express the dependence of water vapour flux ($\bar{V}$ vap) on gradient of total potential of soil (ψ) and gradient of volumetric water content (θ). The vapour flux equation may take the form of either

$$\bar{V}\text{ vap} = -K\psi\text{grad} \qquad (30)$$

$$\bar{V}\text{ vap} = -K\theta\text{grad} \qquad (31)$$

where K is water vapour diffusion constant in soil.

2.10.4 Summary

Soil temperature gradient mostly causes water vapour diffusion in soil. However, the rate of water vapour movement in soil cannot be based on soil porosity and molecular diffusion alone since other factors such as soil surface wind gustiness and atmospheric pressure fluctuations, and soil-vapour-liquid interactions significantly determine the rate of water vapour diffusion especially out of soil.

Wind tunnel and field studies (as in the present research) have shown that turbulent (Holmes *et al.*, 1960), convective heat (Waddams,

1944) and water transfer arising from fluctuations in the macroscopic velocity of soil (Farrell *et al.*, 1966) and atmospheric air significantly determine water evaporation out of soil.

The diffusion rate of water vapour in soil depends on inter-aggregate porosity, aggregate porosity, drained porosity, the sphericity of soil aggregates, and the pore tortuosity and flow impedance. These dependences can be expressed by separate equations.

The mechanisms of water vapour movement in soil were suggested as vapour flow, liquid assisted vapour transfer, and couple transfer.

2.11 Tillage and Soil Temperature

The relationship between soil structure produced by tillage and soil temperature has received no considerable attention. In most cases, general statements are made backed by no data. It is expected that different soil structures produced by tillage will effect differences in heat movement in and out of the tilled soils and in the daily ranges of temperature in the tilled soils. Some research has pointed to the effects of physical properties on soil thermal properties, and the effect of surface microrelief due to tillage on soil temperature has been investigated.

Many related soil physical properties influence soil temperature but bulk density, porosity, water content, and the presence or absence of a surface mulch are the most likely to be affected by tillage and structural change (Spoor and Giles, 1973). Compaction influences the heat conductivity of soil. However, there is usually the dominant effect of water rather than the indirect consequence of the degree of compaction (Raney and Edminster, 1961; Nakshabandi and Kolmke, 1965). Rama, Moha and Raghavendra (1975) observed that fluctuation in soil temperature was more affected by compaction in sandy than in clay soils. It was indicated (Yadav and Saxena, 1973) that compaction had no significant effect on specific heat of soils.

Tillage creates a surface mulch which reduces the heat flux from the surface to the subsurface layers. Soils in their natural structure have a higher thermal conductivity than when they are broken up because many of the intimate contacts between individual particles are destroyed (Smith and Byers, 1938; Van Wijk and Derksen, 1963; Larsen, 1963; Kohnke and Nakshabandi, 1964). The amplitude of the temperature wave is therefore greater at the surface of tilled soil than that of the untilled soil (Van Wijk, 1963; Hay, 1977). Van Duin (1954) had indicated increased amplitude of the daily temperature wave near the surface of tilled soil relative to its subsurface. The damping of daily and seasonal heat waves by tillage caused lower summer soil temperature in tilled soil compared with untilled soil (West, 1932). And the loose layer at the surface caused by tillage had its heat diffusivity reduced to 0.17 of that of original compact soil. Loosening a moist soil surface layer of 2 cm decreased minimum soil temperature as observed in Australia by about $1^{o}C$, and decreased that of a dry surface by about $3^{o}C$.

Decrease in heat conductivity into and out of the tilled layer by tillage is due to resultant increase in the proportions of pores, especially the macropores (Smith and Byers, 1938; Van Wijk, 1963; Van Wijk and Derksen, 1963; Hay, 1977).

Tillages like compaction affects specific thermal properties of soil. Loosening a soil decreases heat capacity ($cal.cm^{-3}\ (^{o}C)^{-1}$) according to the relation (Van Duin, 1956)

$$Cb = 0.46Xv + \theta \qquad (32)$$

where Cb is average heat capacity of soil, Xv is the volume fraction of solids, and θ is the fraction of water. This equation implies that tillage which decreases the volume fraction of solids will decrease the heat capacity of soil.

The microrelief produced by tillage methods which planted corn on a smooth soil surface, ridges, or in furrows caused differences in soil temperature during the early part of the growing season (Burrows, 1963; Larson, 1963). The effect of ridge making on soil temperature was investigated. On smooth ridges facing the sun, soil temperatures at about 5-10 cm depth showed significant increases when compared with temperatures in the horizontal surfaces (Keen, 1931; Shaw and Buchele, 1957; Spoor and Giles, 1973). The average maximum temperature was 2°C higher half-way down the south facing ridge slope than beneath a horizontal surface (Spoor and Giles, 1973).

Increased soil macroporosity due to tillage will increase temperature fluctuation at the surface of tilled soil and decrease temperature fluctuation at the base of tilled soil. Tillage will decrease heat capacity of soil. The aspect of surface micro-relief created by tillage will influence soil temperature, and this could be used to advantage when temperature is limiting seed germination and seedling performance. However, the structural elements mostly affecting heat conductivity into and out of tilled soil have not been identified.

2.12 Summary of Literature Review

The review of topics related to soil structure, tillage, and tillage and soil water and soil temperature was done.

The factors of soil aggregation are cations, clay colloids, organic polymers, and soil microbes. The factors of soil macro-structure formation are wetting and drying, roots, and soil macro-fauna.

Adverse surface soil structure due to rainfall-induced surface crusting leads to reduced macroporosity and undesirable soil physical properties.

Soil compaction caused by farm tractors, implements, and animal stocking adversely affects soil aggregation and physical properties.

The factors affecting and ways of reducing severe soil compaction were mentioned.

The methods which have been used to indicate the structure of soil were reviewed. Each of them has been useful to a certain degree. The inadequacies of the methods include the facts that they are not standardized, they are not very sensitive and they do not indicate undisturbed soil structure and void size distribution. There is need for additional inexpensive, rapid and easy techniques that could be used to evaluate the undisturbed soil macro-structure.

Forms of reduced tillage practices are ideal for seedling establishment due to the need to preserve good soil structure and reduce the cost of land preparation. In general situations, exceptions in form of zero tillage or conventional forms of tillage may be required for soils and crops.

The functions of major farm implements such as the ploughs, tines, and rotary cultivator were discussed. Generalisations have been made on the type of tilths produced by plough and rotary cultivator. However, research is needed to characterise specifically the soil structures produced by tillage implements and systems.

Evaporation as the major avenue for soil water loss, was discussed. It was concluded that coarse-structured tilled layers are less effective than relatively fine-structured tilled layers in conservation of soil water. The empirical and more practical ways of evaluating evaporation were discussed. The importance of insolation and wind intensity as meteorological factors of evaporation were mentioned but the more important of the two could not be identified conclusively by previous researches.

The factors determining water vapour movement in soil were discussed. They include factors which cause vapour pressure gradients in soil especially temperature gradients; and soil structure especially inter- and intra-aggregate porosity and shape. Some empirical equations for water movement based on the above were referred to. The mechanisms proposed for water vapour flow in soil were discussed.

Research has shown that soil physical properties, and microrelief due to tillage affect heat movement and soil temperature. Research is still needed to relate aspects of undisturbed tilled soil structure to variation in heat conductivity and soil temperature.

CHAPTER 3

MEASUREMENT OF INTERNAL STRUCTURE OF TILLED SOIL

This chapter describes the methods used to measure the structures of tilled soil in the present research.

3.1 Introduction

Soil structure was defined (Brewer and Sleeman, 1960) as the physical constitution of a soil expressed by the size, shape and arrangement of soil particles and associated voids. Soil physical properties have been used as the indicator of its structure as described in Chapter 2. However, techniques for measuring the distribution of particles and pores, and for investigating voids larger than 0.3 mm are either not available or are generally inadequate (Dexter, 1976).

Until 1976 (Dexter, 1976) there was no known published work in which the undisturbed macro-structure of field tilled soil was directly quantified as to the distribution of its aggregates and voids.

Tillage mainly affects soil macro-structure. Therefore, the measurement of the structure of tilled soil should be based on the distribution of structural elements at least about 0.5 mm in diameter. Aggregates having 1 to 5 mm diameter have been said to constitute the most suitable seedbed (Edwards, 1957; Russell, 1961, 1973; Cornforth, 1968). According to Greenland (1971), improving soil structure involves both producing and stabilizing aggregates of this class because the pores between them allow air and water to move while the soil still retains adequate water. Aggregates larger than 5 mm in diameter were classified as clods.

In this research, the internal structures of tilled soils *in situ* especially in terms of the proportions of intercepted aggregates and voids at least 1 mm in diameter were evaluated. Other statistical structural parameters were derived from raw structural data collected on sections through impregnated tilths. This approach to quantifying tilth structure is based on the work of Dexter (1976) and Dexter and Hewitt (1978).

The critical appraisal of the new method of quantifying *in situ* tilth structure is performed in Chapter 9.

3.2 Sample Collection

Tillage of any experimental plot was done to a depth of from 8 to 10 cm with reference to the surface of the untilled soil.

Immediately after tillage, steel moulds 460 mm long, 260 mm wide, and 150 mm in height were pressed into tilled soil across the direction of tillage. Paraffin wax (60°C m.p.) was melted on a gas stove and about 3 l was poured into each mould to impregnate the enclosed tilled soil. The paraffin fills pores down to at least 1 mm diameter. A wax layer of about 10 mm thick was left on the impregnated soil so that identification marks could be scratched on the wax layer, and as a way of preventing tilth block breakage. On the following day, the impregnated tilth blocks were removed from the moulds by agitating the moulds, or by heating their sides to melt the adjacent paraffin wax.

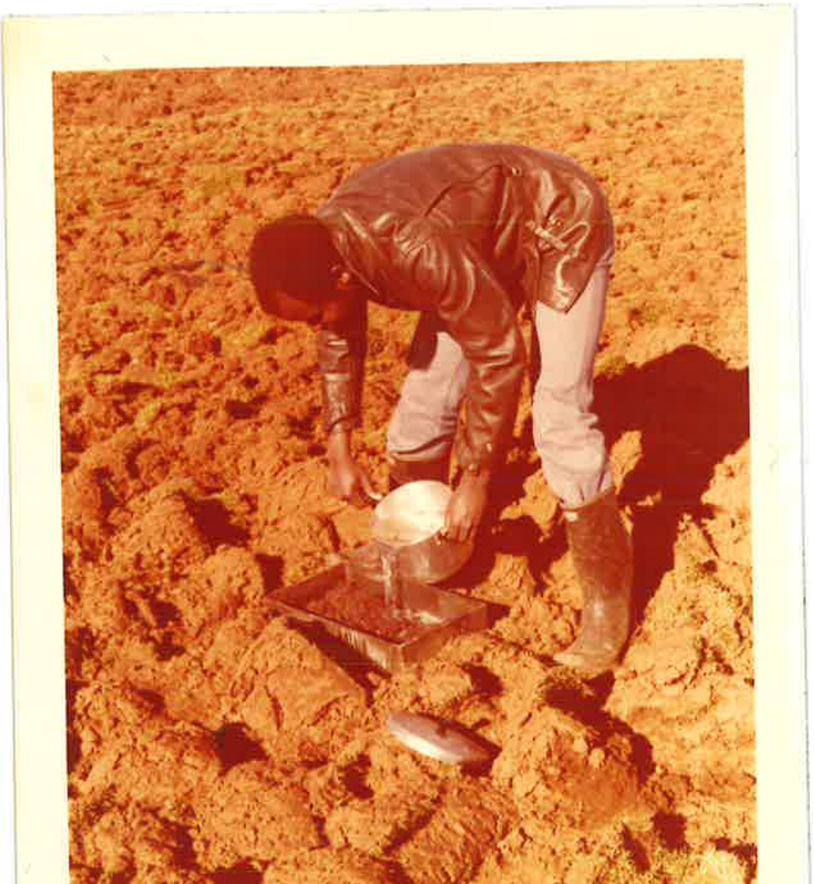
The impregnated blocks were sectioned in the laboratory twice lengthways using machine hacksaw blades (14 teeth per 25 mm). Cuts were made at about 10 cm from the longer sides in order to eliminate edge effects. Kerosene was used to lubricate the saw blades.

3.3 Raw Structural Data

At least two lines, horizontal in the original soil, were scratched across each cut section. At 1 mm intervals on each line,

Plate 1. A steel mould pressed into tilled soil.

Plate 2. The process of pouring hot paraffin liquid into mould-enclosed tilled soil.



raw data of the distributions of structural elements (aggregates and pores) were collected. A 1 was written to represent an aggregate and 0 to represent a pore or void. A pore was indicated by the presence of paraffin. Thus a string of 0's and 1's was produced which represented the structure of the tilth on that section. The lines on which data strings were collected were usually within the top 5 cm of the tilth block sample. The length covered by any string of 0's and 1's was usually about 320 mm.

3.4 Tilth Macroporosity

Macroporosity (ηL) is the percentage or proportion of 0's in a data string containing elements 0 and 1, or the probability of a randomly-chosen element on a data string being an 0 (Dexter and Hewitt, 1978).

3.5 Linear Probabilities

Porosity (as defined above) tells nothing about the structure of the data string (across a tilth block sample), that is, the way in which the 0's and 1's are distributed along it. In order to include this structural information, sixteen different porosities were defined. These are conditional porosities in the sense that the probability of a 0 being in a given position in the string depends on the values (1 or 0) of the elements (aggregate or pore) in the four positions immediately to the left of the element in question. These four elements are called the percursor of the element in question. There are 16 different possible precursors arising from the different combinations of 0 and 1 in those four positions. The set of 16 probabilities of a 0 following the precursors are used to define the structure across a tilled soil.

The 16 possible precursors are 0000, 0001, 0010, 0011, 0100, 0101, 0110, 0111, 1000, 1001, 1010, 1011, 1100, 1101, 1110 and 1111. They are numbered serially from 1 to 16.

Using each data string the probability P(0) of a 0 in a given position following each of 16 possible precursors was calculated. For example, the P(0) for precursor 1011 (i.e. 1011, P(0)) could be estimated from

$$1011,\ P(0) = \frac{\text{Occurrence } 10110}{\text{Occurrence } 10110 + \text{Occurrence } 10111} \qquad (32)$$

The probability of a 1 following 1011 (i.e. 1011, P(1)) is given by

$$1011,\ P(0) \quad = \quad 1 - 1001,\ P(0) \qquad (33)$$

3.6 Calculation of Aggregate and Pore Size Distributions

Instead of calculating the proportions of different sizes of aggregates and pores directly from a data string across a tilth, mathematical calculation of the proportions was performed from the probabilities P_i for the 16 precursors and the occurrence probabilities (Ui) for the precursors. This approach was described by Dexter and Hewitt (1978). The method allows for consistency with the probability values.

A computer program has been written for the calculation of P_i and U_i values. The U_i can be conveniently derived from the P_i values (Dexter and Hewitt, 1978).

For the calculation of pore size distributions, a particle-void interface should be the initial state. The initial state, in this case, must be one of the precursors of numbers 3 = 0010, 7 = 0110, 11 = 1010, or 15 = 1110.

The initial state probabilities may be taken as

$$a_3 = U_3/S \tag{34}$$

$$a_7 = U_7/S \tag{35}$$

$$a_{11} = U_{11}/S \tag{36}$$

$$a_{15} = U_{15}/S \tag{37}$$

where

$$S = U_3 + U_7 + U_{11} + U_{15} \tag{38}$$

The numerical proporation, V, of a void of length 1, 2, 3, 4, and n mm is:

$$V_1 = a_3(1-P_3) + a_7(1-P_7) + a_{11}(1-P_{11}) + a_{15}(1-P_{15}) \tag{39}$$

$$V_2 = (a_3P_3+a_{11}P)(1-P_5) + (a_7P_7+a_{15}P_{15})(1-P_{13}) \tag{40}$$

$$V_3 = (a_3P_3+a_{11}P_{11})P_5 + (a_7P_7+a_{15}P_{15})P_{13}(1-P_9) \tag{41}$$

$$V_4 = (a_3P_3+a_{11}P_{11})P_5 + (a_7P_7+a_{15}P_{15})P_{13}P_9(1-P_1) \tag{42}$$

$$V_n = (n > 4) = V_4.P_1^{n-4} = V_n-1.P_1 \tag{43}$$

As expected

$$\sum_{n=1}^{\infty} V_n = 1 \tag{44}$$

The porosity, η_L, is given by

$$\eta_L = \tfrac{1}{4}\sum_i U_i z_i = \sum_i U_i P_i \tag{45}$$

where Z_i is the number of zeros in the i'th precursor.

For the calculation of aggregate size distributions, a void-particle interface should be the initial state. The initial state, in this case, must be one of the precursors of numbers 2 = 0001, 6 = 0101, 10 = 1001, or 14 = 1101.

The numerical proportion, A, of an aggregate of length 1, 2, 3, 4, and n mm is:

$$A_1 = a_2P_2 + 6P_6 + a_{10}P_{10} + a_{14}P_{14} \quad (46)$$

$$A_2 = a_2(1-P_2)P_4 + 6(1-P_6)P_{12} + a_{10}(1-P_{10})P_4a_{14}(1-P_{14})P_{12} \quad (47)$$

$$A_3 = a_2(1-P_2)(1-P_4)P_8 + a_6(1-P_6)(1-P_{12})P_8 + a_{10}(1-P_{10})(1-P_4) P_8 + a_{14}(1-P_{14})(1-P_{12})P_8 \quad (48)$$

$$A_4 = a_2(1-P_2) + a_{10}(1-P_{10})(1-P_4) + a_6(1-P_6) + a_{14}(1-P_{14})(1-P_{12})(1-P_8)P_{16} \quad (49)$$

$$A_n = P_4(1-P_{16})^{n=4} \quad n > 5 = A_n^{-1}(1-P_{16}) \quad (50)$$

In case of tillage with asymmetrical implements such as mouldboard or disc ploughs, it is possible and perhaps even likely that the sets of 16 probabilities resulting from analysing the data from left to right would be different from those obtained by analysing the data from right to left. Although asymmetric structures may exist, their asymmetry is probably of little consequence for most purposes (Dexter and Hewitt, 1978).

The structural data presented in the Appendices are mainly probabilities or occurrence of the 16 precursors (U_i) and the probabilities of a 0 following the precursors P(0). All calculations were done using the computer. Mean aggregate or pore size was also calculated for each data string.

It should be noted that a 'size' as referred to in this research is an intercepted length and not a diameter as obtained by sieving. Likewise, a 'mean size' is a number-average of intercepted lengths and not the more usual mean weight diameter.

3.7 Tilth Simulation

Measured transition probabilities P(0) can be used to generate simulated 'tilths' in a computer. For example, consider the probabilities P(0) for four precursors (among a set of 16)

0000,P(0)	=	0.836	(51)
0001,P(0)	=	0.113	(52)
0010,P(0)	=	0.800	(53)
0011,P(0)	=	0.076	(54)

The tilth is generated by using random numbers which can conveniently be in the range 0-999. If the first four elements in the tilth are set arbitrarily at 0000, then the fifth element becomes 0 if the random number is < 0.836 and 1 if it is > 0.837. Thus any precursor string can only give rise to one of two possible 'successor' strings.

In the example given above, a sequence of random numbers of 081, 838, 110, 991, ..., would generate the 'tilth' 00000101 ... . Computer generation of tilths using four element precursors (Dexter, 1976) has shown that the original probabilities are reproduced adequately if the number of elements is 1000.

3.8 Entropy of Tilled Soil

Spatial variability or entropy is a principal physical feature of tilled soil. Dexter (1977) introduced the idea of measuring the structural variability or disorganization of tilled soil.

The mean entropy per element, H, of the soil macrostructure was calculated using the equation developed in communications theory (Shannon and Weaver, 1959).

The entropy of a tilled soil was calculated using the probabilities P(0) for the 16 possible four element precursors derived from a data string. The equation is

$$H = -\frac{1}{m} \sum_{x} N_x \sum_{i} P(x,i) \log_2 P(x,i) \qquad 55)$$

where m is the number of elements in a data string; P(x,i) are the probabilities of the symbol i following the precursor x, and i can only take the value 0 or 1, and $P(x,0) = 1-P(x,1)$. The precursor x in this case is a string of the n preceding elements (4). The number of occurrences of a precursor string x is N_x. If the soil has no macropores, the entire string of measured element values will therefore be composed of 1's, and the entropy will then be zero irrespective of the length of the precursor string. Similarly, just above the tilled layer the line passes throughout the air and all the elements are 0's. In between these extremes, in the tilled layer of the soil, the entropy takes the values intermediate between 0 and 1 depending on the structural state. However, if the string has no variability or randomness, e.g. 001100110011 ... or 01010101, then H will also be zero.

The value of the entropy obtained depends on the length η of the precursor string. If n = 0, then each element is considered to be independent of the preceding elements, and

$$H = -(\eta_L \log_2 \eta_L + (1-\eta_L)\log_2(1-\eta_L)) \qquad (56)$$

Here, η_L is the linear porosity of the soil which is defined as the proportion of the elements in a line at a given level which have the value 0. The plot of η_L (0 to 1) against H using the equation (56) is presented in Figure 3. The dependency of entropy on porosity is clearly shown.

It can be shown that H is a monotonically decreasing function of n, with the most accurate estimate of the entropy being obtained as n approaches infinity. In practise, H decreases somewhat erratically with increasing n because of the finite length of the initial measuring data string. This is because many of the possible precursor strings will occur only once and give rise to probabilities of 0 and 1 when perhaps intermediate probabilities would be obtained with longer data

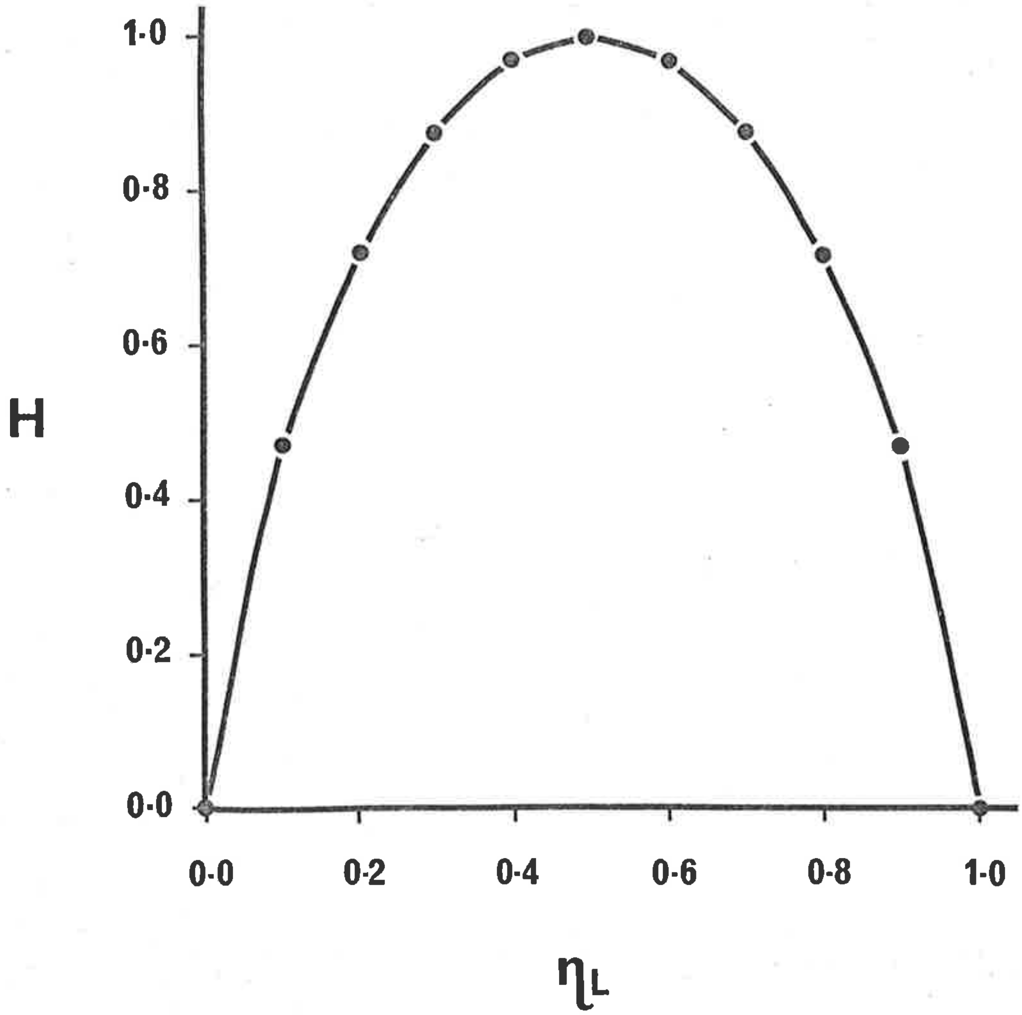


Fig. 3. The relationship between Entropy (H) and Macroporosity (η_L).

strings. According to Dexter (1977), N should rarely be allowed to drop below 4.

For this research, the precursor string length was set at $\bar{\delta} = 4$. Therefore, the calculated entropies include structural features extending over the range of sizes 1 to 5 mm.

Because of the above reason, it was found in the present research that there is a positive correlation between the proportion of small structural elements especially those smaller than 6 mm and the entropy of tilled soil. The reverse was the case for the relationship between entropy and the proportion of larger structural elements (aggregates and pores). A small-size structural element indicates small n or length of precursor string.

3.9 Summary

The following structural parameters were found useful in the present research for the quantification of structure of tilled soils:

(a) the proportions of aggregates and voids of different sizes or size ranges;

(b) mean aggregate size ($\bar{D}$), and mean void size ($\bar{\delta}$);

(c) macroporosity (ηL); and

(d) entropy (H).

One of the objectives of this research is to test this new approach of measuring field tilth structure in the investigation connected with tilth structure and physical factors. Therefore, each of the above structural parameters was used separately as much as possible in the discussion of experimental observations. The information each of them gave was successfully aligned with the information given by the others.

CHAPTER 4

AGGREGATE SORTING AND CLOD FRAGMENTATION DURING TILLAGE

4.1 Introduction

Repeated tillage is often performed to increase the amount of small aggregates in the seedbed. There is still a need to justify this practice with field data in relation to the distribution of small aggregates in the tilled layer of soil when different implements are used.

When repeated tillage is done, there is interplay of two processes. The first is the breakdown of clods, and the second is the sorting of smaller aggregates towards the bottom of the tilled layer. The amount of small aggregates produced at a given depth depends on the relative importance of these two processes.

In the few laboratory and field investigations known, soil samples were collected at different depths and sieving was done for aggregate size distribution. The major points against this approach are that the result depends on the sampling and sieving methods, it is not sensitive, and real structure of tilled soil in place is not measured. The effects of clod breakdown and aggregate sorting on void size distribution are left out. The present research was designed among other things to cater for these deficiencies.

A number of works exist on the effect of harrowing or discing after ploughing. Keen (1931) performed dry sieving on soil samples collected from soils ploughed, harrowed (after mouldboard ploughing), and rotary cultivated. The percentage of aggregates between 38 and 6 mm which was used to indicate the degree of pulverisation of tilled soil was increased by one harrowing (with a tined implement) after ploughing. The data of Pigulevsky (1936), who sieved samples from soils that were given 20 and 4 discings after two ploughings by mouldboard were presented by Russell (1938). The former treatment produced a larger percentage of fine aggregates smaller than 0.25 mm when tillage was done between wilting point and field capacity. Cole (1939) determined the summation percentages of aggregates smaller than 122 mm for soils that had been disced, or harrowed after mouldboard ploughing soils. He detected that discing or harrowing after ploughing increased the percentage of aggregates in tilled loamy soils especially if the soils were originally wet, or cloddy after ploughing.

Some literature is available on the phenomenon of aggregate sorting during tillage. Johnson and Taylor (1960) investigated the response of corn to minimum tillage treatments on lakebed soils. Data were presented to show the effect of number of discings on seedbed fineness. It was concluded after dry sieving of aggregates that additional tillage operations after one or two discings did not ensure a greater proportion of small aggregates at the seed level. It was observed that three discings after ploughing resulted in a smaller proportion of aggregates smaller than 3 mm at seed level and a greater proportion of aggregates larger than 18 mm than one or two discings. Simulated tillage with four secondary tillage tool components to determine their aggregate sorting characteristics at different number of trips was performed by Winkelblech and Johnson (1964). It was observed that larger aggregates were displaced from the 5 to 10 cm depth zone and deposited at or near the surface. The main sorting occurred during the first pass followed by the second. The mixing and sorting of marked soil aggregates placed in a bin during tillage with different types of tines were investigated by Kouwenhoven and

Terpstra (1970). In addition to mean deviation of the concentration of aggregates of different sizes, other qualitative approaches were used to trace the degree of sorting and mixing of soil aggregates. They detected that the wider the tine, the faster the sorting speed. Kouwenhoven and Terpstra (1977) also used the displacement of component parts of a polysized medium of glass spheres to investigate the influence of travelling speed and inclination of tines on the sorting process. Qualitative determinations were carried out with a model tine and quantitative determinations with square tines. Sorting caused relatively large concentrations of larger spheres in the upper layers and of smaller spheres in the lower layers. The process occurred mainly in front of but also behind the tines. The degree of sorting increased with the number of operations carried out, but to a lesser extent in each subsequent operation until, after fifteen operations, an equilibrium state was attained. A high sorting speed was characterised by a strong stratification.

Dexter (1976) developed the technique of statistical evaluation of the distribution of small aggregates and pores in place and on sections cut through impregnated tilth block samples (Chapter 3). Among other things, he tried this technique on the probabilities of detecting 1 to 5 mm aggregates at different levels from the base of tilled soils. He attributed the progressive decrease in the probability of detecting 1 mm aggregates towards the surface of tilled soils to the sorting of the aggregates to the bottom of the tilled layer during tillage. Greater incidence of large pores at least 5 mm in width was observed towards the surface.

The lack of a technique of quantifying tilth structure *in situ* has been a problem to a comparison of tilth structures produced by tillage implements. In the existing works towards this end, only two or three implements are mostly compared which include the plough and rotary cultivator. Dry sieving of soil samples collected from plots tilled with these implements has been done (Chizhevsky and Kolobova, 1935; Russell and Mehta, 1938), and conclusions and statements have been drawn (Keen *et al.*, 1930; Culpin, 1936) concerning the communition effect of rotary cultivator compared with the plough and other conventional implements. Thirdly, the views expressed concerning tillage implements and tilth structure are fundamentally controversial. Singh and Pollard (1956) found after wet sieving of soil samples that the type of tillage implement influenced the size distribution of 2 to 4 mm aggregates within the top 10 cm of soil. Whereas Byers and Webber (1957) using the water characteristic in addition concluded that there was no considerable difference in tilth structures produced by nine different tillage treatments. The lack of considerable difference was certainly due to the insensitive techniques used for assessing soil structures.

In this research the new technique that quantifies the internal structure of tilled soil in place is used to investigate stratification that arose from sorting of aggregates during tillage and the manifestation of this process in aggregate and pore size distributions as a result of multiple trips of single and combined implements. It is expected that results that emanate will be useful in recommending reduced tillage practises for maximum production of small aggregates essential for tilth water conservation (Holmes *et al.*, 1960; Johnson and Buchele, 1961), and optimum seed germination (Greenland, 1971) and seedling growth (Russell, 1961).

4.2 Hypothesis

Repeated tillage will cause progressive breakdown and decrease proportion of larger clods and voids up to a particular number of passes which depends on the type of implement. The particular number of passes which brings about the last fall in proportion of larger clods and voids will be determined by the relative importance of the processes of continuous clod breakdown and aggregates sorting during the tillage. The latter process will increase the proportion of the larger clods and voids, while the former will certainly reduce the proportion at the top zone of tilled soil which constitutes the seedbed.

4.3 Materials and Methods

4.3.1 Sites

Tillage trials were sited at the Mortlock Experiment Station of the Waite Agricultural Research Institute (33° 55'S, 138° 43'E, altitude 430 m) and at the Waite Agricultural Research Institute, South Australia (34° 58'S, 138° 38'E, altitude 22 m). The mechanical analyses of the Red Brown Earths (Stace *et al.*, 1968) on the two sites are presented in Table 1. The mechanical analysis for the site at the Waite Institute is after Turchenek (1975). The sites at the Mortlock Station and at Waite Institute were put to pasture ryegrass for eleven years and at least five years previous to the times of tillage respectively.

4.3.2 Tillage treatments

In the following D, MB, Sc, T, CD and RC stand for disc plough mouldboard plough, a set of tines (scarifier) with wide (195 mm) points, a set of tines with narrow points (smaller than 70 mm in width), combine drill, and rotary cultivator respectively. The measurements carried out on the implements are in Appendix I, and some of the implements are presented in Plates 3 to 6.

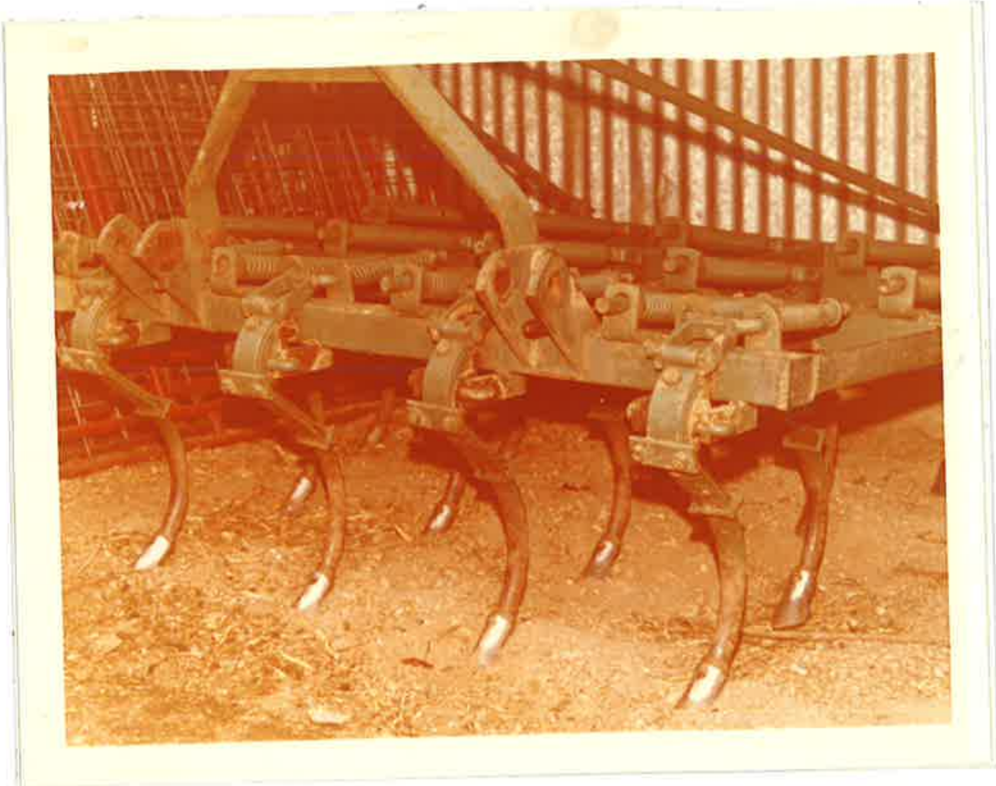
In 1976, eight tillage treatments were performed at the Mortlock Experiment Station. Each tillage treatment was done on 7 July in a North-South direction with (1) disc plough, (2) disc plough + scarifier, (3) disc plough + combine drill, (4) mouldboard plough, (5) mouldboard plough + scarifier, (6) mouldboard plough + combine drill, (7) scarifier,

Plate 3. Mouldboard plough.

Plate 4. Disc plough.

Plate 5. Tined implement with narrow points.

Plate 6. Tined implement with wide points.



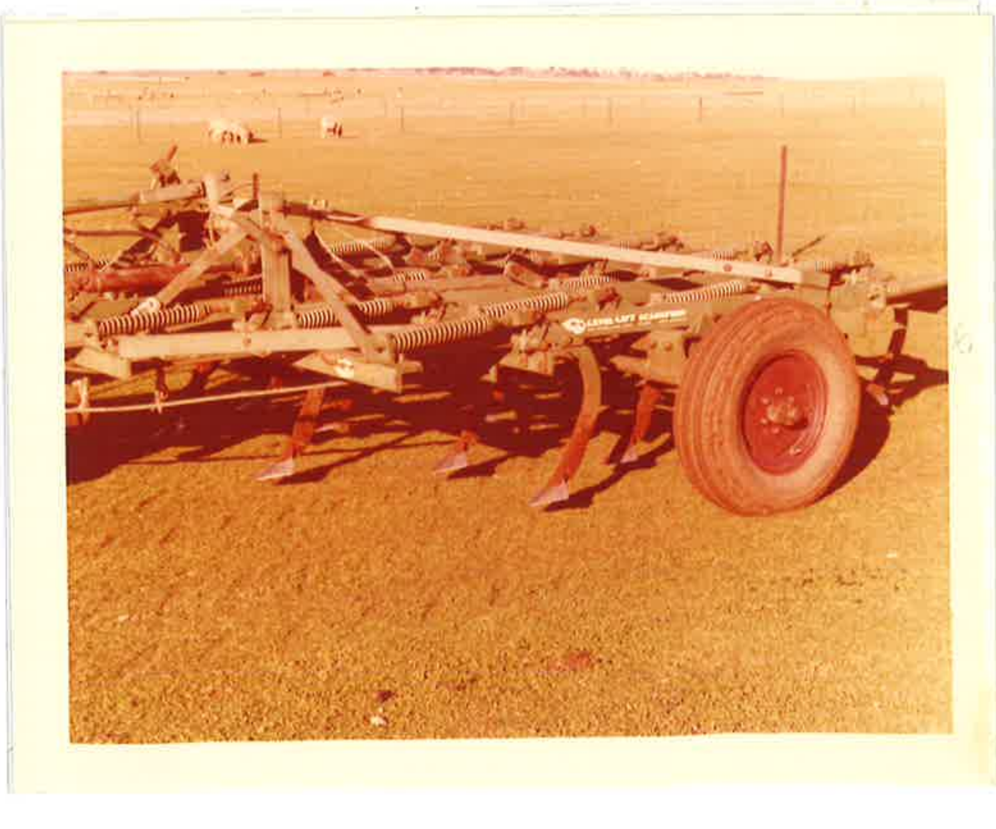

LEVEL LIFT

Table 1. Mechanical analysis of Red Brown Earths.

Fraction	% weight a	b	c
Coarse sand	24	25	19
Fine sand	36	60	32
Silt	23	30	32
Clay	17	15	17
Organic matter	4	5	3
Plastic limit	21.2%	22.5%	19.5%
Dispersion index	5	7	9

a, b Sites tilled at the Mortlock Experiment Station in 1976 and 1977 respectively.

c Site tilled at the Waite Institute in 1977.

and (8) rotary cultivator. Tillage was done at a water content of 22.7 (± 1.5)% (dry weight basis) which is slightly wetter than the Plastic Limit of the soil on the site.

Also at the Mortlock Experiment Station in 1977, sixteen tillage treatments were given on 6th July. The treatments were set in five columns lying side by side in a North-South direction. The treatments consisted of single and multiple passes of different implements as set below.

First column

(1) D (2) D+D (3) D+D+D (4) D+D+D+D

Second column

(5) D+T (6) D+T+T (7) D+T+T+T

Third column

(8) T (9) T+T (10) T+T+T

Fourth column

(11) D+Sc (12) D+Sc+Sc (13) D+Sc+Sc+Sc

Fifth column

(14) Sc (15) Sc+Sc (14) Sc+Sc+Sc

Tillage was done at 22 (± 1.3)% water content which is about the same as the Plastic Limit of the soil.

At the Waite Agricultural Research Institute, tillage was done in a North-South direction at two dates in August, 1977 to attain two different water contents (mean for 12 soil samples as in the above cases) of 12.6 (±1.4) and 25.2 (±1.8)%. Tillage was done with a set of tines with narrow points. Four and three passes of the implement were used at the two water contents respectively.

In all the tillage trials, each plot was 3 mm wide, and at least 25 m long. Tillage was done to 10 cm depth. Water contents cited above were on a dry weight basis and were got by placing wet soil samples in oven at 105^{o}C for 24 hours.

4.3.3 Sample collection and structural data

Sample collection from each tilled plot and data collection from each sample was done by the method of Dexter (1976) as described in Chapter 3. Two sections each at least 10 cm away from the longer side were cut through each of the impregnated tilth block samples collected from the tilled plots. Two tilth block samples were collected from each tilled plot at the Waite Institute, while one tilth block sample was collected from each of the other tilled plots. Data of the distribution of aggregates (each represented by element 1) and pores (each represented by element 0) at 1 mm intervals were collected from each cross-section line taken on a section. Each line was at least 320 mm long.

For the samples collected at the Mortlock Station, two lines were taken at each section at about 4-5 cm depth, thus four sets of primary structural data were collected for each tillage treatment. For the samples collected at the Waite Institute, there were 2 to 5 lines starting at 5 cm depth towards the surface taken on each of four sections belonging to a tilled plot. The lines were spaced at 1 cm intervals. The tillage trials at the Waite Institute were mainly to compare tilth structures at different levels within tilths. The levels at heights of 5, 6, 7, 8 and 9 cm from the base of the tilths were called levels 1, 2, 3, 4 and 5 respectively.

The probabilities, P(0), for the 16 possible four element precursors (each precursor a combination of 0's and 1's) and the respective occurrence probabilities (U_i) for the precursors were calculated by computer from each data string of 0's and 1's collected on each cross-section line. The P(0) is the probability of an 0 following a four element precursor. From the P(0) and U_i values the proportions of different sizes of aggregates and pores were calculated by the method of Dexter and Hewitt (1978) also described in Chapter 3. The probabilities P(0) for the sixteen precursors were used in the calculation of tilth structural entropy (H) using the method of Dexter (1977) described in Chapter 3. Mean aggregate or pore size was calculated from raw structural data. Macroporosity due to voids at least 1 mm in diameter was calculated as the fraction of voids in a data string collected for a cross-section line.

The P(0) and U_i values and macroporosities for plots tilled at the Mortlock Station are presented in Appendix I. For the tilled plots at the Waite Institute the P(0) and U_i values, the aggregate and pore size distributions, macroporosities, and entropies are also presented in Appendix I.

4.4 Results and Discussion

The main items discussed are stated below:

(a) Tilth stratification that occurred as a result of sorting of aggregates during tillage with multiple pass of tine implement. This is based on structural data from tilth block samples collected at the Waite Institute in 1977.

(b) Tilths produced by single pass of different implements.

(c) Multiple passes of a disc plough + tilth structure.

(d) The effect of harrowing (tillage with one pass of a set of tines after ploughing) on tilth structure.

(e) The effect of further tillage with a tined implement after harrowing (first pass of a tined implement after ploughing).

(f) Tilth structures produced by multiple passes of a tined implement.

Except for part of item (f), items (b) to (f) are based on structural data collected from tilth block samples collected at the Mortlock Experiment Station in 1976 and 1977. Discussion is based on proportions of different sizes of aggregates and pores, mean aggregate or pore size, macroporosity, and tilth entropy.

4.4.1 Tilth structure and sorting of aggregates during tillage

4.4.1.1 Aggregate size distribution

Separation of aggregates smaller than 9 mm towards the bottom of the tilled layer during tillage with one to four passes of the tine implement appeared to have occurred. The separation featured more at low water content (12.6%). At 25.2% water content, which is above the plastic limit, evidence of separation or sorting of aggregates was not shown for the three passes of the implement. Tables 2 and 4 show that the proportions of aggregates smaller than 10 mm decreased from the lower level to the upper level of the tilth especially as a result of tillage with one or two passes of tine implement. It is also shown (Table 4) that the proportion of aggregates larger than 8 mm increased from the lower level to the upper level of tilths as a result of tillage with one to four passes of a tined implement at low water content and one to two passes of a tined implement at high water content (also Figures 4 and 6).

The separation of small aggregates towards the bottom of the tilth occurred mostly as a result of tillage with one or two passes of the implement. This is consistent with the findings of Winkelblech and Johnson (1964) and Kouwenhoven and Terpstra (1977) that the degree of sorting increased with the number of operations but to a lesser extent in each subsequent operation. Because of the sorting process, mean a-gregate size increased from the lower to the upper level of tilth (Table 6).

4.4.1.2 Entropy

Progressive decrease in the proportion of smaller structural

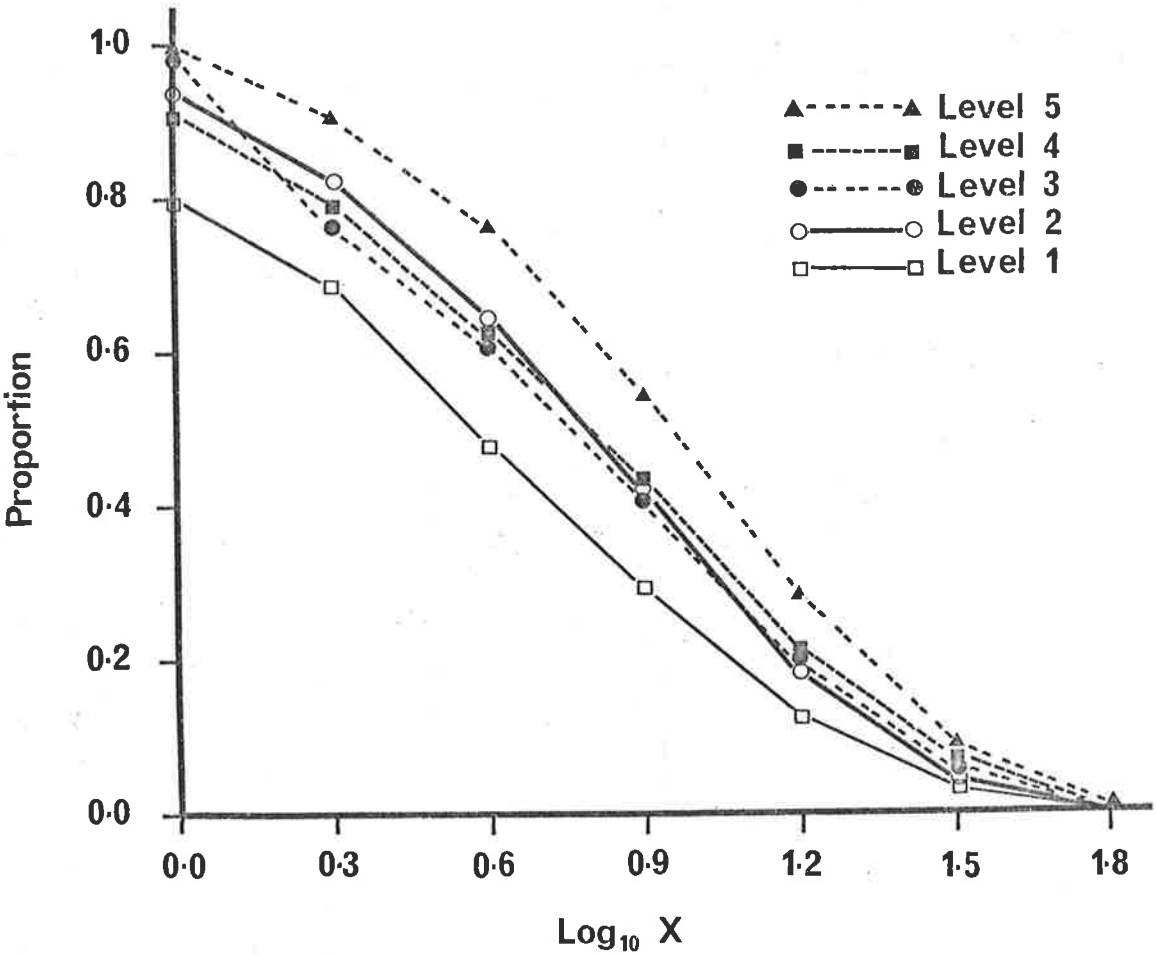


Fig. 4. Mean proportions of aggregates larger than Xmm at different levels (from below) in tilths produced by one to four passes of a set of narrow tines. Tillage was done at 12·6 % water content (dry weight).

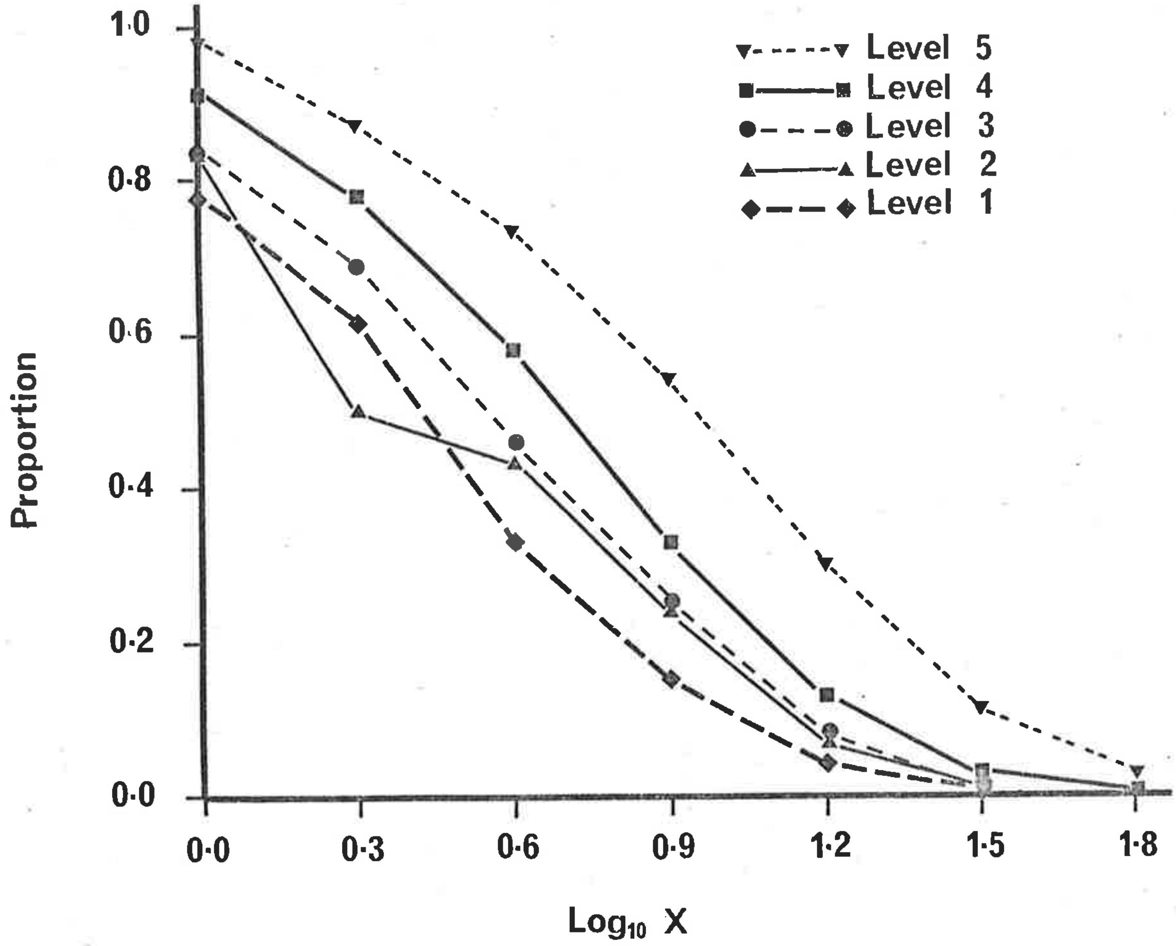


Fig. 5. Mean proportions of pores larger than Xmm at different levels (from below) in tilths produced by one to four passes of a set of narrow tines. Tillage was done at 12·6% water content (dry weight).

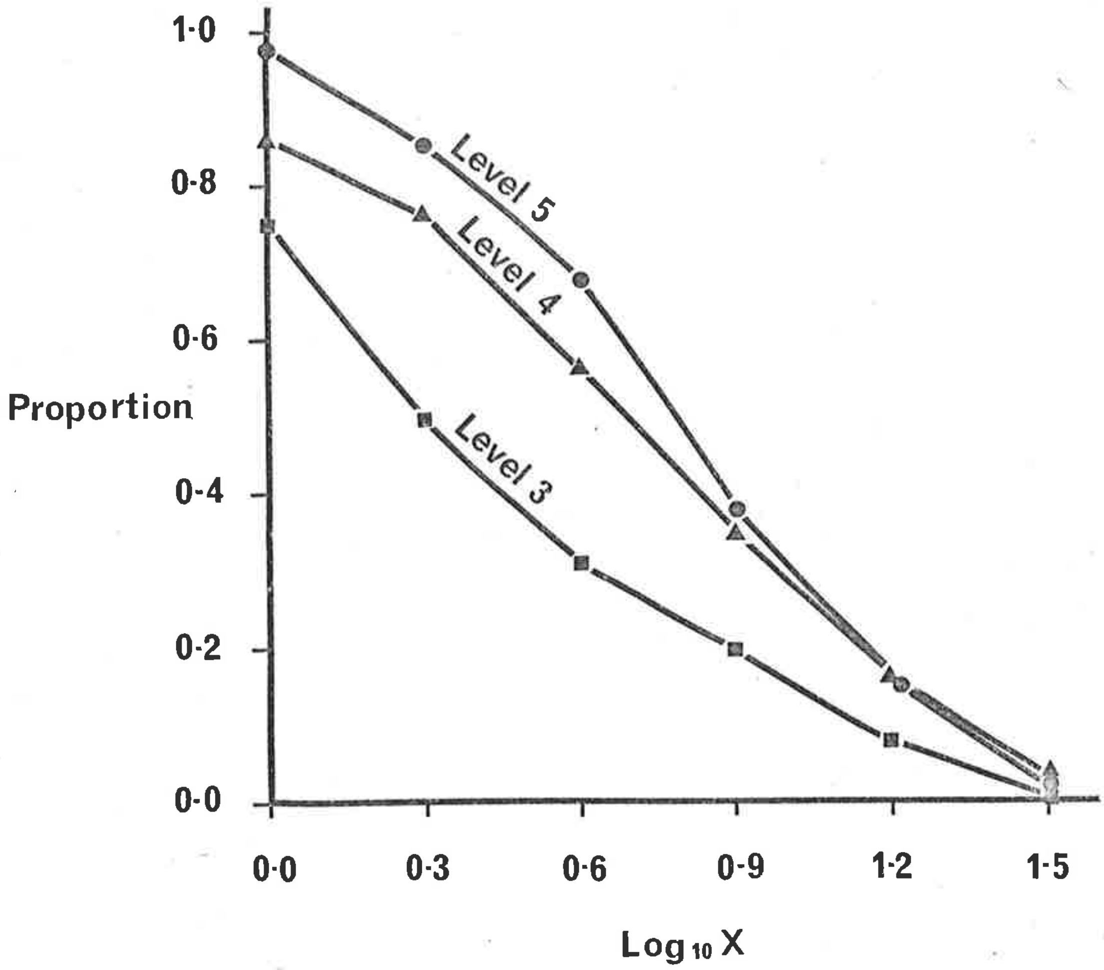


Fig. 6. Mean proportions of aggregates larger than Xmm at different levels (from below) in tilths produced by one to three passes of a set of narrow tines. Tillage was done at 25·2% water content (dry weight).

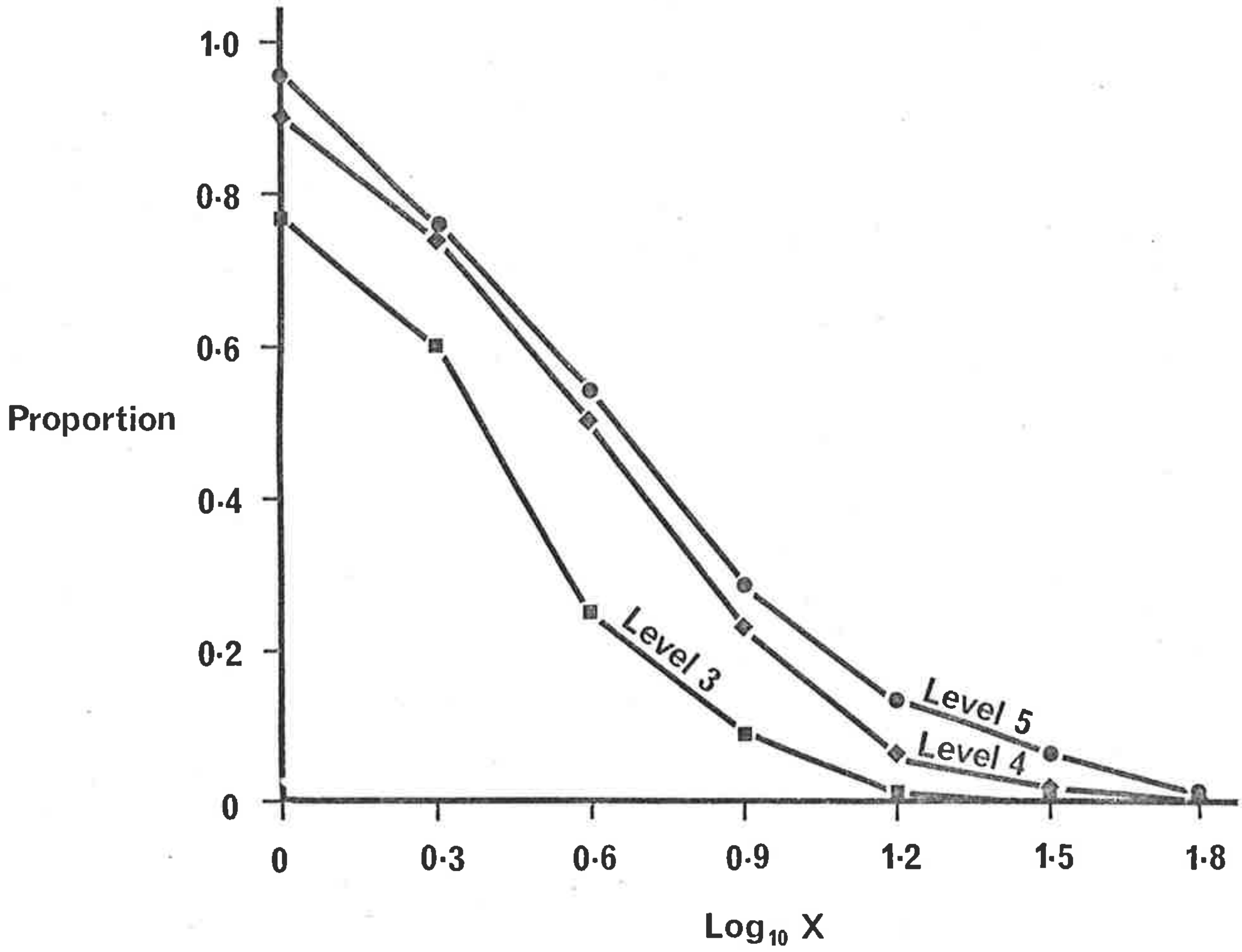


Fig.7. Mean proportions of pores larger than Xmm at different levels (from below) in tilths produced by one to three passes of a set of narrow tines. Tillage was done at 25·2% water content (dry weight).

elements from below to the top of tilth caused a corresponding decrease in the value of entropy from the lower to the upper level of the tilths (Table 6). There is a positive correlation between entropy or tilth structural variability and the frequency of smaller structural elements.

4.4.1.3 Pore size distribution

The separation of small aggregates towards the base of the tilled soil during tillage caused a decrease in the proportion of pores smaller than 10 mm (Tables 3 and 5) from the lower level to the upper level of the tilled soil. This resulted in an increasing proportion of voids larger than 8 mm from the base to the top of the tilth (Table 5, Figures 5 and 7).

4.4.1.4 Macroporosity

Progressive increase in the proportion of voids larger than 8 mm from the lower to the upper levels of tilth as a result of the sorting of aggregates during tillage caused increased macroporosity from the lower to the upper level of tilth (Table 6). It is shown in Chapter 5 (5.1) that the medium-size boids (9-16 mm) mainly determine tilth macroporosity.

Dexter (1976) also presented data to show increasing macroporosity from the lower to the upper levels of tilths produced by mouldboard, tines, and rotary cultivator.

Tillage with one to four passes of tine implement caused sorting of aggregates smaller than 10 mm to the base of the tilled soil during tillage in preference to large aggregates. This process led to an increasing proportion of voids larger than 8 mm and increasing macroporosity from the lower levels to the upper levels in the tilths.

The sorting of aggregates during tillage was more favoured by small number of implement passes (1 or 2), and low soil water content before tillage.

Table 2. Proportions of small size aggregates at different levels (from below) in tilths produced by different numbers of passes of a set of tines.

Number of passes	Level	Size (mm) 1	2	3	4	5	6	7	8	9	Total 1-5	Total 1-9
1**	1	0.20	0.11	0.15	0.06	0.05	0.05	0.04	0.04	0.03	0.57	0.73
	2	0.07	0.11	0.11	0.07	0.06	0.05	0.05	0.04	0.24	0.42	0.79
	3	0.14	0.13	0.12	0.06	0.05	0.05	0.04	0.04	0.04	0.49	0.67
	4	0.14	0.14	0.12	0.06	0.05	0.05	0.04	0.04	0.03	0.51	0.67
	5	0.13	0.07	0.00	0.06	0.06	0.05	0.05	0.05	0.04	0.32	0.51
2**	3	0.03	0.27	0.11	0.07	0.06	0.05	0.04	0.04	0.03	0.54	0.70
	4	0.08	0.14	0.06	0.08	0.07	0.06	0.05	0.05	0.04	0.43	0.63
	5	0.02	0.09	0.03	0.08	0.07	0.07	0.06	0.05	0.05	0.29	0.52
3**	4	0.11	0.16	0.11	0.04	0.04	0.04	0.03	0.03	0.03	0.46	0.59
	5	0.00	0.05	0.09	0.09	0.08	0.08	0.07	0.06	0.05	0.31	0.57
4*	4	0.02	0.07	0.03	0.08	0.08	0.07	0.06	0.05	0.05	0.30	0.51
	5	0.04	0.13	0.18	0.04	0.04	0.03	0.03	0.03	0.03	0.43	0.55
1**	3	0.25	0.25	0.15	0.04	0.03	0.03	0.03	0.02	0.02	0.72	0.82
	4	0.13	0.12	0.15	0.06	0.05	0.04	0.04	0.04	0.04	0.51	0.67
	5	0.07	0.16	0.05	0.08	0.08	0.06	0.05	0.05	0.05	0.44	0.65
2*	3	0.06	0.32	0.06	0.09	0.07	0.06	0.05	0.04	0.04	0.60	0.79
	4	0.12	0.12	0.18	0.06	0.05	0.05	0.04	0.05	0.04	0.53	0.71
	5	0.00	0.07	0.06	0.10	0.09	0.08	0.07	0.06	0.05	0.32	0.58
3*	3	0.15	0.08	0.07	0.06	0.05	0.05	0.04	0.04	0.04	0.41	0.58
	4	0.18	0.06	0.03	0.10	0.08	0.06	0.06	0.05	0.05	0.45	0.67
	5	0.00	0.17	0.08	0.13	0.11	0.09	0.07	0.06	0.04	0.49	0.75

* Tillage was done at 12.6% water content (dry weight basis).

** Tillage was done at 25.2% water content.

Table 3. Proportions of small size pores at different levels (from below) in tilths produced by different numbers of passes of a set of tines.

Number of passes	Level	Size (mm) 1	2	3	4	5	6	7	8	9	Total 1-5	Total 1-9
1*	1	0.23	0.15	0.21	0.08	0.06	0.05	0.04	0.03	0.03	0.73	0.85
	2	0.18	0.34	0.00	0.07	0.06	0.05	0.04	0.04	0.03	0.65	0.81
	3	0.24	0.13	0.06	0.08	0.07	0.06	0.05	0.04	0.04	0.58	0.77
	4	0.09	0.16	0.06	0.06	0.08	0.07	0.06	0.05	0.05	0.45	0.68
	5	0.05	0.19	0.05	0.02	0.04	0.04	0.04	0.03	0.03	0.35	0.48
2*	3	0.11	0.17	0.18	0.12	0.09	0.07	0.05	0.04	0.04	0.67	0.87
	4	0.16	0.11	0.13	0.11	0.09	0.07	0.05	0.04	0.04	0.60	0.80
	5	0.03	0.11	0.09	0.05	0.05	0.04	0.04	0.04	0.03	0.33	0.51
3*	4	0.19	0.05	0.13	0.10	0.08	0.07	0.06	0.05	0.05	0.55	0.78
	5	0.07	0.10	0.08	0.06	0.05	0.05	0.04	0.04	0.04	0.36	0.53
4*	4	0.07	0.11	0.11	0.13	0.11	0.08	0.07	0.06	0.05	0.53	0.79
	5	0.04	0.04	0.07	0.06	0.05	0.05	0.05	0.04	0.04	0.26	0.45
1**	3	0.20	0.10	0.35	0.07	0.06	0.04	0.04	0.03	0.02	0.78	0.91
	4	0.15	0.15	0.13	0.12	0.09	0.07	0.05	0.04	0.03	0.64	0.83
	5	0.03	0.17	0.09	0.07	0.07	0.06	0.05	0.04	0.04	0.43	0.62
2**	3	0.19	0.26	0.21	0.10	0.07	0.05	0.04	0.03	0.02	0.83	0.97
	4	0.13	0.17	0.16	0.12	0.09	0.07	0.05	0.04	0.03	0.67	0.86
	5	0.06	0.24	0.06	0.16	0.11	0.07	0.05	0.04	0.03	0.63	0.82
3**	3	0.31	0.15	0.23	0.06	0.05	0.04	0.03	0.03	0.02	0.80	0.92
	4	0.02	0.17	0.07	0.13	0.11	0.09	0.07	0.06	0.05	0.50	0.77
	5	0.00	0.00	0.08	0.13	0.11	0.10	0.08	0.07	0.06	0.32	0.63

* Tillage was done at 12.6% water content (dry weight basis).

** Tillage was done at 25.2% water content.

Table 4. Mean aggregate size distributions at different levels (from below) in tilths produced by different numbers of passes of a tined implement as expressed by the proportion larger than X mm. Tillage was done at two water contents (w%).

w	Number of passes	Level	X: 1	2	4	8	16	32	64
12.6	1	1	0.80	0.69	0.48	0.30	0.13	0.038	0.005
		2	0.93	0.82	0.64	0.42	0.19	0.04	0.002
		3	0.96	0.78	0.60	0.41	0.20	0.05	0.003
		4	0.97	0.82	0.63	0.44	0.22	0.06	0.01
		5	1.00	0.87	0.81	0.59	0.32	0.09	0.01
	2	3	1.00	0.74	0.62	0.41	0.19	0.06	0.00
		4	0.90	0.78	0.60	0.37	0.16	0.04	0.00
		5	0.98	0.95	0.84	0.59	0.29	0.07	0.004
	3	4	0.89	0.73	0.58	0.43	0.25	0.08	0.01
		5	1.00	0.95	0.76	0.48	0.19	0.03	0.003
	4	4	0.89	0.83	0.67	0.46	0.19	0.03	0.001
		5	0.96	0.83	0.61	0.48	0.32	0.16	0.04
25.2	1	3	0.75	0.50	0.31	0.20	0.08	0.01	0.00
		4	0.87	0.75	0.54	0.36	0.18	0.06	0.01
		5	0.93	0.78	0.64	0.40	0.18	0.03	0.00
	2	4	0.89	0.76	0.52	0.33	0.13	0.028	0.002
		5	1.00	0.93	0.77	0.47	0.18	0.03	0.001
	3	4	0.82	0.76	0.63	0.36	0.16	0.05	0.01
		5	1.00	0.83	0.62	0.28	0.06	0.002	0.00

Table 5. Mean pore size distributions at different levels (from below) in tilths produced by different numbers of passes of a tined implement as expressed by the proportion larger than X mm. Tillage was done at two water contents (w%).

w	Number of passes	Level	X 1	2	4	8	16	32	64
12.6	1	1	0.78	0.62	0.33	0.15	0.04	0.01	0.00
		2	0.83	0.50	0.43	0.24	0.07	0.01	0.00
		3	0.76	0.63	0.49	0.28	0.09	0.01	0.00
		4	0.94	0.83	0.68	0.42	0.16	0.03	0.001
		5	0.95	0.75	0.65	0.50	0.32	0.15	0.05
	2	3	0.90	0.74	0.42	0.18	0.05	0.01	0.00
		4	0.86	0.74	0.47	0.20	0.06	0.02	0.002
		5	0.98	0.86	0.72	0.56	0.35	0.14	0.03
	3	4	0.89	0.73	0.58	0.44	0.25	0.08	0.01
		5	1.00	0.95	0.76	0.48	0.19	0.03	0.002
	4	4	0.93	0.82	0.58	0.26	0.05	0.003	0.00
		5	0.97	0.93	0.80	0.61	0.35	0.13	0.02
25.2	1	3	0.80	0.70	0.28	0.11	0.02	0.001	0.00
		4	0.85	0.70	0.45	0.20	0.06	0.01	0.00
		5	0.97	0.80	0.64	0.43	0.21	0.07	0.011
	2	3	0.81	0.55	0.24	0.06	0.004	0.00	0.00
		4	0.87	0.70	0.43	0.18	0.04	0.004	0.00
		5	0.94	0.91	0.49	0.21	0.09	0.04	0.01
	3	3	0.69	0.54	0.24	0.09	0.01	0.00	0.00
		4	0.99	0.82	0.62	0.31	0.08	0.006	0.00
		5	0.94	0.71	0.49	0.21	0.09	0.04	0.01

Table 6. Structural characteristics at different levels (from below) in tilths produced by tillage with different numbers of passes of a tined implement. Tillage was done at water contents of 12.6 and 25.2%.

Number of passes	Level	Mean aggregate size (mm)		Mean pore size (mm)		Macro-porosity		Entropy	
		12.6	25.2	12.6	25.2	12.6	25.2	12.6	25.2
1	1	8.2		5.6		0.383		0.53	
	2	10.0							
	3	10.1	5.5	6.7	4.3	0.39	0.434	0.48	0.64
	4	11.2	10.0	9.6	5.9	0.469	0.382	0.43	0.51
	5	14.7	9.6	17.2	11.6	0.52	0.442	0.32	0.43
2	3	9.7	6.0	5.7	3.5	0.388	0.37	0.49	0.65
	4	10.1	8.3	6.6	5.4	0.401	0.391	0.42	0.53
	5	13.6	10.7	16.7	7.7	0.512	0.40	0.33	0.45
3	3		10.7		3.7		0.252		0.50
	4	11.8	9.5	6.8	6.5	0.373	0.442	0.45	0.47
	5	11.0	7.1	13.6	9.2	0.543	0.556	0.40	0.49

4.4.2 Comparison of tilths produced by different single implements

4.4.2.1 Mouldboard, disc plough, scarifier and rotary cultivator

The data from tilth block samples collected at the Mortlock Station in 1976 has enabled the internal structures of the tilths produced by mouldboard plough, disc plough, scarifier, and rotary cultivator to be compared.

4.4.2.1.1 Aggregate size distribution

Ploughing by mouldboard causes a relatively small production of small aggregates compared with tillage with scarifier or rotary cultivator. The proportion of 1 to 5 mm aggregates in the tilths produced by the mouldboard, disc plough, scarifier, and rotary cultivator were 0.06, 0.20, 0.20, and 0.10 respectively. The large proportion produced by the disc plough is surprising.

The rotary cultivator produced the greatest proportion of fine aggregates about 2 mm in diameter compared with the mouldboard and tines. This observation lends support to that of Dexter (1976) that the tilth produced by the rotary cultivator had the greatest probability of encountering isolated aggregates over 2 mm distances compared with the tilths produced by mouldboard and tines.

The proportion of clods larger than 32 mm was greater in the tilths produced by the mouldboard or disc plough respectively than in the tilth produced by the scarifier or rotary cultivator (Table 7). The scarifier produced the least cloddy tilth out of the four implements being considered.

The proportion of 1 mm aggregates at the 5 cm depth in the tilths produced by the implements was almost nil except for a very small proportion recorded for the tilth produced by the scarifier. This could be

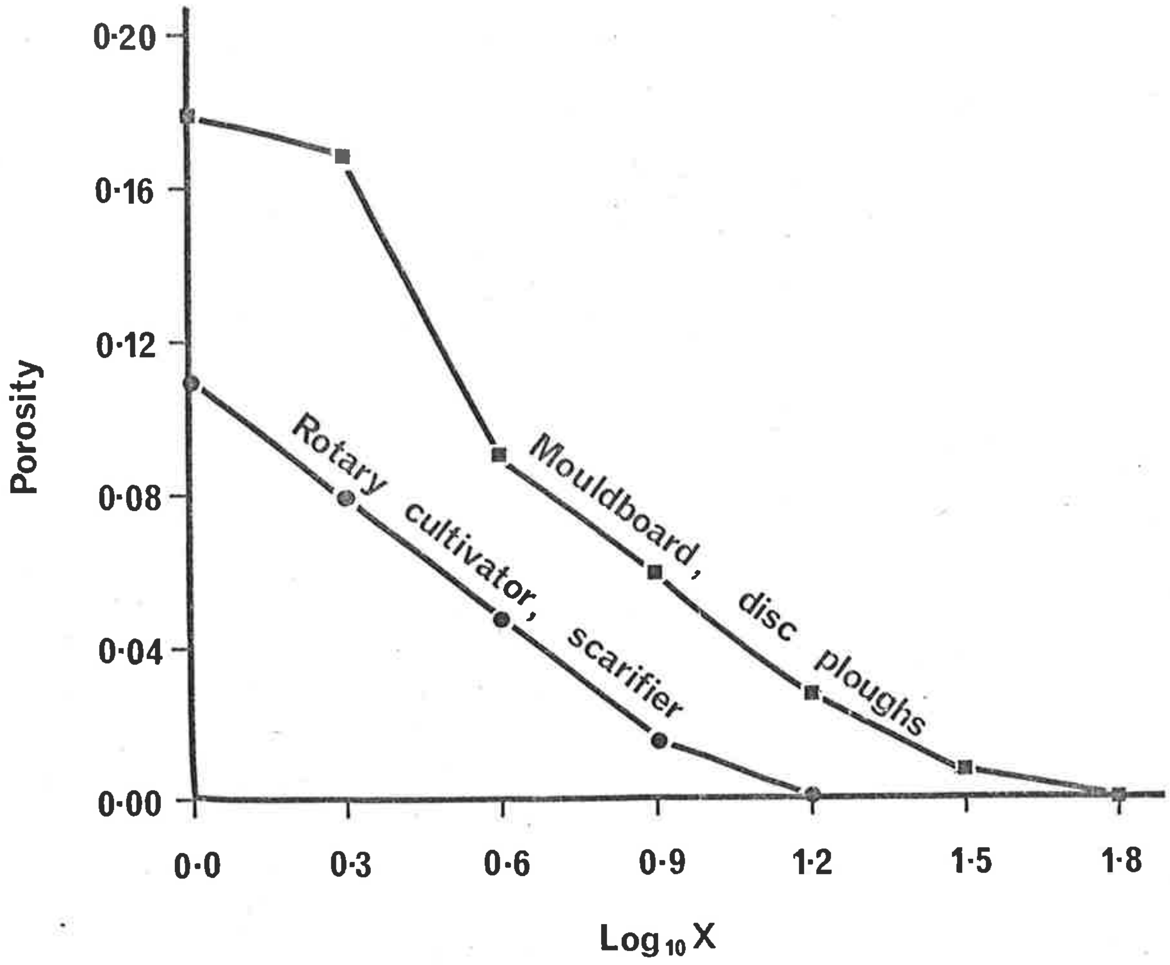


Fig 8. Porosities in pore sizes larger than Xmm in tilths produced by tillage implements.

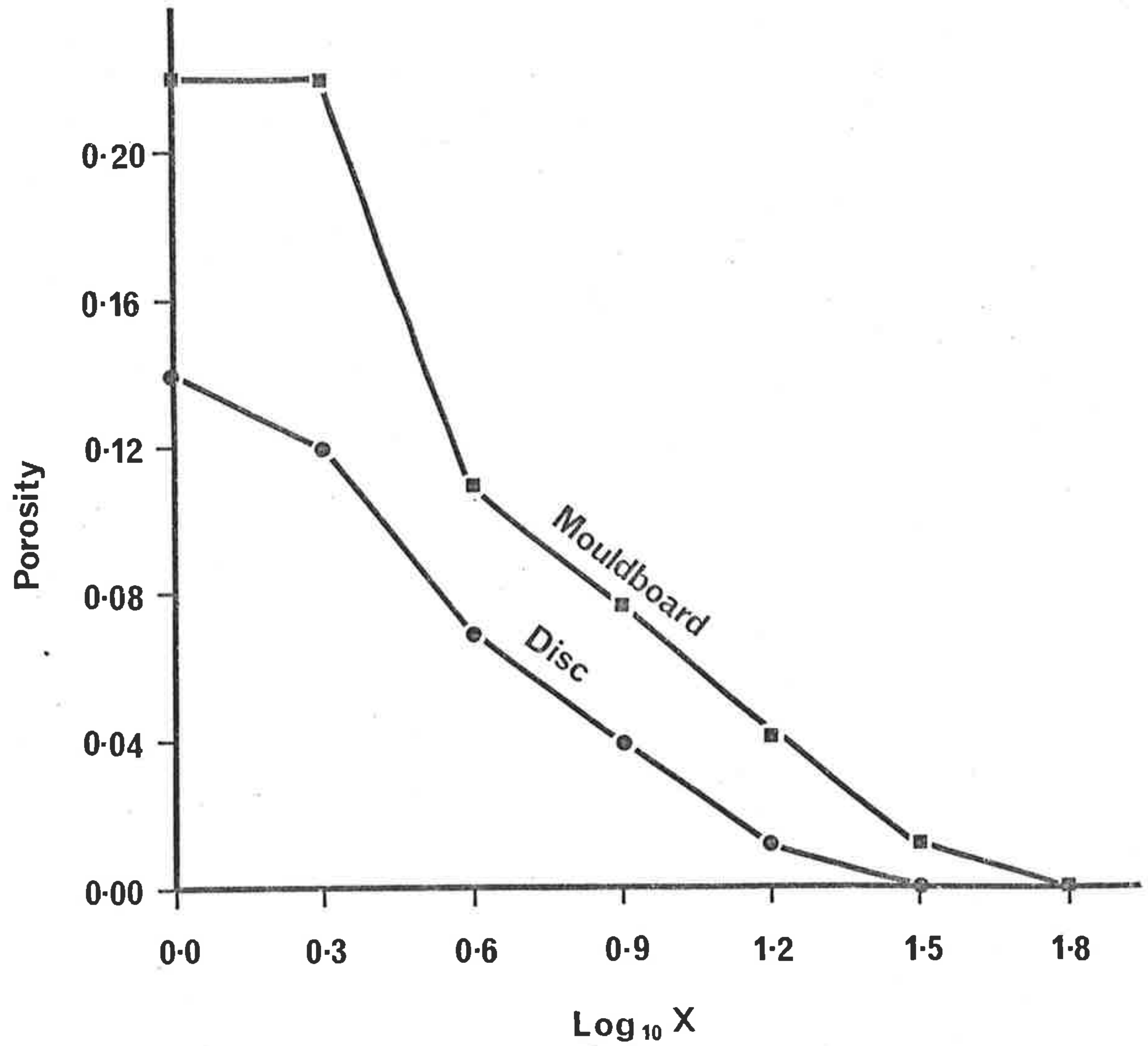


Fig. 9. Porosities in pore sizes larger than Xmm in tilths produced by mouldboard and disc ploughs.

attributed to the sorting of small aggregates to the bottom of the tilth during tillage (Dexter, 1976).

4.4.2.1.2 Pore size distribution

The proportion of pores larger than 8 mm was greater in the tilths produced by ploughing than in those produced by the rotary cultivator and the scarifier. The rotary cultivator produced the least proportion of large pores (Table 7). The greater proportion of large pores in the tilth produced by ploughing was because the tilth was comparatively cloddy.

The porosities contributed by pore sizes as presented in Figure 8 show that ploughs produced greater macroporosities than the scarifier or rotary cultivator. In fact, pores larger than 32 mm were almost non-existent in the tilths produced by the latter implements.

Macroporosities in large pores were greater as a result of tillage with the mouldboard plough than tillage with the disc plough (Figure 9).

4.4.2.1.3 Entropy

Because of the relative cloddiness of the tilth produced by ploughing, it had the smaller entropy compared with the tilth produced by the scarifier (Table 19b). The rotary cultivator produced a very small entropy compared with the scarifier.

Entropy indicates the amount of puncutation of spatial tilth structure by small structural elements. The proportion of small structural elements is positively correlated with tilth entropy.

The scarifier produced a less cloddy tilth than the rotary cultivator, although both of them produced less cloddy tilths than produced by ploughing. The present finding lends support to the previous statements of Culpin (1936), Russell and Mehta (1938) and others in connection with the coarseness of the tilth produced by ploughing compared with that produced

Table 7. Aggregate and pore size distributions in tilths produced by single tillage implements as expressed by the proportion larger than X mm.

X	Proportion			
	Mouldboard	Disc	Rotary	Scarifier
1	1.00	1.00	1.00	0.92
2	1.00	0.94	0.95	0.92
4	0.97	0.81	0.92	0.84
8	0.85	0.73	0.82	0.73
16	0.66	0.58	0.63	0.56
32	0.40	0.38	0.38	0.33
64	0.15	0.15	0.14	0.11
1*	1.00	0.87	1.00	0.73
2*	1.00	0.74	0.77	0.50
4*	0.49	0.43	0.43	0.32
8*	0.36	0.24	0.08	0.14
16*	0.19	0.07	0.003	0.028
32*	0.05	0.007	0.00	0.001
64*	0.004	0.0001	0.00	0.00
Mean aggregate size	35.3	33.0	33.1	29.1
Mean pore size	9.9	6.3	4.7	4.6
Macroporosity	0.22	0.16	0.12	0.13

* Pore size distributions.

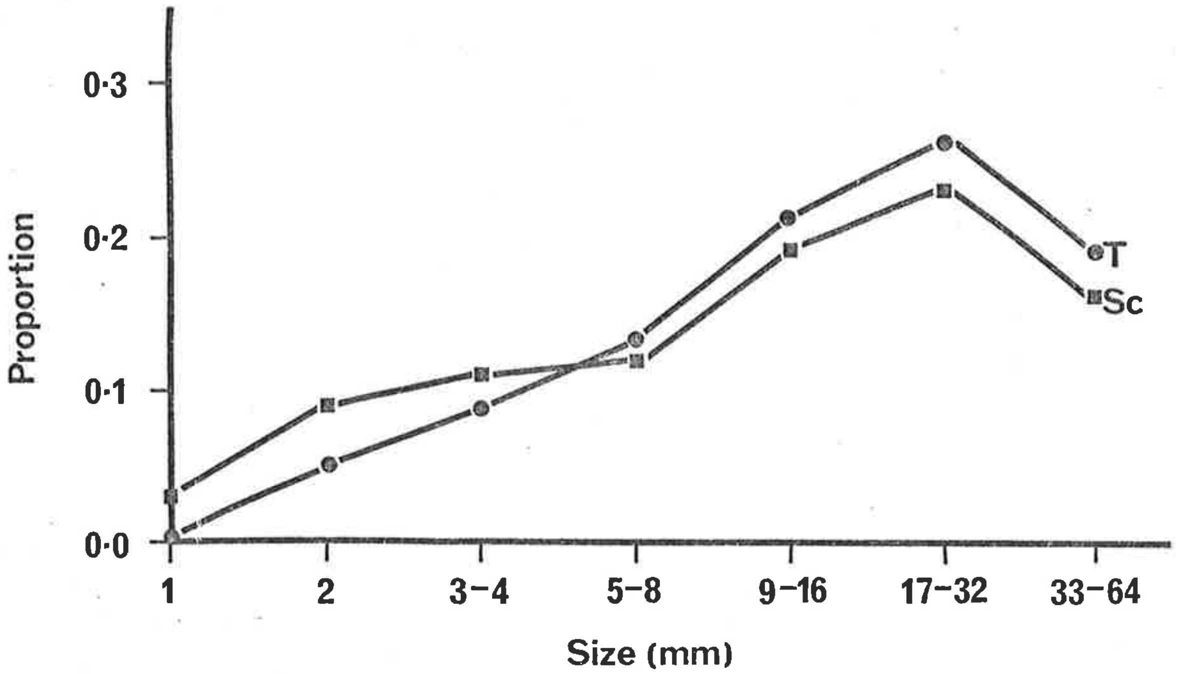


Fig. 10. Aggregate size distributions in tilths produced by tines with wide(Sc) and narrow(T) points when used alone.

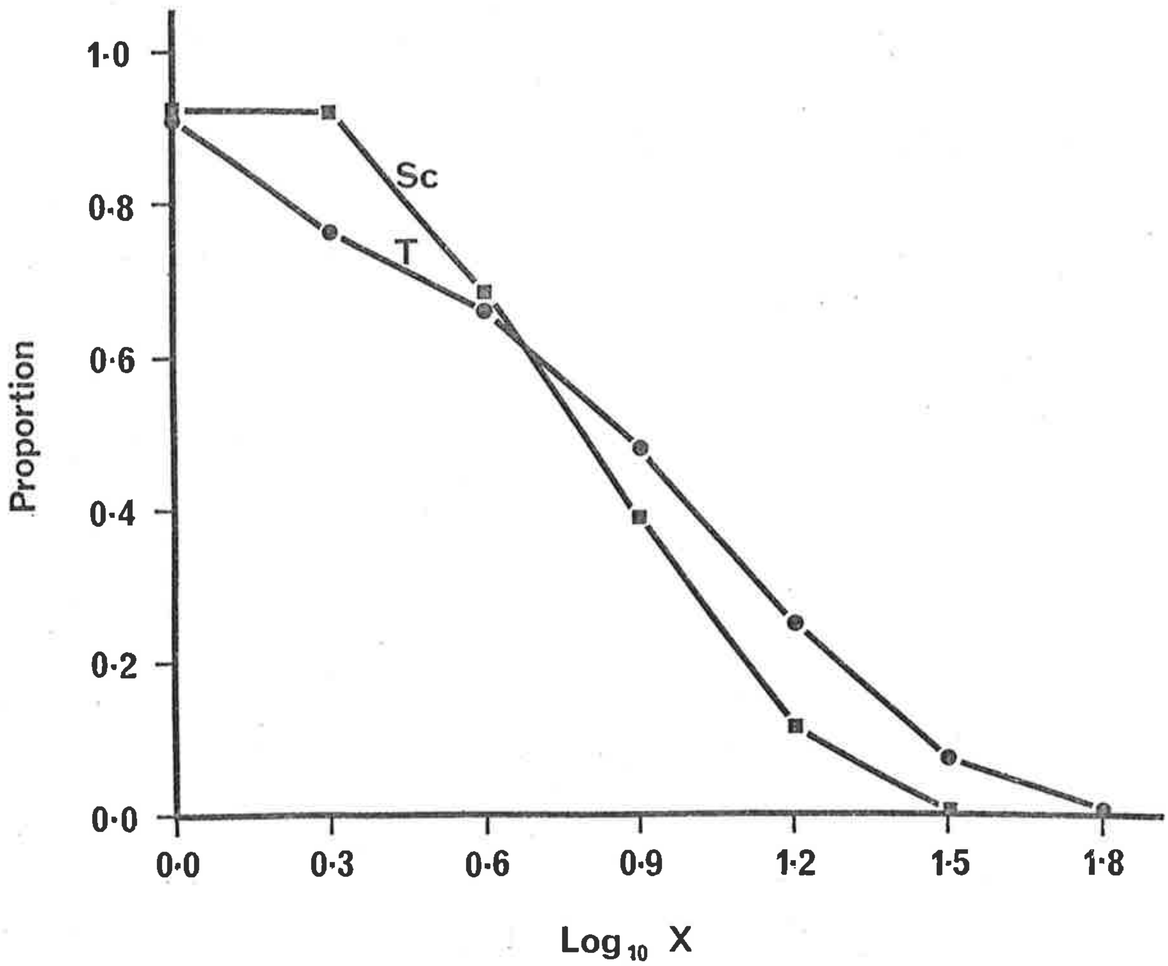


Fig. 11. Proportion of pores larger than Xmm in tilths produced by tines with wide (Sc) and narrow (T) points when used alone.

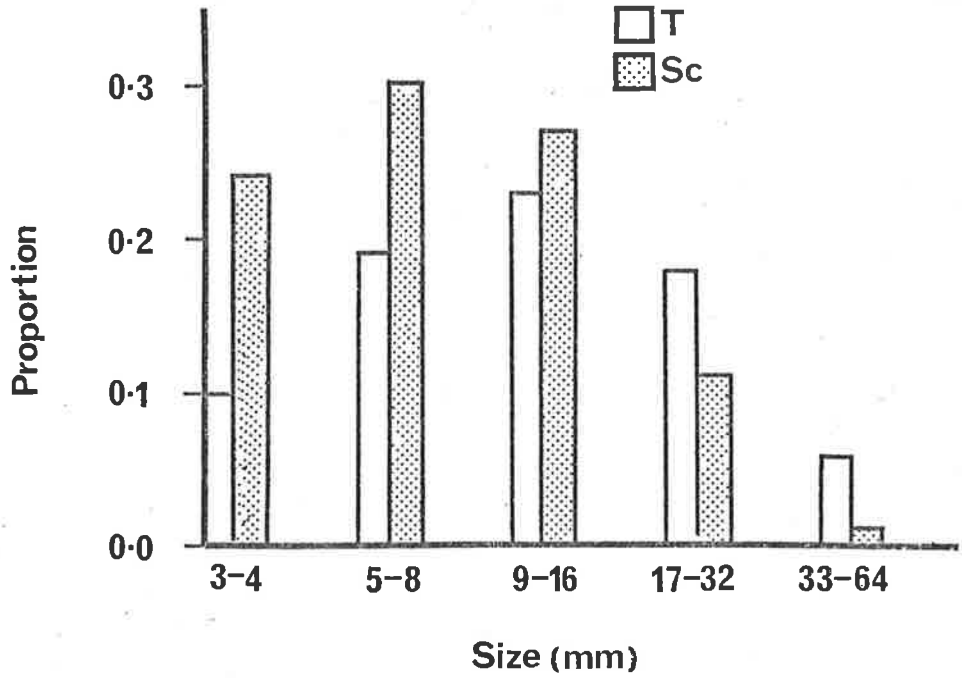


Fig. 12. Pore size distributions in tilths produced by tines with wide (Sc) and narrow (T) points when used alone.

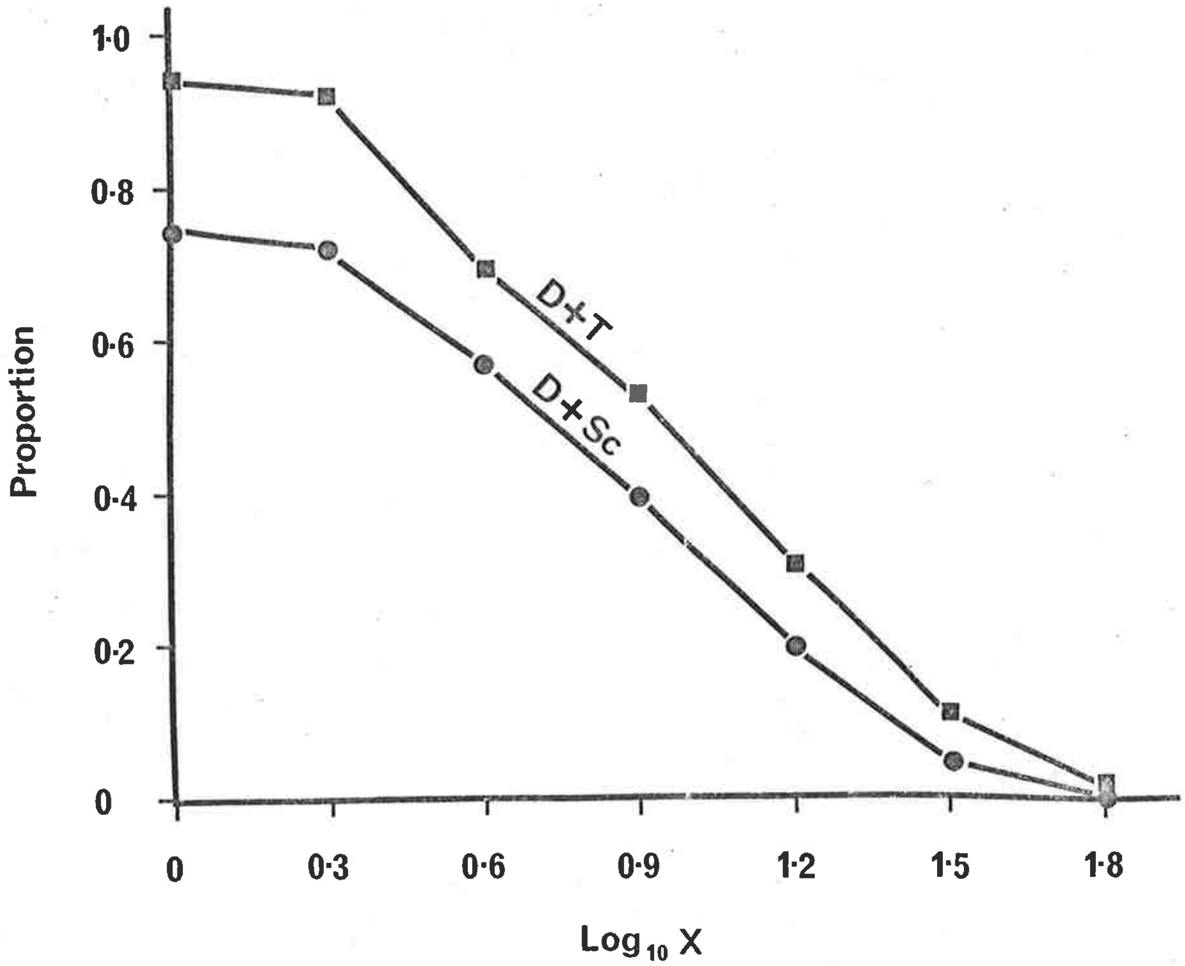


Fig. 13. Proportion of aggregates larger than Xmm in tilths produced by tines with wide (Sc) and narrow (T) points after ploughing (D).

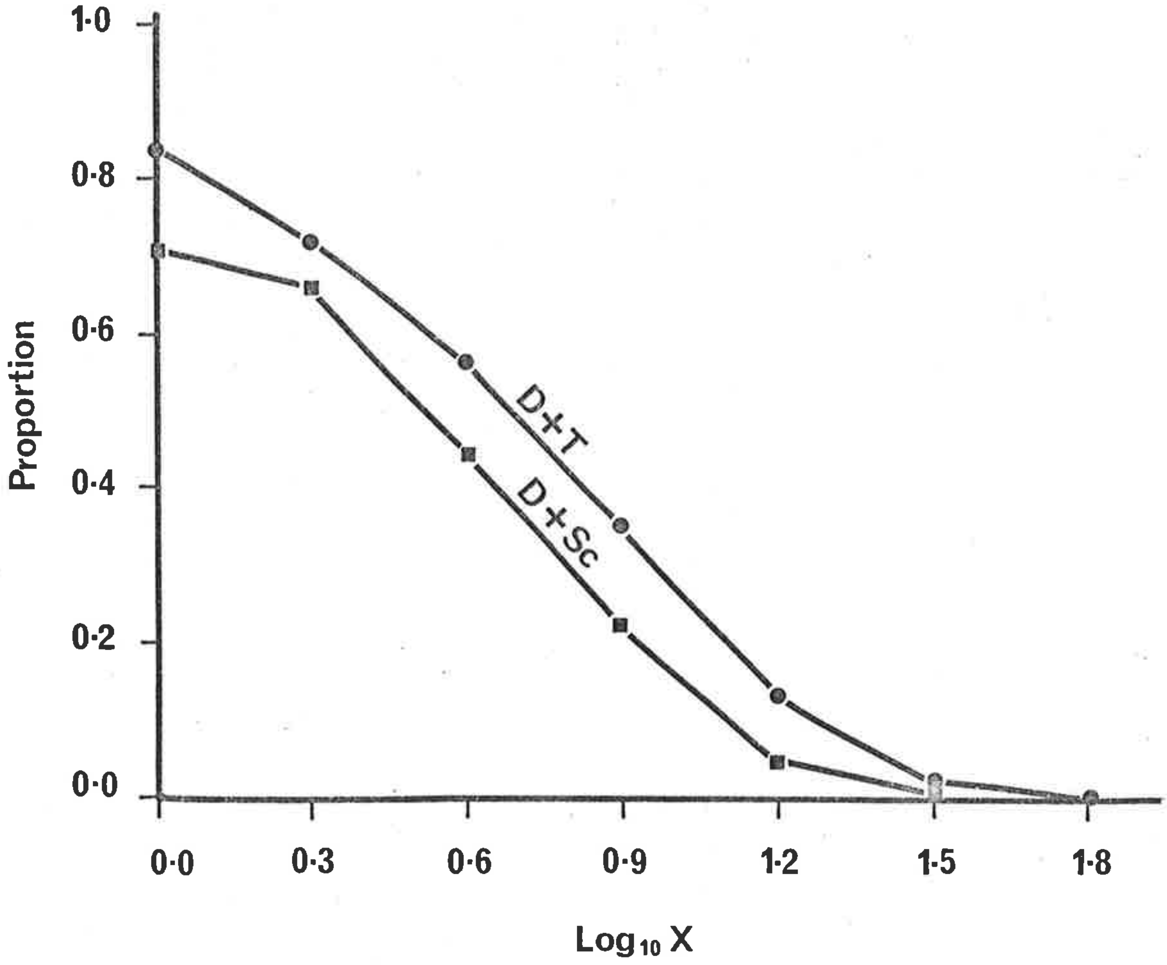


Fig. 14. Proportion of pores larger than Xmm in tilths produced by tines with wide (Sc) and narrow (T) points after ploughing (D).

by a rotary cultivator.

That the order of cloddiness of tilths produced by single implements was Plough > Rotary cultivator > Scarifier is further confirmed by the fact that the order for the mean aggregate or mean pore sizes of the tilths was Plough > Rotary > Scarifier.

4.4.2.2 Tines with wide points and narrow points

A single pass of a set of tines with wide, and narrow points is used alone or after ploughing. In reduced tillage practice such as Spray-seed (Wheat Research, 1977), a single pass of a tined implement alone (during seed drilling) is used (D. Correll, South Australian farmer of Winulta - personal communication, 1977). The tilths produced by tine implements with narrow (65-67 mm) and wide points (195 mm) when used alone or after a single pass of a disc plough are now compared. The measurements carried out on the tine implements are presented in Appendix I. The two types of tine implement are represented by T and Sc respectively. The structural data collected at Mortlock Station in 1977 are used.

4.4.2.2.1 Aggregate size distribution

Tines with wide points produced more small aggregates including those smaller than 6 mm than tines with narrow points when used alone or after disc plough (D). Therefore, the proportion of clods including those larger than 8 mm was greater in the tilth produced by the latter than in that produced by the former.

The aggregate and pore size distributions in tilths produced when tine implement with narrow points, and wide points when used alone are compared in Figures 10 and 12; and in Figures 13 and 14 for when they were used after a pass of a plough (D).

The above effect of the tine implement with wide points compared with that with narrow points could be due to its more soil coverage during tillage because of the wider points of tines. The latter would cause more soil movement and agitation and smaller mean aggregate size. When tine implements with wide points, and narrow points were used alone, the proportions of 1 to 4 mm aggregates were 0.23 and 0.13 respectively in their tilths, and when they were used after ploughing the equivalent proportions were 0.43 and 0.32.

4.4.2.2.2 Pore size distribution

The greater proportion of small aggregates in tilths produced when tine implement with wide points was used alone and after ploughing compared with when the implement with narrow points was used led to small proportions of large voids being produced by the former. For example, the resultant mean pore sizes when tines with wide, and narrow points were used after ploughing were respectively 5.6 and 8.2 mm.

4.4.2.2.3 Entropy

The greater proportion of small structural elements as a result of tillage with tines having wide points compared with tines having narrow points caused larger entropy of the tilth produced by the former relative to the tilth produced by the latter. The mean values of entropy for the tilths produced by tines with wide, and narrow points when used alone were 0.32 and 0.28 respectively, while the equivalent values when they were used after ploughing were 0.50 and 0.40.

4.4.3 Multiple passes of a plough

Change in tilth structure with increasing number of passes of a disc plough is now considered.

4.4.3.1 Aggregate size distribution

The greatest proportion of small aggregates (including those smaller than 6 mm in diameter) occurred after the second pass of a disc plough. The third pass of the plough caused visible clod formation at the surface and possibly separation of small aggregates to the bottom of the tilth that led to reduction in the proportion of small aggregates at

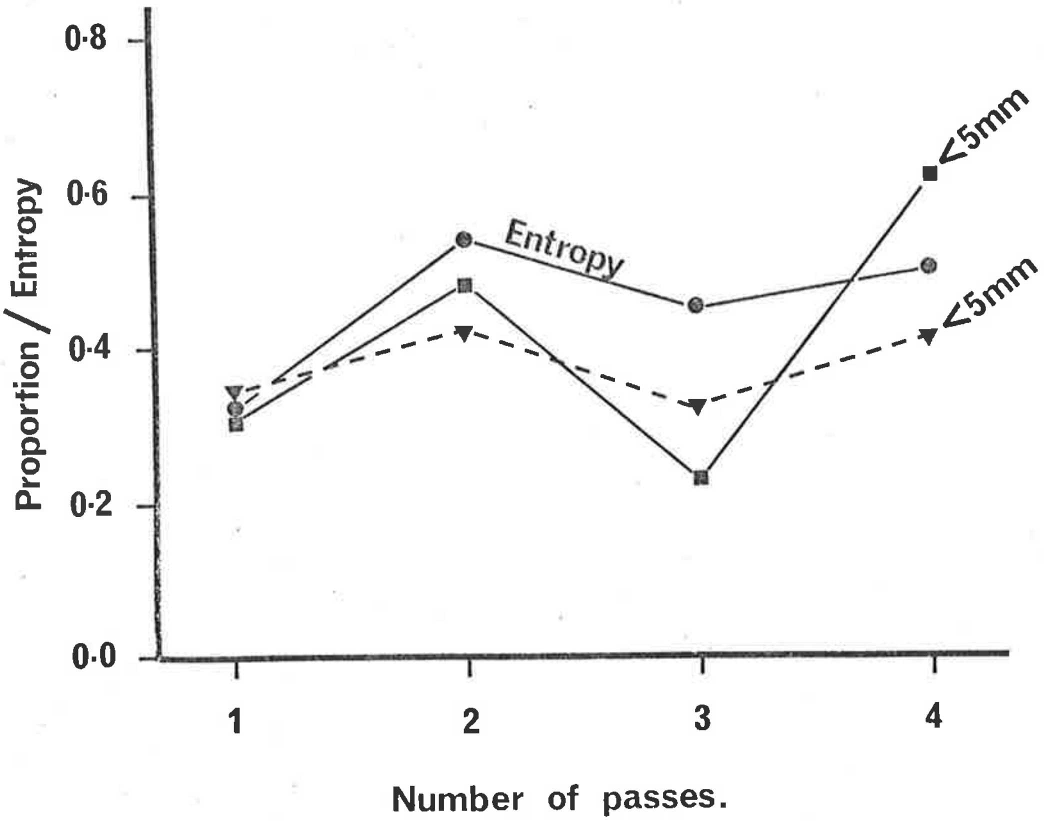


Fig. 15. Aggregate (■——■) and pore (▼- - -▼) size distributions after tillage with different number of passes of disc plough (in proportion).

Table 8. Aggregate size distributions in tilths produced by different number of passes of disc plough (D) as expressed by the proportion larger than X mm.

X	Proportion			
	D	D+D	D+D+D	D+D+D+D
1	0.93	0.95	0.95	0.86
2	0.81	0.70	0.89	0.69
4	0.69	0.52	0.77	0.54
8	0.57	0.33	0.48	0.31
16	0.39	0.13	0.18	0.10
32	0.18	0.02	0.03	0.01
64	0.04	0.0005	0.0006	0.0001
Mean aggregate size	18.1	8.0	10.5	7.3

Table 9. Pore size distributions in tilths produced by different number of passes of disc plough (D) as expressed by the proportion larger than X mm.

X	Proportion			
	D	D+D	D+D+D	D+D+D+D
1	0.88	0.95	0.94	0.95
2	0.75	0.89	0.79	0.86
4	0.66	0.58	0.63	0.59
8	0.48	0.26	0.36	0.36
16	0.25	0.05	0.11	0.13
32	0.07	0.002	0.01	0.02
64	0.006	0.00	0.0001	0.0003
Macroporosity	0.40	0.46	0.44	0.54
Mean pore size	11.9	6.8	8.2	8.6

Plate 7. Plates 7A, 7B, and 7C respectively following show tilth structures after 1, 2, and 4 passes of disc plough. Finer structure was produced by the second pass compared with the first pass. The clodding as a result of the fourth pass is shown.

the top zone of the tilth. Continuous breakdown of clods was, however, more important than sorting of aggregates during the fourth pass of the plough and increased proportion of small aggregates was recorded at the 5 cm depth. The trend in the proportions of aggregates smaller than 5 mm with increasing number of passes of disc plough is shown in Figure 15.

4.4.3.2 Mean aggregate size

The mean aggregate sizes for tilths produced by different numbers of passes of a disc plough and the proportions of aggregates larger than 5 mm in the tilths were directly correlated. One of the two smallest mean aggregate sizes occurred after the second pass of the plough and the greatest mean occurred after the first pass of the plough. After the third pass, the mean aggregate size increased due to clod formation and possible separation of aggregates. Winkelblech and Johnson (1964) indicated that sorting of aggregates mostly occurred during the first pass of an implement after the maximum concentration of small aggregates in soil had been produced.

4.4.3.3 Pore size distribution

The information given by the pore size distributions (Table 9) in tilths and that given by the aggregate size distributions (Table 8) are the same. The order for the distribution of pores smaller than 5 mm was D+D > D+D+D+D > D+D+D > D (Figure 15) and the order was reversed for the distribution of larger pores. The clod formation and possibly sorting of aggregates which resulted from further tillage after the second pass of the plough caused an increased proportion of medium to large size pores which led to an increase in macroporosity.

4.4.3.4 Entropy

The entropies of the tilths reflect the relative frequencies of aggregates and pores smaller than 5 mm in the tilths. The largest amount of structural variability or entropy occurred in the tilth after the second pass of the plough, whereas the least entropy occurred after the first pass of the plough due to relatively great proportion of clods and large voids. The larger entropy recorded for the fourth pass as compared with third pass would be due to further breakdown of clods which was then more important than clod formation and sorting of aggregates.

The sorting of aggregates as discussed earlier (section 4.4.1) might have caused the smallest proportion of aggregates smaller than 5 mm recorded after the third pass of the plough in addition to clod formation. These processes were more important than breakdown of clods during the third pass. Further breakdown of clods produced by the first pass of the plough was achieved by the second pass and the largest proportion of small aggregates was then recorded. The increased proportion of small aggregates after the fourth pass of the plough points to the fact that the processes of clod fragmentation into small aggregates and sorting of aggregates might be alternating in relative importance during repeated tillage.

4.4.4 Tillage with one pass of tine implement after ploughing

Harrowing (with a pass of a tine implement) after ploughing is often required to prepare the 10 cm of soil so that seed can be placed uniformly at the correct depth, that soil-seed contact is adequate to provide water for germination and early growth, and so that seedling root and shoot are not obstructed by large clods. The function of harrowing implies that it is expected to break clods further into smaller pieces after ploughing.

The mean *in situ* structural data of plots tilled with ploughs (MB, D) alone are now compared with those of the plots tilled with tine implements (one pass) after ploughing (MB+CD, MB+Sc, D+Sc, D+CD, D+T, D+Sc). The data of 1976 and 1977 were from tilth block samples collected at the Mortlock Station.

4.4.4.1 Aggregate size distribution

Harrowing with a pass of a tined implement (after ploughing) caused an increased proportion of aggregates smaller than 6 mm in diameter. The aggregate size distributions in tilths produced by ploughing, and further tillage with a pass of a tined implement (after ploughing) are presented in Table 10. The mean proportions of 1 to 5 mm aggregates in the tilths produced by ploughing, and further harrowing (with a pass of tine implement) were 0.13 and 0.15 respectively in 1976, while the equivalent values for 1977 were 0.31 and 0.37.

As a result of breakdown of clods by harrowing, clods larger than 16 mm were most frequent in the tilth produced by ploughing compared with the tilth produced by additional first pass harrowing. The proportions of different size ranges of aggregates as derived from 1977 are presented in Figure 16.

4.4.4.2 Mean aggregate size

It is shown (Table 10) that the mean aggregate size was larger in the tilth produced by ploughing alone compared with the tilth produced by additional harrowing (with one pass of tine implement).

4.4.4.3 Entropy

The greater proportion of small aggregates in the tilth produced by first pass harrowing after ploughing led to increased tilth entropy compared with the condition after ploughing alone. The data collected in two years showed the mean entropy values of the tilths produced by ploughing and first pass harrowing to be 0.27 and 0.34 respectively (Table 19).

Table 10. Aggregate and pore size distributions in tilths produced by ploughing (P), and additional harrowing (P+H) as expressed by the proportion of aggregates and pores larger than X mm.

X	1977 P	1977 P+H	1978 P	1978 P+H
	Proportion aggregates			
1	0.93	0.85	1.00	1.00
2	0.81	0.82	0.97	0.94
4	0.69	0.63	0.90	0.88
8	0.57	0.46	0.80	0.78
16	0.39	0.26	0.63	0.62
32	0.18	0.08	0.40	0.39
64	0.04	0.008	0.15	0.16
	Proportion pores			
1	0.88	0.78	0.94	0.90
2	0.75	0.69	0.87	0.69
4	0.66	0.50	0.46	0.44
8	0.48	0.28	0.30	0.19
16	0.25	0.09	0.13	0.06
32	0.07	0.01	0.03	0.008
64	0.006	0.00	0.002	0.00
Macroporosity	0.40	0.36	0.19	0.12
Mean pore size	11.9	6.9	8.1	5.9
Mean aggregate size	18.1	12.1	34.1	37.0

P (1976) = Treatments D and MB combined; 4 replicates.
P+H (1976) = Treatments D+Sc, D+CD, MB+Sc, MB+CD combined; 8 replicates.
P (1977) = Treatments D only; 2 replicates.
P+H (1977) = Treatments D+T and D+Sc combined; 4 replicates.

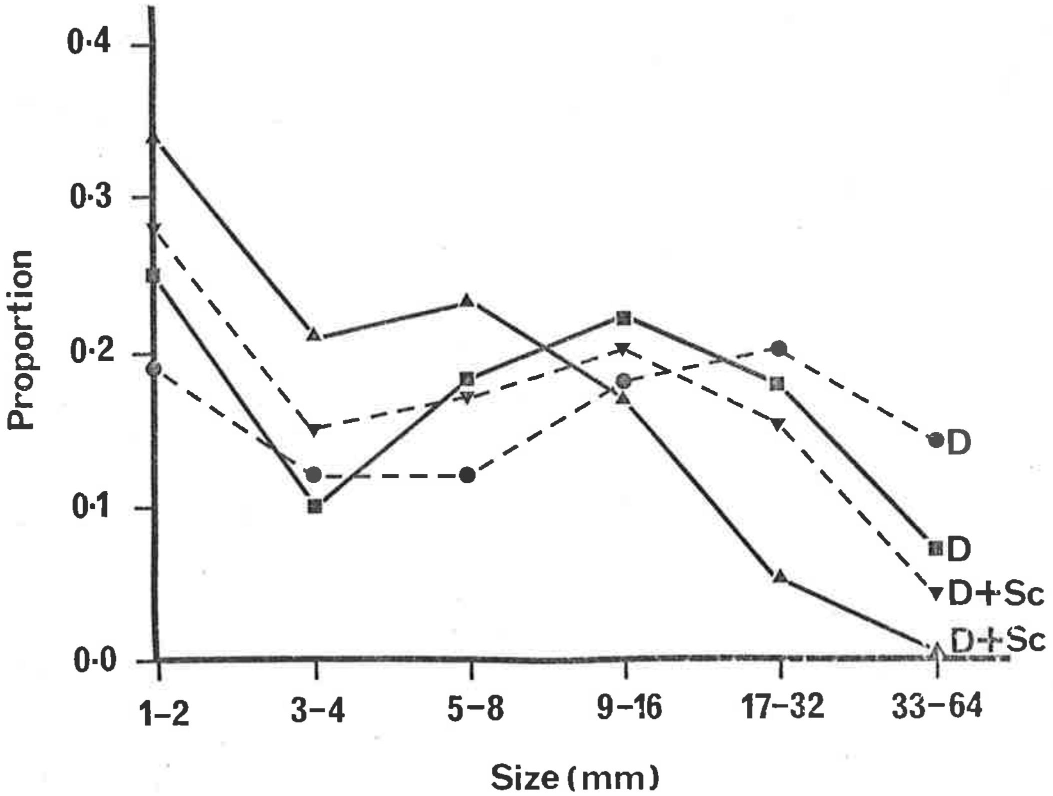


Fig. 16. Aggregate (– – –) and pore (——) size distributions in tilths produced by plough (D) and plough followed by scarifier (D + Sc) — (2 replicates of each treatment, 1977).

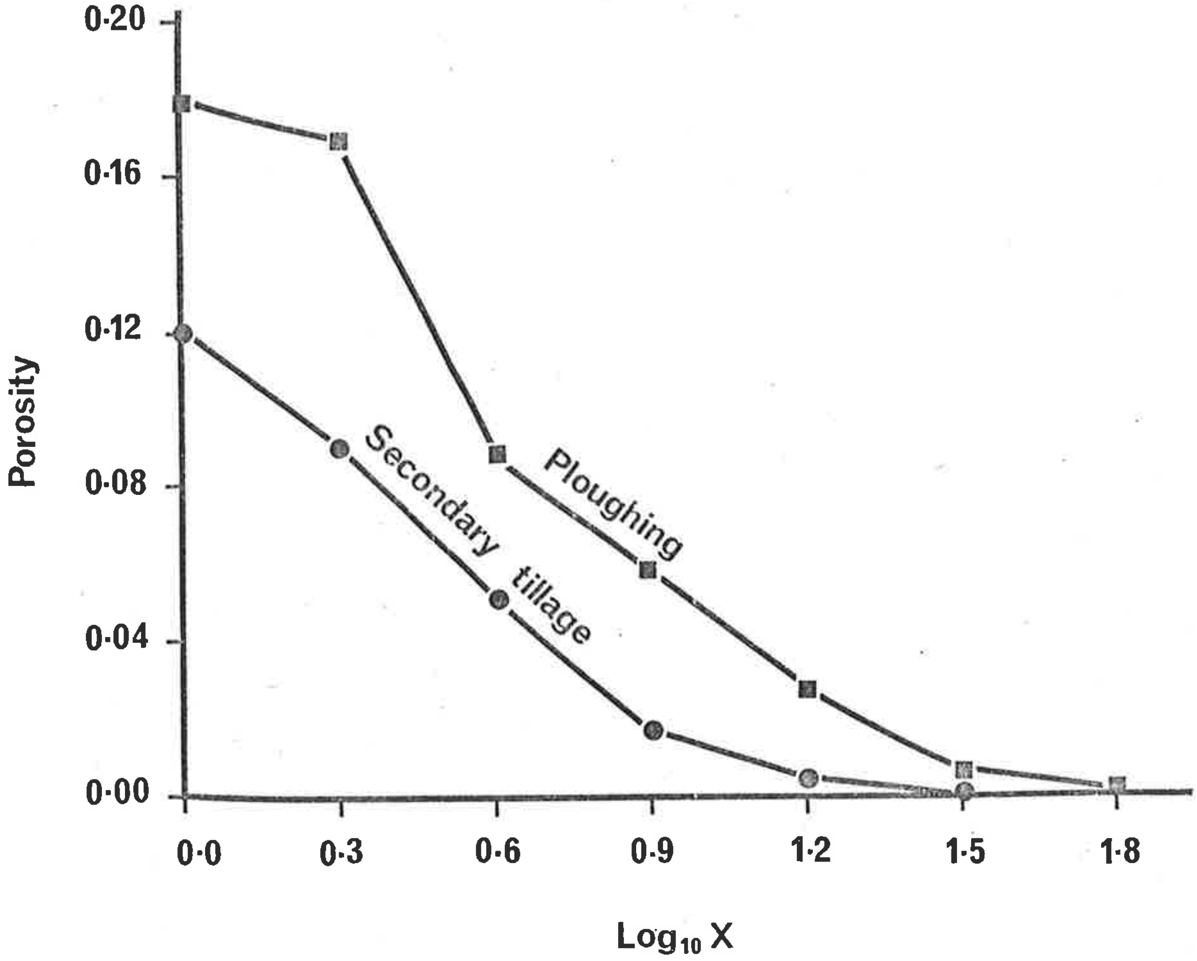


Fig. 17. Porosities in pore sizes larger than Xmm in tilths produced by ploughing and secondary tillage.

4.4.4.4 Pore size distribution

The greater proportion of clods in the tilth that resulted from ploughing alone caused greater proportion of large voids in the tilth compared with that produced by first pass harrowing (Table 10). The pore size distributions of the tilths produced by ploughing, and harrowing in 1977 are compared in Figure 16. It is shown that the former had a smaller proportion of pores smaller than 8 mm than the latter.

4.4.4.5 Macroporosity

The greater proportion of pores larger than 8 mm as a result of ploughing compared with additional harrowing led to greater macro-porosity of the tilth produced by the former. The macroporosities by the medium to large pore sizes (1976) are shown (Figure 17) to be greater in the tilth produced by disc ploughing than in that produced by additional harrowing.

In Chapter 5, the data from tilth block samples collected in 1976 are used to show that the medium-size (9-16 mm) pores determine tilth macroporosity. Hence the greater macroporosity of the tilth produced by ploughing compared with that produced by additional one pass harrowing could easily be understood.

4.4.5 Tillage with two and three passes of a tined implement after ploughing

It was of interest to investigate whether additional passes of a harrow after ploughing would increase the proportion of small aggregates by further breakdown of clods. It has been (in section 4.4.4) shown that first pass harrowing (with a tined implement) after a pass of a plough caused considerable breakdown of clods into smaller aggregates.

The mean structural data of tilths produced by second pass, and third pass harrowing (by two, and three passes of a tined implement) are compared with the mean structural data of the tilths produced by using

The treatments by one pass harrowing in 1977 are represented by D+T and D+Sc in the tables provided at the end of this chapter, the tilths produced by second pass harrowing are represented by D+T+T and D+Sc+Sc, while the tilths produced by third pass harrowing are represented by D+T+T+T and D+Sc+Sc+Sc.

The aggregate and pore size distributions of the tilths produced by first pass, second pass, and third pass harrowing are presented in Table 11.

4.4.5.1 Aggregate size distribution

For the production of small aggregates, there is no advantage in further harrowing after first pass harrowing (with tined implements). Further harrowing after first pass harrowing did not increase the proportion of small aggregates (including those smaller than 6 mm), rather it decreased it. For example, the proportions of 1 to 4 mm aggregates for treatments D+T, D+2T, and D+3T were 0.37, 0.23, and 0.24 respectively. It is shown that further tillage after first pass harrowing considerably increased the proportion of aggregates larger than 8 mm and did not considerably decrease the mean aggregate size at the 5 cm depth.

The trend in the proportions of large aggregates, and mean aggregate and pore sizes show that the second pass harrowing caused sorting of small aggregates to the bottom of the tilth. The latter led to a decrease in the proportion of small aggregates at the top of the tilth. Kouwenhoven and Terpstra (1970) who worked in the laboratory characterised tine implements especially with this sorting tendency.

4.4.5.2 Pore size distribution

The decreased proportion of small aggregates and the corresponding increased proportion of large aggregates as a result of

Plate 8. Plates 8A and 8B show tilth structure after one pass harrowing and two pass harrowing respectively. The latter is coarser than the former.

further tillage after first pass harrowing led to increased proportion of large voids, increased macroporosity (due to increased frequency of medium to large-size voids), and increased mean pore size.

4.4.5.3 Entropy

Since tilth structural variability (or entropy) depends on the presence of smaller structural elements (Dexter, 1977), decreased proportion of these elements due to tillage after first pass harrowing led to decreased entropy. For treatments D+T and D+2T the respective mean entropies were 0.45 and 0.32.

Decreased proportion of small aggregates due to further tillage after first pass harrowing (following ploughing) is attributed to sorting of these aggregates mostly produced by the latter to the base of the tilled layer. This caused a singificant drop in structural variability of tilths from treatment D+T to D+2T because the sorting process mainly occurs as a result of the first pass of the implement after the greatest proportion of small aggregates has been produced (Winkelblech and Johnson, 1964).

The present finding could be used to explain the observation of Pigulevsky (1936, cited by Russell, 1938) that the percentage of aggregates larger than 5 mm increased from 33 to 40% when 20 discings after two ploughings (with mouldboard) were performed compared with four discings.

4.4.6 Multiple passes of tined implements

In reduced tillage practices, land preparation is often performed by single and multiple passes of tined implements. This method of land preparation could be adequate on a light soil (such as a loam) or when herbicide is used along with tillage. Soil mulching for water

Table 11. Aggregate and pore size distributions in tilths produced by one (D+T), two (D+2T), and three (D+3T) passes of a tined implement after ploughing as expressed by the proportion larger than X mm.

X	Proportion (aggregates) D+T	D+2T	D+3T	Proportion (Pores) D+T	D+2T	D+3T
1	0.85	0.95	0.90	0.78	0.90	0.93
2	0.82	0.76	0.77	0.69	0.84	0.88
4	0.63	0.64	0.66	0.50	0.71	0.62
8	0.46	0.54	0.49	0.28	0.47	0.31
16	0.26	0.38	0.29	0.09	0.22	0.08
32	0.08	0.19	0.12	0.01	0.04	0.01
64	0.008	0.05	0.03	0.00	0.002	0.001
Macroporosity				0.36	0.37	0.373
Mean pore size				6.9	11.0	7.6
Mean aggregate size	18.0	18.9	15.0			

conservation in the period between two crops is done by multiple passes of a set of tines in dry-land farming in South Australia. The thought behind the use of multiple pass of a set of tines is that the proportion of small aggregates and pores indicated (Greenland, 1971) to be essential for optimum seed germination, and soil water conservation will be increased. However, the justification of this by field measurements on undisturbed tilths does not appear to have been attempted previously.

The mean structural data (1977) of the tilths produced by one to three passes of a set of narrow and wide tines taken together are compared. Tillage was done at the Mortlock Station. Treatments by one to three passes of tine implements are represented by T, 2T and 3T respectively.

The structural data of the tilths produced by one to three passes of a tined implement on the Waite Institute site are compared. Tillage was done at two water contents. The aggregate and pore size distributions of the tilths that resulted are presented in Tables 13 and 14. Two tilth block samples were collected from each tilled plot. The primary data are presented in Appendix II(A).

4.4.6.1 <u>Aggregate size distribution</u>

For the production of small aggregates, there is an advantage in the use of multiple passes of a tined implement up to three passes. Repeated use of a tine implement (especially one with narrow points) caused further breakdown of large aggregates for treatments T, 2T and 3T. The mean proportions of 1 to 4 mm aggregates (Mortlock Station data) were 0.18, 0.29 and 0.53 respectively at the 5 cm depth. The mean aggregate size decreased with increasing number of passes of tines. The proportion of aggregates larger than 8 mm was decreasing with increasing number of passes of the tined implement up to three.

Plate 9. Plates 9A and 9B show tilth structures after two and three passes of tined implement with narrow points. The former produced coarser tilth than the latter treatment.

Table 12. Mean aggregate and pore size distributions in tilths produced by one to three (T, 2T, 3T) passes of tine implements as expressed by the proportion larger than X mm.

X	Proportion (aggregates) T	Proportion (aggregates) 2T	Proportion (aggregates) 3T	Proportion (Pores) T	Proportion (Pores) 2T	Proportion (Pores) 3T
1	0.99	0.91	0.89	0.92	0.95	0.98
2	0.91	0.83	0.67	0.85	0.85	0.87
4	0.82	0.72	0.48	0.68	0.60	0.59
8	0.69	0.61	0.35	0.43	0.43	0.30
16	0.49	0.45	0.20	0.18	0.25	0.08
32	0.25	0.26	0.06	0.04	0.08	0.008
64	0.10	0.10	0.006	0.002	0.01	0.00
Mean pore size				10.3	12.3	7.5
Mean aggregate size	22.9	26.5	9.9			

Table 13. Aggregate size distributions in tilths produced by different number of passes of narrow tines (T) at different water contents (w%) as expressed by the proportion larger than X mm*.

X	Proportion (w = 12.6%) T	Proportion (w = 12.6%) 2T	Proportion (w = 12.6%) 3T	Proportion (w = 25.2%) T	Proportion (w = 25.2%) 2T	Proportion (w = 25.2%) 3T
1	0.99	0.96	0.95	0.90	0.95	0.91
2	0.84	0.86	0.84	0.77	0.85	0.80
4	0.72	0.74	0.67	0.59	0.65	0.62
8	0.51	0.50	0.46	0.39	0.40	0.32
16	0.22	0.24	0.23	0.18	0.16	0.11
32	0.07	0.06	0.05	0.04	0.03	0.025
64	0.007	0.004	0.004	0.005	0.001	0.003
Mean aggregate size	13.0	11.9	11.3	9.8	9.5	9.3

* Data collected from tilth block samples collected at Waite Agricultural Research Institute.

Table 14. Pore size distributions in tilths produced by different numbers of passes of narrow tines (T) at different water contents (W%) as expressed by the proportion larger than X mm*.

X	Proportion (w = 12.6%)			Proportion (w = 25.2%)		
	T	2T	3T	T	2T	3T
1	0.95	0.91	0.87	0.91	0.90	0.99
2	0.79	0.79	0.79	0.75	0.70	0.91
4	0.65	0.60	0.61	0.55	0.46	0.70
8	0.52	0.40	0.39	0.31	0.19	0.36
16	0.24	0.21	0.19	0.14	0.08	0.09
32	0.09	0.08	0.01	0.01	0.07	0.007
64	0.03	0.02	0.001	0.005	0.004	0.00
Macroporosity	0.50	0.46	0.46	0.41	0.40	0.50
Mean pore size	13.4	11.7	10.2	8.8	6.6	7.8

* Data collected from tilth block samples collected at Waite Agricultural Research Institute.

4.4.6.2 Entropy

The increasing proportion of small structural elements with increasing number of passes of tine implements caused progressive increase in mean entropy. The approximate mean entropies for treatments T, 2T and 3T were 0.30, 0.30, and 0.47 respectively. The latter indicates increasing tilth structural variability with repeated tillage caused by an increasing proportion of small aggregates and pores.

4.4.6.3 Pore size distribution

Continual soil fragmentation into small aggregates with increasing number of passes of tined implements caused an increase in the proportion of small pores. This observation features more especially after the third pass of the implement. For treatments T, 2T, and 3T, the proportion of 1 to 4 mm pores with 0.54, 0.34 and 0.78 respectively. The mean pore size was decreasing with increasing number of passes of the tines.

The trend in the aggregate and void size distributions with increasing numbers of passes of a tined implement was most pronounced with the use of tines with narrow points. A slight increase in the proportion of clods was observed after the second pass of tines with wide points. The proportions of aggregates larger than 8 mm increased from 0.64 to 0.71 after the second pass of tines with wide points. This will be due to the effect of the sorting of small aggregates out of the top zone of tilth in preference to large aggregates. Kouwenhoven and Terpstra (1970) found that the wide tines sorted aggregates faster than the narrow tines. The greater sorting characteristic of tined implements with wide points, as reflected in this field research when repeated tillage was done, will be due to the fact that it produced a larger proportion of small aggregates during the first pass than the tine implements with narrow points. It was observed that the proportion of

Table 15. Aggregate and pore size distribution in tilths produced by tillage with scarifier (Sc) and combine drill (D) after ploughing (MB or D) as expressed by the proportion larger than X mm.

X	Proportion (aggregates)			
	D+Sc	D+CD	MB+Sc	MB+CD
1	1.00	1.00	1.00	1.00
2	0.94	0.94	1.00	0.87
4	0.81	0.92	0.85	0.79
8	0.73	0.86	0.76	0.69
16	0.58	0.74	0.60	0.52
32	0.37	0.55	0.38	0.30
64	0.15	0.31	0.15	0.10
	Proportion (pores)			
1	0.84	0.92	0.91	0.93
2	0.61	0.87	0.80	0.49
4	0.31	0.55	0.57	0.37
8	0.06	0.11	0.35	0.22
16	0.002	0.005	0.14	0.08
32	0.00	0.00	0.02	0.01
64	0.00	0.00	0.00	0.00
Macroporosity	0.065	0.14	0.197	0.181
Mean pore size	3.8	5.3	8.4	6.0
Mean aggregate size	55.1	32.4	34.3	27.0

*Table 16*a. Aggregate and pore size distributions in tilths produced by tillage with different numbers of passes of tines with narrow points (T) as expressed by the proportion larger than X mm.

X	Proportion (aggregates)			Proportion (pores)		
	T	T+T	T+T+T	T	T+T	T+T+T
1	1.00	0.95	0.85	0.92	0.94	0.96
2	0.95	0.78	0.58	0.77	0.90	0.89
4	0.87	0.65	0.43	0.67	0.62	0.58
8	0.73	0.50	0.33	0.48	0.49	0.34
16	0.53	0.31	0.20	0.25	0.31	0.11
32	0.27	0.11	0.07	0.07	0.13	0.01
64	0.07	0.02	0.009	0.01	0.02	0.00
Mean pore size				11.8	14.6	8.1
Mean aggregate size	24.9	14.1	9.7			

Table 16b. Aggregate and pore size distributions in tilths produced by tillage with different numbers of passes of tines with wide points (Sc) as expressed by the proportion larger than X mm.

X	Proportion (aggregates)			Proportion (pores)		
	Sc	Sc+Sc	Sc+Sc+Sc	Sc	Sc+Sc	Sc+Sc+Sc
1	0.97	0.87	0.93	0.93	0.97	1.00
2	0.87	0.87	0.76	0.93	0.80	0.86
4	0.77	0.78	0.52	0.69	0.58	0.59
8	0.64	0.71	0.38	0.39	0.40	0.26
16	0.44	0.59	0.20	0.12	0.19	0.05
32	0.22	0.42	0.06	0.01	0.04	0.002
64	0.05	0.20	0.004	0.00	0.002	0.00
Mean pore size				8.0	9.9	6.8
Mean aggregate size	21.0	38.8	10.0			

Table 17. Aggregate and pore size distributions in tilths produced by tillage with different numbers of passes of tines with narrow points (T) after ploughing (D) as expressed by the proportion larger than X mm.

X	Proportion (aggregates)			Proportion (pores)		
	D+T	D+T+T	D+T+T+T	D+T	D+T+T	D+T+T+T
1	0.94	0.94	0.82	0.84	0.91	0.94
2	0.92	0.75	0.67	0.72	0.91	0.82
4	0.69	0.65	0.54	0.56	0.80	0.55
8	0.53	0.52	0.34	0.35	0.54	0.24
16	0.31	0.33	0.13	0.13	0.24	0.05
32	0.11	0.13	0.01	0.02	0.05	0.002
64	0.01	0.02	0.00	0.001	0.002	0.00
Macroporosity				0.36	0.44	0.44
Mean pore size				8.2	12.1	6.4
Mean aggregate size	14.4	15.1	8.0			

Table 18. Aggregate and pore size distributions in tilths produced by tillage with different numbers of passes of tines with wide points (Sc) after ploughing (D) as expressed by the proportion larger than X mm.

X	Proportion (aggregates)			Proportion (pores)		
	D+Sc	D+Sc+Sc	D+Sc+Sc+Sc	D+Sc	D+Sc+Sc	D+Sc+Sc+Sc
1	0.75	0.95	0.97	0.71	0.91	0.93
2	0.72	0.76	0.87	0.66	0.76	0.93
4	0.57	0.63	0.77	0.45	0.61	0.69
8	0.40	0.55	0.64	0.22	0.41	0.39
16	0.20	0.42	0.44	0.05	0.19	0.12
32	0.05	0.25	0.22	0.003	0.04	0.012
64	0.003	0.08	0.05	0.00	0.002	0.001
Macroporosity				0.36	0.30	0.30
Mean pore size				5.6	9.9	8.8
Mean aggregate size	9.8	22.6	20.9			

Table 19a. Entropies (H) of tilths produced by different tillage treatments (1977).

Treatment	H (replicates)		Mean
D	0.310	0.359	0.335
D+D	0.439	0.571	0.532
D+D+D	0.526	0.365	0.446
D+D+D+D	0.470	0.535	0.503
D+T	0.407	0.397	0.402
D+T+T	0.302	0.365	0.334
D+T+T+T	0.365	0.637	0.501
T	0.325	0.239	0.282
T+T	0.441	0.247	0.344
T+T+T	0.498	0.399	0.449
D+Sc	0.600	0.403	0.502
D+Sc+Sc	0.277	0.314	0.296
D+Sc+Sc+Sc	0.397	0.313	0.355
Sc	0.407	0.226	0.317
Sc+Sc	0.236	0.154	0.195
Sc+Sc+Sc	0.463	0.506	0.485

Table 19b. Entropies (H) of tilths produced by different tillage treatments (1976).

Treatment	H (replicates)		Mean
D	0.223	0.25	0.237
D+Sc	0.174	0.138	0.156
D+CD	0.190	0.29	0.24
MB	0.281	0.135	0.208
MB+Sc	0.218	0.262	0.24
MB+CD	0.314	0.165	0.24
Sc	0.264	0.277	0.271
RC	0.321	0.131	0.226

aggregates smaller than 8 mm in the tilth produced by the former was 0.36, while it was 0.27 in the tilth produced by the latter.

4.5 Statistical Analysis of Aggregate Fragmentation and Sorting

This chapter is mainly based on projects connected with two major processes occurring during tillage as they affect the ultimate structure of tilled soil.

To examine the significance of these factors, the proportion of clods, that is aggregates larger than 8 mm (A8), was regressed on the equivalent number of passes of a tined implement (NP) and the level (L) of structural measurement in tilled soil (from below). The first factor (NP) effects continuous aggregate fragmentation during repeated tillage, and the latter factor indicates stratification as a result of aggregate sorting. The primary data (Appendix I) collected from plots tilled with three, and four passes of a tined implement (with narrow points) at the Waite Institute were used. Tillage was done at two water contents.

The regression equations of A8 on L and NP for tillage at 12.6 and 25.2% water contents are given in Equations (48) and (49) respectively.

$$A8 = 0.072L - 0.076NP - 0.015 \quad (48)$$

$$A8 = 0.067L + 0.018NP + 0.042 \quad (49)$$

The above equations confirm the finding that the proportion of large aggregates and clods increases from the lower levels to the upper levels of tilled soils. For tilths produced at smaller water contents, equation (48) shows that the proportion of clods decreases with increasing number of passes of a tined implement with narrow points. Equation (49) shows that this does not appear to apply if tillage is done at water content significantly greater than the plastic limit. When water content is far greater than the plastic range (Baver, 1961), shearing by tillage decreases to practically zero and cohesion between soil particles is about maximum.

Table 20. Analysis of variance for the regression of the proportion of aggregates larger than 8 mm (A8) on the layer number in tilled soil and the number of implement passes.

Source of Variation	df	SSD	MSD	F	Test
Vsriation due to regression	2	0.035	0.018	0.04	NS
Residual	38	18.64	0.491		
Total	40				

Table 21. Analysis of variance for proportions of aggregate sizes (larger than X = 1, 2, 4, 8, 16, 32, 64 mm) after tillage with different number of passes of single and combined implements. Test for significant structural differences.

Source of Variation	df	SSD	MSD	F	Test (99%)
1,2,3,4 passes of disc plough	3	0.125	0.042	14	***
Residual "	9	0.033	0.003		
2,3,4 passes of disc plough	2	0.062	0.031	10.7	***
Residual "	10	0.029	0.003		
Ploughing, Ploughing + Harrowing	1	0.017	0.017	17.9	***
Residual "	6	0.006	0.001		
1,2,3 passes of tines after ploughing	2	0.007	0.0034	2.13	NS
Residual "	12	0.019	0.0016		
1,2,3 passes of tines	2	0.20	0.10	28.04	***
Residual "	12	0.043	0.0036		

While the information given by the above equations appears correct, the equations could not be used for predictive purposes because the regression is not significant (Table 20). This could be due to the fact that a number of soil factors such as water content and organic matter content need to be inserted into the equations. Calculated values of A8 are usually at least about 0.05 smaller than the actual values.

However, layering as a result of aggregate sorting, and clod breakdown with repeated tillage are important factors influencing the distribution of clods in tilled soil. For example, the correlation coefficient (r) between A8 and L although small (r = 0.32) is significant at the 95% level. And the correlation coefficient between A8 and NP (r = 0.20) is significant at the 75% level of test.

Analyses of variance of proportions of aggregate sizes (larger than X = 1, 2, 4, 8, 16, 32, 64 mm) as a result of tillage with single and multiple passes of implements (Table 21) confirm that tillage with sharp-pointed implements (except after one pass harrowing) tend to cause significant changes in the structure of tilled soil. This is essentially consistent with the initial hypothesis. The changes occurred mostly in the form of reduction in the proportion of aggregates larger than 8 mm and increased proportion of smaller aggregates as shown by the present findings. The statistical analyses indicate that further research of the type described in this Chapter would be worthwhile.

4.6 Summary

Primary data of aggregate and pore size distribution were collected from cut sections of impregnated tilth block samples collected from plots tilled with different number of passes of implements in two years. The structural data were collected within the top 5 cm of tilled soils. From the primary data, the proportions of different sizes of aggregate and pore, mean aggregate and pore sizes, and tilth structural variabilities were calculated. Tillage was done on a light-textured soil.

The findings are consistent with the initial hypothesis that repeated tillage will cause a progressive decrease in the proportion of large voids and aggregates and a corresponding increase in the proportions of small structural elements. This hypothesis applies to the use of disc plough (up to two passes) and a tined implement with narrow points (up to three passes).

Continual aggregate breakdown, and sorting of aggregates during tillage, and change in their relative importance with repeated tillage were shown to determine aggregate and pore size distributions that resulted from repeated tillage with different implements.

For the maximum production of small aggregates and pores, seedbeds could be prepared by two passes of a disc plough, or three passes of a tined implement, or tillage with one pass of a tined implement after ploughing. The above treatments produced comparatively small proportions of aggregates and voids larger than 8 mm.

4.7 Conclusions

Progressive decrease in the proportion of small aggregates, and increase in proportion of large aggregates and voids and macroporosity were observed from the lower levels to the upper levels of tilled soils. This was explained on the basis of sorting of the small aggregates to the bottom of the tilled layer during tillage. The above change in tilth structure from the lower to the upper levels featured more especially when tillage was done at low soil water content and with two or three passes of an implement.

The tilth produced by ploughing was more cloddy than that produced by tillage with rotary cultivator or scarifier. The scarifier produced the least cloddy tilth. The proportion of small aggregates and pores was least in the tilth produced by the mouldboard plough and was greatest in the tilth produced by the scarifier.

Maximum production of small aggregates by disc ploughing was attained after the second pass of the implement.

Tillage with a pass of a tined implement after ploughing caused increased proportions of small aggregates and pores and reduced mean aggregate size and macroporosity.

Tillage with a pass of wide tines alone or after ploughing produced a less cloddy tilth and greater proportion of aggregates and pores smaller than 8 mm than tillage with a pass of narrow tines.

Repeated tillage with tined implements up to three consecutive passes caused progressive increases in the proportions of small aggregates and pores and decreases in the proportions of aggregates larger than 8 mm.

CHAPTER 5

FACTORS DETERMINING TILTH STRUCTURE

This chapter describes research into factors determining tilth structure before it is produced by tillage and after its production. The research involved the use of a new sensitive technique for the measurement of the internal macro-structure of tilled soil in the field.

Two of the factors determining the structures of tilths produced by tillage are the previous cropping history of the soil and the soil water content at the time of tillage. These are described in section 5.1.

The major natural factor affecting tilth structure after its production by tillage is rainfall. Changes in the internal structure of tilled soil under rainfall were traced and are reported in section 5.2.

5.1 Soil Factors Affecting the Macro-structures Produced by Tillage

5.1.1 Introduction

For seedbeds, it is generally accepted that an aggregate size range of 1 to 5 mm is required (Russell, 1961). However, it is still not possible to predict what tillage operations are necessary to convert soil in a given condition into a seedbed. The soil structure produced by any given tillage implement depends on a number of factors including the water content of the soil and the history of cropping or other use of the soil.

Most of the work which has been done on the comparison of tillage operations has involved the sieving-out of the different aggregate size fractions produced. Sieving, although useful, tends to produce a rather arbitrary amount of breakdown especially on crumbly soils (Chapman, 1927) and in any case, gives no information about the void size distribution or about the relative dispositions of the aggregates and voids within the tilths.

There have been very few studies on the effects of soil cropping history on the tilths produced by tillage. Chapman (1927) compared the aggregation of a heavy clay which had been under two different crop rotations for 10 to 15 years. The rotations were corn - barley - clover - wheat (the 'clover plot') and corn - barley - timothy (or millet) - wheat (the 'timothy plot'). The difference between the two plots was so great that 53.7 percent of the timothy sample remained on a 44.5 mm sieve compared with 3.7 percent in the case of the clover sample. Only 10.8 percent of the soil from the timothy plot passed a 1.6 mm sieve compared with the 55.7 percent of the soil from the clover plot. It was observed that the aggregates from the timothy plot had sharp edges and tended to break in two directions or with a conchoidal fracture. The aggregates from the clover plot were rounded and irregular. The difference was attributed to greater organic matter content in the clover plot and three possible mechanisms for aggregate formation were hypothesized. In another experiment involving dry sieving, Siddoway (1963) found that the inclusion of grasses in rotation with winter wheat and fallow resulted in a smaller proportion of large clods than the wheat-fallow rotation alone.

The effects of water content at the time of tillage on the structures produced have been investigated by several workers. Russell (1938) cited early Russian work which showed that if the water content is too high tillage tends to produce large clods, and if it is too low the main effect of tillage may be that existing aggregates are broken-up by the implement and that little or no structure is built-up. Cole (1939) used the aggregate size distribution as the indicator of the degree of pulverization of Yolo loam (composition or physical properties were not specified) produced by tillage. He found that more small aggregates and fewer clods were produced when tillage was done between 17 and 20% water content than when the water content was greater than 20%. Lyles and Woodruff (1962) effected changes in soil water content by shading and irrigation and later tilled the soils differently. Their objective was to produce large clods for wind erosion control on a silty clay loam (properties unspecified). It was found that the largest clods were most frequent on the plots tilled at the lowest water content (8 percent) and the smallest clods were formed at intermediate water contents of around 19 percent. Bhushan and Ghildyal (1972) examined the mean weight diameters of aggregates produced by tilling a lateritic sandy loam with seven different implements. Tillage was done at water contents of 5.6, 7.2 and 9.2 percent and the Plastic Limit, PL, of the soil was 9.9 percent. These water contents therefore correspond to 0.60 PL, 0.77 PL, and 0.99 PL. They found that a more cloddy seedbed was more often produced by tillage at 0.60 PL and 0.99 PL than at 0.77 PL although there were differences between implements. With some implements, the cloddiness appeared to be still decreasing at water contents of 0.99 PL.

This project presents the results of a study of the effects of soil conditions on the structure produced by a tillage implement. Soil structure is quantified statistically by the method of Dexter (1976) and Dexter and Hewitt (1978). It is shown that both the previous use of the soil and the water content at the time of tillage significantly influence the resulting soil structure.

5.1.2 Hypotheses

1. Cropping history influences the structures of tilths through its effects on the density or planes of weakness in the soil. Therefore, an hypothesis is set that less small aggregates will be produced by tillage carried out on continuously cropped soil compared with soil that has been given a fallow break between crops, and on soil that is cropped compared with soil under pasture.

2. Soil strength increases with decreasing water content. Tillage at large soil water content especially if larger than Plastic Limit tends

to cause clod formation when tillage is being done because scouring of the implement by soil will be reduced and because the soil will deform plastically and will not fracture.

5.1.3 Materials and methods

5.1.3.1 Tillage treatments and sites

Tillage of permanent rotation plots and plots at different water contents was performed in 1976 and 1977 at the Waite Agricultural Research Institute using a set of tines with narrow points. The tines (each 65 mm in width) in four rows were spaced at 30 cm intervals in each row. The tines in the rows were staggered such that with one pass of the implement, tine centres had passed through the soil at 5 cm intervals. The soil on the site of tillage has 31% sand, 52% silt, and 17% clay. The Plastic Limit of the soil is 19.5%, and the Field Capacity (at 0.1 bar suction) is 18%.

Eight rotation plots were tilled in 1976 at a water content (mean for seven samples) of 20% ($\pm$ 1.2) and ten were tilled in 1977 at a water content of 13% ($\pm$ 0.9) dry weight basis. The rotations were wheat-fallow (WF), wheat - pasture - fallow (WPF), wheat - pasture - pasture - fallow (WPPF), wheat - pasture - pasture (WPP) and continuous wheat (CW). The CW, WF, and WPF rotations have continued in an unbroken sequence since 1925. The WPP and WPPF rotations have been in existence since 1952.

Rotation plots were also classified on the basis of the last annual crop or treatment on them. They fell into the plots coming out of fallow (COF), coming out of wheat (COW), and coming out of pasture (COP).

In 1976, there were 4 WF (prefix figure indicates the number of plots belonging to the rotation system), 1 WPF, 1 WPPF, 1 WPP, and 1 CW. Whereas in 1977 there were 4 WF, 2 WPF, 2 WPPF, 1 WPP, and 1 CW. In 1976, plots that fell into COF, COW and COP were 4, 3, and 1 in number respectively, while the equivalent figures for 1977 were 4, 3, and 3.

In 1977 soil was also tilled at different dates at water contents of 10.7 ($\pm$ 1.4), 12.6 ($\pm$1.9), 15.8 ($\pm$ 2.8), 17 ($\pm$ 0.9), 18.3 ($\pm$1.1), and 25.2 ($\pm$2.8)%. Twelve samples of each were dried at 105^{o}C for 24 hours for gravimetric water content determination.

Tillage was done to about 10 cm depth.

5.1.3.2 Sample collection and structural data

Tilth block samples were collected from tilled plots by the method of Dexter (1976) as described in Chapter 3. One tilth block sample was collected from each tilled rotation plot whereas two were collected from each of the plots tilled at different water contents. Each impregnated block was sectioned twice lengthways at about 10 cm from the longer sides in order to eliminate edge effects. Data strings of the distribution of aggregates and pores on each of two 320 mm long lines taken on each section around 4-5 cm depth of tilths were collected. Thus there were four sets of structural data from each tilth block sample. Each data string was analysed on the computer to calculate the probabilities, P(0), of 0's in given positions following the sixteen possible precursors or combinations of 0 (representing a 1 mm pore) and 1 (representing a 1 mm aggregate) in the four positions immediately to the left of the position in question. The occurrence probabilities (U_i) of the sixteen possible precursors were also calculated from the P(0) values (Dexter and Hewitt, 1978). Tilth entropy was calculated using the set of 16 P(0) values and the equivalent occurrences of precursors by the method of Dexter (1977) described in Chapter 3. Macroporosity which is the fraction of a data string made up of 0's was evaluated.

Calculation of the proportions of different sizes of aggregate and pore by the use of each set of sixteen P(0) and U_i values was performed by the method of Dexter and Hewitt (1978) as described in Chapter 3.

Table 22. Tilth structures produced on different rotation plots. Values of P(0) are the probabilities of 0 following the sixteen possible precursors (Means).

Precursors	P(O) for Rotation				
	WF	WPF	WPPF	WPP	CW
0000	0.837	0.844	0.875	0.824	0.762
0001	0.053	0.093	0.000	0.114	0.000
0010	1.000	0.786	*	1.000	1.000
0011	0.116	0.079	0.046	0.084	0.057
0100	0.729	1.000	*	1.000	0.000
0101	*	0.333	*	0.000	*
0110	0.781	0.900	1.000	0.750	1.000
0111	0.097	0.055	0.059	0.053	0.037
1000	0.751	0.850	0.817	0.747	0.838
1001	0.005	0.084	0.000	0.000	0.071
1010	1.000	1.000	*	0.000	*
1011	0.050	0.500	0.000	0.025	0.000
1100	0.785	0.896	0.904	0.824	0.902
1101	0.063	0.500	0.000	0.125	0.000
1110	0.892	0.968	0.962	0.849	0.866
1111	0.049	0.073	0.068	0.046	0.027

* Indicates that the precursor had no occurrences. Mean data for 1976 and 1977.

Table 23. Tilth structures produced at different water contents. Values of P(0) are the probabilities of an 0 following the sixteen possible precursors (Means).

Precursor	P(0) for Water Content (%)					
	10.7	12.6	15.8	17.0	18.3	25.2
0000	0.890	0.885	0.907	0.870	0.883	0.806
0001	0.037	0.019	0.088	0.063	0.024	0.110
0010	1.000	0.000	1.000	1.000	1.000	1.000
0011	0.096	0.141	0.180	0.269	0.070	0.134
0100	0.000	0.000	1.000	0.813	0.833	1.000
0101	*	1.000	*	*	*	*
0110	0.833	0.889	1.000	0.813	0.833	0.833
0111	0.067	0.156	0.184	0.253	0.193	0.168
1000	0.813	0.929	0.885	0.782	0.956	0.810
1001	0.000	0.000	0.133	0.111	0.250	0.167
1010	*	1.000	*	1.000	*	*
1011	0.000	0.500	0.167	0.500	0.000	0.500
1100	0.920	0.891	0.766	0.803	0.932	0.829
1101	0.000	0.000	0.000	0.125	0.000	0.000
1110	0.968	0.969	0.866	0.865	0.942	0.950
1111	0.057	0.095	0.075	0.100	0.093	0.079

* Indicates that the precursor had no occurrences.

From the above proportion, the proportions of structural elements larger or smaller than a particular size were derived. Mean aggregate or pore size was calculated from the primary structural data of the distribution of aggregates and pores.

The mean P(0) values for tilths of permanent rotation plots and tilths produced at different water contents are presented in Tables 22 and 23. Other mean structural data are presented in the text.

5.1.3.3 Organic matter content determination

The organic matter contents of the rotation plots were determined by using the weight loss after 20 g soil sample was warmed in concentrated hydrogen peroxide (Robinson, 1927), and treated with concentrated hydrochloric acid. Three determinations were made for each plot in 1977.

5.1.4 Results and discussion

Tilth structures produced as a result of different cropping treatments are first compared. Then tilth structures that resulted from different soil water contents are compared. Discussion is based on aggregate and pore size distributions, mean aggregate and pore sizes, and macroporosities.

5.1.4.1 Annual crop or treatment

The tilths produced as a result of tillage of plots that came out of pasture (COP), fallow (COF), and wheat (COW) were compared.

5.1.4.1.1. Aggregate and pore size distributions

Clods and voids larger than 16 mm were fewer in the tilths produced after pasture than in those produced after wheat or bare fallow (Table 24). Accordingly, the former had greater proportions of aggregates and pores smaller than 8 mm (Table 25). The tilth produced after fallow had a smaller proportion of clods and greater proportion of small aggregates than that produced after cereal cropping.

Table 24. Aggregate and pore size distribution in tilths of permanent rotation plots that came out of fallow (COF), pasture (COP) and wheat (COW) as expressed by the proportion larger than X mm.

Aggregate X	Proportion (1977) COP	Proportion (1977) COF	Proportion (1977) COW	Proportion (1976) COF	Proportion (1976) COW
1	0.96	0.98	0.95	0.89	0.98
2	0.96	0.90	0.87	0.77	0.90
4	0.88	0.81	0.78	0.65	0.79
8	0.69	0.68	0.66	0.48	0.68
16	0.42	0.48	0.47	0.25	0.50
32	0.16	0.24	0.24	0.07	0.27
64	0.02	0.06	0.06	0.006	0.08
1*	0.95	0.98	0.93	0.89	0.89
2*	0.89	0.91	0.88	0.71	0.63
4*	0.69	0.78	0.69	0.37	0.33
8*	0.42	0.52	0.45	0.17	0.07
16*	0.16	0.23	0.19	0.03	0.002
32*	0.02	0.04	0.034	0.00	0.00
64*	0.00	0.002	0.001	0.00	0.000
Mean aggregate size	24.7	32.0	32.2	17.3	36.2
Mean pore size	9.6	11.9	10.4	5.2	4.0
Macroporosity	0.345	0.345	0.316	0.301	0.139

* Pore size distribution.

Table 25. Proportions of small size aggregates and pores in tilths of permanent rotation plots that came out of fallow (COF), pasture (COP), and wheat (COW).

Year	Plot	Size (mm) 1	2	3	4	5	6	7	8	Total 1-5	Total 4-8
1977	COP	0.037	0.000	0.024	0.056	0.053	0.050	0.047	0.044	0.170	0.250
	COF	0.026	0.077	0.049	0.037	0.035	0.033	0.032	0.031	0.224	0.168
	COW	0.049	0.077	0.055	0.034	0.033	0.032	0.030	0.029	0.248	0.158
1976	COF	0.107	0.123	0.062	0.054	0.050	0.046	0.042	0.039	0.396	0.231
	COW	0.025	0.075	0.082	0.030	0.029	0.028	0.027	0.026	0.241	0.140
1977*	COP	0.048	0.060	0.114	0.090	0.080	0.071	0.062	0.055	0.392	0.358
	COF	0.019	0.071	0.046	0.083	0.075	0.068	0.061	0.055	0.294	0.342
	COW	0.073	0.050	0.107	0.079	0.071	0.063	0.057	0.051	0.380	0.321

* Pores.

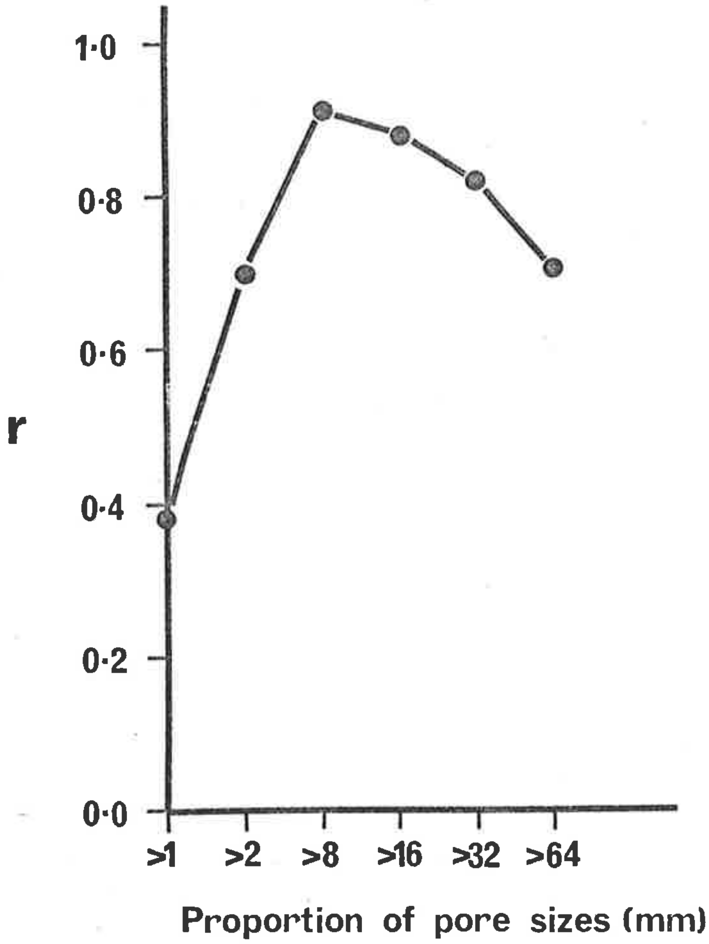


Fig. 18. Correlations between pore size distribution and tilth macroporosity (η_L) on differently tilled plots (Mortlock Station – 1976).

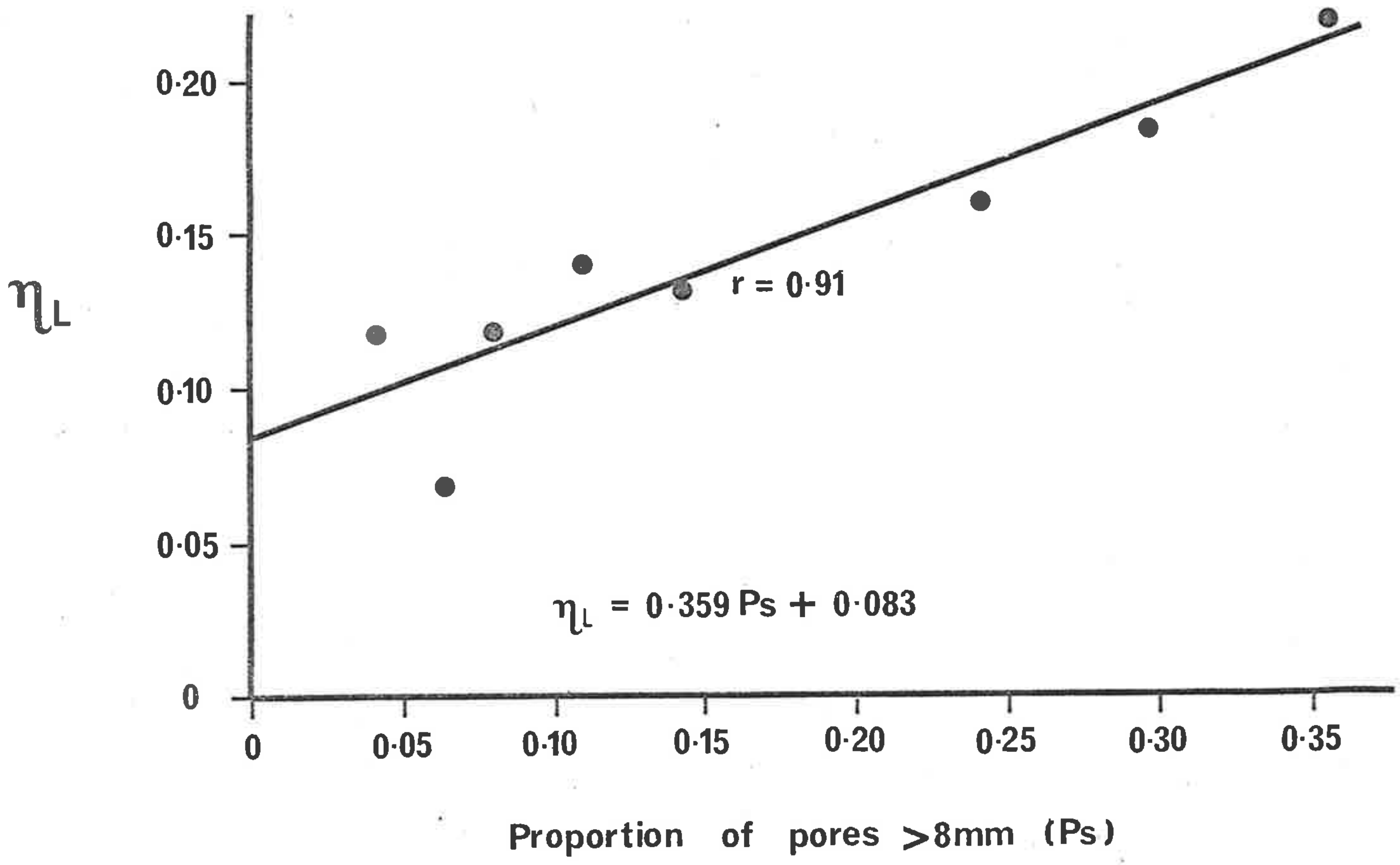


Fig. 19. The relationship between tilth macroporosity (η_L) and void size distribution on differently tilled plots (Mortlock Station — 1976).

The smallest degree of small aggregates after tillage occurred on the plot that had been under wheat.

5.1.4.1.2 Macroporosity

The greater proportion of medium-size pores in the tilth produced by tillage of the plot that was under fallow and the associated smaller proportion of aggregates larger than 8 mm resulted in its larger macroporosity compared with the tilth of the plot that came out of wheat. There was no considerable difference between the tilth of the former and that of the plot that came out of pasture.

The medium-size pores which have diameters between 9-16 mm mostly determine tilth macroporosity compared with smaller or larger pore size ranges. This is shown by Figure 18. A correlation coefficient of 0.91 was recorded between macroporosity (η_L) and the proportion of pores between 9 and 16 mm in diameter (Figure 19). The data involved in Figures 18 and 19 are those collected in 1976 from eight differently tilled plots situated at the Mortlock Experiment Station (see Chapter 4). In most soils, there is a wide distribution of particle diameters present, and this distribution influences porosity.

5.1.4.1.3 Mean aggregate or pore size

The tilth produced by tillage on the plot that came out of pasture, as a result of its smallest proportion of large aggregates, had the smallest mean aggregate or pore size compared with the tilths produced on plots that came out of wheat and fallow.

5.1.4.1.4 Entropy

The greatest proportion of small structural elements in the tilth produced on the plot that came out of pasture compared with the tilths produced on the plots that came out of fallow or wheat led to its larger structural entropy than the others. The mean entropies for COP, COF, and

COW were 0.33 (±0.002), 0.29 (±0.027) and 0.29 (±0.007) respectively.

The breaking-up of the plots that were under pasture in the previous year into more small aggregates and pores under tillage compared with the plots that were not under pasture will be due to the ramification of the soil bulk by the fine roots of the pasture ryegrass (Greenland, 1971). For example greater mean organic matter content (as index of root concentration) was recorded for the rotation plots on which pasture was grown (WPP) compared with those on which pasture was not grown (4.3% > 2.9%). Greacen (1958) indicated that during crop production there will be decline in the supply of organic matter because the dense grass root system intensively associated with the soil will be replaced by more sparsely rooted crop system. The ramification of the soil by fine roots of ryegrass and the attendant dehydration, fractures, and dead roots would make the soil more easily broken-up by tillage into more small aggregates compared with soils under cereal crop or fallow. The present result is in agreement with the results of Chapman (1927) for the effects of organic matter on tilth.

A number of factors that could account for the larger proportion of small aggregates produced as a result of tillage of the plot that came out of fallow compared with the plot that came out of cereal cropping are briefly examined.

(a) The higher frequency of tillage of plots under fallow. The fallow period in South Australia is a long fallow. It extends for about 17 months from one harvest in, say, November, through the next year and up until the sowing of the next crop in, say, May of the following year (Webber *et al.*, 1976). Fallow is practised especially where there is a clay subsoil, and where the average rainfall is less than 450 mm per year. During the fallow period, mulching by repeated tillage with tined implements is practised for soil water conservation. Another benefit of fallowing is the improvement of soil nitrogen status through mineralization of organic matter.

The fallow plots sampled on 20th May, 1976 had been chisel ploughed on 6th October, 1975 and tine cultivated on 17th October, 1975. The fallow plots sampled on 28th March, 1977 had been tine cultivated on 27th May, 1976. This represents a minimal fallow mulching. Sometimes as many as eight tillage treatments are used. A higher frequency of tillage will lead to increased decomposition of accumulated organic matter (Rovira and Greacen, 1957) and weakening of the framework of the soil structure.

(b) Smaller water content of the fallow plot. It was derived from the primary data (Appendix IV) of cropped and bare tilled plots that the water content (within 10 cm depth) of the former was averagely 2% larger than that of the latter, while its temperature was averagely 3°C higher (Appendix III). However, the differences in water content between bare and cropped tilths were not statistically significant. Before tillage, the water contents (within 5 cm depth) of plots belonging to COF, COP, and COW were 12.9 ($\pm$ 1.3), 13.3 ($\pm$ 0.9), and 13.3 ($\pm$ 1.2)% (dry weight basis, means for 12 soil samples) respectively.

It is shown in Table 26 that if the tilth structures produced above 15% soil water contents are compared, the drier soils tend to produce tilths with more aggregates smaller than 5 mm.

5.1.4.2 Fallowing and continuous cropping

The tilths of rotation plots given a fallow break between crops (including pasture) such as WF and WPF were compared with those of plots continuously under crop or pasture (WPP, CW). The mean structural data of the two sets of tilled plots are now compared.

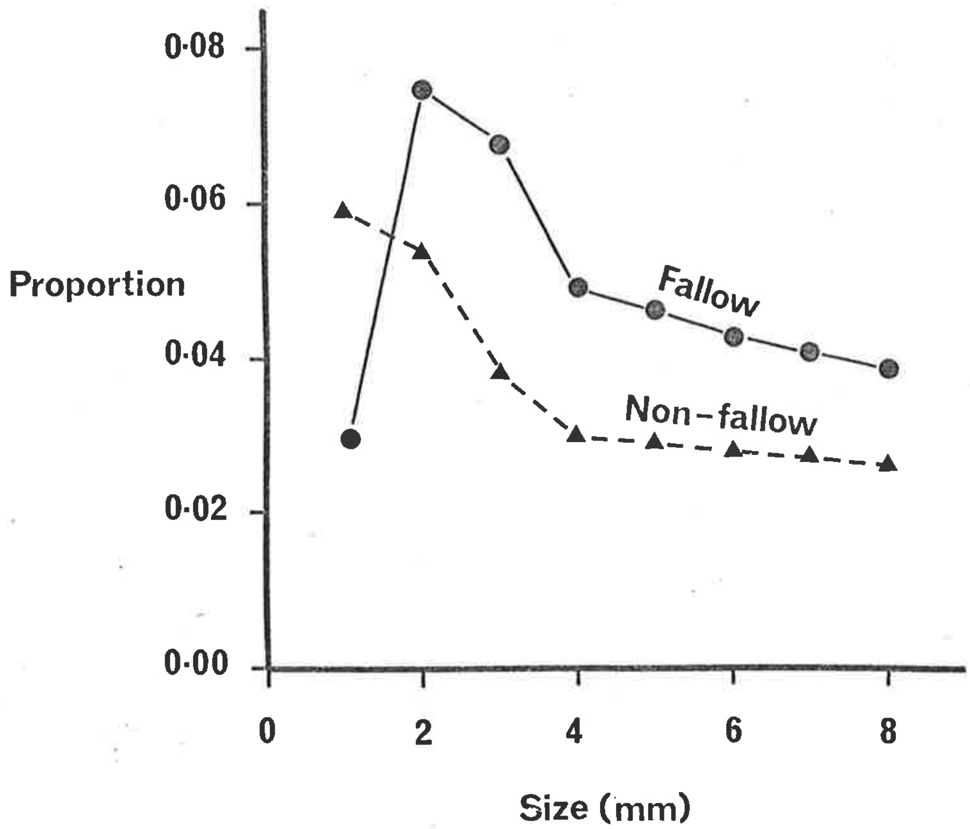


Fig. 20. Mean proportions of small size aggregates in tilths of plots continuously cropped (non-fallow) and of those plots given a year fallow in rotation.

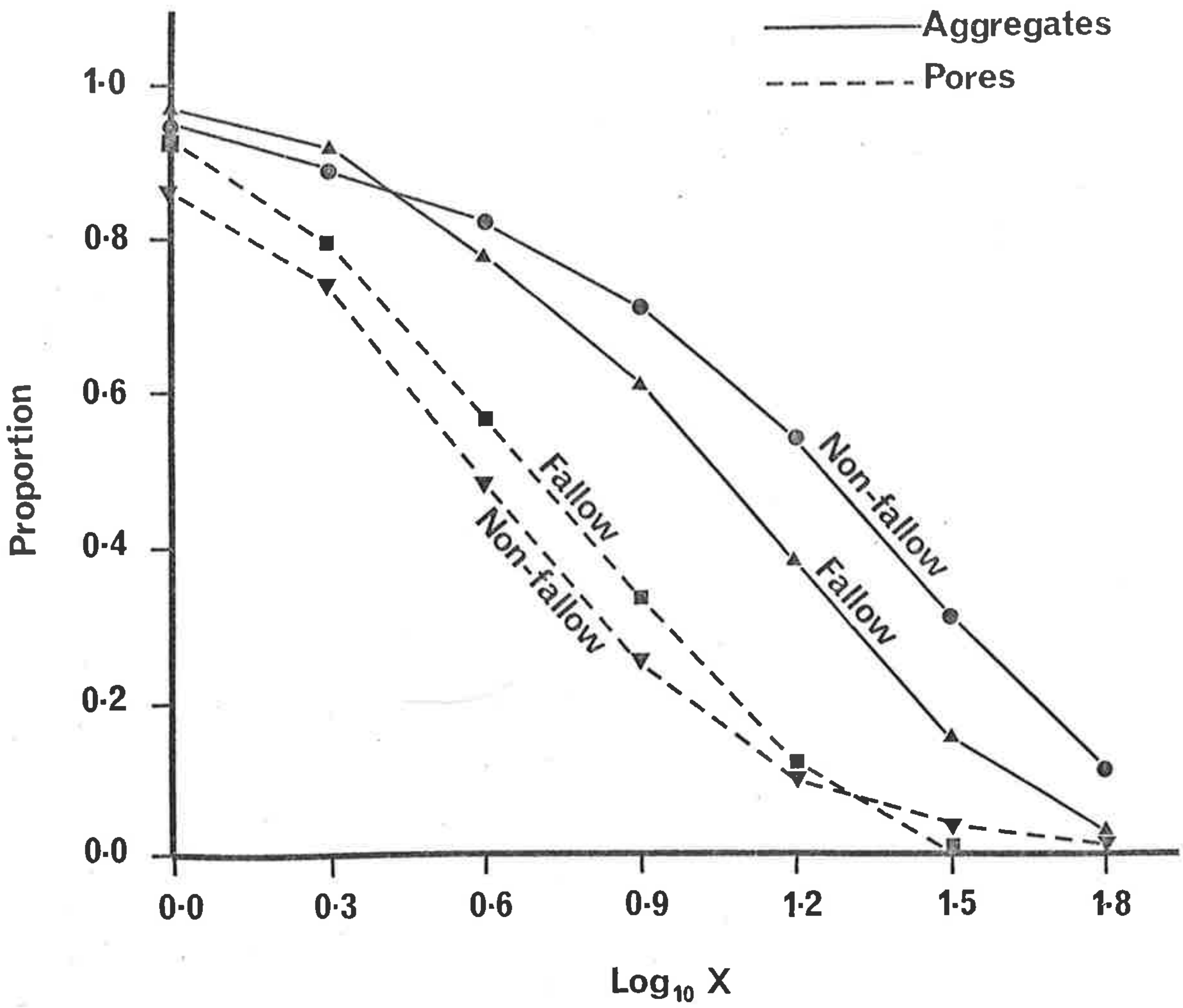


Fig. 21. Mean proportions of aggregates and pores larger than Xmm in tilths of plots continuously cropped (non-fallow) and those of plots given a year fallow in rotation.

5.1.4.2.1 Aggregate and pore size distributions

It is shown (Figure 20) that the plots that were given a fallow break broke into more small aggregates when tilled than those continuously cropped. As a result the proportion of clods (including those larger than 64 mm) and large pores were larger for the latter (Figure 21).

5.1.4.2.2 Macroporosity

Because there were less clods in the tilth produced on the rotation plot given 1 fallow break compared with that of the plot continuously cropped, the former had a greater proportion of medium-size (9-16 mm) pores which determine tilth macroporosity and therefore had the greater mean macroporosity (0.309 > 0.203).

5.1.4.2.3 Entropy

The smaller proportion of small structural elements in tilth produced on continuously cropped land compared with the one produced on fallowed land led to a greater structural entropy or variability being recorded for the latter (0.369) than for the former (0.250).

The reasons why a higher frequency of tillage and smaller water content cause the breaking of fallowed land when tilled into more small aggregates than cropped land was discussed in section 5.1.4.1. The discussion is applicable in the explanation of the greater proportion of small structural elements in the tilth of rotation plot given fallow treatment than in that of the rotation plot not given fallow treatment.

It is also shown in section 5.1.4.4 that tillage at a small water content about the Plastic Limit caused the production of the tilth with the most small aggregates.

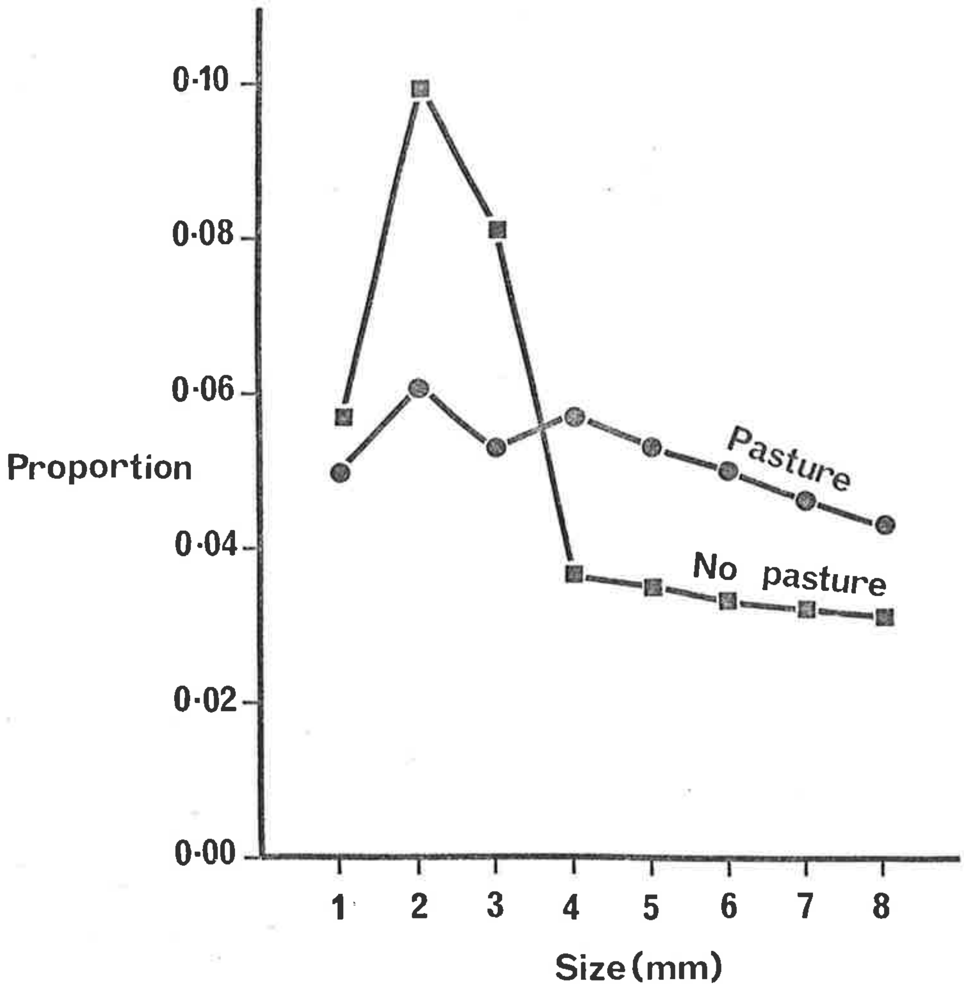


Fig. 22. Mean proportions of small size aggregates in tilths of rotation plots that were under pasture and not under pasture.

5.1.4.3 The inclusion of pasture in rotation

To investigate the effects of the inclusion of pasture in rotation, the tilth structural data of the rotation plots that were never sown to pasture (WF) were compared with those of the two sets of rotation plots that were sown to pasture for a year or two consecutive years (WPF and WPPF).

The role of organic matter is not considered because the mean organic matter contents of the plots being considered were not significantly different. For rotation plots WF, WPF, and WPPF, the mean organic matter contents were 3.5 ($\pm$ 0.7), 3.2 ($\pm$ 0.08) and 3.4 ($\pm$ 0.7)% respectively. The uniform organic matter contents will be due to the effect of the bare fallow included in each rotation. Bare fallowing of land, and especially if the land is mulched by tillage will lead to significant loss of organic matter, and the first order rate equation (Greenland , 1971) will be applicable. This equation shows that the plots with more organic matter lose more, and this tends to eliminate differences.

5.1.4.3.1 Aggregate and pore size distributions

The inclusion of pasture ryegrass in rotation caused increased proportion of small aggregates (Figure 22) and reduced the proportion of aggregates larger than 16 mm (Table 26), when tillage was performed. As a result of greater proportion of small to medium-size aggregates in the tilth of the plots sown to pasture compared with those of the plots not sown to pasture, the former had greater proportion of small to medium-size voids while the latter had more large voids.

However, it is shown that the tilths of the rotation plots not sown to pasture had greater proportions of aggregates smaller than 4 mm than the tilths of the plots sown to pasture. This indicates that the roots of the pasture ryegrass increased soil aggregation.

Table 26. Aggregate and pore size distributions in tilths on rotation plots expressed by the proportion larger than X mm (Means).

Aggregate Size X	Proportion for Rotation WF	WPF	WPPF	WPP	CW
1	0.94	0.90	1.00	0.89	0.99
2	0.84	0.83	0.96	0.83	0.95
4	0.72	0.73	0.84	0.75	0.89
8	0.59	0.55	0.64	0.64	0.80
16	0.39	0.33	0.37	0.43	0.64
32	0.18	0.12	0.12	0.21	0.41
64	0.04	0.02	0.02	0.05	0.17
1*	0.88	0.94	0.96	0.84	0.88
2*	0.71	0.85	0.87	0.71	0.77
4*	0.49	0.61	0.63	0.46	0.50
8*	0.28	0.32	0.38	0.24	0.26
16*	0.10	0.10	0.05	0.07	0.14
32*	0.02	0.01	0.02	0.01	0.05
64*	0.00	0.00	0.00	0.00	0.01
Mean aggregate size	18.3	15.3	16.6	20.5	37.1
Mean pore size	7.2	8.0	9.1	6.4	8.6
Macroporosity	0.27	0.36	0.35	0.23	0.18

* Pore size distribution.

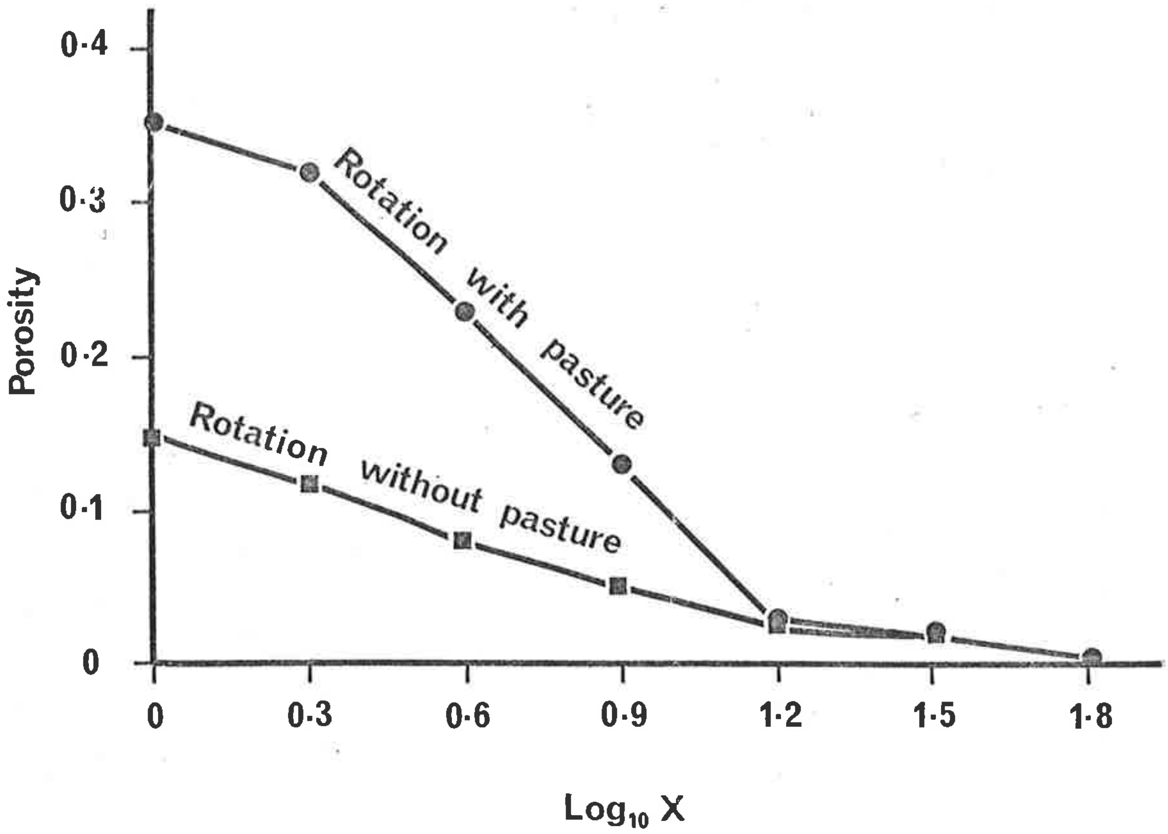


Fig. 23. Porosities in pore sizes larger than Xmm in tilths of rotation plots that were under pasture and not under pasture.

5.1.4.3.2 Mean aggregate or pore size

The presence of more small to medium-size aggregates and pores in the tilths of the rotation plots under pasture than in those of the plots not under pasture led to smaller mean aggregate or pore size of the former than that of the latter which had more of large clods and voids. This is also shown if the two sets of tilths belonging to continuously cropped plots (CW, WPP) are considered.

5.1.4.3.3 Macroporosity

The greater proportion of medium-size (9-16 mm) voids in the tilths produced on rotation plots sown to pasture compared with those not sown to pasture led to a greater macroporosity in the former than in the latter. Figure 23 shows that the macroporosities in these voids were greater in the tilths produced on the plots sown to pasture than in the tilths produced by tillage on those plots not sown to pasture. It was shown earlier (5.1.4.1) that the medium-size voids determine tilth macroporosity.

Even under continuous cropping the effect of the inclusion of pasture in rotation which led to increased proportion of small aggregates and voids was manifested. If plots WPP and CW are compared, the tilth of the former had more of small aggregates than that of the latter (Table 26). As a result the tilth of rotation CW had more of clods, larger voids, and smaller macroporosity because it did not have considerably greater proportion of medium-size pores.

5.1.4.4 Soil water content and tilth structure

To examine how tillage at different soil water content determines tilth structure, the tilth structures of the tilths produced at different water contents were compared.

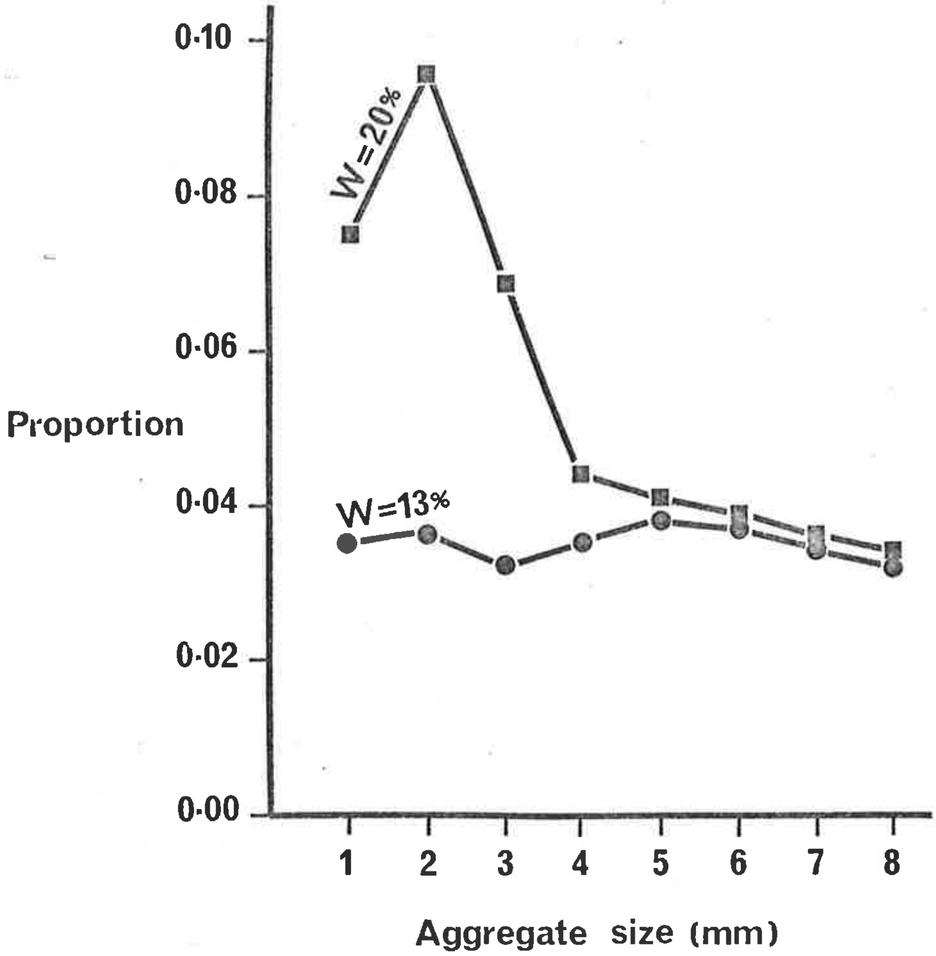


Fig. 24. Proportions of small size aggregates in tilths produced at different soil water contents (W%).

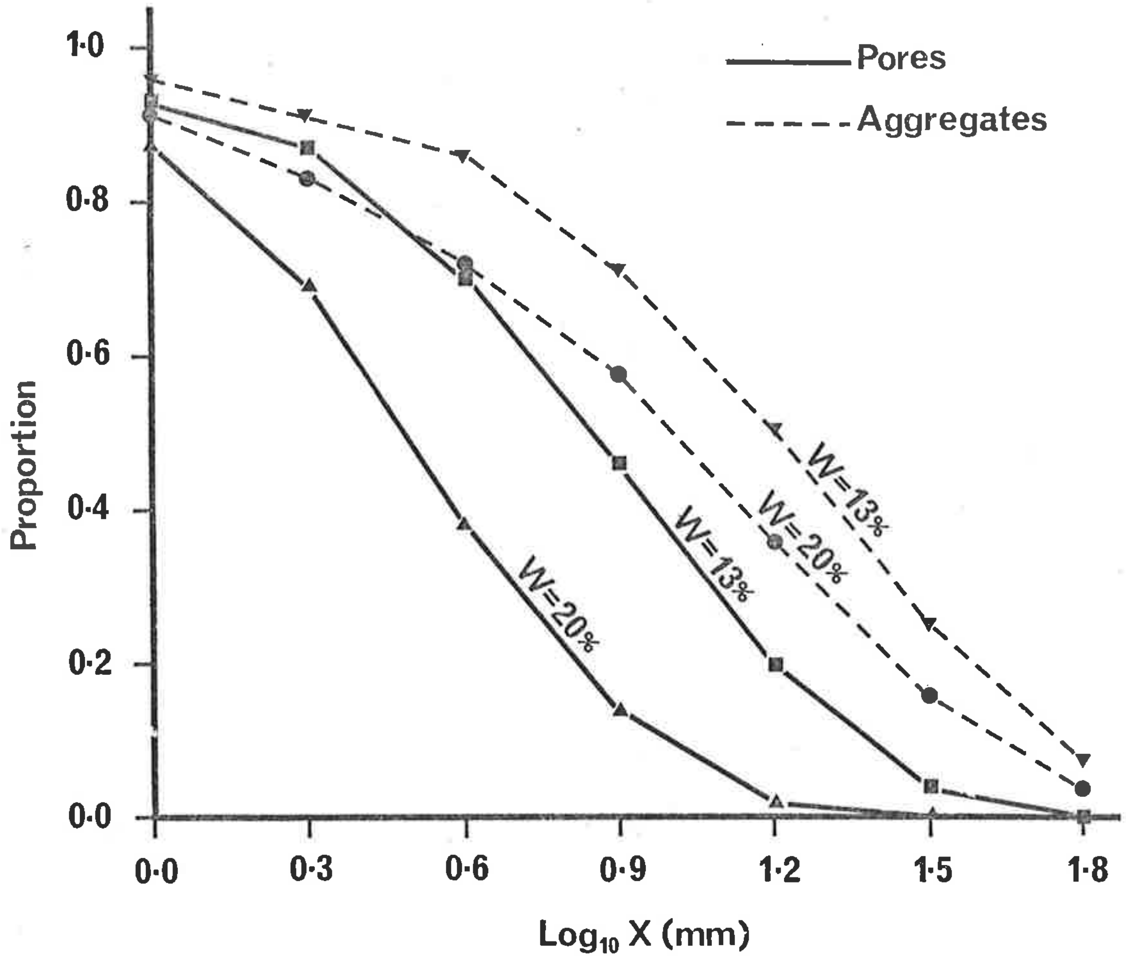


Fig. 25. Proportions of pores and aggregates larger than Xmm in tilths produced by tillage at soil water contents (W) of 13 and 20%.

5.1.4.4.1 Aggregate size distribution

Tillage at water content of 17% which is slightly below the Plastic Limit or Field Capacity produced the smallest proportion of large aggregates and the largest proportion of small aggregates including those smaller than 6 mm compared with tillage at smaller or larger water contents (Table 27). It is shown that there was a progressive decrease in the propostion of larger aggregate sizes as soil water content for tillage increased from 11 to 17% and afterwards the proportions rise. The greatest proportion of clods was due to tillage at the smallest water content. This confirms the finding of Lyles and Woodruff (1962) that more clods were produced when tillage was done at the smallest water contents around 8% than at larger water contents.

In Figure 24 the mean proportions of small size aggregates in tilths of permanent rotation plots tilled in 1976 at 20% water content and in 1977 at 13% water content are compared. It could be seen that small aggregates were more frequent in the former than in the latter thus supporting the suggestion that more small aggregates and fewer clods (Figure 25) are produced when tillage is done at about the Plastic Limit than at a smaller water content.

5.1.4.4.2 Pore size distribution

The trend in the proportions of large void sizes as a result of tillage at different soil water contents follow the trend in the proportions of large aggregates. This observation further confirms the finding under the discussion of the aggregate size distributions. There was a progressive decrease in the proportion of large voids up to those larger than 64 mm with increasing soil water content at tillage up to 17% and afterwards the proportion increased (Table 27). This could be extended to the explanation of how larger voids were more frequent in the tilth produced by tillage of rotation plots at 13% (in 1977) compared with

Table 27. Aggregate and pore size distributions in tilths produced at different water contents (%) as expressed by the proportion larger than X mm.

X	Proportion 10.7%	12.6%	15.8%	17%	18.3%	25.2%
1	0.97	0.98	0.92	0.91	0.96	0.89
2	0.88	0.82	0.75	0.67	0.90	0.75
4	0.78	0.63	0.57	0.46	0.66	0.58
8	0.61	0.44	0.42	0.30	0.45	0.41
16	0.39	0.22	0.22	0.13	0.21	0.21
32	0.15	0.063	0.06	0.025	0.04	0.07
64	0.02	0.006	0.005	0.001	0.002	0.01
1*	0.95	0.94	0.90	0.87	0.94	0.93
2*	0.86	0.83	0.71	0.67	0.87	0.79
4*	0.63	0.68	0.57	0.46	0.73	0.52
8*	0.45	0.42	0.38	0.26	0.44	0.25
16*	0.23	0.16	0.18	0.10	0.16	0.08
32*	0.06	0.025	0.04	0.023	0.022	0.012
64*	0.004	0.002	0.001	0.001	0.001	0.001
Mean aggregate size	17.1	11.2	10.9	7.7	10.7	10.9
Mean pore size	11.2	9.6	9.3	7.0	9.9	7.0
Macroporosity	0.40	0.47	0.462	0.47	0.48	0.39

* Pore size distribution.

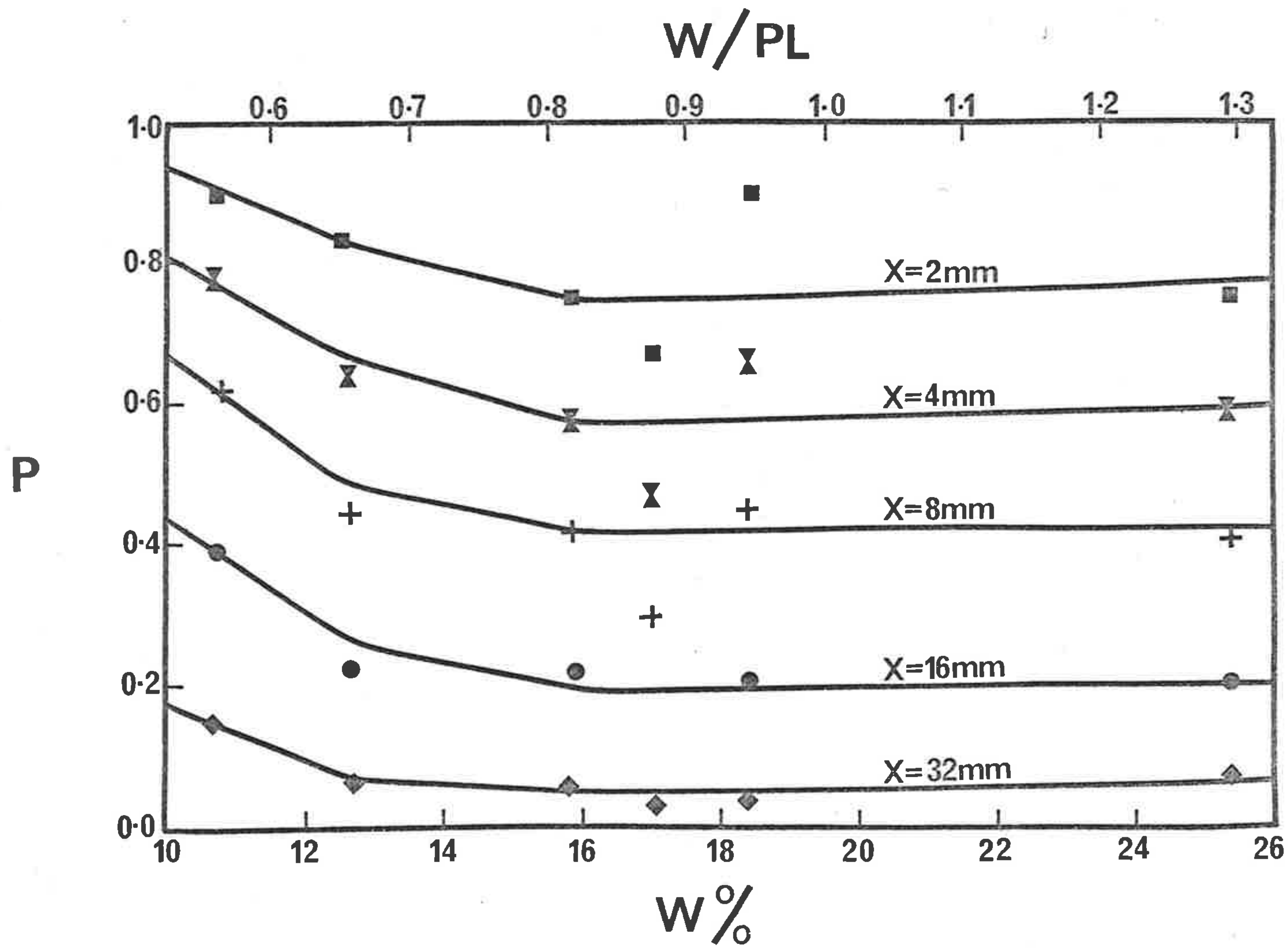


Fig. 26. Proportions (P) of aggregates larger than Xmm in tilths produced at different soil water contents.

tillage at 20% (in 1976) as shown in Figure 25.

5.1.4.4.3 Mean aggregate or pore size

That the largest proportions of clods in tilths occurred as a result of tillage at the smallest water content rather than at slightly below the Plastic Limit. This is further confirmed by the fact that there was progressive decrease in mean aggregate or mean void size as water content increased from 10.7 to 17% and afterwards these values rose.

5.1.4.4.4 Entropy

Because of the largest proportion of small aggregates and pores in the tilth produced when tillage was done at slightly below the Plastic Limit or Field Capacity, the tilth produced had the largest entropy (structural variability) compared with the tilths produced at larger or smaller water contents. There was progressive increase in tilth structural entropy from 11 to 17% water content, and after 17% entropy decreased. For tilths produced at 10.7, 12.6, 15.8, 17, 18.3 and 25.2% water contents, the mean entropies were 0.33, 0.43, 0.42, 0.52, 0.41 and o.45 respectively. The frequency of small structural elements dictates tilth structural entropy.

5.1.4.4.5 Quadratic equations

Figure 26 shows curves for the proportions of the aggregates having sizes larger than given values produced by tillage at different soil water contents with reference to the Plastic Limit (or lower Atterberg Limit), PL. The reference to the Plastic Limit will enable results to be comparable with those for other soils of different composition. the Plastic Limit is thought to be the appropriate 'fixed point' because it is the water content where soil has certain mechanical properties and also because it falls within the range of water contents of interest.

It can be seen that there is a minimum (of aggregates larger than X mm) somewhere in the region of 0.9 PL. These results were fitted (Ojeniyi and Dexter, 1978) to the quadratic equation

$$P_i = a + b\left(\frac{W}{PL}\right) + c\left(\frac{W}{PL}\right)^2 \qquad (50)$$

where P_i is the proportion of the aggregates having sizes larger than i mm, W is the gravimetric water content, and a, b, and c are adjustable parameters. This was the equation used by Lyles and Woodruff (1962). The results are

$$P_1 = 1.07 - 0.19\left(\frac{W}{PL}\right) + 0.041\left(\frac{W}{PL}\right)^2 \qquad (51)$$

$$P_2 = 1.12 - 0.73\left(\frac{W}{PL}\right) + 0.33\left(\frac{W}{PL}\right)^2 \qquad (52)$$

$$P_4 = 1.51 - 1.89\left(\frac{W}{PL}\right) + 0.91\left(\frac{W}{PL}\right)^2 \qquad (53)$$

$$P_8 = 1.35 - 1.94\left(\frac{W}{PL}\right) + 0.94\left(\frac{W}{PL}\right)^2 \qquad (54)$$

$$P_{16} = 1.08 - 1.81\left(\frac{W}{PL}\right) + 0.89\left(\frac{W}{PL}\right)^2 \qquad (55)$$

$$P_{32} = 0.56 - 1.06\left(\frac{W}{PL}\right) + 0.53\left(\frac{W}{PL}\right)^2 \qquad (56)$$

For the production of a seedbed one wants to produce aggregates in the range 1-5 mm (Russell, 1961; 1973). One therefore wants to till the soil to minimize the proportion of aggregates larger than, say, 4 mm.

The water content at which to do this tillage can be found by differentiating P4 with respect to the water content as shown in Equation 57.

$$\frac{dP4}{d\left(\frac{W}{PL}\right)} = -1.89 + 1.82\left(\frac{W}{PL}\right) = 0 \qquad (57)$$

This yields an optimum water content for the tillage of

$$W = 1.04\ PL \qquad (58)$$

Equation 50 can also be applied to the void size distributions in Table 27. However, the resulting parameters do not follow steady trends and tend to vary erratically. However, the mean values of b and c are

$$\overline{b} = -0.43, \quad \overline{c} = 0.18 \qquad (59)$$

In order to conserve soil water, one wants to till the soil to minimize the proportion of voids larger than about 8 mm. It has been found that it is in voids larger than this that convective flows of air resulting from atmospheric turbulence can occur (Holmes *et al.*, 1960; also Chapter 6). This can result in accelerated soil drying (Chapter 7). A rough estimate of the water content for tillage to achieve this can be obtained by putting the values in Equation 59 into Equation 57. This produces the estimate

$$W = 1.19 \text{ PL} \qquad (60)$$

All the above is based on the assumption that the quadratic of Equation 50 is an accurate fit to the data. It is impossible to test this accurately when three parameters are being fitted to only six somewhat scattered points.

From the data actually obtained the largest proportion of small aggregates and the smallest proportion of large voids both occurred at

$$W = 0.87\text{PL} \qquad (61)$$

None of these conclusions can be considered to be inconsistent with the results of Bhushan and Ghildyal (1972) who, performing different measurements, found maximum soil fragmentation between 0.77 PL and 0.99 PL on a quite different soil type.

5.1.5 Summary and implications of findings

A new method of quantifying the internal macro-structure of tilled soil has enabled the tilth structures that were produced on soils under different cropping systems and at different water contents to be examined in the field.

The use of fallow in rotation, the inclusion of pasture in rotation, and tillage at a water content slightly below the Plastic Limit (0.87 Plastic Limit) or Field Capacity (0.94 Field Capacity) caused an increased proportion of small aggregates and pores when tillage was done. Figure 26 shows curves for the proportions of the aggregates having sizes larger than given values. It can be seen that there is a minimum somewhere in the region of 0.9 Plastic Limit (PL).

Since aggregates smaller than 6 mm provide the optimum environment for seed germination and retain more water (Johnson and Buchele, 1961; Greenland, 1971) and because large voids are more responsible for evaporation from tilled soil (Holmes *et al.*, 1960; also Chapter 7), it is advocated that seedbed preparation should be performed on land having the above treatments or conditions as much as possible. This recommendation could assist in efforts to minimize the frequency of tillage and number of passes of implements.

The logic expressed in each of the initial hypotheses is largely consistent with these findings. The findings concerning water content for tillage could not be said to deviate significantly from those of Cole (1939), Lyles and Woodruff (1962), and Bhusan and Ghildyal (1972) earlier referred to. However, the expression of the results empirically (equations 51 to 56) in terms of normalized water contents (W/PL) makes these results more generally applicable.

5.2 Rainfall and Tilth Macro-structure

5.2.1 Introduction

Climate affects soil structure mainly through wetting (as a result of rainfall) and drying of soil aggregates. The drying process and its effect certainly depend on rainfall and wetting. Since the drying period follows rainfall and *vice versa*, the effect of climate on soil structure could be assessed solely on the basis of the effect of rainfall.

There has been very little research on the effects of rainfall on the internal structure of tilled soil. This is because of lack of a composite technique of measuring the internal structure of tilled soil in the field. Low (1972) attempted to study seasonal changes in the structure of tilled soils and soils permanently under grass using changes in their physical properties such as water stability, percentage of pore space, and the distribution of biopores. He concluded that no one measurement adequately described the extent of loss of structure of tilled grassland soils, and that the measurement of water stability of aggregates under-rated the differences between soils.

However, Dexter (1976) introducing a new technique of measuring tilth structure *in situ*, briefly compared probability distributions of structural elements at different levels within tilled soils and at different dates. He adduced a decrease in the probability of detecting 1 mm aggregates at all levels over a period to their coalescence with larger aggregates during rain.

Rainfall can affect the internal structure of tilled soil in the following ways. Firstly, by the detachment of small aggregates and fine particles from the surface clods of 'open' freshly tilled soil. Singh and Pollard (1956) set up a tillage experiment which involved deep ploughing to 20 cm depth, shallow ploughing to 10 cm depth, and tine tillage to 5 cm depth. They measured seasonal variations in wet sieving aggregate size distributions at different depths of the tilled soils to 12 cm. increased proportion of smaller aggregates between 0 to 5 cm depth was attributed to rainfall disruption of aggregates larger than 4 mm.

Secondly, increased soil water content as a result of rainfall, and rapid water infiltration could cause disruption of small aggregates and their subsequent coalescence with larger aggregates and clods. Singh and Pollard (1956) experienced aggregation at depths within moist tilled soils. The physical conditions of the A horizon of soils were examined by Pizer (1962). He observed that seedbeds which had become rather dry slaked readily when heavy rain fell on them. The depth of slaking depended on the openness of tilth, the water holding capacity of the soil and the amount of rain that fell. Loamy sand soils were found slaked to a depth of 25 cm.

The washing-in of fine soil particles by percolating rain water (Schefer, 1948; Dexter, 1976) has been indicated (Singh and Pollard, 1956) to be an insignificant process in the field. Singh and Pollard carried out the balancing of the losses of aggregates and gains of particles smaller than 0.05 mm for depths of tilled soils. They concluded that fine material did not leach from the upper to the lower depths.

The aims of the present project are (a) to use a new technique that measures the internal structure of tilled soil *in situ* to trace changes in aggregate size distributions of tilled soils in a cropping season, and (b) to examine the manifestation of the changes in aggregate size distributions on void size distributions and other statistical parameters.

The knowledge of the effect of seasonal rainfall in relation to the distribution of small structural elements and the method of reducing the effect will help in efforts to reduce frequency of tillage.

5.2.2 Hypothesis

Processes accompanying rainfall such as soil detachment at the surface of tilths and aggregate wetting, disruptions, and coalescence with larger units will cause changes in the frequency of small aggregates and pores within tilled soil. The last complex process will cause ultimate reduction in the proportion of small structural elements at the end of the cropping season compared with its beginning.

5.2.3 Materials and Methods

5.2.3.1 Tillage treatments

Eight tillage treatments were performed on a Red Brown Earth (Stace *et al.*, 1968) having 60% sand, 23% silt, and 17% clay at the Mortlock Experiment Station of the Waite Agricultural Research Institute (33^{o} 55'S, 138^{o} 43'E, altitude 430 mm). The tillage treatments performed on 6th July, 1976 included tillage with the mouldboard plough (MB), disc plough (D), mouldboard plough + scarifier (MB+Sc), mouldboard plough + combine drill (MC+CD), disc plough + scarifier (D+Sc), disc plough + combine drill (MB+CD) scarifier (Sc), and rotary cultivator (RC). There were other two plots treated with MB+CD and D+CD and sown with barley (BL) which produced a foliage cover within two months.

Tilth block samples were collected from the eight bare plots by the method of Dexter (1976) already described in Chapter 3. Subsequently samples from the entire ten plots were collected on 11th October, 1976 (Spring), and 10th January, 1977 (Summer) respectively.

5.2.3.2 Structural data

The primary structural data from tilth block samples collected in August and January are presented in Appendix II, while those of tilth block samples collected in July are in Appendix 1. The different placement of the primary data was due to the different use made of them.

The data in the appendices consist of probabilities P(0) for sixteen possible four element precursors and their equivalent occurrence probabilities (Ui). The probabilities were calculated by computer from the raw structural data of the linear distribution of aggregate (represented by element 1) and pores (represented by element 0) on two sections cut through each tilth block sample. Two lines were taken across each section at about 4-5 cm depth and two sets of structural data were collected from each section. From the probabilities, the proportions of different sizes of aggregate and pore were calculated by the method of Dexter and Hewitt (1978) described in Chapter 3. Calculation of the statistical values of mean aggregate or pore size was performed using raw structural data, tilth entropy was calculated from P(0) values (Dexter, 1977) and occurrences of precursors, and macroporosity was also calculated. The primary data of aggregate and pore size distributions, macroporosities, and entropies are also placed in Appendices I and II.

The derived mean structural data covering tilled bare plots and for the sampling periods are presented in Tables and Figures in the text. For the interval of Spring to Summer (October to January) when the crops were less actively growing, the role of foliage cover in preventing the direct effect of rainfall on the internal tilth structure was investigated. The summer mean structural data of cropped tilled plots and those of equivalent bare tilled plots were compared. Two plots were involved in each category. This exercise provides a way of testing the effect of weather or rainfall on tilth structure during the growing season.

5.2.3.3 Meteorological information

The meteorological station at the site of the experiment did not provide information on rainfall intensity. However, data were available on the amount of rainfall. Therefore, the number of rainfall days in each of the intervals under consideration could be obtained.

The interval between Winter and Spring (7th July to 10th October, 1976) constituted the period of rainfall peak compared with the interval between Spring and Summer (11th October, 1976 to 10th January, 1977). In the first interval, the total amount of rainfall was 179 mm, while the number of rainfall days was 43. The equivalent figures for the second interval were 104 mm and 17. The total numbers of days in the intervals were almost the same.

5.2.4 Results and Discussion

Discussion of results will be performed under two main topics which are based on the two separate sources of data. The comparison of the mean structural data of bare tilths collected in Winter, Spring and Summer is first performed to examine the effect of rainfall over these periods. Secondly, the data of cropped and bare tilled plots at the end of the second interval are compared to show how the vegetative cover had protected the internal tilth structure against the effect of rainfall as will be seen in the first discussion.

5.2.4.1 Tilth structure and rainfall

5.2.4.1.1 Aggregate size distribution

Within the top 5 cm of tilled soil, there was a decrease in the proportion of small aggregates at the end of the growing season compared with the beginning of the season (Figure 27). However, at the period of peak rainfall between Winter and Spring, there was slight increase in the proportion of the small aggregates which could be attributed to detachment of small aggregates from the surface clods at the top of the 'open' tilth. The proportions of 1-5 mm aggregates were 0.14, 0.17, and 0.11 for Winter, Spring, and Summer periods, while the equivalent values for 1-8 mm aggregates were 0.22, 0.25, and 0.20.

Soil detachment has been shown (Hagen *et al.*, 1975) to be a complicated process which depends on size and intensity of rainfall,

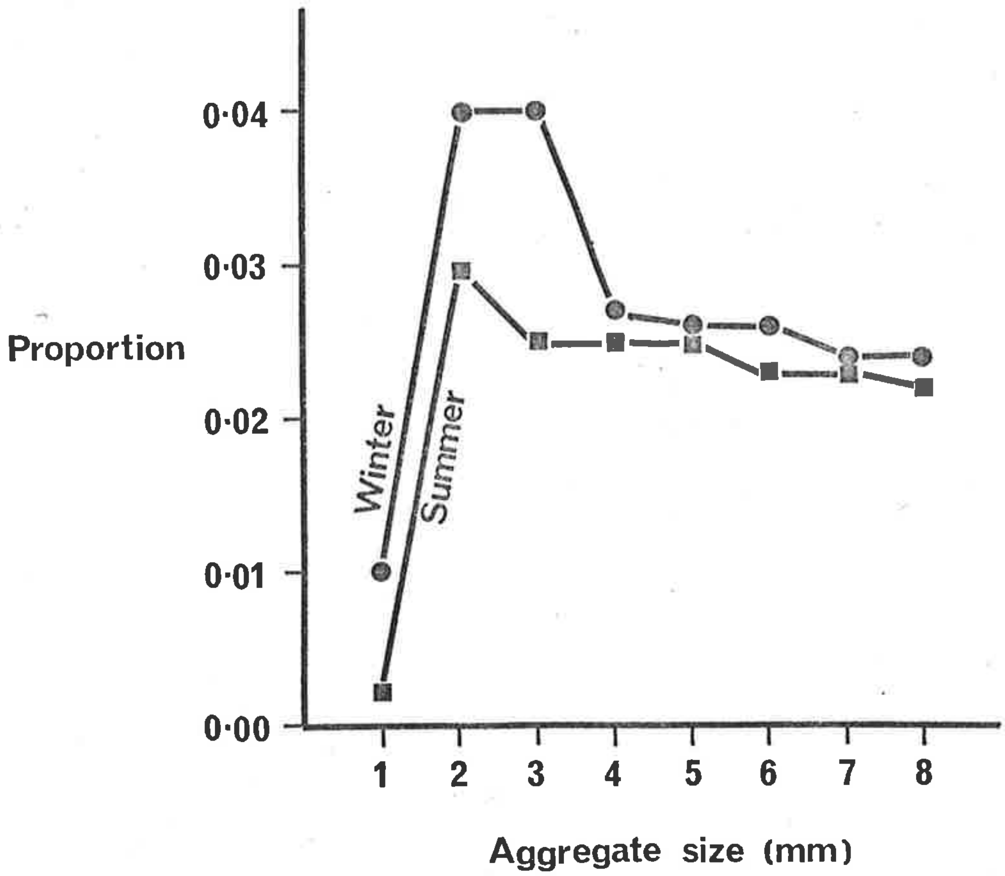


Fig. 27. Seasonal variation in the mean proportions of small size aggregates within bare tilths.

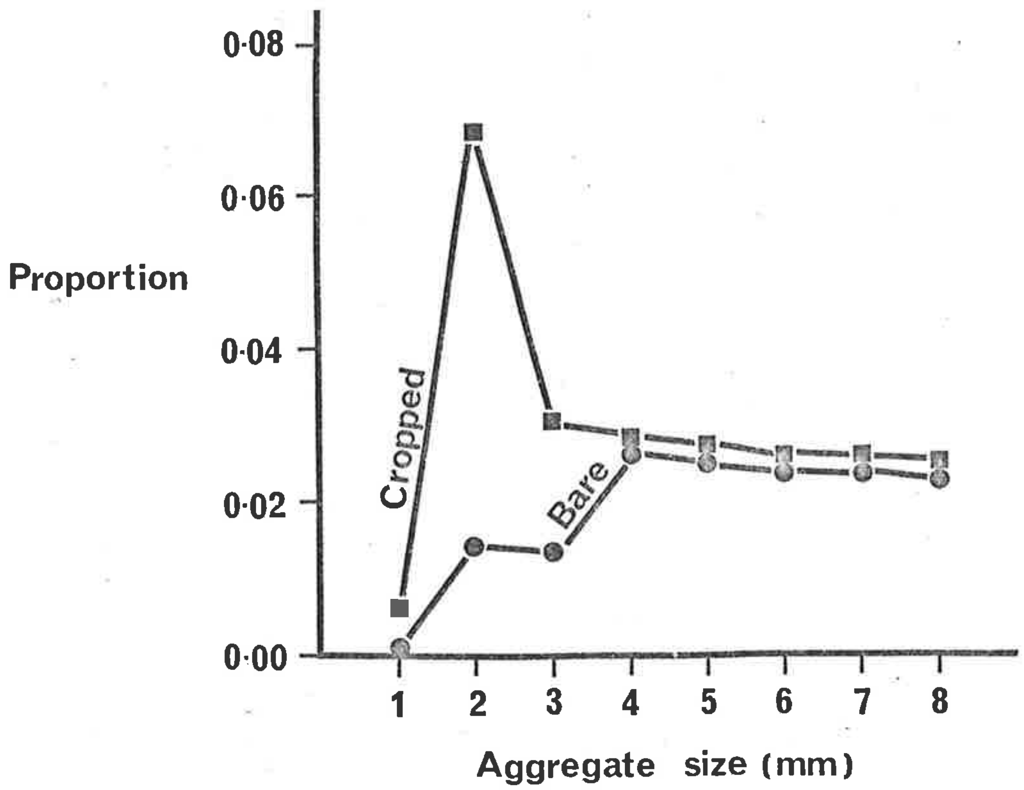


Fig. 28. Mean proportions of small size aggregates in bare and cropped tilths in summer.

windspeed, and surface covers as well as the interactions among these factors.

The ultimate reduction in the proportion of small aggregates at the end of the growing season could be due to coalescence of small aggregates with surrounding large aggregates and clods or it could be due to washing down of small aggregates to below the level of structural measurement.

5.2.4.1.2 Entropy

As a result of the decrease in the proportion of small aggregates at the top zone of tilth over the wet period attributed to their disruption and coalescence with larger aggregates and clods, there was slight reduction by 0.1) in tilth structural entropy between Winter and Summer. However, detachment of soil from clods by Winter rainfall caused a considerable increase in entropy between Winter and Spring which later fell (from 0.25 to 0.22) due to the reason already given.

5.2.4.1.3 Pore size distribution

There was a reduction in the proportion of small aggregates over the cropping season. This is consistent with the idea of the small aggregates merging or coalescing with clods. The sizes of the latter were increased to reduce the number of the larger voids (Table 28).

As a result of reduction in the frequency of the small aggregates, the proportion of small pores was also slightly reduced. The proportions of 1-5 mm pores were 0.65 and 0.62 in Winter and Summer respectively.

The observation that the number or proportion of the larger voids decreased with time is consistent with that of Dexter (1976) who recorded a decrease in the probability of a void being at least 5 mm in width at depths within 5 cm of tilled soils at consecutive intervals of 51 and 54 days after tillage.

Table 28. Aggregate and pore size distributions within bare tilths at different seasons as expressed by the mean proportion larger than X mm.

X	Proportion (aggregates)			Proportion (pores)		
	Winter	Spring	Summer	Winter	Spring	Summer
1	0.99	0.97	1.00	0.90	0.94	0.89
2	0.95	0.93	0.97	0.73	0.79	0.71
4	0.81	0.86	0.92	0.44	0.62	0.49
8	0.78	0.75	0.83	0.20	0.39	0.20
16	0.62	0.58	0.67	0.065	0.17	0.048
32	0.39	0.35	0.44	0.012	0.046	0.004
64	0.16	0.13	0.20	0.001	0.006	0.000
Mean aggregate size	35.0	31.0	41.0			
Mean pore size				6.1	10.0	5.9
Macroporosity				0.153	0.242	0.131

Detachment of small particles from clods within the top of the tilth in Winter (after tillage) should have caused an increased proportion of small pores between Winter and Spring (Table 28), although the reverse was the case in the subsequent drier interval possibly as a result of fusion of the small aggregates with clods (Gish and Browning, 1948).

5.2.4.1.4 Macroporosity

From Winter to Summer, macroporosity at the 4-5 cm depth in the tilth fell and this could be attributed to fusion of small aggregates with clods which led to slight reduction in the proportion of medium-size pores (9-16 mm) and mean pore size, and increase in mean aggregate size.

Considerable increased macroporosity occurred in the period of peak rainfall due to increased proportion of voids larger than 8 mm as a result of decrease in mean aggregate size possibly brought about by soil detachment from clods.

Rainfall caused a decrease in the proportion of small aggregates including those smaller than 6 mm at the 4-5 cm depth in tilled soil. This led among other things to increased proportion of large aggregates, decreased proportion of large voids especially those larger than 16 mm, and decreased macroporosity from Winter to Summer. This effect of rainfall was attributed to the disruption of the small aggregates and their coalescence with large aggregates and clods. However, the reverse was the case in the period of peak rainfall between Winter and Spring.

The next step is to further test the above conclusion by examining the role of plant cover.

5.2.4.2 Plant cover and the effect of rainfall on tilth structure

5.2.4.2.1 Preamble

The internal structures of bare tilths and those tilths sown with barley were compared at the end of the growing season (Summer) to examine the role of foliage cover against the effect of rainfall on the internal tilth structure.

The presence of the crop cover certainly increased soil water content, and this should have acted against effective coalescence or aggregation of small aggregates with larger ones and clods which has been shown (Singh and Pollard, 1956) to occur especially under less wet conditions. Tilth water contents of cropped and bare tilled plots (Appendix IV) showed that the former had, on average, a 2% greater water content (dry weight basis) than the latter.

Singh and Pollard recorded a negative correlation between percentage aggregation and soil water content. Gish and Browning (1948) who in the laboratory investigated the factors affecting the stability of soil aggregates observed an inverse relationship between aggregation > 2.0 mm and soil water content. The coalescence of small aggregates with larger ones or themselves is synonymous with aggregation in the present discussion.

Another way by which plant cover would reduce coalescence, disruption, and loss in the proportion of small aggregates in tilled soil is by preventing the direct effect of rainfall on the soil. The resultant reduced rate of wetting of soil aggregates will certainly reduce their disruption and loss of separate identity. Also a larger soil water content in the soil under crop cover should contribute to a reduced unsaturated infiltration rate.

5.2.4.2.2 Aggregate size distribution

Due to plant cover, the proportion of small aggregates including those smaller than 6 mm in diameter was greater in the tilled soil planted with barley than in bare soil (Figure 28). The foliage cover largely prevented disruption of soil aggregates and their fusion with clods by protecting the tilth against the direct effect of rainfall.

As a result of the above, the proportion of larger aggregates up to those larger than 64 mm in diameter, and mean aggregate size, were smaller in the cropped tilth than in the bare tilth (Table 29).

5.2.4.2.3 Entropy

The larger proportion of small aggregates due to the role of plant cover against disruption of tilth aggregates by direct effect of rainfall caused a larger entropy of the cropped tilth (0.25) than that of the bare tilth (0.21). Tilth structural variability or entropy depends on the proportion of smaller structural elements.

The present discussion shows that the ways in which rainfall, plant cover, and soil water content affect the internal structure of tilled soil could hardly be separated. Similarly, Singh and Pollard (1956) hinted that the effects of crop cover on aggregation cannot be distinguished from those of soil water and rainfall.

5.2.4.2.4 Pore size distribution

As a result of the greater proportion of small aggregates in the tilth of the cropped plot relative to that of bare plot, the former had a smaller proportion of large pores (Table 29), and a larger proportion of small pores than the latter. The mean proportions of 1-5 mm pores in cropped and bare tilths were 0.79 and 0.59 respectively, while the equivalent mean pore size was larger for the latter than for the former.

Table 29. Aggregate and pore size distributions in bare and cropped tilths in summer as expressed by the proportion larger than X mm.

X	Proportion (aggregates)		Proportion (pores)	
	Bare	Cropped	Bare	Cropped
1	1.00	1.00	0.95	0.85
2	1.00	0.97	0.67	0.60
4	0.95	0.93	0.50	0.29
8	0.85	0.77	0.22	0.10
16	0.69	0.59	0.06	0.02
32	0.45	0.36	0.02	0.00
64	0.19	0.13	0.00	0.00
Mean aggregate size	39.8	32.0		
Mean pore size			6.2	4.2
Macroporosity			0.14	0.12

5.2.4.2.5 Macroporosity

Due to the smaller proportion of medium-large size voids in the cropped tilth as a result of its larger proportion of small aggregates and voids, it had smaller macroporosity compared with the bare tilth. The proportion of medium-size voids (9-16 mm) mainly determines tilth macroporosity.

5.2.5 Summary and Implication of Findings

Seasonal change in the macrostructure of tilled soils was traced using structural data from sectioned tilth block samples impregnated with paraffin wax. The aggregate and pore size distributions and some other parameters related to them were measured for the 4-5 cm depth within tilled soils.

Reduction in the proportion of small aggregates including those smaller than 6 mm as a result of rainfall during the growing season was explained on the basis of rapid wetting of aggregates and their ultimate disruption, and coalescence with larger aggregates and clods. The importance of the latter factor is supported by the fact that crop cover prevented the effects of rainfall observed on the bare plots.

The effects of rainfall, soil water, and crop cover on internal structure of tilled soil appeared inseparable.

It is suggested that natural soil compaction under weather and cost of tillage for seedbed preparation could be reduced by mulching with crop residue after planting, and early crop cover if practised consistently.

The present project needs to be repeated several times before the effects of rainfall on the internal structure of tilled soil are known precisely. However, the hypothesis set at the beginning of this write-up is consistent with the findings.

5.3 Statistical Evidence

Analysis of variance (Table 30) of proportions of aggregate sizes (sizes larger than X = 1, 2, 4, 8, 16, 32 and 64 mm) shows that previous cropping rotation, water content at tillage; and seasonal climatic change (especially rainfall) significantly determined the tilth structure produced and change in internal tilth structure respectively.

The results have shown that the inclusion of pasture or fallow in rotation significantly increased the proportion of small aggregates, in the tilth produced, and that continuous cropping had the reverse effect. To further demonstrate these revelations, the rotation that had the maximum fallow (F), or the maximum pasture (P), or the maximum wheat and pasture (indicating the frequency of land cropping or use) was given the maximum score of +3, +3 and -3 respectively and other plots were graded down accordingly. For the fallow factor, the scores for rotations WF, WPF, WPPF, WPP, and CW are 3, 2, 1, 0, 0 respectively. The equivalent scores for factor pasture are 0, 1, 2, 3, 0; while the equivalent scores for factor continuous cropping are 3, 2, 1, -3, -3. The addition of scores for the rotations give respectively 6, 5, 4, 0, and -3. These figures were correlated with the equivalent proportions of aggregates larger than 8 mm (A8) which are 0.57, 0.27, 0.56, 0.53 and 0.80 (1977 data). The correlation coefficient r = -0.983 was recorded. This confirms that fallowing and the inclusion of pasture in rotation significantly caused decreased proportion of clods in the seedbed zone when tillage was done.

The proportion of aggregates (A8) or pores (P8) larger than 8 mm was regressed on water content at tillage (Wt). However, there were only six data points because there were only six water contents. The same operation was performed for mean aggregate size ($\overline{As}$), and mean pore size ($\overline{Ps}$). The resultant regression equations for A8 on Wt, P8 on Wt,

Table 30. Analysis of variance for proportions of aggregate size (larger than X = 1,2,4,8,16,32,64 mm) in tilths produced on plots under different rotations, at different soil water contents, and at different seasons of the year. Test for significant structural differences.

Source of Variation	df	SSD	MSD	F	Test (99%)
Rotation (1977)	4	0.362	0.091	24.6	***
Residual "	24	0.09	0.0037		
Rotation (1976)	4	0.15	0.038	38.0	***
Residual "	16	0.0001	0.000006		
Season	2	0.013	0.0065	32.5	***
Residual "	12	0.0026	0.0002		
Water content at tillage	5	0.147	0.029	15.03	***
Residual "	25	0.049	0.002		

$\overline{As}$ on Wt, and $\overline{Ps}$ on Wt are respectively

$$A8 = -0.01Wt + 0.605 \quad (r = -0.51) \qquad (62)$$

$$P8 = -0.013Wt + 0.578 \quad (r = -0.72) \qquad (63)$$

$$\overline{As} = -0.31Wt + 16.5 \quad (r = -0.51) \qquad (64)$$

$$\overline{Ps} = -0.25Wt + 13.1 \quad (r = -0.72) \qquad (65)$$

The r values are significant at 75, 90, 75, 90% level respectively.

The above equations confirm that the greatest proportion of clods was produced when tillage was done at the smallest water content.

This statistical evidence is consistent with the relevent hypotheses set, and the significant effects of factors show that this research was worthwhile.

5.4 Conclusions

A new technique which measures aggregate and pore size distributions of tilled soils in the field by sectioning of tilth block samples was used to examine factors that determine tilth structure to be produced by tillage and the effect of rainfall on the structure after it has been produced. The following conclusions were made with the use of structural data collected in the top 5 cm of tilled soils.

Continuous cropping as opposed to the inclusion of fallow in rotation led to greater proportions of large aggregates and voids and smaller proportions of small structural elements in tilled soils.

The inclusion of pasture in rotation with wheat and fallow increased the amount of small aggregates and pores and reduced the proportion of large aggregates in tilled soils. The same attributes applied to plots that came out of pasture compared with those that came out of fallow and wheat.

Tillage at a water content slightly below Plastic Limit (0.87 Plastic Limit) or Field Capacity (0.94 Field Capacity) produced the smallest proportion of clods and larger voids with more than 8 mm in diameter compared with tillage at greater or smaller water contents. The greatest proportion of clods occurred in tilths produced at the smallest water content.

Rainfall during the growing season caused reductions in the proportion of small aggregates and pores and increased proportions of larger aggregates in the top zone of tilled soils. This effect of rainfall can be prevented by early crop cover.

CHAPTER 6

EFFECT OF SOIL STRUCTURE ON TEMPERATURE IN TILLED SOIL

6.1 Introduction

Only a few field studies have investigated temperature in soil having a tilled surface layer overlying uniform, undisturbed soil. West (1932) studied the effects of a 10 cm deep soil mulch (i.e. a finely tilled layer) on soil temperatures at 15, 30 and 60 cm depths. He concluded that the equivalent thermal diffusivity of the tilled layer was 0.17 of that of the untilled soil. However, neither effects of the structure of the tilled layer, nor the temperature regime within the tilled layer was considered.

Van Duin (1954) developed a theoretical model to cope with heat flow in a two-layered soil. Heat transfer was assumed to occur entirely by the mechanism of conduction through the homogenous layers. De Vries (1963) considered heat conduction through heterogeneous soils by a method of partitioning the flow between the solid, liquid and gas phases. This leads to the conclusion that a tilled soil will have a smaller thermal diffusivity than an untilled soil, in agreement with the results of West (1932), on account of the greater proportion of air space within it. This method has the feature that the effective thermal diffusivity is a function of the air-filled porosity but is independent of the diameter of the air-filled pores. Van Wijk and Derkson (1963) considered layered soils in general and tilled layers overlying undisturbed layers in particular. Again they based their work on the concept of heat conduction. They noted a severe shortage of experimental data on the physical properties of tilled soil.

The significance of convection as a transport process in tilled soils is being increasingly recognised. Holmes *et al.* (1960) performed experiments on pots containing different sizes of aggregates. They were able to control the wind speed and the radiant energy on the soil surfaces. Smaller thermal diffusivities, as indicated by greater surface temperature rises, were found with the finer tilths. When white smoke was introduced into the air stream over the pots, it was observed to enter and then empty from the larger pore spaces with a rapid turbulent motion. This supports the finding of Waddams (1944) that the flow of heat through a bed of steel spheres increases greatly when the particle diameter exceeds 5 mm. They concluded that for particle dimensions of greater than about 10 mm, pore dimensions become large enough to accommodate eddies which enhance convective transport.

Effects of air turbulence on soil gas exchange have been investigated by Kimball and Lemon (1971). They did this by measuring the flux of heptane vapour through beds of different sizes of particles. They found heptane fluxes of between three and ten times the predicted diffusion flux through beds of 18 mm diameter particles, and between two and four times the predicted diffusion flux through beds of 3 mm diameter particles. The increase in each case coincided with an increase in wind velocity from 0 to 14 $km.hr^{-1}$. Farrell *et al.* (1966) investigated this problem theoretically, and concluded that with a wind speed of 24 $km.hr^{-1}$, surface air can penetrate coarsely-structured soil to a depth of several cm. For particles of 10 mm diameter, they predicted the gas flux across the soil surface could be as much as 100 times the molecular diffusion flux and that the air flow would extend to a depth of about 6 cm. Their analysis was later extended by Farrell and Larson (1973) to include effects of intra-aggregate diffusion on the oscillatory fluxes.

This project extends the above work through a field study of the influence of tilth structure on the effects of meteorological factors on the temperature regime in tilled soils.

6.2 Hypothesis

Temperature in tilled soil will be governed by the presence of pores larger than 8 mm. Convection of atmospheric air through these pores will increase the effective thermal conductivity of the tilled layer. This convection of atmospheric air will also lead to increased daily fluctuation of temperature at the top of the tilled layer.

6.3 Materials and Methods

6.3.1 Tillage treatments

The field experiment was sited at the Mortlock Experiment Station of the Waite Agricultural Research Institute (33° 55'S, 138° 43'E, altitude 430 m). The soil on the site is a loam (60% sand, 21% silt, 19% clay) and belongs to the Red Brown Earth Group (Stace *et al.*, 1968). Each tillage treatment was done on 7th July, 1976 in a North-South direction with (1) disc plough, (2) disc plough + scarifier, (3) disc plough + combine drill, (4) mouldboard plough, (5) mouldboard + scarifier, (6) mouldboard + combine drill, (7) scarifier, and (8) rotary cultivator. Tillage was done at a water content of 22.7% (dry weight basis). This is slightly wetter than the Plastic Limit for this soil (21.2%). In the following D, Sc, CD, MB, and RC stand for disc plough, scarifier, combine drill, mouldboard plough, and rotary cultivator respectively.

6.3.2 Sample collection and structural data

Tilth block samples were collected from the tilled plots immediately after tillage on 7th July, 1976; and also on 18th October, 1976, and 11th January, 1977. The method of Dexter (1976) described in Chapter 3 was used. Raw structural data were collected from two sections of each of the 8 tilth blocks, while data from each section were collected separately from two cross-section lines. Therefore, there were four different structural data collected from each of the tilth blocks collected at three different times. The structural data show the distribution of structural elements, pores and aggregates. The raw structural data (collected at about 4-5 cm depth) were processed along lines already described (Chapter 3) to get the following data.

(1) The probabilities, P(0), of 0's following the 16 precursors of structural elements (1 to 5 mm diameter), and the occurrence probabilities (Ui) for the 16 precursors are given in Tables 31 and 32 respectively.

(2) From (1), the void size distributions (Table 33) for each treatment plot were calculated by the method of Dexter and Hewitt (1978). The method is described in Chapter 3.

Structural data present in this chapter are means for three sets of samples. The primary structural data for tilth block samples collected in July, October and January are presented in Appendices I and II.

6.3.3 Tilth temperature and water content

Tilth temperature (^{o}C) at 5 and 10 cm depths in the tilled soils were measured as much as possible at 3 hr intervals in Winter for eight days (8th July to 15th July, 1976), in Spring for five days (18th to 22nd October, 1976), and Summer for three days (11th to 13th January, 1977). They were replicated three times at each depth on each plot. Temperatures were measured with GB 22 thermistors which were individually calibrated in the laboratory before the experiment. The thermistors were inserted

Table 31. Structures of differently tilled plots. Values of P(0) are the probabilities of a 0 following the sixteen possible precursors. An asterisk indicates that the precursor had no occurrence. Mean values for Winter, Spring, and Summer.

Precursor	P(0) for Plot							
	D	D+Sc	D+CD	MB	MB+Sc	MB+CD	Sc	RC
0000	0.862	0.743	0.827	0.821	0.878	0.767	0.741	0.737
0001	0.009	0.000	0.000	0.014	0.000	0.000	0.000	0.000
0010	1.000	1.000	1.000	*	*	1.000	*	1.000
0011	0.059	0.357	0.029	0.000	0.008	0.064	0.024	0.063
0100	1.000	1.000	1.000	1.000	*	1.000	0.500	1.000
0101	*	*	*	*	*	1.000	*	*
0110	0.667	0.500	1.000	1.000	1.000	0.875	1.000	1.000
0111	0.036	0.032	0.009	0.030	0.063	0.046	0.044	0.065
1000	0.850	0.814	0.923	0.770	0.816	0.917	0.854	0.800
1001	0.000	0.033	0.033	0.300	0.000	0.083	0.000	0.133
1010	*	0.000	*	*	*	*	1.000	1.000
1011	0.000	0.250	0.000	*	0.000	0.174	0.000	0.000
1100	0.821	0.730	0.830	0.974	0.929	0.645	0.731	0.797
1101	0.000	0.000	0.000	*	0.000	0.222	0.402	0.167
1110	0.935	0.916	0.910	1.000	0.937	0.962	0.728	0.947
1111	0.031	0.023	0.030	0.025	0.028	0.033	0.028	0.034

Table 32. Structures of differently tilled plots. Values of Ui are the occurrence probabilities for the sixteen possible precursors. Mean values for Winter, Spring and Summer.

Precursor	Ui for Plot							
	D	D+Sc	D+CD	MB	MB+Sc	MB+CD	Sc	RC
0000	0.117	0.082	0.145	0.117	0.137	0.094	0.089	0.079
0001	0.019	0.013	0.017	0.020	0.021	0.018	0.013	0.023
0010	0.0002	0.0003	0.0001	0.0005	0.0005	0.0004	0.000	0.0004
0011	0.023	0.017	0.020	0.020	0.022	0.027	0.018	0.028
0100	0.0002	0.0003	0.000	0.0005	0.000	0.001	0.001	0.0007
0101	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0110	0.0013	0.002	0.0004	0.0007	0.0002	0.002	0.0003	0.002
0111	0.024	0.018	0.022	0.019	0.023	0.025	0.023	0.027
1000	0.019	0.013	0.017	0.020	0.021	0.018	0.013	0.023
1001	0.004	0.005	0.003	0.0005	0.002	0.009	0.005	0.006
1010	0.000	0.000	0.000	0.000	0.000	0.0005	0.001	0.000
1011	0.002	0.003	0.002	0.000	0.001	0.0006	0.005	0.001
1100	0.023	0.017	0.020	0.020	0.022	0.026	0.017	0.028
1101	0.002	0.003	0.002	0.000	0.001	0.001	0.006	0.001
1110	0.024	0.002	0.022	0.019	0.023	0.026	0.023	0.027
1111	0.742	0.809	0.728	0.761	0.726	0.750	0.785	0.753

Table 33. Pore size distributions in differently tilled plots as expressed by the proportion of the macropores in pores larger than X mm. Means for Winter, Spring and Summer.

X	Proportion							
	D	D+Sc	D+CD	MB	MB+Sc	MB+CD	Sc	RC
1	0.92	0.88	0.91	1.00	0.94	0.96	0.74	0.96
2	0.76	0.64	0.76	0.97	0.87	0.62	0.55	0.77
4	0.56	0.38	0.57	0.63	0.62	0.45	0.38	0.46
8	0.31	0.15	0.30	0.33	0.37	0.20	0.20	0.16
16	0.09	0.06	0.15	0.13	0.13	0.05	0.05	0.03
32	0.009	0.002	0.01	0.02	0.016	0.006	0.00	0.00
Macro-porosity	0.186	0.133	0.185	0.170	0.203	0.167	0.144	0.158

to the appropriate depths using thin calibrated pegs. Resistances (kΩ) were measured with a battery-powered digital multimeter. The primary temperature data are presented in Appendix III.

Thermistors have a large negative coefficient of resistivity. The resistance varies as

$$R = Ae^{B/T} \qquad (66)$$

where A and B are adjustable parameters. Equation (66) solves into

$$T = \frac{B}{\log_e (R/A)} \qquad (67)$$

Equation 67 was used to convert resistance to temperature ($^{\circ}$C). B is the slope when $\log_e R$ is plotted against 1/T and $\log_e$ A is the intercept. The values of A and B were obtained by calibration in a water bath over the range starting from 0°C to 69°C. A computer programme was written to produce values of A and B for each thermistor used in the field.

Tilth water contents at 5 and 10 cm depths were determined on a dry weight basis by drying samples for 24 hr at 105°C. As nearly as possible, soil samples were collected at the same times at which the temperatures were measured. Each water content measurement was replicated twice. Metal containers with lids were used in collecting soil samples.

Data of soil water content are presented in Appendix IV.

6.3.4 Meteorological data

A meteorological station was located about 1 km from the experimental site on land with a similar aspect. Air temperature ($^{\circ}$C) and relative humidity (%) values were obtained from an automatic recorder 2 m above the ground level. Wind speeds (km.hr^{-1}) were from an anemometer 0.5 m above the ground. There was no rain in any experimental period.

Solar radiation figures for the experimental site were not available.

Meteorological data are presented in Appendix III.

6.4 Results and Discussion

The tilth temperature data that were collected in different seasons from the tilled plots were subjected to statistical analysis. Linear relationships were assumed in the regressions of tilth temperature and temperature gradient on meteorological factors. This is a gross assumption which is untenable on physical grounds. However, it served to illustrate the relative importance of the variables under investigation. A more rigorous approach does not seem justified in a field experiment until some data has been collected on air flow velocities in soil macro-pores.

6.4.1 Tilth temperature, tillage treatment, and meteorological factors

Mean temperatures for different times of day for Winter, Spring and Summer were compared. Tilth temperature varied significantly between different times and seasons (Table 34). Mean daily tilth temperatures in Winter, Spring and Summer periods were 8.3, 15.7 and 29.9^{o}C respectively. For these same periods, the mean air temperatures were 10.9, 14.7, and 24.5^{o}C, mean relative humidities were 69, 64 and 38.5%, mean solar radiations (at the Waite Institute campus) were 8.6, 17.1 and 28.3 $MJm^{-2}day^{-1}$, and mean cloud covers were 53, 88, and 40% respectively.

Multiple linear regression was performed with tilth temperature (Tt^{o}C) at the different times of sampling on air temperature, Ta (^{o}C), relative humidity, h(%), and tilth water content, w(%), for each plot. Tt here is the mean of the temperatures at the 5 and 10 cm depths. Summer tilth temperature data could not be used in the regression because of its paucity. After the regression equations of all the plots had been obtained, the question was whether the regression coefficients obtained

Table 34. Analysis of variance of mean tilth temperatures for Winter, Spring, and Summer periods.

Source of Variation	df	SSD	MSD	F	Test (95%)
Treatment (5 cm)	7	2.22	0.32	0.77	NS
Treatment (10 cm)	7	1.98	0.28	0.53	NS
Time	6	969.73	111.62	647.71	***
Season	2	1858.1	929.1	60.68	***
Depth	1	0.2	0.2	0.1	NS
Residual	42	10.48	0.25		
Total	55	981.6			

Table 35. Analysis of variance for regression of tilth temperature, Tt on air temperature, Ta, relative humidity, h, and tilth water content, w (Winter).

Source of Variation	df	SSD	MSD	Test (99.9%)
Treatments	7	6.3	0.9	NS
Regression within each treatment	24	220.5		
Global regression	3	190.7	63.6	***
Difference due to regression within treatment	21	29.8	1.42	NS
Regression on Ta and h	2			
Difference due to regression on w	1	3.2	3.2	NS
Regression on w and Ta	2			
Difference due to regression on h	1	21.8	21.8	***
Regression on w and h	2			
Difference due to regression on Ta	4	110.9	110.9	***
Residual	146	481.1	3.3	
Total	177	707.9		

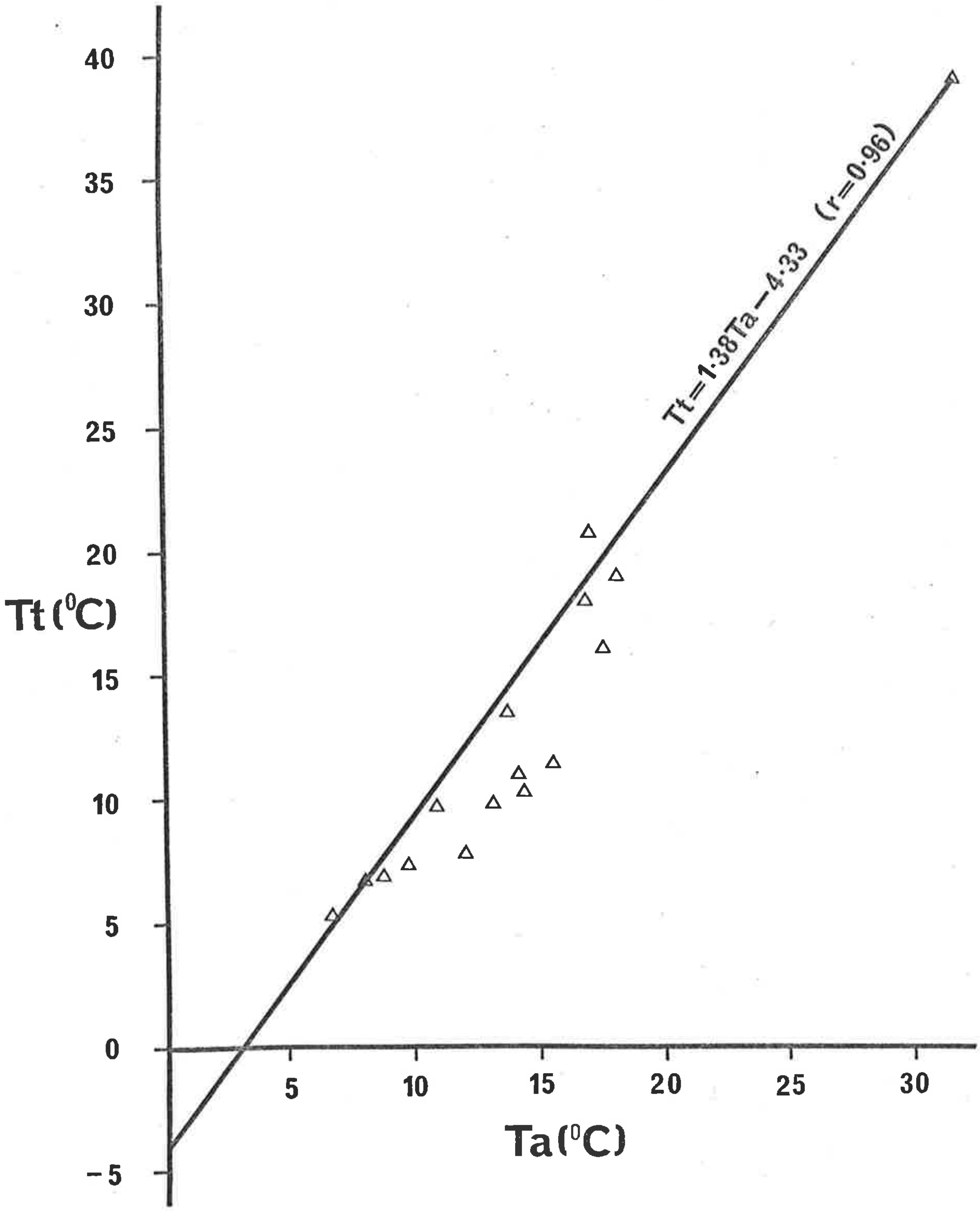


Fig. 29. The relationship between air temperature (Ta) and tilth temperature (Tt).

for the different tillage treatments were significantly different. The errors in the 'independent' variables were almost certainly not negligible relative to those in the dependent variables, and some other multivariate technique seemed more appropriate.

Analysis of variance was performed interactively using a model called the Rothamsted Generalized Linear Model. Analysis of variance (ANOVA) was performed separately for data collected in Winter and Spring and the ANOVA tables are presented (Tables 35 and 36). The conclusions to be drawn from the two tables are the same.

Separate analysis of variance at the 95% level showed that there was no significant effect due to tillage treatment on mean (for depth and plots) tilth temperature (Table 34). Thus there was no need to assign a different equation for each treatment plot. There was a significant variation in tilth temperature due to air temperature and relative humidity, although there was no suggestion that the dependence on these variables was different between different tillage treatments.

The equations describing the dependence of tilth temperature, Tt, on Ta and h irrespective of tillage treatment are given in Equation 68 for Winter and in Equation 69 for Spring.

$$Tt = \underset{(\pm 1.8)}{1.1} + \underset{(\pm 0.07)}{0.42Ta} + \underset{(\pm 0.018)}{0.047h}, \ ^{o}C \qquad (68)$$

$$Tt = \underset{(\pm 4.2)}{10.8} + \underset{(\pm 0.12)}{0.76Ta} - \underset{(\pm 0.04)}{0.14h}, \ ^{o}C \qquad (69)$$

Correlation coefficients between Tt and Ta were 0.90, 0.95 and 0.93 for Winter, Spring and Summer periods respectively. However, when data for the three periods were pooled a larger correlation (0.96) was obtained. Figure 29 shows the dependence of tilth temperature on air temperature. It is shown that a 1.4^{o}C rise in tilth temperature

Table 36. Analysis of variance for regression of tilth temperature, Tt, on air temperature, Ta, relative humidity, h, and tilth water content, w (Spring).

Source of Variation	df	SSD	MSD	Test (99.9%)
Treatments	9	14.1	1.57	NS
Regression within each treatment	30	1167.9		
Global regression	3	1039.4		
Difference due to regression within treatments	27	128.5	4.75	NS
Regression on Ta and h	2	1038.4		
Difference due to regression on w	1	1.0	1.0	NS
Regression on w and Ta	2	1027.8		
Difference due to regression on h	1	11.6	11.6	***
Regression on w and h	2	999.8		
Difference due to regression on Ta	1	39.6	39.6	***
Residual	30	96.29	3.21	
Total (corrected)	69	11.28		

Table 37. Mean daily temperature ranges (maximum minus minimum) at 5 cm and 10 cm depths in the eight tillage treatments in ^{o}C.

Treatment	Winter		Spring		Summer	
	5 cm	10cm	5 cm	10 cm	5 cm	10 cm
D	8.1	5.0	11.9	10.4	23.9	17.8
D+Sc	6.6	4.2	13.9	10.1	27.5	25.6
D+CD	7.8	4.0	14.8	9.9	25.5	17.6
MB	7.7	4.1	15.0	11.3	25.1	18.0
MB+Sc	9.6	4.6	15.2	10.3	26.8	18.4
MB+CD	7.4	4.6	14.7	9.6	21.1	18.8
Sc	6.4	4.1	12.2	10.3	22.4	21.2
RC	7.1	6.0	13.1	10.8	21.4	21.3
Means	7.6	4.6	13.9	10.3	24.2	19.8

accompanies a 1.0°C rise in air temperature. The correlation coefficients between Tt and h were 0.12 and -0.92 for Winter and Spring respectively.

The positive correlation between Tt and h in Winter may be a consequence of absorption and re-emission back to earth of out-going long-wave radiation associated with the greater relative humidities of the Winter season.

6.4.2 Tilth Temperature Variations

6.4.2.1 Daily variation

Although the mean temperatures due to the different tillage treatments did not differ significantly, there were considerable differences in the daily temperature ranges. The latter are summarized in Table 37. The daily minimum tilth temperature occurred just before 0900 hr in Winter and just before 0600 in Spring and Summer. The daily maximum occurred at 1200 or 1500 (usually the latter). The mean daily air temperature ranges were 8.7°C in the Winter, 7.3°C in the Spring, and 14.9°C in the Summer experimental periods.

The rate of growth of cereals is very small at temperatures below about 8°C. In the Winter, which is the cereal growing period in South Australia, the tilth temperatures were below 8°C for approximately 14 hr each day. The number of accumulated degree-hours above 8°C is greatest in the tilths exhibiting the greatest daily temperature range. In the summer period, temperatures at 5 cm were in excess of the lethal 35°C (Walker, 1969) for approximately 6 hr each day.

There are positive correlations between the daily temperature ranges at 5 cm depth and the macro-porosities of the different treatments.

The best correlation is obtained with porosity in pores larger than about 8 mm. This is in accord with the conclusions of Waddams (1944) and Holmes *et al.* (1960) referred to earlier. The correlation between the daily temperature range, R, at 5 cm depth and the porosity, $\eta 8$, in pores larger than 8 mm is given by

$$R = 45\eta 8 + 5.6, \quad (r = 0.90) \tag{68}$$

The correlation coefficients between the daily temperature ranges and porosities in pores larger than 1, 2, and 4 mm are 0.49, 0.58 and 0.58 respectively.

There is no correlation between the temperature range at 10 cm depth and any soil structural factor examined. These findings suggest that the convection of atmospheric air has a significant effect on temperatures at 5 cm depth in tilled soil, but not at 10 cm depth. This agrees with the theoretical prediction of airflow through beds of 10 mm diameter particles by Farrell *et al.* (1966).

The dependence of daily tilth temperature range (R) on macroporosity (n_L) is shown by Equation 69.

$$R = 25.9\eta_L + 10.8, \quad (r = 0.50) \tag{69}$$

The mean daily temperature ranges of tilled plots at 5 cm for Winter, Spring and Summer periods are shown in Table 37. It is shown that tilth temperature range was increased about twice from Winter to Spring, and from Spring to Summer. Therefore, in addition to structural factors, the range of temperature within the tilth is expected to depend significantly on meteorological factors.

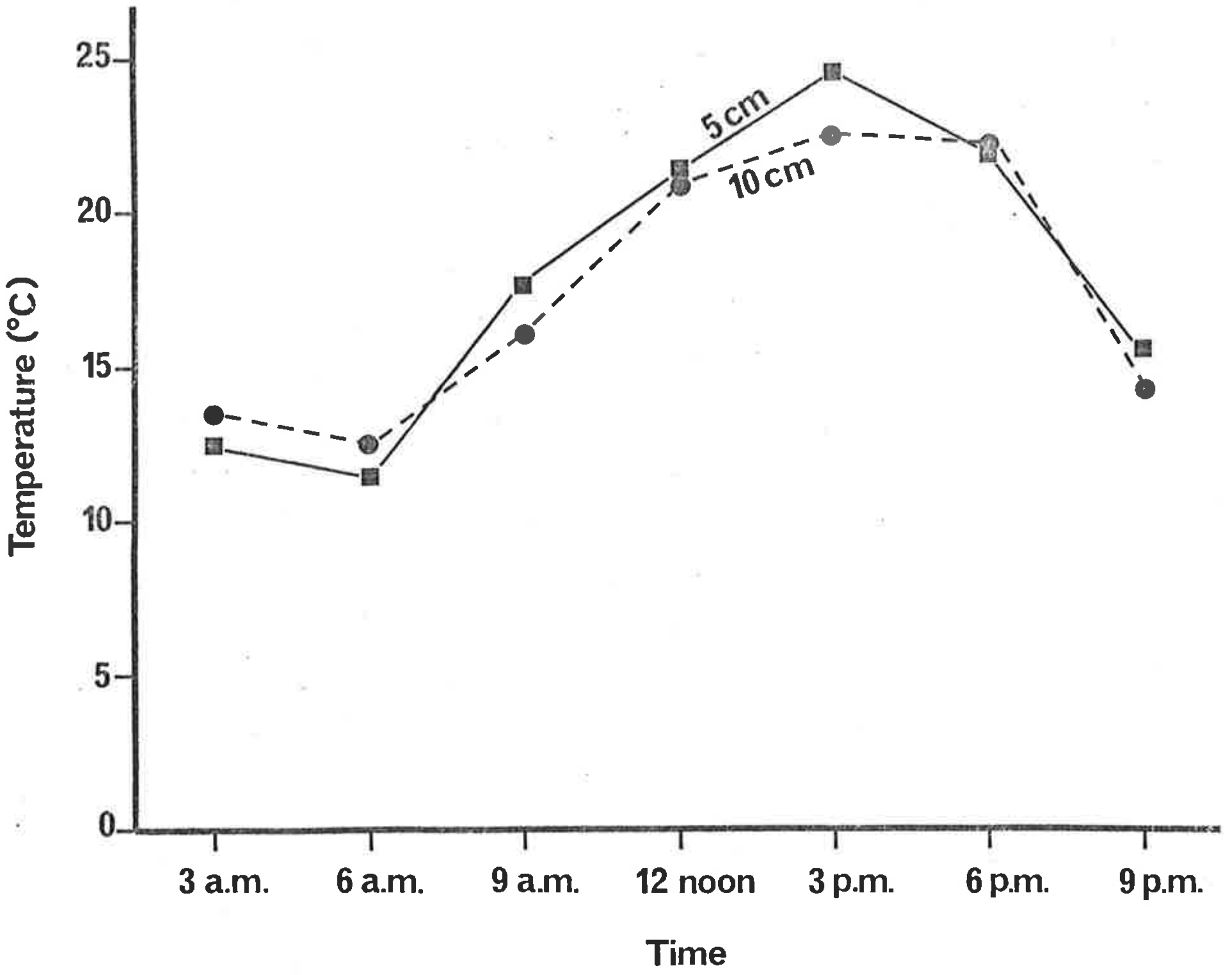


Fig. 30. Mean temperatures in winter, spring, and summer for depths (cm) within tilled soils.

6.4.2.2 Temperature as a function of depth

Mean temperatures at 5 and 10 cm depths were not significantly different (Table 38). Mean temperatures at times of day for the two depths are presented in Figure 30. On average, the temperature difference between the 5 and 10 cm depths was less than 2^{o}C. The greatest difference was usually at 1200 or 1500 (the hottest times of day) when greater temperature were recorded at 5 cm. For the night (2100 to 0600 hr) temperatures were greater at 10 cm than 5 cm depth.

The fact that the greatest temperature difference between 5 and 10 cm occurred during the hottest time of day could be a pointer to the statement that atmospheric air only penetrates tilled soil to about 5 cm depth.

6.4.2.3 Temperature gradient and meteorological factors

Temperature gradients G ($^{o}C.cm^{-1}$) were calculated between the 5 and 10 cm depths, and were regressed on a set of meteorological variables and tilth water contents to examine the role of these in the distribution of tilth heat. Windspeed, U, was substituted for air temperature. The statistical model could not accommodate sufficient variables for Ta to be included. Values of G at 1200 and 1500 were used because G was then a maximum. At this time, the mean (for Winter, Spring and Summer) air temperature, windspeed, and relative humidity were 15.9^{o}C, 8.2 km.hr^{-1} and 49% respectively. The mean tilth water content (the mean of the values at 5 and 10 cm depths) was 14.3% (for Winter and Spring). In this soil, this water content is equivalent to an equilibrium relative humidity of about 99%. The water characteristic curves (drying and wetting) for the soil is given in Chapter 7.

There were significant contributions to variations in G due to tillage treatment and all three independent variables considered (Table 39). There was a consistent positive correlation between G and U. An increase in

Table 38. Summary of tilth temperatures (^{o}C) at depths within differently tilled plots in Winter, Spring, and Summer.

Time	D		D+Sc		D+CD		MB		MB+Sc		MB+CD		Sc		RC	
	Depth (cm)															
	5	10	5	10	5	10	5	10	5	10	5	10	5	10	5	10
0600	11.1	12.7	11.0	11.8	10.8	12.9	11.2	12.3	10.6	12.4	11.6	12.8	12.0	12.7	11.8	11.6
0900	18.1	16.8	18.6	17.5	17.5	16.4	18.4	15.8	18.6	15.8	16.9	15.4	16.9	15.1	16.8	16.9
1200	23.9	20.8	24.7	22.6	23.9	20.4	24.9	20.4	25.6	20.3	23.1	20.5	23.6	21.5	23.2	22.9
1500	24.2	22.5	24.5	23.4	25.2	22.0	25.3	22.0	25.2	22.2	24.3	22.4	23.6	22.7	23.9	20.7
1800	19.5	19.8	19.9	19.8	20.2	20.3	19.6	19.9	19.8	19.8	19.6	20.0	18.8	18.6	19.2	19.2
2100	16.3	17.0	15.6	16.3	15.5	16.8	15.0	16.9	15.0	17.3	15.3	17.1	15.5	16.2	15.1	15.7
0300**	12.4	14.0	11.8	12.3	11.5	14.2	12.2	13.1	11.5	12.7	12.6	14.0	13.2	13.1	12.5	13.4
Depth Means	17.9	17.7	18.0	15.9	17.8	17.6	18.1	17.2	18.0	17.4	17.6	17.5	17.7	17.1	17.5	17.3
Plot Means***	17.8		17.0		17.7		17.7		17.7		17.6		17.4		17.4	

** Data not available for Winter.

*** Shows that structural differences did not cause significant differences in mean temperatures in tilled soils.

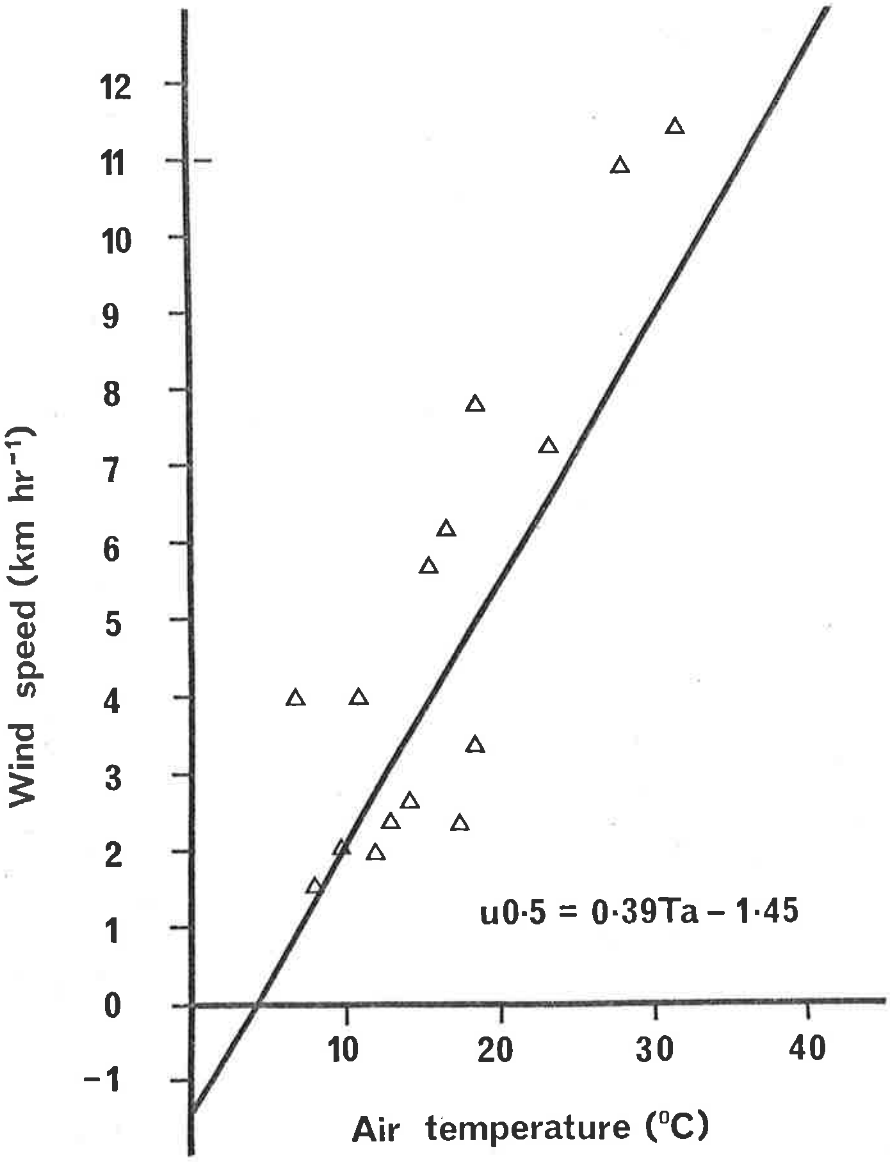


Fig. 31. Relationship between air temperature and wind speed. ⧖

⧖ Values are means between 15·00 and 06·00 hr in winter, spring, and summer.

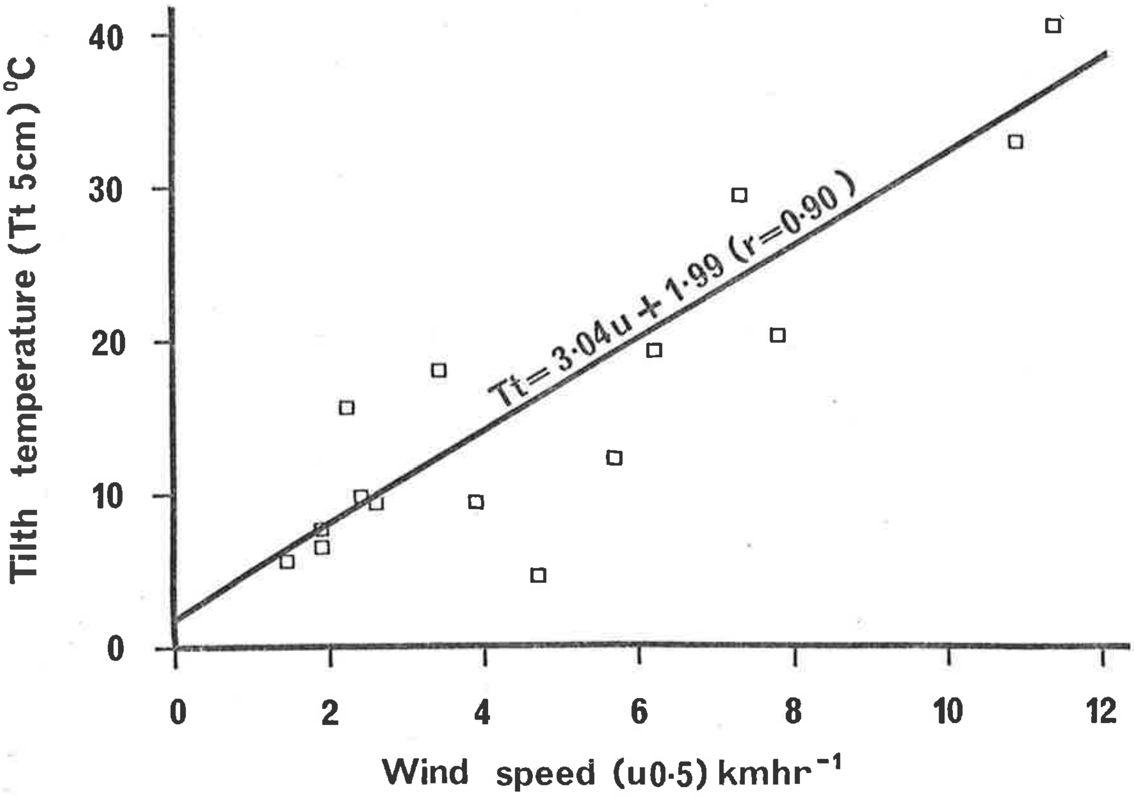


Fig. 32. Relationship between tilth temperature and wind speed.

windspeed tends to make the tilth temperature at 5 cm depth more nearly equal to air temperature and thus increases G. Increased wind turbulence with increased air temperature (Figure 31) is logical because if heating occurs at one point of the earth surface, the isobaric surfaces are disturbed and a pressure gradient which induces air movement (Farrell *et al.*, 1966) is established (Horrocks, 1966). Skidmore and Hagen (1973) also observed that winds were stronger when temperatures were greater in the U.S.A. Therefore, increased wind turbulence in the day brings hot air into the soil and raises the temperature considerably at the top of tilled soil (Equation 71). This may be considered to be another piece of evidence for the turbulent flow of atmospheric air through soil macro-pores.

However, the positive correlation between air and tilth temperatures and windspeed is not surprising. This is because the windspeed drops at night when surface cooling produces a stable atmospheric inversion layer.

The regression of tilth temperature ($Tt^{o}C$) on windspeed (u km hr^{-1}) therefore gave

$$Tt = 2.85u + 8.69 \quad (r = 0.88) \qquad (70)$$

Measurements between 1500 and 0600 hr were used for the regression. A greater correlation ($r = 0.90$) was obtained with the use of temperatures at 5 cm depth. The relationship between tilth temperature at 5 cm and windspeed is shown in Figure 32. The average difference between tilth temperature at 5 cm and air temperature were smaller than $4^{o}C$ in Winter and Spring.

Table 39. Analysis of variance for regression of tilth temperature gradient G on tilth water content, w, relative humidity, h, and wind speed, u.

Source of Variation	df	SSD	MSD	Test (99.9%)
Treatments	7	2.94	0.42	***
Regression within each treatment	24	3.3	0.14	***
Global regression	3	2.24	0.75	
Difference due to regression within treatments	21	1.06	0.05	NS
Regression on w and h	2	1.61		
Difference due to regression on u	1	0.63	0.63	***
Regression on w and u	2	0.93		
Difference due to regression on h	1	1.31	1.31	***
Regression on u and h	2	2.04		
Difference due to regression on w	1	0.2	0.2	*
Residual within treatment regression	72	3.09	0.04	
Total (corrected)	103	9.33		

Table 40. Mean afternoon temperature gradients between 5 and 10 cm depths in tilled plots during Winter, Spring and Summer period ($^{o}C\ cm^{-1}$).

Plot	Winter	Spring	Summer
D	0.23	0.24	0.26
D+Sc	0.27	0.57	0.33
D+CD	0.37	0.56	0.51
MB	0.30	0.53	0.33
MB+Sc	0.62	0.83	0.70
MB+CD	0.25	0.67	0.39
Sc	0.20	0.14	0.17
RC	0.14	0.29	0.17
Mean	0.30	0.48	0.36

6.4.2.4 Tilth structure and temperature gradient

The regression equation for the dependence of temperature gradient, G, on windspeed, u, relative humidity, h, and tillage treatment effect, α, was

$$G = \underset{(\pm 0.18)}{0.24} + \alpha + \underset{(\pm 0.007)}{0.028u} - \underset{(\pm 0.002)}{0.011h} + \underset{(\pm 0.009)}{0.019w}, \ {}^{o}C\ cm^{-1} \quad (71)$$

The values of α for the plots tilled with D, D+Sc, D+CD, MB, MB+Sc, MB+CD, and Sc relative to $\alpha = 0$ for RC are 0.085, 0.016, 0.345, 0.016, 0.532, 0.222, and 0.002 respectively.

Equation 71 shows that the difference in temperature with depths in tilled soil has to be explained on the basis of difference in structures and water contents, and the influence of meteorological factors.

A feature of the regression analysis was the plot of the ranked residuals against the normal order statistic which should be linear if the implied assumption of normally distributed errors is correct. In fact there was rather steep curvature at the positive end of the plot. That is, some points deviated much more from the proposed model than one might reasonably expect on the assumption that errors were normally distributed. This is a consequence of the gross simplification in the assumption that all effects are linearly additive.

The mean temperature gradients in the tilled plots at 1200 and 1500 are presented in Table 40. The smaller temperature gradients in Winter compared with the other, hotter seasons would be due to its smaller intensities of factors such as air temperature and wind turbulence. These are major factors positively determining tilth temperature especially in the top zone of tilth.

$$\alpha \quad = \quad 6.19\eta_L - 0.89, \quad (r = 0.73) \qquad (72)$$

Correlations of the α values and the corresponding porosities of tilled plots in pore sizes were then examined. The latter values were obtained by multiplying total macroporosities of tilled plots by their respective proportions of void sizes as shown in Table 33. Once again, the best correlation was obtained between α and porosity, η8 in pores larger than 8 mm rather than in pores larger than 2 or 4 mm. The correlation is represented by

$$\alpha \quad = \quad 7.45\eta 8 - 0.42, \quad (r = 0.75) \qquad (73)$$

Correlation coefficients between α and porosities in pores larger than 4, 2, and 1 mm respectively were 0.64, 0.51, and 0.61.

Equation (73) shows that porosity in pores larger than 8 mm mainly determine the convective transfer of heat into tilled soil. Slow heat transfer principally by the other mechanisms of diffusion and conduction to the base of tilled soil will lead to heat accumulation at the top of tilths with loose structures, and thus increase in temperature gradient.

The regression of G on total macroporosity (η_L) gave

$$G \quad = \quad 4.93\eta_L - 0.47, \quad (r = 0.66) \qquad (74)$$

Equations 71 and 74 taken together are consistent with the earlier conclusion that atmospheric air penetrates tilled soil to a depth of at least 5 cm but not 10 cm. An increase in the porosity in pores larger than 8 mm makes the temperature at 5 cm depth more nearly equal to air temperature. At 1200 or 1500 hours local time, this is normally a temperature increase, and so there is a positive correlation between G and η8. Similarly, an increase in windspeed, u, tends to make the temperature at 5 cm depth more nearly equal to air temperature. The cooling effect of evaporation of water at 5 cm could be responsible for the negative correlation of G and h. The positive correlation of G with w may be a consequence of increased conduction of heat downwards into the untilled soil in the presence of more water. This would reduce temperature at the 10 cm depth and hence increase G. Elucidation of these points awaits theoretical analysis of the physical processes involved.

6.5 Conclusions

A new method for quantifying the internal structure of tilled soil has enabled the effects of structure on the temperature regime in tilled soils to be examined in the field.

Soil structure had no effect on mean tilth temperature, but was significantly correlated with daily temperature range and maximum temperature gradient in tilled soil. Tillage practices therefore could influence the germination of seeds because, for many plant species, the temperature fluctuations are just as important for germination as the mean temperature. Germination is, of course, desirable for crop plants but undesirable for weeds. The magnitude of the differences in daily temperature range at 5 cm depth (1 or 2°C) which can be modified by different tillage practices are large enough to influence the relative percentage germination of certain species (Thompson *et al.*, 1977). Tillage-induced structure can also modify the proportion of the day that the tilth is above the lethal maximum temperature and can modify the total daily degree-hours for root growth. The influence of tillage practice on daily temperature range at smaller depths would be greater than that at the 5 cm depth discussed here.

Tilth daily temperature range and temperature gradient were correlated with meteorological variables and with different portions of the macro-pore size distribution. For simplicity, all effects were assumed to be independent and linearly additive. Although this is not justified on theoretical grounds, it served to illustrate the relative importance of the different meteorological variables in influencing tilth temperature. It cannot be expected that the resulting equations will be valid for different soil types of different climatic regions, but the general principles will be the same.

The soil structural parameter giving the best correlation with tilth daily temperature range and temperature gradient was the porosity in pores larger than 8 mm. This is consistent with the results of the theoretical and laboratory studies referred to in the introduction and also with the hypothesis set at the beginning of the chapter.

The conclusion is that in tilled soils, a major mechanism for transport of heat is convection of atmospheric air through pores larger than 8 mm. If a tilled soil has no pores approaching this size, then classical conduction of heat will predominate. If conduction is the mechanism, then the heat flow will only be a function of total porosity and not of the distribution of pore sizes as found in this project. If a tilled soil has many pores about 8 mm or larger, then convective transport predominates. The effect, in this trial, extended to a depth of 5 cm but not to 10 cm.

6.6 Summary

Soil was tilled with a range of implements to provide different structures. Soil structure was measured directly from sections cut through impregnated blocks of the tilth. Temperatures and water contents were measured at 5 cm and 10 cm depths in the tilths over periods of several days in Winter, Spring and Summer.

Tilth structure had no significant effect on mean tilth temperature. However, tilth macroporosity was correlated with the daily temperature range and the vertical gradient of tilth temperature. Multiple regression equations of mean tilth temperature on major meteorological factors, and tilth temperature range and gradient on meteorological factors and tilth structure have been developed. It is concluded that atmospheric air penetrates tilled soils to a depth of 5 cm but not 10 cm and that this transport occurs mainly in pores larger than 8 mm.

Tilth temperature was correlated with air temperature, windspeed, and relative humidity. An increase in tilth water content reduced the daily maximum temperature at the base of the tilth and increased the vertical temperature gradient. The effect of tilth water content was small compared with those of meteorological factors.

6.7 Practical Implications of Findings

In Chapter 8 it is shown that evaporation of water from a tilth occurs mainly from the 6 cm layer immediately below the heated surface even in the absence of wind turbulence. For this reason, as well as for the reason described in this chapter, it is advocated that the deeper that seeds are sown, the greater is the chance of survival of seedlings during the critical period following germination.

The present conclusion that the atmospheric air mainly penetrates tilled soils to a depth of about 5 cm aligns with the above observation and recommendation.

In Chapter 7, it is recommended that the seedbeds should be made fairly fine to consist more of pores smaller than 8 mm in diameter because it was observed that the presence of voids larger than 8 mm was mostly responsible for evaporation of water from the seedbed.

The present conclusion that the turbulent transport of atmospheric air into tilled soil mainly occurs in voids larger than 8 mm aligns with the above observation and recommendation.

For uniform distribution of seedbed temperature and for the prevention of lethal temperature under hot climate, the top zone of tilled soil which constitutes the seedbed should be made fine enough so as not to contain voids larger than 8 mm.

CHAPTER 7

EFFECT OF SOIL STRUCTURE ON WATER CONTENT IN TILLED SOIL

7.1 Introduction

Hide (1954) said that no attempt had been made to evaluate the influence of pore space distribution on the different phases of the evaporation process, and that soil variability must influence the different stages of the process. With reference to seedbeds, he said that the phase of evaporation in which water loss depends on vapour movement would need to be investigated in the field.

Since that time, there have been a number of studies on the effects of soil structure on water loss but very few of these have been done in the field. An important mechanism for evaporative loss from dry soil is molecular diffusion. This can be calculated directly from a knowledge of the air-filled porosity of the soil and a diffusion coefficient (Smiles, 1977). However, other studies have shown that with aggregated soil structures, convection processes can become dominant.

Holmes *et al.* (1960) conducted a wind tunnel experiment in which windspeed and the radiant energy on soil surfaces could be varied. They found greater evaporative water loss from tilths with larger aggregates than from those with smaller aggregates. When white smoke was introduced into the air-stream, it was observed to enter and then empty from the larger pore spaces with a rapid, turbulent motion. Farrell *et al.* (1966) concluded that with a windspeed of 24 km hr^{-1}, surface air can penetrate a coarsely-structured soil to a depth of several cm. They predicted that for particles of 10 mm diameter, the gas flux across the soil surface could be as much as 100 times the molecular diffusion flux. Kimball and Lemon (1971) measured the flux of heptane vapour through beds of different sized aggregates. They found heptane fluxes of between three and ten times the predicted diffusion flux through beds of 18 mm aggregates and of between two and four times the predicted flux through beds of 3 mm aggregates. Hydrodynamic dispersion in beds of aggregates due to air turbulence was examined by Scotter and Raats (1969). They predicted vapour fluxes of from two or four times the molecular diffusion flux for evaporation from a depth of 2 cm below the surface of a random packing of spheres of 40 to 60 mm diameter.

Meteorological factors, as well as soil structure, influence the rate of loss of water from soil. Various combinations of radiant energy, wind speed, air temperature, and relative humidity have been simulated in many experiments to examine the relative importance of these factors in causing evaporation of water. In most cases, the experiments have been conducted under isothermal and steady state conditions. The effect of radiation is well known, but the effects of the other factors are less well understood.

Aristotle was quoted by Penman (1956) as saying that wind is the most important factor in evaporation because it carries the vapour away. In a wind tunnel experiment, Hanks and Woodruff (1958) measured the evaporation rate from a wet soil with a soil mulch on top of it. The evaporation rate was increased two or six times when windspeed was increased from 0 to 40 km hr^{-1}. Porous materials, including soils and beads were packed into cylinders by Scotter *et al.* (1967). The dispersion of oxygen was found to be at least 50% greater when there was wind than when there was no wind. Hadas (1975) investigated the drying of layered soil columns under controlled but non-isothermal conditions. Sieved wet loamy soils were packed into insulated columns and subjected to continuous infra-red radiation, intermittent radiation, and alternate wind. Cumulate evaporations over thirty days were in the order wind > continuous radiation > intermittent radiation.

The effects of wind and radiation interact. In their wind tunnel experiments, Holmes *et al.* (1960) found that the evaporation rate from aggregate beds was considerably larger when wind and radiation were both present than when either was present separately. Field measurements of radiation, air temperature, relative humidity, and wind speed were conducted by Skidmore *et al.* (1959). The wind dominant and radiation dominant components of evaporation were separated using equations based on Penman's (1948) approach. On representative and consecutive 'non windy' and 'windy' days (mean wind speeds at 45 cm of 3.2 and 8.1 k.p.h.), the wind dominant term contributed 33% and 113% respectively as much as the radiation dominant term to the total evaporation. Skidmore and Hagen (1967) calculated evaporation rates from meteorological data collected in different parts of the U.S.A. They found that when radiation dominates, that is, when both the vapour pressure deficit and wind speed are small, a windbreak reduces evaporation only slightly. When vapour pressure deficit and wind speed are high, a windbreak greatly reduces water loss by evaporation.

Hide (1954) calculated the water vapour pressure as a function of depth in the top 10 cm of soil. He concluded that the driving force for evaporation is the vapour pressure difference between the air into which the water vapour is moving and that in the upper layer of soil from which evaporation is taking place. The temperature of the layer of soil from which evaporation is taking place is a factor controlling the vapour pressure in that layer. In the laboratory, Cary (1967) gave moist soil columns nine different treatments including artificial radiation and different ambient vapour pressures. He concluded that the most effective method of reducing evaporative water loss depends in part on the vapour pressure of water in the air above the soil surface. If the vapour pressure is relatively high, then evaporation is best reduced by screening the surface from incoming radiation so that it does not heat-up to the point where its water vapour pressure is greater than that of the air at the surface. On the other hand, if the atmosphere is very dry, evaporation control will require a reduction in the coefficient of transfer of water vapour to the soil surface. Because most of the transfer occurs through the soil pores, this approach requires a knowledge of the pore size distribution in the dry surface layer. This chapter presents the results of a field study of the effects of soil macro-structure on the effects of meteorological conditions on the water content of the tilled layer of soil. The work is aimed at determining those structural features of tilled soil which are associated with evaporative loss of water. The production of seedbeds which do not contain those features should conserve maximum tilth water and should contribute to the optimum germination and survival of seedlings in the critical post-sowing period.

7.2 Hypothesis

As a result of air turbulence, atmospheric air penetrates tilled soil mainly through pores larger than 8 mm and to a depth of about 5 cm (Chapter 6). It is therefore hypothesized that these pores will also form a structural factor mostly responsible for water evaporation.

This hypothesis is based upon the concept that heat carried into tilled soil and air flow are both very important for evaporation.

7.3 Materials and Methods

7.3.1 Tillage treatments

The field experiment was located at the Mortlock Experiment Station of the Waite Agricultural Research Institute (33° 55'S, 138° 43'E, attitude 430 m). The soil on the site is a loam (60% sand, 21% silt, 19% clay) and belongs to the Red-Brown Earth group (Stace *et al.*, 1968). Each tillage treatment was done on 7th July, 1976 in a North-South direction and to a depth of 10 cm with a disc plough (D), disc plough + scarifier (D + Sc), disc plough + combine drill (D + CD), mouldboard plough (MB), mouldboard plough + combine drill (MB + CD), scarifier (Sc), and rotary cultivator (RC). These treatments provided a range of eight different soil macro-structures. Tillage was done at a water content of 22.7% (dry weight basis). This is slightly wetter than the Plastic Limit for this soil (21.2%).

7.3.2 Sample collection and structural data

Tilth block samples were collected from tilled plots immediately after tillage on 7th July, 1976; and also on 18th October, 1976, and 11th January, 1977. The method of Dexter (1976) described in Chapter 3 was used. Structural data were collected at about the 5 cm depth from two sawn sections on each of the eight tilth block samples, while data from each section were collected separately from two cross-section lines. Therefore, there were four sets of structural data collected from each of the tilth blocks. The form of the structural data has also been described. The data consist of linear distribution of aggregates and pores at 1 mm intervals across the section. The raw structural data were processed along lines already described to get the following data. Structural data presented in the text are the means from the July and October data.

(1) The probabilities P(O) of 0 following the 16 possible structural precursors and the occurrence probabilities U_i for the precursors (Tables

4.1 and 4.2).

(2) From (1), the void size distributions (Table 4.6) for each treatment were calculated by the method of Dexter and Hewitt (1977) described in Chapter 3.

The primary structural data for July are given in Appendix I for the eight differently-tilled plots, while the data for October samples are given in Appendix II.

7.3.3 Water content and temperature data

Samples for gravimetric water content determination were collected at 5 and 10 cm depths from each tilled plot. Temperatures (^{o}C) at these depths were measured as much as possible at 3 hr intervals in Winter for 8 days (July 8th to 15th, 1976), and in Spring for 5 days (October 18th to 22nd, 1976).

Soil samples were collected as nearly as possible at the same times at which soil temperatures were measured. Each water content was replicated twice. Soil samples were dried in an oven for 24 hr at 105^{o}C.

Temperature measurements were replicated three times at each depth on each tilled plot. Temperatures were measured with thermistors which were individually calibrated in the laboratory before the experiment. The calibration of the thermistors has been discussed in Chapter 6. Thermistors were inserted to the appropriate depths using calibrated pegs. The resistance values of the thermistors were measured with a battery-powered portable multimeter.

Water content and temperature measurements were also made in Summer for three days (January 11th to 13th, 1977). They are not used in this Chapter because the water content data were scanty. The water content

Table 41. Structures of differently tilled plots. Values of P(0) are the probabilities of a 0 following the sixteen precursors. An asterisk indicates that the precursor had no occurrence.

Precursor	P(0) for Plot							
	D	D+Sc	D+CD	MB	MB+Sc	MB+CD	Sc	RC
0000	0.852	0.797	0.813	0.885	0.894	0.755	0.870	0.758
0001	0.014	0.000	0.000	0.021	0.000	0.000	0.000	0.000
0010	1.000	1.000	1.000	1.000	*	1.000	*	1.000
0011	0.048	0.055	0.015	0.050	0.000	0.100	0.036	0.023
0100	1.000	1.000	1.000	1.000	*	1.000	0.500	1.000
0101	*	*	*	*	*	*	*	*
0110	0.500	0.250	1.000	1.000	*	0.875	1.000	1.000
0111	0.054	0.049	0.000	0.046	0.084	0.069	0.028	0.056
1000	0.775	0.763	0.967	0.748	0.725	0.875	0.859	0.853
1001	0.000	0.050	0.050	1.000	0.000	0.125	0.000	0.200
1010	*	0.000	*	*	*	*	1.000	*
1011	0.000	0.375	0.000	*	0.000	0.000	0.000	*
1100	0.857	0.695	0.846	0.984	0.894	0.662	0.791	0.817
1101	0.000	0.000	0.000	*	0.000	0.334	0.167	*
1110	0.865	0.897	0.905	1.000	0.943	0.956	0.791	1.000
1111	0.032	0.026	0.032	0.028	0.032	0.037	0.031	0.030

Table 42. Structures of differently tilled plots. Values of Ui are the occurrence probabilities for the sixteen precursors.

Precursor	Ui for Plot							
	D	D+Sc	D+CD	MB	MB+Sc	MB+CD	Sc	RC
0000	0.111	0.108	0.171	0.145	0.143	0.111	0.128	0.090
0001	0.021	0.013	0.018	0.022	0.021	0.021	0.015	0.021
0010	0.0003	0.0004	0.0002	0.0008	0.00	0.0005	0.00	0.0005
0011	0.024	0.019	0.021	0.002	0.023	0.031	0.020	0.025
0100	0.0003	0.0004	0.0002	0.0008	0.00	0.001	0.001	0.0005
0101	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0110	0.001	0.002	0.0004	0.001	0.00	0.003	0.0005	0.0005
0111	0.025	0.024	0.022	0.021	0.024	0.028	0.023	0.024
1000	0.021	0.013	0.018	0.022	0.021	0.020	0.015	0.021
1001	0.004	0.006	0.003	0.0004	0.003	0.010	0.005	0.005
1010	0.00	0.00	0.00	0.00	0.00	0.001	0.001	0.00
1011	0.001	0.003	0.002	0.00	0.001	0.001	0.004	0.00
1100	0.024	0.019	0.021	0.02	0.024	0.029	0.019	0.025
1101	0.001	0.003	0.002	0.00	0.001	0.001	0.005	0.00
1110	0.025	0.020	0.022	0.021	0.024	0.028	0.024	0.024
1111	0.740	0.771	0.700	0.723	0.715	0.713	0.739	0.763

values were very small (less than 5%).

The primary water content data are in Appendix IV, while the temperature measurements are presented in Appendix III.

7.3.4 Meteorological data

A meteorological station was located 1 km from the experimental site on land with a similar aspect. Air temperature (^{o}C) and relative humidity (%) values were obtained from an automatic recorder 2 m above the ground level.

Wind speeds (km hr^{-1}) were obtained from a recording anemometer 0.5 m above the ground. There was no rain in any experimental period. Solar radiation figures for the site were not available.

7.3.5 Water characteristic curve

The wetting and drying curves of the water characteristic of this soil were constructed (Fig. 33). These were obtained using sintered glass funnels for water potentials of -0.1 bar and below, ceramic plate extractors for potentials up to -15 bar, and desiccators containing saturated solutions of salts for potentials greater than -15 bar.

The relationship between matric potential and relative humidity is expressed, in the absence of dissolved salts, by

$$\Psi_m = C \log_e \left(\frac{h}{100}\right) \qquad (75)$$

where Ψ_m is the matric water potential or suction (bar), h is the relative humidity (%), and C is given by

$$C = \frac{\rho RT}{M} \qquad (76)$$

Here, ρ is the density of water (1000 kgm^{-3}), R is the gas constant

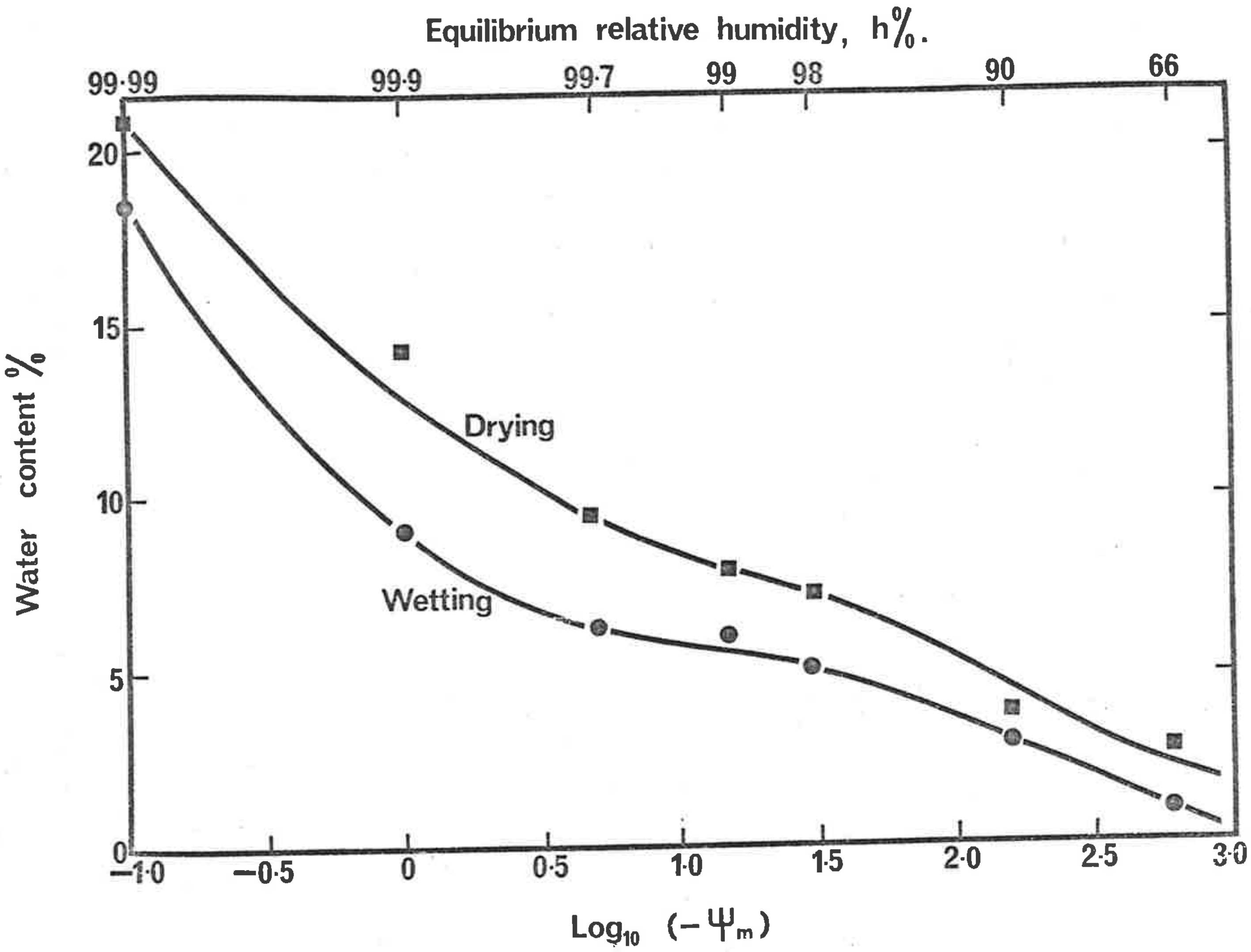


Fig. 33. The water characteristic (wetting and drying) of the red brown earth loam at Mortlock Experiment Station. The water potential, Ψ_m, is in bar.

(8.314×10^3 JK^{-1} $mole^{-1}$), T is absolute temperature (K), and M is the molecular weight of water (18 kg). The value of C is 1377 bar at 25°C.

Potentials of -572, -145, and -32 bar were applied by the use of saturated solutions of $NaNO_2$ (h = 66%), $ZnSO_4$ (h = 90%), and KCl (h = 97.7%) respectively at 25°C.

7.4 Results and Discussion

The tilth water content data collected in Winter and Spring were subjected to statistical analysis. Linear relationships were assumed in the regressions of tilth water content and water content gradient on meteorological factors. The soil structural factors responsible for tilth water loss are considered, and as a result, void size distribution is related to tilth water content.

7.4.1 Trends in water contents of tilled soil

The mean water contents of differently tilled soils were significantly different as shown by statistical analyses (Table 42). The mean water contents are means for the two depths at each time of day for Winter and Spring. The differences in structures of soils tilled with different implements led to their different water contents.

Water contents in tilled soils varied significantly from one season to the other. The mean water contents for the two depths and for all days were 13% and 16% in Winter and Spring periods respectively. The total amount of rainfall before tillage in 1976 and 121 mm, and it was 207 mm in the interval between the two experimental periods. Mean air temperatures were 10.9°C and 14.7°C in Winter and Spring, and the equivalent mean tilth temperatures were 8.3 and 15.7°C. Solar radiation figures for the Waite Agricultural Research Institute (34° 58'S, 138° 38'E, altitude 122 m), which experienced similar weather patterns during the experimental periods, averaged 8.6 and 17.1 MJm^{-2} day^{-1} respectively. The mean wind speeds were 4.1 and 5.3 km hr^{-1}, and the mean relative humidities were 69% and 64% respectively. Therefore all the factors which could cause loss of tilth water were more intense in the Spring period.

Table 43. Analysis of variance of tilth water contents.

Source of Variation	df	SSD	MSD	F	Test (95%)
Total (Winter)	39	443.6			
Tillage plot (Spring)	7	29.03	4.15	15.37	***
Tillage plot, 5 cm (Winter)	7	27.44	3.92	3.88	***
Depth (Spring)	1	19.46	19.46	4.14	***
Depth (Winter)	1	46.88	46.88	6.32	***
Time (Winter)	4	311.76	77.94	132.49	***
Residual (Spring)	18	4.89	0.27		

Tilth water decreased progressively from sunrise to sunset each day. Mean (for both depths and all tillage treatments) water contents at 06.00, 09.00, 12.00, 15.00, and 18.00 hrs C.A.S.T. (Central Australian Standard Time) were 16.1, 14.5, 13.4, 12.9, and 7.7% in Winter. In Spring, mean (for both depths and all tillage treatments) tilth water contents at 06.00, 12.00, and 18.00 hrs were 18.1, 16.3, and 14.3% respectively.

7.4.2 Regression of water content on tillage treatment effect and meteorological factors

The mean water contents for each time of day on the tilled plots, and the values of the independent variables at the times of water content measurement were merged for the purpose of regression. The independent variables were tilth temperature, air temperature, wind speed, and relative humidity.

Multiple regression of water content on the independent variables was first performed separately for each plot and for each experimental period. The query then was whether the regression coefficients obtained for the different tillage treatment plots were significantly different. It was noted that errors in the 'independent' variables were almost certainly not negligible relative to those in the dependent variable, and some other multivariate analysis technique seemed more appropriate. More progress was made by interactive analysis of variance using a model called Rothamsted Generalized Linear Model program, GLIM.

For the Winter data, the mean square (MSD) for treatments plus regression is very close to the residual mean square ($F_{39, 138} = 0.77$) as shown in Table 44. It therefore appears that this attempt to attribute the observed variation in tilth water contents to differences in tilth structure and to meteorological factors was unsuccessful. However, separate analysis of variance performed to test differences in water contents at the 5 cm depth (Table 43) showed that the values of water content were significantly different at 95% level. The values at the 10 cm depth were, however, not significantly different.

The insignificant effects of meteorological factors such as air temperature and wind on water content inside tilled soil in Winter would be due mainly to their low intensities and the resultant low evaporation.

For the Spring data, the full model of main effects, covariates and their interactions with the main effects was slightly too large for the analysis package GLIM. However sufficient reduction in model size was obtained by omitting just one interaction. A larger number of treatment

Table 44. Analysis of variance for the regression of tilth water content on air temperature, tilth temperature, relative humidity, and windspeed - Winter data.

Source of Variation	df	SSD	MSD
Treatments + regression on all variables within each treatment	39	548	14.05
Residual	138	2531	18.34
Total	177	3079	

Table 45. Analysis of variance for the regression of tilth water content on air temperature (Ta), tilth temperature (Tt), relative humidity (h), and windspeed (u) - Winter data (A).

Source of Variation	df	SSD	MSD	Test (99.9%)
Treatments				
Regression on Ta, u and h within each treatment + global regression on Tt (model I)	31	387.7		
Global regression on all variables	4	354.1		
Differences due to regression on Ta, u, and h within treatments	27	33.6	1.24	NS
Residual (model I)	29	68.64	2.36	
Regression on Tt, Ta and u within each treatment + global regression on h (model II)	31	390.99		
Difference due to regression on Tt, Ta and u within treatments	27	36.89	1.36	NS
Residual (model II)	29	65.11	2.25	
Total	69	561.9		

Table 46. Analysis of variance for the regression of tilth water content on air temperature (Ta), tilth temperature (Tt), relative humidity (h), and windspeed (u) - Spring data (B).

Source of Variation	df	SSD	MSD	Test (99.9%)
Treatments	9	105.8	11.76	***
Regression on Tt, Ta, u and h	4	354.1		
Regression on Ta, u and h	3	353.6		
Difference due to regression on Tt	1	0.5	0.5	NS
Regression on Tt, u and h	3	221.0		
Difference due to regression on Ta	1	133.1	133.1	***
Regression on Tt, Ta and h	3	336.8		
Difference due to regression on u	1	17.3	17.3	***
Regression on Tt, Ta and u	3	285.7		
Difference due to regression on h	1	68.4	68.4	***
Residual	56	102.0	1.82	
Total (corrected)	69	561.9		

plots just planted with barley (BL). The plots were given tillage treatments as D + CD and MB + CD. At 95% level water contents from MB + CD and MB + CD + BL on one hand; and D + CD and D + CD + BL on the other hand were not significantly different. The differences were less than 2%. Consideration of models which were complete except for a single interaction showed that there was no advantage in fitting separate regression coefficients within each treatment (Table 44).

For the Spring data, analysis of variance showed that the tillage treatment effect (β), the air temperature (Ta), the relative humidity (h), and the wind speed (u) all contributed significantly to variations in tilth water content. The analysis of variance using pooled estimates of regression coefficients is shown by Table 46. The only covariate which does not contribute significantly to the total variation in tilth water content is the tilth temperature (Tt).

The fitted model for the percentage water content, w, is

$$w = \underset{(\pm\ 4.1)}{54.4} + \beta - \underset{(\pm\ 0.12)}{1.25Ta} - \underset{(\pm\ 0.03)}{0.10u} - \underset{(\pm\ 0.04)}{0.25h}, \qquad (77)$$

where the figures in brackets are standard errors of the coefficients. The tillage treatment effects, β, took the values -4.01, -2.57, -4.20, -3.53, -3.06, -2.75, and -1.92 for treatments D, D + Sc, D + CD, MB, MB + Sc, MB + CD, and Sc relative to the value of 0 for the RC treatment.

A plot of the ranked residuals (observed minus expected values) against the normal order statistic was approximately linear, suggesting that the implicit assumption of normally distributed errors was not unreasonable.

When the above model was tested with reference to the plot tilled with the disc plough, values of predicted water contents were considerably (by about 5%) larger than the actual water contents when air temperature was lower than 14°C. This probably indicates that a factor which could

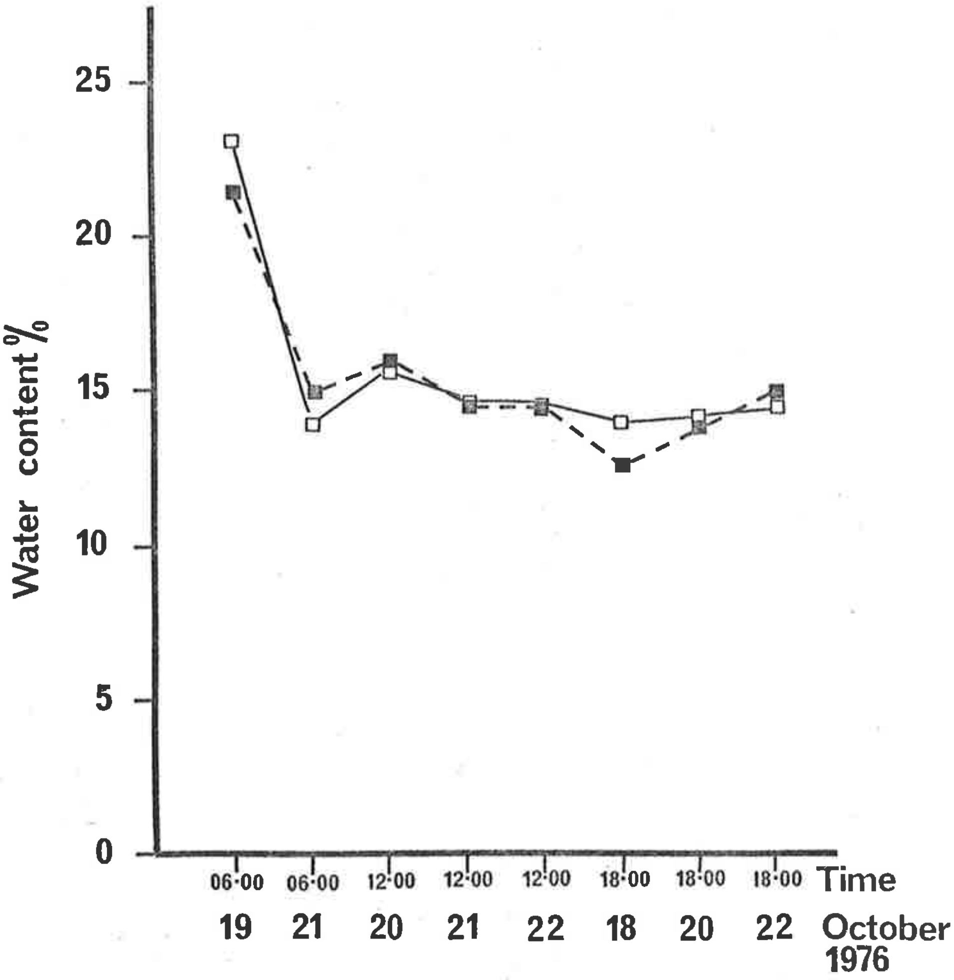


Fig. 34. Actual(□——□) and predicted(■– – ■) water contents of a disc ploughed soil. Predicted values are obtained by substituting meteorological values into equation 77.

account directly for the intensity of solar radiation, or cloud cover might be needed to be incorporated into the model.

The predicted and actual water contents when air temperature was not lower than $14^{o}C$ are presented in Fig. 34. The model predicts tilth water content to within 2% under this condition.

7.4.3 Tilth structure and water content

The mean values of macroporosity (η_L) for Winter and Spring were correlated with the equivalent mean water contents of the tilled plots. The statistically-derived tillage treatment effects (β) were also correlated with values of η_L.

7.4.3.1 Structural factor determining water evaporation

The regression of tilth water content (w) on η_L gave

$$w = -28.0\eta_L + 20.1 \quad (\gamma = -0.68) \qquad (78)$$

The regression of treatment effect (β) on η_L gave

$$w = -38.1\eta_L + 4.6 \quad (\gamma = -0.69) \qquad (79)$$

The above results show that water loss from a prepared seed bed is determined mainly by the presence of pores larger than 1 mm in diameter.

7.4.3.2 Pore size distribution and tilth water loss

In order to determine what void size range relates best with the observed trends in tilth water content, regression of tilth water content on macroporosities in pore size ranges less than or equal to 2, 4, 8, 16, and 32 mm was done. The porosity contributed by a pore size range was obtained by multiplying tilth macroporosity by the proportion of the pore size range in the tilth.

Table 47. Pore size distributions in differently tilled plots expressed by the macroporosity (n_L) in a pore smaller or equal to X mm.

X	Porosity							
	D	D+Sc	D+CD	MB	MB+Sc	MB+CD	Sc	RC
2	0.036	0.067	0.053	0.000	0.034	0.072	0.069	0.029
4	0.085	0.106	0.094	0.058	0.096	0.110	0.096	0.075
8	0.132	0.134	0.158	0.077	0.138	0.156	0.130	0.128
16	0.169	0.149	0.189	0.181	0.182	0.182	0.162	0.154
32	0.182	0.154	0.212	0.206	0.206	0.193	0.182	0.162
Total n_L	0.183	0.164	0.232	0.213	0.211	0.195	0.189	0.162

Table 48. Correlations between macroporosity in pores smaller or equal to X mm (n_L), tillage treatment effect (β), and tilth water content (w).

X	Regression w/n_L	Correlation $w \infty n_L$	Correlation $\beta \infty n_L$
2	$w = 1.45n_L + 14.57$	0.04	0.08
4	$w = 9.02n_L + 7.83$	-0.15	-0.03
8	$w = 13.09n_L + 16.35$	-0.33	-0.06
16	$w = 49.03n_L + 23.02$	-0.72	-0.67
32	$w = -31.03n_L + 20.44$	-0.67	-0.65

Negative correlations between mean macroporosities in pore size ranges and mean water contents of tilled soils (Table 48) confirm that the structural factor mainly responsible for evaporation from tilled soil are the pores larger than 1 mm. But the pores that are mostly responsible for water evaporation from the tilth are those larger than 8 mm, and especially those between 8 and 16 mm in diameter. It can be seen that the correlation coefficient is very low for pores smaller than 8 mm, but suddenly increases when porosity in the range 8-16 mm is included.

It is concluded that the convective flow of air which occurs mainly through pores larger than 8 mm (Chapter 6) results in evaporative water loss, and is the principal mechanism for the drying of the tilled layer of soil.

The large effect of the pores having 8-16 mm diameter on the evaporative loss of tilth water will be due to their great frequency, in addition to their largeness. It is shown in Chapter 5 that the pores between 9 and 16 mm which are usually the most frequent mostly determine tilth macroporosity.

The negative correlations (Table 48) between tillage treatment effect (β) and macroporosities in different pore size ranges show that tillage increases the proportion of pores that are mostly responsible for water evaporation. This means that a relatively compact and less coarse seedbed will conserve more water than a highly porous and coarse seedbed. The above conclusion is relevant especially to the kind of climatic condition that exists in most parts of Australia where wheat is grown with as little as 250 mm of annual rainfall and where potential annual evaporation is up to 2000 mm. Braunack and Dexter (1977) conducted open air experiments at the Waite Agricultural Research Institute and found that compaction of beds of aggregates could reduce evaporation by as much as 10%.

7.4.4 Effects of temperature and wind speed on tilth water evaporation

When meteorological factors exert significant influence on water evaporation from a tilth, the temperature dominant evaporation will be more than wind dominant evaporation. The relative effects of temperature and wind intensity in evaporation are depicted in eq. 77. High soil temperature increases vapour pressure within the tilth, and the vapour pressure gradient from the tilth to the atmosphere is greatest in the afternoon (Hide, 1954). Wind speed is a matter of degree, thus a perfectly still air seems impossible. Mild surface turbulence significantly increases the rate of water vapour diffusion out of the soil especially when soil temperature is high as shown in eq. 77 above. Cary (1967) said that even low wind velocities over the surface produce a viscous soil air flow of a magnitude equal to that of molecular diffusion. Wind also carries into the soil a quantity of energy that causes evaporation. Nocturnal evaporation which varies between 10 to 50% of daily evaporation was attributed in part (Rosenberg, 1969) to the turbulent transfer of sensible heat from the surface air. Therefore, the effects of wind and radiation interact, and it will be unrealistic to demarcate strictly between the effects of temperature and wind in evaporation.

When evaporation is small as a result of reduced temperatures and large percentage of cloud cover as in Winter, wind will be more effective in evaporation than temperature. The mean tilth water contents for the different times of day were correlated with equivalent values of temperature and windspeed. As expected, the correlation coefficients were very small. At 5 cm, the correlation between tilth water content and air temperature, and windspeed were -0.01, and respectively -0.32. At 10 cm they were -0.14

and -0.18. It can be seen that in the cold weather wind becomes the more important meteorological factor of evaporation.

It is also shown by the above results that wind exerts its main influence down to the 5 cm depth but not to 10 cm. This confirms the finding in Chapter 6 and that of Farrell *et al.* (1966) that surface air penetrates in main to within 6 cm depth of tilled soil.

The above discussion lends support to the conclusions of Hide (1954) and Cary (1967) that evaporation could effectively be controlled by lowering the temperature of the upper fringe of moist soil to reduce vapour pressure which provides the driving force for evaporation.

7.4.5 Negative relationship between tilth water content and relative humidity

Tilth water content is negatively regressed on atmospheric relative humidity (eq. 77). Cary (1967) also presented data to show that ambient vapour pressure and soil water loss were not related by an inversely proportional constant as usually suggested. The explanation was that as evaporation is reduced by lowered vapour-diffusion coefficient, more of the energy supplied to the soil surface is used in warming the soil. The increase in soil temperature will raise the vapour pressure of the soil water and as a result increase the vapour pressure gradient towards the surface. Consequently, the rate of water loss will be something less than inversely proportional to the ambient pressure. The increase in relative humidity that accompanies a decrease in soil water content is therefore a result of increased water loss from the soil to the atmosphere. Wind turbulence that reduces the accumulation of water vapour above the soil is intermittent.

7.4.6 Depth variation in tilth water content

7.4.6.1 Tilth water gradient

Winter and Spring data were pooled together. Tilth water content was always greater at the 10 cm depth than at the 5 cm depth. The differences in w between the two depths are shown for different times of day in Table 49.

The tilth water content gradient was regressed on mean tilth temperature, wind speed, and atmospheric relative humidity. After the regression was performed separately for each treatment plot, it was intended to test for variation within treatments, and the significance of the effect of each independent factor. The closeness of the values of residual and treatment mean squares (Table 48) shows that the factors which might have been expected to influence water content gradient had an insignificant effect, particularly in Winter. This result parallels the insignificant effects of meteorological and treatment factors on tilth water content in Winter, referred to earlier (Section 7.4.2).

The difference between water contents at 10 cm and 5 cm depths decreased slightly during the mornings and increased more strongly from mid-day until evening (Table). Over this same period of the day, the mean water contents of the tilled plots decreased progressively. This shows that the meteorological factors of evaporation were more effective at the 5 cm depth than at 10 cm.

Two factors contribute to the greater water content at the base of the tilth relative to the top. One of them is the continual replenishment that occurs from the 'stored' water in the undistrubed soil underlying the tilth. Another, and often overlooked factor, is the downward movement of water evaporated from the top of the tilth. This effect is greatest in the middle of the day when temperature, and hence

Table 49. Analysis of variance for the regression of water gradient on tilth temperature, relative humidity, and windspeed.

Source of Variation	df	SSD	MSD
Treatments and full regression within each plot treatment	31	12.92	0.417
Residual	136	46.55	0.342
Total	167	59.47	

Table 50. Difference in water contents at 10 and 5 cm depths of differently tilled soils (w10 - w15%).

Time*	Plot								Mean
	D	D+Sc	D+CD	MB	MB+Sc	MB+CD	Sc	RC	
0600	3.74	5.64	5.35	4.53	3.76	3.92	4.29	6.92	4.77
0900	2.69	4.52	3.02	4.42	4.76	3.69	6.19	4.82	4.26
1200	3.15	4.78	3.57	4.06	4.20	2.20	4.16	7.26	4.17
1500	5.02	4.9	4.05	5.99	5.19	4.74	5.83	7.34	5.38
1800	5.93	8.13	5.60	7.08	4.83	6.03	7.29	7.56	6.56

* Mean for each time in Winter and Spring.

water vapour pressure, decreases with depth (Rose, 1968; Jury and Miller, 1974). Observed mean temperature gradients in tilled soils between the 5 cm and 10 cm depths from 12.00 to 15.00 hrs were 0.3 and $0.4^{o}C\ cm^{-1}$ in Winter and Spring respectively. Between these times, increases in water content at 10 cm depth in the eight differently-tilled plots being considered varied between 0.3 to 7% in four days in Winter.

It was neither possible nor sensible to calculate vapour pressure gradients and diffusion rates in the tilled soils. In the macro-structured soil, convective and turbulent effects predominate, and equilibrium or steady state conditions do not exist.

7.4.6.2 Daily loss of tilth water

The losses of water in three days at the 5 cm and 10 cm depths in the tilths during the day (06.00 to 18.00 hrs) are shown in Table 51. Of course, the night-time gains of water are equal to these losses (Chapter 8). The loss of water was, on average, 2% greater at the 5 cm depth than at the 10 cm depth.

There was no significant correlation between these water content changes and any soil structural parameter examined. However, as can be seen from the Moisture Characteristic Curve (Fig. 36), a given change in water content in a drier soil corresponds to a larger change in matric potential than would be the case in a wetter soil. Since eqs. 69 and 70 show that soils with greater macroporosities have smaller mean water contents, it can be inferred that soils with greater macro-porosities will suffer a greater daily fluctuation in water matric potential. An exact analysis of this effect is confounded by the hysteresis phenomenon.

Water was constantly being evaporated from the tilth because at all times of the day especially in Winter and Spring a potential gradient was existing from the tilth to the air. This is shown by Table 52. The

Table 51. Water losses at 5 and 10 cm depths in differently tilled plots (%)*.

Date	Depth (cm)	D	D+Sc	D+CD	MB	MB+Sc	MB+CD	Sc	RC	Mean
July	5	9.0	8.2	3.2	3.4	3.3	3.1	0.3	2.5	4.1
12th	10	7.7	5.9	1.9	1.8	6.5	1.3	-2.5	1.0	2.9
July	5	24.0	23.1	13.9	17.7	20.4	15.2	27.9	21.4	20.5
14th	10	19.2	19.8	15.6	10.2	18.4	12.0	24.6	24.6	18.1
October	5	13.9	11.3	9.9	9.3	11.9	10.6	11.3	10.8	11.1
20th	10	12.2	9.6	10.6	8.1	11.2	8.7	9.4	11.9	10.2

* Between 0600 and 1800 hrs local time.

Table 52. Mean values of water content, water potential, relative humidity, tilth and atmosphere average over the eight tilled plots and all days of observation.

Date 1976	Time	Mean tilth w (%)	Water potential (bar) Soil***	Water potential (bar) Atmosphere**	Soil h/100***	Atmosphere h/100*
July	1200	13.5	-0.7	-848.5	0.99	0.54
	1500	12.9	-1.0	-1040.0	0.99	0.47
	1800	7.7	-14.1	-774.0	0.97	0.57
	0900	14.5	-0.6	-433.4	0.98	0.73
	0600	16.9	-0.3	-377.9	0.99	0.76
Oct.	0600	18.2	-0.2	-491.1	0.99	0.70
	1200	16.4	-0.3	-954.5	0.99	0.50
	1800	14.5	-0.6	-823.2	0.98	0.55

* Meteorological data.

** Calculated from meteorological data.

*** Estimated from water characteristic curve (drying).

highest vapour pressure recorded in the atmosphere during Winter and Spring periods was 0.76 (at 06.00 hr). The minimum tilth water content was 7.7% (at 18.00 hr) and the equivalent relative humidity (as derived from the drying Water Characteristic Curve) was 0.99. Therefore, except when tilth water content is as low as 2% when the vapour pressure and suction (water potential) will be 0.66 and -572 bar respectively, water will be evaporated from the tilth.

The values of soil water potential given in Table 52 are underestimated (at 25°C) relative to that of the atmosphere since no mean tilth temperature (for the eight differently tilled plots and for the days of observation) was as high as 25°C. This lends more support to the above argument.

7.5 Conclusions

This field study attempted to investigate the effects of macro-structure on the water content of tilled soil. A method of structure measurement was used which took account of soil variability. However, the variability in the water content measurements was large and further replication of sampling would have been an advantage. This would not be possible without an extensive automatic recording system.

In spite of the limitations of the experiment, it has been shown that macro-structure can modify the mean water content of soil by several percent, but does not influence the diurnal range of water content. This is the opposite of the findings with soil temperature, where macro-structure modified the range but not the mean (Chapter 6).

Correlation with different portions of the pore size distribution showed that differences in tilth mean water content were associated with the porosity in pores larger than 8 mm. This is consistent with the hypothesis that the drying of tilled soils occurs mainly by the convective transport of water vapour through these large pores. This supports the findings of earlier theoretical, laboratory, and field studies on beds on sieved aggregates.

Effects of meteorological factors were assumed, for convenience, to be additive. Air temperature had the greatest effect on tilth water content followed by wind speed. Radiation was the most important meteorological factor omitted from this study. However, it is unlikely that it would have a direct influence on phenomena beneath the soil surface except through its influence on soil temperature (which was not significantly correlated with water content).

Tillage with different implements produces different soil macro-structures which can influence the water status of the soil. If there are pores larger than 8 mm, then significant drying can occur by convective transport of water vapour. If there are no pores larger than 2 mm, then water loss will be confined to the more usual mechanisms of diffusion through the void spaces and conduction through the regions of mutual contact of aggregates.

7.6 Practical implications of findings

Because the presence of pores larger than 8 mm in diameter is mostly responsible (as a structural factor) for water evaporation from a tilled soil, a few centimeters of loose, pulverised soil around the seed is necessary as a measure against fast dehydration of the soil, and seed in the critical post-plating period.

Other workers (Kolasew, 1941 (cited by Johnson and Buchele, 1961); Blake, 1963; Braunack and Dexter, 1977) have indicated that fine compacted granule layer can provide a layer of high resistance to water vapour loss.

Secondly, under hot climatic conditions, planted rows could be protected against intense wind turbulence, high temperature, and thus high evaporation rate by mulching with a layer, a few centimeters thick, of crop residues or similar materials.

The observations that water was mainly evaporated from the top 5 cm of tilled soil, and that the voids larger than 8 mm were mostly responsible are consistent with the hypothesis initially set.

CHAPTER 8

TRANSFER AND ADSORPTION OF WATER VAPOUR IN TILLED SOIL

8.1 Introduction

The mechanism of thermally-induced transfer of water vapour in soil were discussed by Philip and de Vries (1957), Rose (1963), and Philip (1968). Some researchers (Rose, 1968a; Matthes and Bowen, 1963; Cary, 1966) gave indications about the agricultural significance of transfer and adsorption of water vapour in soil.

Rose (1968a) developed a theoretical equation for water and vapour flux in two contiguous layers within the 12 cm surface layer of a previously saturated soil. Under conditions of a maximum temperature gradient of $10^{o}C\ cm^{-1}$ and a water potential more negative than -5 bar, net vapour fluxes between the two layers of the soil profile entirely controlled their changes in water content. Rose said that until further investigation was done, the possible importance of vapour transfer in the germination of seeds and in the establishment of plants should not be denied significance. Variations in temperature and water content along soil columns were measured by Matthes and Bowen (1963) when the soils were subjected to temperature gradients. They concluded that the control of water vapour movement could become a practical tool for increasing germination under adverse water conditions. The daily reversal of the temperature gradient in soil was said to furnish an undiminishing source of 'power'. Cary (1966), who reviewed the state of knowledge concerning thermally-induced transport of water, suggested that some water vapour might condense directly on plant roots, and this could be a factor in the reestablishment of plant turgidity during the night. The thickness of water films, diffusion path length, degree of hydration, and elongation of roots (Olsen *et al.*, 1961) are controlling factors of plant uptake of mineral nutrient from soil.

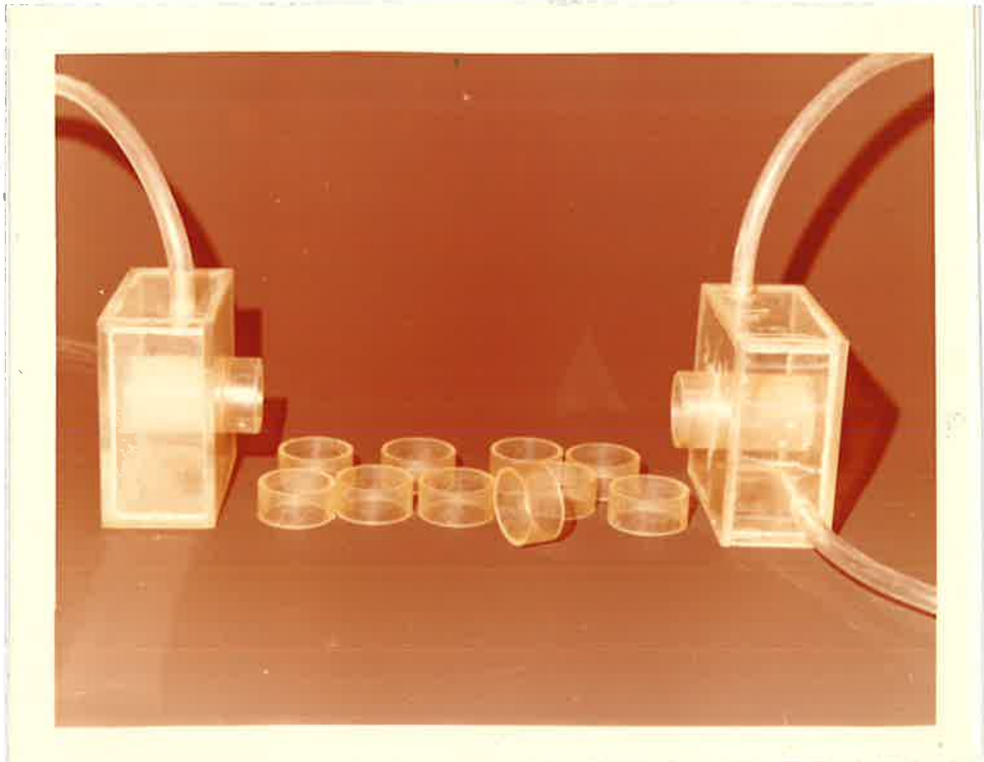
There is a need for field data to show that vapour condensation in the seedbed due to temperature gradients could furnish a significant water supply in the seedbed to help to counteract evaporative loss and to maintain seedling establishment.

Vapour transfer in soil is mainly due to temperature gradients (Marshall, 1959). Joshua and De Jong (1973) imposed three temperature gradients smaller than $1.6^{o}C\ cm^{-1}$ on fine sandy loam soils kept at different water contents. They predicted from calculations of coupling between heat and water flux that more interaction occurred between heat and water flow between -0.1 bar and -15 bar than at other potentials. Hadas (1968) applied heat treatments to wet soil samples for periods up to 32 min. and sampled the columns of soil for water distribution from the hot to the cold end. Water evaporated mainly within 2 cm from the source of heat and when the longest heat treatments were applied, water mainly condensed at about 4 cm from the source of heat.

While there now exists a considerable body of theoretical information on transfer of water, gases, and heat in soil, the practical application of theory to agriculturally-important situations is not particularly advanced (Smiles, 1977).

It was thought to be useful for this work to conduct a laboratory project on transfer and adsorption of evaporated water in soil and collect information on the amount of water involved, the extent of vapour condensation and on the position of the zone of peak condensation. The aim was to relate the results to observed variations in water content at different depths within the tilled soils in the field. It may be possible, as a result of this kind of work, to recommend some

Plate 10. Water jackets with 10 rings used to form a soil column between them.



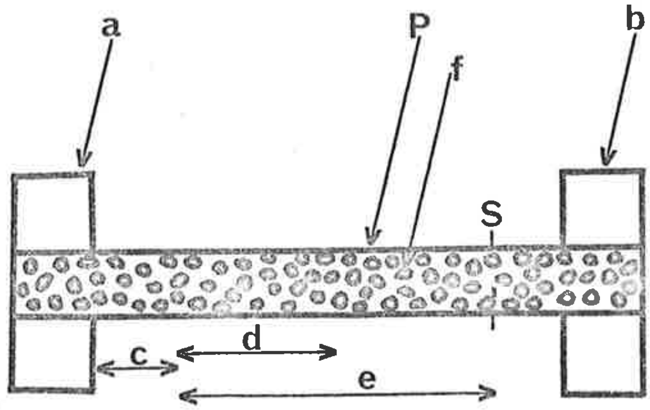


Fig. 35. Diagram of apparatus for setting packed soil aggregates in a temperature gradient.

a = hot water jacket

b = cold water jacket

c = evaporation zone (6 cm)

d = "visible" condensation zone (5-8cm)

e = "estimated" condensation zone (22cm)

f = soil aggregates

P = perspex column

S = last point associated with change in soil temperature and water content due to applied temperature gradient approaches to tilth water conservation for crop establishment.

8.2 Hypothesis

Different magnitudes of variation in water content at different depths within tilled soil will be due to their relative positions in relation to the source of heat and the direction of the temperature gradient.

The above hypothesis is based upon the fact that when water is not limiting, heat is the most important factor causing evaporation (as concluded in Chapter 6).

8.3 Materials and Methods

8.3.1 Soil columns

A perspex apparatus was made (Plate 10, Figure 35). It consisted of two square water jackets with a soil column between them. The length of soil column could be varied by changing the number of perspex rings used to form a continuous column between the two water jackets. Each jacket was 120 mm and 60 mm in length and thickness respectively. Each ring was 44 mm, 20 mm, and 3 mm in diameter, length and wall thickness respectively. Each jacket had a portion of tubing of the same diameter as the rings inside it which extended 2 cm outside the jacket. The net volume of each jacket was about 520 cm^3. When 10 rings were used to link the jackets, the system had a volume of 360 cm^3 which could be filled with soil. The system could be filled with aggregates of the desired size range. The apparatus was tapped during filling to ensure that the maximum packing density was obtained.

The experiment was performed in a constant temperature room

(20^{o}C). One of the jackets contained warm water which was pumped from a constant temperature water bath through rubber tubing. The other jacket contained tap water at close to 21^{o}C. The initial temperature of the enclosed soil was 20^{o}C. A temperature gradient could be set through the column of soil aggregates. The apparatus could be held horizontally or vertically either way. A thick layer of cotton wool insulation was used around the column between the jackets.

Runs were made at three effective differential temperatures of about 30.7, 22.2, and 12.3^{o}C which were equivalent to mean temperature gradients of 1.4, 1.0, and 0.5^{o}C cm^{-1} respectively. These are the gradients that would exist along the whole column after an infinite time. In fact, much greater gradients existed nearer the hot end of the columns initially. Runs were made for 3, 6, 9, and 12 hr periods. The five aggregate size ranges of 7.0-4.0 mm, 4.0-2.0 mm, 2.0-1.0 mm, 1.0-0.5 mm, and a mixed fraction of volume ratio 1.0 : 1.5 : 1.5 : 1.0 were used. This ratio was that at which the fractions were obtained from soil after sieving. In addition to runs in the horizontal position, the apparatus was used vertically both ways for 6 hr runs with all aggregate size ranges to isolate any possible effects of gravity on vapour movement. This could result from the asymmetric nature of thermally-induced convection current. The initial water content of the aggregates was determined in each case.

Immediately after each run, closely equal sections of enclosed soil column were got by breaking it up from the hot end to the cold end for water content determination on a dry weight basis. Wet soil samples were oven-dried at 105^{o}C for about 24 hours. Sectioning at 2 cm intervals was not ideal since the water content varied within and between sections. The distance between two sections was 2 cm which was also the same as the distance between their centre points. Sectioning of the part of the column inside each jacket was made to check for water loss from the warm end. The soil inside each jacket was sectioned into two parts.

The water contents of the soil sections are given in Appendix V. The distances given are from the dry end of the column where the water was evaporated.

8.3.2 Temperatures in soil columns

In order to investigate the temperature profile along columns as a function of time, some additional experiments were performed. Aggregates in the size range 7.0 - 4.0 mm were used and temperatures in the soil columns were measured by inserting thermistors between the perspex rings. This was done for each of the three applied temperatures. Temperatures at these points within the soil columns are presented in Appendix V. Constant temperatures were reached between 70 to 180 min. Further increases mostly 0.1^{o}C in 10 min. were neglected. This confirms the observation of Taylor and Cary (1960) who set columns of silt loam soil within a temperature gradient of 3.6^{o}C cm^{-1}. They obtained steady temperature gradients in 60 to 180 min.

8.3.3 Control treatments

Control treatments were performed by enclosing columns of 7.0 - 4.0 mm fraction in the perspex apparatus with cold water at both ends. Soil columns initially at 14.5, 10.7, 17.0, and 14.9% water contents with no temperature gradient for 3, 6, 9, and 12 hr periods respectively had on average (for different sections of one column)

0, +0.8, +0.7, and 0% water content changes (δw) respectively.

8.3.4 Obtaining wet soil aggregates

The different aggregate size fractions were initially at water contents from 4 to 18%. The field capacity (ψ_m = -0.1 bar) of Urrbrae loam soil (Stace *et al.*, 1968) from which the fractions were sieved out is 18%, while the permanent wilting point is 7% (ψ = -15 bar).

To obtain wet aggregates, slow wetting of dry aggregates was performed. Sieves (1.0 or 0.5 mm) containing dry aggregates were placed on thick cotton wool which had been soaked in hot water in a tray. Hot water was used to reduce the disruption of the aggregates during wetting. After intervals of 5 to 15 min., the wetted portion of soil aggregates was separated from the completely dry portion on top, and the former was air-dried to the required water content. This technique was about 50% efficient in terms of the amount of wet soil aggregates yielded in useful form.

On other occasions, fairly wet soil from the field was sieved, and the resultant aggregate fractions were used directly.

The prepared soils were exposed for at least 3 hours in the constant temperature laboratory before being packed into the apparatus used for the experiment.

8.3.5 Condensation zone

The condensation zone is the portion of soil column in which the water evaporated from the dry end condenses.

After each run, the last section in which evaporated water from the hot end condensed was marked on the perspex. Condensed water could easily be seen on the perspex column. However, this method was not accurate. Changes in water content and temperature attributable to applied mean temperature gradients were detected and traced to points more distant than those indicated by the visual method (Figures 36 and 37). However, the visual method could show the zone where most of the evaporated water condensed. The net loss of water from the hot end was always the same as the aggregated net increase in the condensation zone.

8.3.6 Changes in water content

Changes in water content in sections of the soil columns were calculated. The total increase in water content in sections within the condensation zone was divided by the number of sections involved to get the mean increase in water content. Beyond the visible condensation zone, changes in water content (δw) were not emphasised because the values (< 1%) were generally below those obtained in the control treatments. However, the values were useful in tracing the maximum distances of the influence of applied mean temperature gradients and evaporated water.

The fractions of total condensed water in three sections closest to the evaporation zone were calculated.

8.3.7 Evaporation zone

Water was evaporated from the soil in the tube within the water jacket and from any or all of the three sections nearest (but outside) the water jacket. Evaporation therefore occurred within 6 cm (three sections each 2 cm in length) from the source of heat.

8.4 Alignment of Laboratory and Field Conditions

The three temperature gradients used in the laboratory experiment fell within the limits recorded in the field. The mean temperature gradients used were 0.5, 1.0, and 1.4°C cm^{-1}; while the daily maximum temperature gradients between 5 and 10 cm depths of tilled soils in Winter, Spring, and Summer fell within limits of 0.1 - 1.2, 0.3 - 1.0, and 0.2 - 1.0°C cm^{-1} as shown by data from the experiment sited at the Mortlock Experiment Station (Chapter 6, and Appendix III). Average daily maximum temperature gradients in these seasons were 0.2, 0.6, and 0.5°C cm^{-1} respectively.

The above temperature gradients are considerably smaller than the maximum temperature gradient of 10°C cm^{-1} recorded by Rose (1968a) under the hotter climate of the Northern Territory of Australia. Joshua and De Jong (1973) also imposed gradients of 0.5, 1.0, and 1.5°C cm^{-1} on soil columns at different water contents in their experiment.

Since laboratory temperature data show that temperature changed with time, each temperature gradient used in the laboratory experiment is a mean temperature gradient and is non-steady.

The water contents of the aggregates were within the range of values recorded in the field. In Winter and Spring tilth water contents at 5 and 10 cm depths at the Mortlock Experiment Station (Appendix IV) varied between 3 and 24%, and 13 to 25% respectively, but were mostly in the range of 9 to 15%. The water contents of aggregates used in the laboratory experiment were between 4 and 18%, and mostly in the range of 7 to 11%. These water contents also fall between the wilting point and field capacity which is the range in which coupled transfer of heat and water vapour mainly takes place as described in Section 8.1.

In the laboratory the soil columns could not be exposed to air turbulence resulting from wind between the 5 and 10 cm depths in tilled soil since it has been shown that air turbulence mainly penetrates the top 5 cm.

8.5 Results and Discussion

The changes in soil water content due to condensation of evaporated water, the distances of the condensation zone from the dry end, and the proportions of the total condensed water in the three sections nearest to the dry end are presented in Tables 54, 56 and 57 respectively.

The changes during the day in water content at different depths in tilled soils as observed in the field are presented in Table 53. The data so presented are from the tillage experiment sited at the Mortlock Experiment Station of the University of Adelaide in 1976. The intervals shown cover all days on which water content measurements were done. The figures in brackets are the standard errors of the means from the eight replicates.

Results from the laboratory experiments are compared with field observations.

8.5.1 Change in soil water content due to condensation

As a result of applied temperature gradients, increases in soil water content in the laboratory experiments mainly varied between

Table 53. Mean changes (δw%) in the water contents in eight differently tilled plots at the Mortlock Experiment Station. Figures in brackets are the standard errors of the means.*

Time Interval	Date (1976)	Depth (cm)	δw(%)				
0900-1500	7,9 July	5	-5.8(±1.34)	+3.1(±0.66)			
		10	-4.7(±1.23)	+0.5(±0.80)			
1500-2100	7 July	5	+0.4(±0.86)				
		10	+2.4(±0.80)				
2100-1200	7 July	5	+2.9(±1.36)				
		10	+1.8(±0.90)				
1200-1500	8,9,10,13,15 July	5	+4.0(±2.15)	-6.6(±1.62)	-0.7(±1.23)	-2.2(±1.10)	-0.4(±0.62)
		10	-3.0(±0.73)	-1.2(±1.01)	+1.7(±1.42)	-1.4(±0.64)	+0.7(±0.84)
1500-2400	8 July	5	+3.5(±0.74)				
		10	+3.2(±0.55)				
2400-1200	9 July	5	+1.8(±1.25)				
		10	+3.2(±0.55)				
1200-1800	12,14 July	5	-2.1(±1.04)	-2.9(±0.80)			
		10	-0.7(±0.65)	-2.9(±0.84)			
	19,20,22 October	5	-4.2(±0.45)	-0.9(±0.43)	-0.1(±1.65)		
		10	-3.5(±0.30)	-1.1(±0.39)	-0.4(±0.30)		
1800-0600	12/13,14/15 July	5	+5.4(±0.76)	+10.1(±0.73)			
		10	+3.3(±0.76)	+8.7(±0.57)			
	18/19, 19/20 October	5	+4.4(±0.49)	+9.7(±0.56)			
		10	+3.6(±0.43)	+8.2(±0.41)			
0600-0900	12,13,14,15 July	5	+0.4(±0.61)	+2.3(±1.10)	-12.2(±4.77)	-0.5(±0.79)	
		10	-1.8(±1.57)	-0.6(±1.18)	-9.4(±1.51)	-0.1(±0.72)	
1200-1200	21/22 October	5	-0.3(±0.54)				
		10	+0.8(±0.77)				
1500-0600	10,13 July	5	-1.7(±1.07)	+10.9(±1.58)			
		10	-1.1(±1.06)	+8.5(±1.58)			
0600-1200	17,20,21 October	5	-6.9(±0.34)	+0.9(±0.40)	+0.2(±0.55)		
		10	-6.7(±0.58)	+1.3(±0.38)			

* Primary data are given in Appendix IV.

1 to 2% (Table 54). However, single figures varied between 0.1 and 5%. In the field, when increases in water content as a result of temperature gradients were recorded, the figures fell mainly in the range of 1 to 2% during the hottest times of day.

The suggestion of Cary (1966) was that in response to a temperature gradient, the upward moving water vapour when totally condensed in the soil 4 cm above the evaporation zone would cause an increase in soil water content of less than 0.5% in a soil with bulk density of 1.2. This statement of Cary may sometimes be correct as shown by the present results.

It is proposed that the observed increases in tilth water content during the day at 10 cm depth were due to the condensation of water evaporated from within the top 5 cm of the tilled soil as a result of its greater temperature than that of the zone beneath it. For example, during the hottest times of the day (1200 - 1500 hr) mean increases in water content (for 8 differently tilled plots) on two days of 0.7 and 1.7% were recorded (Table 53) at the 10 cm depth of tilths, and losses of up to 7% were recorded at the 5 cm depth in Winter and Spring. However, as can be seen by the standard errors of these mean values, these changes were not significant. In spite of this lack of significance, in the following the results will be assumed to be correct for the sake of the argument.

Hadas (1968) indicated that the upper 25 to 40 cm of soil is subject to significant diurnal temperature fluctuations, but the most pronounced effects of water movement accompanying changes in thermal gradients occur in the upper 5 to 10 cm.

For the night period (1800 to 0600 hr), field data show increases in water content within 10 cm thick tilths which varied mainly between 3 and 8%. A few increases of up to 12% were recorded. Therefore in this situation, figures from the laboratory are considerably smaller than those from the field. This could be due to the large volume of untilled soil (beneath the tilled layer) from which water moved towards the surface when the direction of temperature gradient was reversed over the night. This movement would be mainly by the mechanisms of conduction and diffusion, however.

8.5.2 Significance of water condensation in tilths

Only a few increases in tilth water content in the field were recorded during the day light hours compared with losses. Secondly, the magnitudes of increases were generally smaller relative to the magnitudes of losses. The increases mainly varied between 1 to 3%, while the losses varied between 1 to 7%. There was obviously a net loss of tilth water by evaporation during the day.

During the night there was a general increase in tilth water, which mainly varied between 3 to 8%. Therefore, under temperate climatic conditions condensation of water vapour in tilth due to daily reversal of temperature gradient will at least reduce the daily loss in water content from seedbeds during the critical period of crop establishment.

8.5.3 Factors affecting water vapour transfer and condensation

The influences of structure, temperature, time, and gravity factors on transfer and adsorption of evaporated water in the soil were examined.

8.5.3.1 Aggregate size and temperature gradient

The effect of aggregate size on the adsorption of water vapour

Table 54. Mean increases in water content (%) in the condensation zone at different mean temperature gradients ($\Delta T^{o}C\ cm^{-1}$).*

$\Delta T(^{o}C\ cm^{-1})$	Time Length (hr)	Aggregate size range (mm) 7.0-4.0	4.0-2.0	2.0-1.0	1.0-0.5	Mixed
1.4	3	1.5	1.3	1.0	1.4	2.0
	6	3.0	2.5	1.8	0.3***	2.0
	6CH	3.2	2.2	1.5	1.5	1.6
	6HC	2.0	2.7	2.1	2.2	1.9
	9	2.3	2.5	2.8	1.7	2.9
	12	2.1	3.5	1.2	2.7	3.1
1.0	3	3.3	0.5	1.1	1.3	0.7
	6	1.6	0.5	1.6	2.9	1.4
	6CH	1.5	1.4	2.0	1.5	2.6
	6HC	1.8	0.3	1.7	3.1	4.8
	9	0.2	2.0	2.1	2.3	0.7
	12	1.1	2.9	1.8	1.0	2.9
0.5	3	1.1	0.7	1.2	1.3	0.4
	6	0.5	0.5	1.7	1.6	1.1
	6CH	1.0	1.2	0.5	0.8	0.2
	6HC	1.3	0.4	0.7	0.3	1.2
	9	0.1	0.4	1.6	1.7	0.4
	12	2.5	2.9	1.5	0.7	0.2
Mean ($1.4^{o}C\ cm^{-1}$)		2.3	2.4	1.7	1.6	2.2
Mean ($1.0^{o}C\ cm^{-1}$)		1.6	1.3	1.7	2.0	2.2
Mean ($0.5^{o}C\ cm^{-1}$)		1.1	1.0	1.2	1.1	0.6

CH, HC = Soil column held vertically with hot end at the top and below respectively.

* = Water contents of samples between 4 and 18%.

*** = Excluded from mean. The soil column involved had the least initial water content.

Table 55. Analysis of variance of increases in soil water content due to water vapour condensation.

Treatment	df	SSD	MSD	F	Test (95%)
Total (a)	19	12.55			
Aggregate size (a)	4	3	0.75	1.54	NS
Aggregate size (b)	4	0.53	0.13	0.11	NS
Aggregate size (c)	4	2.19	0.55	0.96	NS
Time length (a)	3	3.7	1.23	2.52	NS
Time length (b)	3	0.93	0.31	0.26	NS
Time length (c)	3	1.55	0.52	0.91	NS
Axis of column (a)	2	0.17	0.09	0.15	NS
Residual (a)	12	5.85	0.49		

a = Mean temperature gradient was $1.4^{o}C\ cm^{-1}$.

b = Mean temperature gradient was $1.0^{o}C\ cm^{-1}$.

c = Mean temperature gradient was $0.5^{o}C\ cm^{-1}$.

was examined to see if the aggregate size factor could account for the difference in water content at different depths in tilled soils. The initial mean water contents of the different aggregate size fractions were not significantly different. For 7.0-4.0, 4.0-2.0, 2.0-1.0, 1.0-0.5 mm, and mixed size fractions, the respective mean water contents (for the six time periods used) were 12.9, 13.0, 10, 9.1, and 10%.

The mean increases in water content in different aggregate sizes after different times were compared. There was no consistent and statistically significant difference in increases in water content (+ δw) recorded for size fractions smaller than 7 mm (Table 55). The mean values of +δw varied between 1.5 and 2% for all aggregate size ranges used (Table 54).

The sizes of the pores are proportional to the sizes of the aggregates in aggregate beds with such narrow ranges of size. However, the porosity is independent of aggregate size. Since intra-aggregate diffusion of water vapour depends only on the porosity (Section 2.10.3.2), it is to be expected that it will be independent of aggregate size.

Also, Orchiston (1953) collected adsorption data for water vapour at 25^{o}C on a wide range of New Zealand soils. He shows that it is the specific surface areas of soils that determine the amount of water vapour adsorbed. The term 'specific surface' is used to assess the dispersed state of fine soil such as clay in a liquid medium. Therefore the use of different size fractions of large aggregates larger than 0.5 mm as in this laboratory project will not effect considerable differences in the amount of water vapour adsorbed by the soil fractions.

It is concluded, in Chapters 4 and 5 that tillage with different implements and different numbers of passes of implements, and tillage of differently cropped soils and soils at different water contents produced different macro-aggregate size distributions. The present finding as to the lack of effect of aggregate size on the amount of water vapour adsorbed by soil indicates that the different aggregate size distributions of tilths does not account for their different water contents. It is concluded in Chapter 7 that differences in the proportions of pores larger than 8 mm in tilled soils determine their different water contents. It is these pores that determine the effective depth of penetration of convective air movement (Chapters 6 and 7).

The present finding is consistent with that of Middleton (1927) who studied the effects of time, temperature, vapour pressure, and the degree of evacuation on the amount of water vapour adsorbed by soil aggregates smaller than 0.25 mm and their colloids. He observed only very slight differences in the adsorption of water vapour by soil aggregates of different sizes and suggested that any difference in adsorptive capacity could occur in microscopic aggregates rather than in macroscopic aggregates.

Results from the laboratory project show that (for all aggregate size fractions and for all time lengths) mean increases in water content at mean temperature gradients of 1.4, 1.0, and 0.5^{o}C cm^{-1} were 2.2, 1.5, and 1.0% respectively. The positive correlation between temperature gradient or temperature difference and increase in soil water content as a result of vapour transfer is clearly shown in Figure 36, which shows values of temperature and the corresponding changes in soil water content. The heat released as a result of condensation of water vapour led to increased soil temperature.

Due to the dependence of water vapour flux on temperature and temperature gradient, the lengths of the main condensation zones recorded at 1.4, 1.0, and 0.5 $^{o}C\ cm^{-1}$ were on average 9, 6, and 5 cm respectively (Table 56). It is shown ahead that the estimated maximum distances of the condensation zone from the dry end were respectively 20, 18, and 12 cm at the above respective temperature gradients.

8.5.3.2 Heat of condensation and gravity

At 14% water content, temperatures taken within 180 min. at points in a column of 7.0 - 4.0 mm aggregates with no temperature gradient varied between 19.2 and 21 ^{o}C. Therefore, when a temperature gradient was set between two ends of a soil column, a temperature at a point greater than 21 ^{o}C indicated the influence of evaporated water and its heat of condensation. This enabled the farthest point reached by evaporated water to be estimated (Figures 35 and 36). The farthest point is represented by 'S' in Figures 35 and 36.

Cary and Taylor (1962) attributed an increased heat transfer in soil to an increased rate of water vapour movement and said that water moving in the vapour phase could transport 2.43 kJg^{-1} which is the latent heat of vapourization. However, the heat released by condensed water could not account for the whole temperature increase observed in the soil column. Heat transfer in the soil column by the process of conduction (apart from convection and diffusion) would have contributed significantly to increased soil temperature along soil column. For example the maximum increase in soil water content of about 0.05 g would yield 122J as heat of condensation. The dry weight of soil

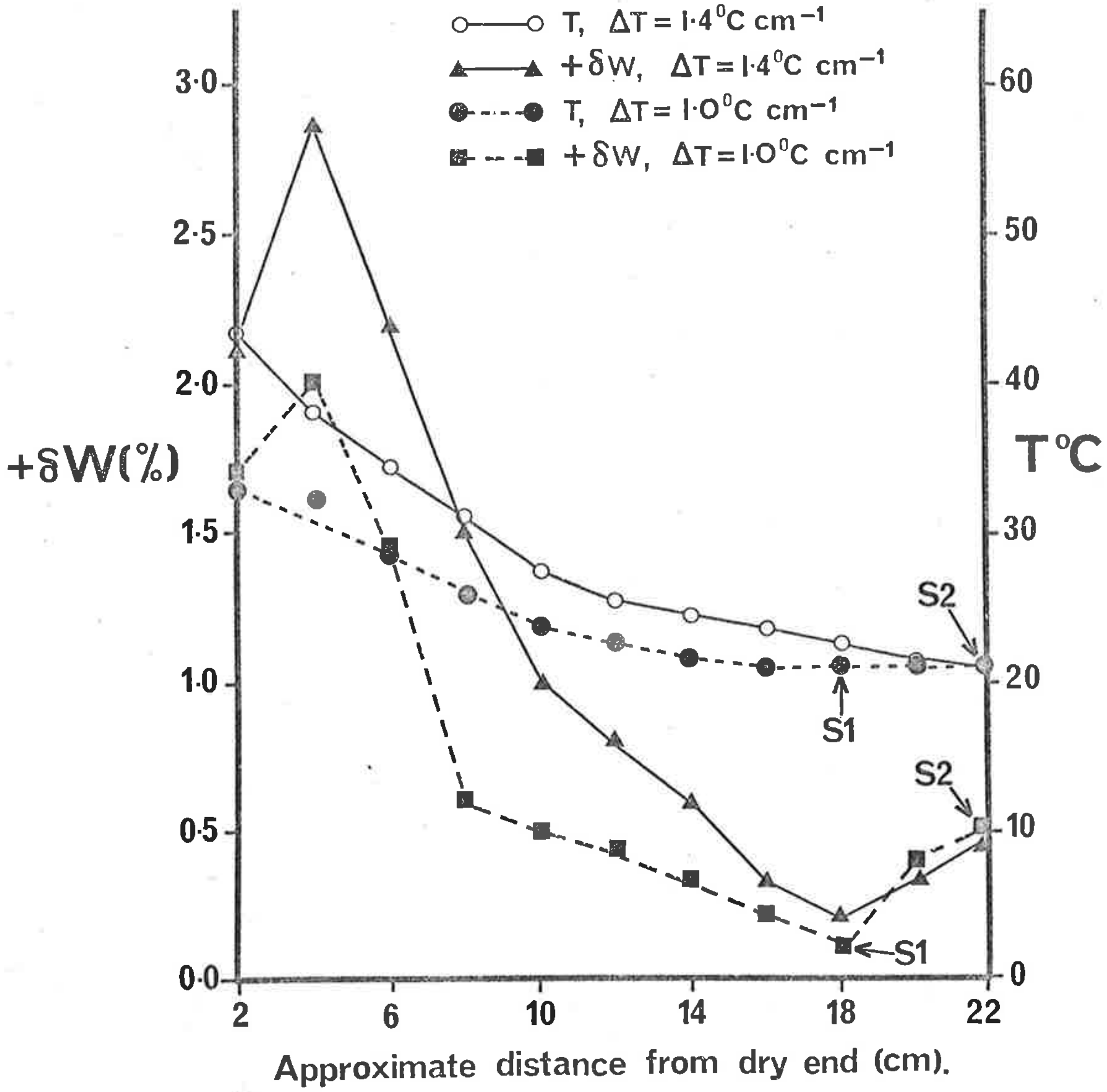


Fig. 36. Relationship between temperature (T) and change in water content (δW) in soil columns with different temperature gradients. S points show the estimated farthest points reached by evaporated water and applied temperature gradient.

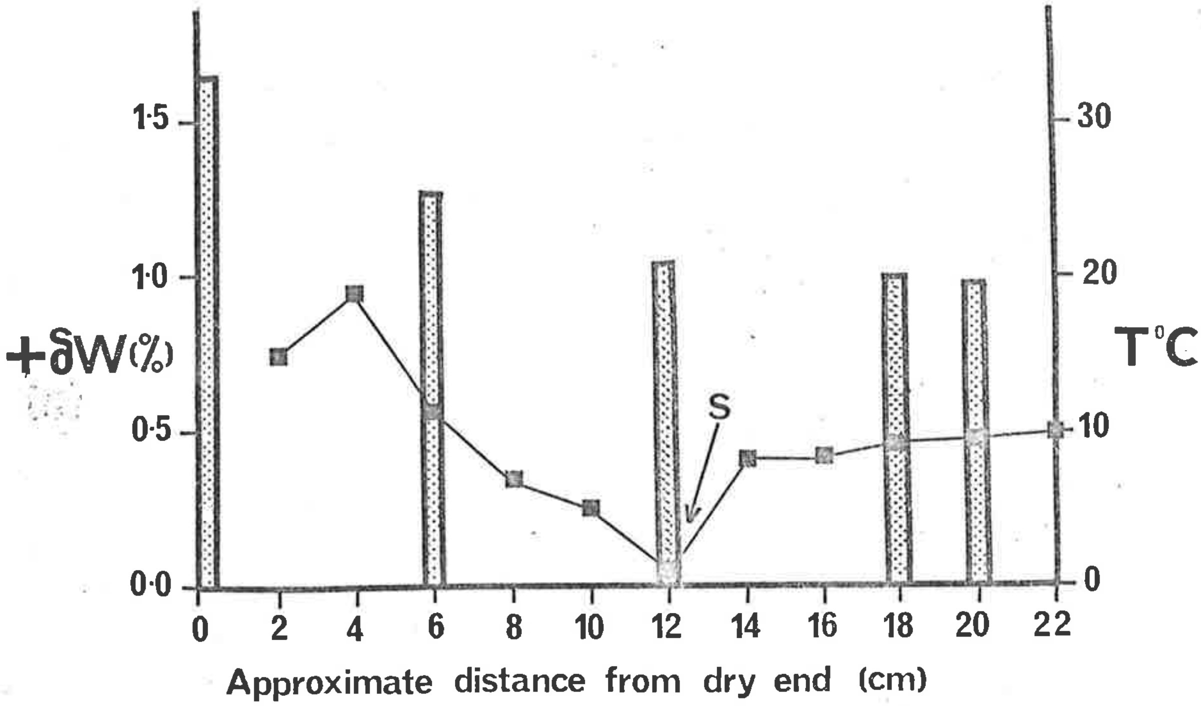


Fig. 37. Relationship between temperature (T) and change in water content (δW) in soil columns with a temperature gradient ($\Delta T = 0{\cdot}5\,^{\circ}C\ cm^{-1}$). S indicates estimated farthest point reached by evaporated water and applied temperature gradient.

aggregates in a soil section (2 cm in length) and the weight of associated water content were respectively about 31g and 5g. For their temperature to be raised by 1°C, 55J heat would be needed. The specific heat of loam soil was taken as 1.1 $Jg^{-1}K^{-1}$ for garden soil (Baver, 1961) and that of water as 4.2 $Jg^{-1}K^{-1}$. Therefore, vapour condensation contributed the maximum of about 2.2°C to the observed increase in soil temperature (at about the peak condensation zone in soil column). The minimum increase in soil water content of 0.001g would not have contributed significantly to increased soil temperature especially at sections more distant than 18 cm from the dry end. That the gradient of the temperature curves more gradually drops from the source of heat (Figure 36) and were more regular in shape compared with the water content change curves indicates that conduction of heat was occurring. Hence, changes in temperature along the soil column could not be due to coupled transfer of heat and water vapour (by convection and diffusion) alone, conduction of heat could have played a significant role.

The plots of average values of δw and temperature (T) at different points of soil columns subjected to different mean temperature gradients are presented in Figures 36 and 37. Up to the distance S (as defined above) the δw curves are sigmoidal. Taylor and Cary (1960) observed that thermal distribution curves had a sigmoid shape characterised by a drop in temperature near the warm side followed by a more or less linear portion through the centre of soil column and a rapid cooling near the cool surface. This was not observed here for the temperature curves.

The S points on the $+\delta w$ and T curves coincide with the control temperature of 21°C. Greater correlation coefficients were obtained between $+\delta w$ and T at S points relative to other points ahead of them showing the greater influence of heat-water vapour coupling at the former points than the latter points. For example, under a temperature gradient of 1.4^{o}C cm^{-1}, the correlation (r) between +δw and T at point S = 20 cm from the dry zone was 0.92 whereas it was 0.91 at S = 22 cm. With a gradient of 1.0^{o}C cm^{-1}, the greatest correlation between +δw and T of 0.95 was recorded at S = 18 cm compared with 0.95 and 0.94 recorded at S = 20 and S = 22 cm respectively. Therefore, it could be said that the farthest distance to which evaporated water condensed in the direction of applied temperature gradients of 1.4 and 1.0^{o}C cm^{-1} were 20 and 18 cm respectively. For the temperature gradient of 0.5^{o}C cm^{-1}, it was 12 cm.

The above results demonstrate the coupled transfer of heat and water vapour. The greater the temperature the farther the zone on which evaporated water will condense. Beyond the distant 'S' points associated with coupled influence of heat and water vapour, the increases in water content were of similar magnitudes recorded in the control trials, and are not attributable to applied temperature gradients.

Analysis of variance (Table 55) showed that the direction of flow (horizontal or vertical) of water vapour was not an important factor determining water vapour movement. There was no significant difference in the estimated lengths of the condensation zone when wet soils were subjected to temperature gradients for 6 hours in the two vertical directions, and in a horizontal position.

Muskat (1937) discussing the flow of gas in soil said that owing to the low density of gases the effect of gravity might be entirely neglected in the discussion of the flow of gases through porous media insofar as any direct effect on gas was concerned. However, this work shows that any asymmetric effects due to convection currents were insignificant.

8.5.3.3 Time factor

When water is not limiting, the longer the time during which soil is subjected to a temperature gradient, the farther the evaporated water is transported from the source of heat and the more the amount of water that is transported.

Average increases in soil water content (for all fractions and time periods) when soil was subjected to temperature gradients for 3, 6, 9, and 12 hours were 1.3, 1.5, 1.6, and 2% respectively.

The mean distances (from the dry end) of the end of the condensation zone when soil was subjected to temperature gradients for 3, 6, 9, and 12 hours were 6.5, 6.8, 6.9, and 8.0 cm respectively (Table 56).

However, because the differences in the amount of water adsorbed by soils in times of 3 to 12 hours were not statistically significant (Table 55), it could be said that energy and water availability more determine the agricultural significance of water vapour transfer in soil.

Middleton (1927) also observed that there was increase in water vapour adsorption with time up to 7 days.

Increases in soil water content at the bottom of tilths (10 cm) between 1200 and 1500 hr were due to the greatest surface temperature and temperature gradient at that time of the day, and the concomitant advance of the evaporation zone and especially the condensation zone. Losses in water content were generally recorded at the 5 cm depth during this interval because soil water was being evaporated downward as well as being lost to the atmosphere.

8.5.4 Condensation zone

It was found that water vapour condensed mainly within distances varying from 5 to 8 cm from where evaporation occurred (Table 56). However, it is estimated that some water condensed up to 20 cm from where evaporation occurred (8.5.3.2).

Johnson and Buchele (1961) subjected the surface of a bed of wet aggregates (1-9 mm) to radiant energy and recorded that two-thirds to three-quarters of the evaporated water condensed within 7.5 cm from the surface of packed soils. After taking negative adsorption into account, Richards *et al.* (1956) concluded from data of vertical distribution of chloride in soil that water transferred in the vapour phase below the 10 cm depth in profile was of negligible agricultural importance.

In the field, the base of the tilled layer of soil (at 10 cm depth) fell within the main condensation zone while the subsurface (at 5 cm) was in the evaporation zone during the day. This statement is based on the observation that evaporation occurred within 6 cm from the heat source or soil surface (also shown ahead) while the main condensation zone fell within 8 cm from the evaporation zone.

The proportions of the total condensed water that condensed in the three sections closest to the evaporation zones were calculated (Table 57). It is shown that the zone of peak condensation was about 4 cm from the evaporation zone or at about 6 to 10 cm from the heat source. In the field the heat source is usually equivalent to the soil surface.

Table 56. Approximate distances of the end of the condensation zone (cm) from dry end in soils subjected to different temperature gradients ($\Delta T^{o}C\ cm^{-1}$).*

ΔT	Time Length (hr)	Aggregate size range (mm)				
		7.0-4.0	4.0-2.0	2.0-1.0	1.0-0.5	Mixed
1.4	3	10	10	12	6	8
	6	6	10	10	6	10
	6CH	8	10	12	8	6
	6HC	8	6	12	10	6
	9	8	10	14	6	8
	12	14	12	8	10	10
1.0	3	6	4	6	6	4
	6	6	8	6	10	4
	6CH	4	4	6	8	6
	6HC	6	4	8	6	4
	9	4	10	6	6	6
	12	6	8	8	8	6
0.5	3	6	6	4	6	4
	6	4	8	6	4	4
	6CH	4	6	2	4	4
	6HC	6	6	4	4	2
	9	2	8	6	8	2
	12	6	6	10	4	4
Mean ($1.4^{o}C\ cm^{-1}$)		9.0	9.7	11.3	7.7	8.0
Mean ($1.0^{o}C\ cm^{-1}$)		5.3	6.3	6.7	7.3	5.0
Mean ($0.5^{o}C\ cm^{-1}$)		4.7	6.7	5.3	5.0	3.3

* Water contents of soil samples varied between 4 and 18%. CH, HC soil column held vertically with hot end at the top and below respectively.

Table 57. Proportions of total condensed water at different distances from the evaporation zone in soil columns under different mean temperature gradients ($\Delta T^{o}C\ cm^{-1}$).*

ΔT	Time Length (hr)	Distance (cm) 2	4	6
1.4	3	0.22	0.27	0.24
	6	0.28	0.37	0.21
	6CH	0.24	0.32	0.23
	6HC	0.22	0.36	0.27
	9	0.19	0.29	0.23
	12	0.19	0.33	0.23
1.0	3	0.31	0.39	0.25
	6	0.28	0.43	0.19
	6CH	0.30	0.47	0.18
	6HC	0.30	0.46	0.18
	9	0.27	0.33	0.30
	12	0.22	0.30	0.31
0.5	3	0.21	0.54	0.25
	6	0.45	0.43	0.10
	6CH	0.47	0.40	0.10
	6HC	0.22	0.55	0.22
	9	0.17	0.39	0.30
	12	0.31	0.46	0.16
Mean ($1.4^{o}C\ cm^{-1}$)		0.22	0.32	0.24
Mean ($1.0^{o}C\ cm^{-1}$)		0.28	0.40	0.28
Mean ($0.5^{o}C\ cm^{-1}$)		0.31	0.46	0.19

* Water contents of soil samples between 4 and 18%.
CH, HC soil column held vertically with hot end at the top and below respectively.

Gurr *et al.* (1952) also recorded greatest water contents between 7 to 9 cm from the hot ends of soil columns which had initial water contents of 16 to 25% and were subjected to temperature gradients of about 1.6^{o}C cm^{-1}. Hadas (1968) also found that evaporated water mainly condensed at about 4 cm from the evaporation zone when heat was applied to wet soils.

Field data show that gain in water over the night was greater at the immediate subsurface depth (5 cm) than the bottom (10 cm) of the tilled layer. This was partly because the relative heat status of the two depths were reversed to those of the day, and partly because the upper soil, being drier, is capable of absorbing more water.

8.5.5 Evaporation zone

Water evaporated within 6 cm distance from the heat source (warm water jacket) when soils were subjected to different temperature gradients. This is shown by the data of the length of soil column from where water was evaporated as presented in Appendix V. Water mostly evaporated within 2 cm from the heat source and was followed by 2 to 4 cm and 4 to 6 cm respectively. This is consistent with the field observation that losses in water occurred more at the 5 cm depth at the hottest time of day compared with the 10 cm depth of tilled soil.

The major evaporation zone was within 0 to 2 cm from the source. A value smaller than 2 cm might have been got in the laboratory experiment if sectioning was done at less than 2 cm intervals. When the temperature of the hot end was as small as 24^{o}C when the smallest temperature gradient

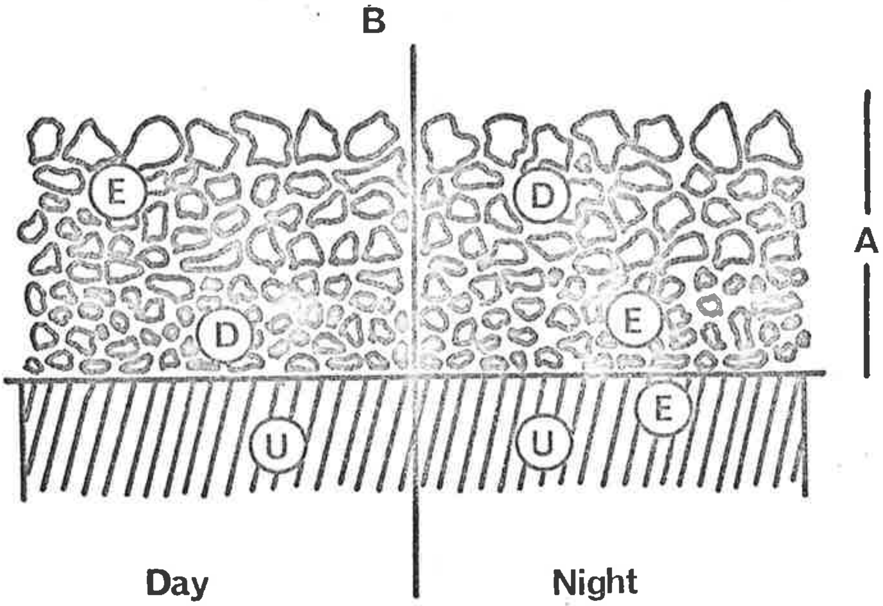


Fig. 38. Evaporation and condensation of water in tilth.

A = Tilth
B = Atmosphere
D = Main condensation zone
E = Main evaporation zones
U = Untilled soil

(0.5°C cm^{-1}) was being used, there was no significant loss of water from the soil section nearest to the heat source.

The present finding is consistent with the observation of Hadas (1968) that water was mainly evaporated within 2 cm from applied heat source when wet soils were subjected to heat treatment for periods up to 32 min. Fritton *et al.* (1957) subjected thirty cylinders containing a silt loam soil to various evaporation potentials for several durations, and measured the chloride distribution. It was also concluded that evaporation zones lay between 0 to 7 cm depth depending on evaporation potential.

8.5.6 Water vapour movement and condensation in tilths

The thermal transfer of water vapour and its condensation across the tilled soil as observed in field and laboratory studies are presented in Figure 38.

In Chapter 7 (Table 52) it is shown that there was always a gradient of relative humidity from inside the tilled soil to the atmosphere in both Winter and Spring. For example, early on a Winter morning (0600 hr) when the atmosphere had the greatest relative humidity of about 0.76, the tilth, water content was about 16.9% and the tilled soil had a water potential less negative than -15 bar while the atmospheric water vapour had an effective potential of greater than -350 bar. The relative humidity gradient from the tilled soil to the atmosphere is reduced over the night due to conduction, diffusion and condensation of water from the warmer untilled soil.

Some slight increases in the water content at the bottom of the tilled layer occurred during the hottest time of the day and this is attributed to condensation of water evaporated from the upper 5 cm of the tilth. At 1500 hr the mean water content, and water potential at the 5 cm depth were respectively 10.2%, and about -4 bar in Winter, while the equivalent values for 10 cm depth were 16.0% and -1.0 bar. The water and potential gradients might at first sight be expected to induce water vapour movement from the 10 cm to 5 cm depth. However, the greater temperature at 5 cm resulted in a greater equilibrium vapour pressure at that depth and have the tendency for water vapour to move downwards. The respective temperatures at 5 and 10 cm depths at the period referred to above were 12.3 and 10.8^{o}C. Therefore, when water content is not limiting and in soil which is wetter than the wilting point (7% in this case) the temperature gradient is a more important factor in water vapour transfer than the water potential gradient.

Over the night all factors determining the direction of water vapour movement ensure that vapour moves from below the tilth (e.g. 10 cm) to its top (e.g. 5 cm) and to the atmosphere. Temperature gradient, vapour pressure gradient, and water gradient existed from the base to the top of tilled soil, while potential gradients existed from the top to the base of tilled soil. For example in July 8th, 1976 (Winter) and at 2400 hr, the soil temperature, relative humidity, water content, and suction were 7.9^{o}C, 1.00, 17.3%, and 0.1 bar at 10 cm. The equivalent values for 5 cm were 5.9^{o}C, 0.99, 12.8%, and 1.0 bar.

It is further shown that the temperature gradient mostly determines the direction of water vapour movement in tilled soil and that it can influence the periodic variation in water content in tilled soil. Using mean (for 2 replicates and 8 differently-tilled plots) water contents (w) for indicated times (Table 58), the relative humidity (h) and total water potential (ψ_m) at 5 and 10 cm depths in tilled soil were estimated from the drying water characteristic curve (Figure 33) presented in Chapter 7. The water contents measured in Winter (July 1976) were used. For this calculation, it was assumed that water matric potential was independent of temperature. This is a reasonable assumption since the matric potential, ψ, is related to the diameter of the largest water-filled pores, δ, and the surface tension, σ, of water by

$$\psi = -4\sigma/\delta \qquad (80)$$

δ may be expected to be temperature independent, and σ only drops by 3% from 5 to 20^{o}C. The relationship between ψ and $P/P_o = h$ is given in equation (75) in Chapter 7.

It is shown (Table 58) that all times during day and night the water content and humidity (relative) were greater at 10 cm depth than 5 cm depth. Therefore, the water potential was greater at the latter depth than at the former depth. That a water content gradient always existed from the base to the top of tilled soil and water potential gradient from top to the base of tilled soil may partly account for general greater increase in water content during night times at 5 cm depth compared with 10 cm depth (Table 53). However, this could not account for any increase in water content recorded at the 10 cm depth during the hottest times of day.

The equilibrium values of saturated vapour pressure at both 5 and 10 cm depths at the different tilth temperatures were got from the 54th edition of Handbook of Chemistry and Physics (Weast, 1973). These values were used to estimate the equilibrium unsaturated vapour pressure values at the indicated tilth temperatures using values of relative humidity from the water characteristic curve (Figure 33). At the range of soil water contents (about 10-18%) under consideration, relative humidity values are all close to 99.9%.

During the day-light hours and in soil wetter than the wilting point, the temperature and the vapour pressure both decrease from the 5 cm to the 10 cm depth in tilled soil. During the night and in the morning (especially in Winter) the vapour pressure and the temperature both decrease from the 10 cm to the 5 cm depth in tilled soil. A greater increase in water content during the night at the immediate subsurface depth of tilled soil relative to the base of tilled soil, and a few increases at the latter depth compared with no increase at the former depth were recorded. These could be explained on the basis of the temperature gradient and the relative positions of the depths in tilled soil rather than on the basis of water gradient or water potential gradient.

The standard errors presented with δw values in Table 53 appear to vary more widely between the dates than between the depths. This indicates that differences in daily changes in soil water content due to water vapour movement along temperature gradients may not be significant.

It is shown ahead that the differences in the values of periodic change in water content at 5 and 10 cm depths of tilled soil could be significant.

8.5.7 Significance of the findings in tilled soil

Although some instances were recorded where there were increases in water content at the 10 cm depth at the hottest times of day, these changes were not statistically significant.

Table 58. Equilibrium values of relative humidity (h), saturated (P_o) and unsaturated (P) vapour pressure, and water potential (ψ_m) at 5 and 10 cm depths in tilled soil. Equivalent values of soil water content (w%) and temperature (T^ok) are given.

Date* 7/1976	Time	w(%)		T^ok		h%**		ψ_m(bar)		P_o(mbar)		P***(mbar)	
		5 cm	10 cm	5 cm	10 cm	5 cm	10 cm	5 cm	10 cm	5 cm	10 cm	5 cm	10 cm
8th	1200	13.30	17.03	286.7	284.1	99.90	99.96	-1.33	-0.53	15.47	13.02	15.45	13.01
7th	1500	10.01	12.86	286.4	284.2	99.70	99.9	-3.98	-1.31	15.17	13.12	15.12	13.11
7th	2100	10.44	15.27	280.3	281.2	99.74	99.93	-3.37	-0.94	10.08	10.88	10.05	10.86
8th	2400	12.8	17.33	278.9	280.7	99.90	99.94	-1.29	-0.78	9.14	10.36	9.13	10.35
7th	0900	16.68	17.64	279.5	279.9	99.95	99.96	-0.65	-0.52	9.55	9.81	9.55	9.81

* Date when data were available for both soil water content and soil temperature.

** Estimated from drying water characteristic curve, equilibrium values.

*** Estimated using the relationship $h = \frac{P}{P_o}$.

However, it has been shown that under equilibrium conditions, there is a gradient of water vapour pressure from the 5 cm to the 10 cm depth in tilled soil in the field at the hottest time of the day. This could be expected to reverse the upwards movement of water vapour in tilths or at least to reduce it.

There are several factors which complicate the comparison of the field and laboratory results. Firstly, the water vapour flux would be proportional to the gradient of vapour pressure when diffusion was the transport mechanism (as it probably was in the laboratory experiments). In this case, the flux would be dependent on the air-filled porosity but not on the pore size distribution (see Equation 27 in Chapter 2). However, it has been shown in Chapters 6 and 7 that transport in tilled soils in the field is mainly associated with the porosity in pores larger than 8 mm. This effect was attributed to the convection of atmospheric air through the tilths as observed by other researchers and described elsewhere in this thesis. Under such conditions, discussion of equilibrium vapour pressure gradients is not valid.

Secondly, for simplicity, the drying limb of the water characteristic was used. However, in practice, there is a whole family of hysteresis curves which describe the water characteristic between any two water contents. This hysteresis effect confounds the analysis when small and variable changes in water content are being considered.

To obtain statistically-significant results, it would probably be necessary to use a large automatic data logging system on a much bigger, replicated experiment. This was beyond the means of the present project.

In spite of the limitations of this experiment, it has given additional insight into the possible importance of a rather neglected mechanism for water movement in tilled soil.

8.6 Conclusions

Field observations of the contribution of temperature-induced water vapour movement to variations in water content at different depths in tilled soil were related to observations in laboratory experiments dealing with water vapour transfer and adsorption in soil. The observations from both sources were compared. In some cases, there was a mean (but not statistically significant) increase in water content of 1 to 2% at the bottom of tilled soils during the hottest period of day. There was a net loss of tilth water during the day, but the magnitudes of loss which varied between 1 to 8% were almost the same as the magnitudes of gain overnight which in instances were close to 12% (dry weight basis).

Evaporation took place most intensely within 2 cm from the soil surface or heat source but extended down to 6 cm.

Under temperature gradients smaller than 1.5^{o}C cm^{-1}, water vapour mainly condensed within 8 cm from the zone of evaporation, while the greatest water content was detected about 4 cm from the evaporation zone.

Soil temperature gradient and its duration of application were directly related to the amount of water vapour transferred and how far it was transferred in soils of water contents between wilting point and field capacity. Different water contents and variations in water content at different depths in tilled soil were due to their relative positions in relation to the direction of temperature gradient.

8.7 Practical Implications of Findings

To avoid dehydration and lethal temperatures, seeds should be placed at least 2 cm below the surface of tilled soil. Depending on the seed size, the deeper the planting depth up to 6 cm, the greater the chance of seedling survival in the case of a break in post-planting rainfall. It was discovered (Chapter 6) that a temperature gradient from the top to the base of tilled soil was positively correlated with the proportion of voids larger than 8 mm. Temperature was confirmed as the most important meteorological factor of evaporation.

CHAPTER 9

GENERAL DISCUSSION

9.1 Techniques

This research successfully applied a new method of measuring the internal macro-structure of tilled soils in the field. Tillage mainly affects the macro-structure of soil. Paraffin wax was used to impregnate blocks of tilled soils. Aggregates could easily be discerned from pores filled with paraffin wax on sections sawn through the impregnated blocks. Raw data of the distribution of aggregates and pores at 1 mm intervals were collected at different levels in the range of depths from 1 to 5 cm. Calculation of the proportions of different sizes of aggregates and pores was performed. Other statistical structural parameters were derived. The method is inexpensive, sensitive, and easy to use.

Instead of hand-sawn, impregnated tilth blocks could be machine-sawn. Since molten paraffin does not penetrate very fine tilths as obtained at the bottom of seedbeds, another substance such as epoxy-resin could be used for tilth impregnation. However, the latter is more expensive and difficult to saw when it hardens. Nevertheless, paraffin wax impregnates without difficulty at least threequarters of the depth of tilled soils.

Mechanical sawing of tilth blocks would have enabled the use of more replicates of each treatment and thus increased the effective length of the primary data strings from which the probabilities, P(0), were derived. The P(0) represent the probabilities of 0 following the 16 possible combinations of 0 and 1 in the four sampling points immediately to the left of the point in question.

A risk was taken by using only four replicates for any applied treatment. More replicates are necessary to ensure longer data string for calculation of aggregate and pore size distributions.

Dexter and Hewitt (1978) examined the effects of data string length on the accuracy of the probabilities, P(0), using data for the random close packing of equal spheres. They calculated standard deviations for each of the 16 P(0) values, for four different sphere diameters. Each set of 16 P(0) values was derived from a 2000 element (i.e. 0 for pore, or 1 for aggregate) data string. Each standard deviation was calculated using ten P(0) values. The standard deviations of the P(0) vary as $1/\sqrt{x}$ where x is the length of the data string. Because the length of data string used by Dexter and Hewitt (2000 elements of 1 and 0) was about 1.7 times longer than as used in this research (4 (replicates) x 320 = 1280) each of the 16 standard deviations presented by Dexter and Hewitt for each set of 16 P(0) values was multiplied by the factor $\sqrt{1.7} = 1.3$ to obtain estimates of the standard deviation of the P(0) values in this work. The standard deviations of P(0) for 4 representative sphere diameters based on those presented by the latter authors are presented in Appendix VI. Because aggregates in tilled soil have a range of diameters in contrast to the equal spheres studied by Dexter and Hewitt, the standard deviations presented are probably underestimated.

The standard deviations for P(0) were small compared with typical mean values of P(0) derived from field data. Although a few of the P(0) values have large standard deviations (for example, 1010, P(0) for diameter, 5 spheres and 0101, P(0) for diameter 10 spheres), this is of little or no consequence. The precursors in these cases have only small or zero numbers of occurrences and have a negligible effect on the overall structure of data string. The structures which occur the more frequently have the over-riding effect on the structure, and it is these that have the P(0) with the smaller standard deviations. For example, the P(0) values for precursor 1111 as derived from 3 cm depth structural data collected from four cut sections (a section is a replicate) of two tilth blocks (Tillage was done with a pass of tine implement with narrow points) were 0.082, 0.077, 0.084, and 0.113. The standard deviations for the P(0) of the precursor as derived from data strings from packed spheres vary from 0.005 to 0.017. It could be seen that any of the standard deviations (although for a more organized medium) is very small compared with any of the P(0) values (for a soil medium). It was not plausible to calculate the standard errors of the P(0) values because about ten replicates of each treatment would be required. However, more replicates than four would ensure reduced variability of structural parameters belonging to a treatment.

It was not possible to estimate the effects on derived quantities, such as the pore-size distribution, from the standard errors of the P(0)s. This is because the errors in the P(0) are not independent, and their dependence will vary from case to case.

What appears would be the major limitation of the technique of measuring the internal structure of tilled soil is that it may not be suitable for use on stony soils because of the need to section impregnated samples.

9.2 Summary of Results

The technique of measuring the internal structure of tilled soil was applied in tillage investigations. The investigations involved characterisation of the tilth structures produced by different tillage systems, tilth structures that resulted from different initial soil water contents, tilth structures that were produced on soils which had different cropping histories, and the change in internal tilth structure under weather. The investigations are recorded in Chapters 4 and 5.

Towards the need to mobilise the structure of the seedbed for its optimum physical state, investigations were performed on how structural features interact with meteorological factors to determine the magnitude, variation, and the distribution of the two most important factors in the seedbed which are water and temperature. The investigations are recorded in Chapters 6, 7 and 8.

The findings from the above investigations correlated well. It was concluded among other things that atmospheric air penetrates by convection to a depth of at least 5 cm in tilled soil and mainly through pores larger than 8 mm. This reflected on temperature and water distribution in tilled soils. Water loss by evaporation was discovered to occur mainly from the top 5 cm depth of tilled soils and pores larger than 8 mm were mainly responsible for the water loss.

For the maximum production of aggregates and pores smaller than 8 mm, seed beds could be prepared by two passes of a disc plough, or three passes of a tined implement, or tillage with one pass of a tined implement after ploughing. It is also advocated for the same reason that tillage should be performed at a water content slightly below the plastic limit, on a land which has been given fallow break between crops and/or which has been sown to pasture in rotation.

9.3 Implications of Findings for Agriculture

9.3.1 Crop yield

That the findings in this research could be applied in efforts to increase economic crop yield is broadly discussed below. References are made to some other works.

9.3.1.1 Seed germination and root growth

Previous experiments led to the conclusion that the finer the seedbed the greater the seed germination percentage and seedling growth rate. Edwards (1957) carried out experiments on the emergence of barley and oats to test for the effects of aggregate size of soil separates, sowing date, and seedbed compaction on the sowing-to-emergence interval. He observed that the finest seedbeds usually had an advantage over the coarsest of about 10% in emergence percentage. Experiments extending over four years (Keen *et al.*, 1930) were carried out to compare rotary cultivation which produced the finest seedbed with other conventional methods for the production of seedbeds. Rotary cultivation gave earlier and better germination of barley seeds, and this was followed by better growth.

It has been found in the present research that the absence of voids larger than 8 mm in the seedbed reduces water evaporation by the mechanism of convective transport of heat and air through tilled soil

The next step is to examine how the presence of small aggregates and pores in the seedbed could contribute to greater germination percentage and seedling growth rate. It is suggested that the positive effect of finer seedbed on crop performance would be due to its associated greater water content.

Downward growing seedling roots proliferate more readily in the wetter zone of soil. The greater the soil water content, the greater the nutrient availability, and the smaller the soil shearing strength, and the faster the growth rate of crop roots.

9.3.1.2 Nutrient availability

Attention is now focused on how observed greater soil water content due to the presence of more aggregates and pores smaller than 8 mm could contribute to availability of major soil nutrients especially to a young crop.

Two major principal mechanisms by which nutrients in the soil are taken up by crop especially under semi-arid and arid conditions are by root extension (as indicated above) and diffusion along osmotic gradient (Lewis and Quirk, 1967). Even at the wilting point the soil solution is dilute, and has an osmotic pressure appreciably smaller than 10 to 20 bar (Russell, 1973).

The mobility of most nutrients as measured by the effective diffusivity, is dependent on soil water content (Talsma and Philip, 1971). At greater water contents (above a critical value), the diffusivity is proportional to water content. Thus, a greater soil water content should lead to a greater rate of nutrient movement along the osmotic gradient towards the absorbing surfaces of roots.

Responses to nitrogenous fertilizers may be limited by lack of water. Rainfall limits crop utilization of applied nitrogen in South Australia. Russell (1967) carried out experiments to examine conditions under which nitrogen was a factor limiting wheat yields. Like other workers, he found positive correlation between rainfall and response to nitrogen. Below 100-150 mm of seasonal rainfall, there was little response to nitrogen.

In Australia, crop production is limited over enormous areas by availability of phosphate which depends also on water supply.

This research found tillage systems and approaches to maximise the proportion of small aggregates and pores in tilled soil and thus to conserve more water. The possible reasons why a greater proportion of small aggregates produces an increase in germination percentage has been discussed above. Greater proportions of small aggregates and pores in tilled soil could lead to increased root growth, and increased nutrient uptake. McIntyre (1955) measured physical properties of soil on experimental plots which showed poor germination of wheat under very wet conditions. Millington (1961) collected data of seedling establishment from wheat plots in long-term rotation experiments in South Australia. McIntyre and Millington both established that wheat yields could be correlated with seedling emergence.

From the above it could be concluded that this type of research that investigates factors that increase the proportion of small aggregates and pores in tilled soil and examines structural and meteorological factors determining water content in tilled soil may contribute to efforts to increase the yield of food crops.

9.3.2 Control of seed bed physical conditions

This section deals with how this type of research could contribute to the control of seed bed physical conditions.

In South Australia, the tilth temperatures were below 8°C for approximately 14 hr each day in the planting season. The fact that the optimum soil temperature for the growth of many temperate crops is about 20^{o}C (Russell, 1973) indicates that tillage efforts to increase the temperature in the seed bed may be required. Also, the roots of at least some cool temperate crops such as grasses and cereals only grow appreciably at temperatures in excess of 8^{o}C. To increase the number of accumulated degree-hours above 8^{o}C, a coarse seed bed with pores larger than 8 mm in diameter would have to be prepared to enhance convective transport of atmospheric air into the seed bed. However, seed bed water content is often indicated to be more critical for germination in South Australia and other semi-arid and arid regions. It has already been shown that a finer seed bed provides a greater water contact. Rainfall mainly determines the kind of farming practised in South Australia. Therefore, a fine seed bed has to be prepared using any of the methods mentioned earlier especially on light-textured soil.

However, the mobilisation of temperature distribution in tilled soil could be critical because the magnitude of the differences in daily temperature range observed between differently-tilled soils (1 or 2^{o}C) are large enough to influence the relative percentage germination of certain plant species (Thompson *et al.*, 1977).

Calculations were made to show that the findings from the projects in this research align and could jointly provide a basis for the control of seed bed physical conditions to the benefit of the seedling.

Tilth structures produced by the same tillage implement but at different soil water contents were compared (Chapter 5). The proportions of the aggregates having sizes larger than given values were presented for plots tilled at different water contents. There was a minimum proportion of large aggregates and voids when tillage was done at a water content of 0.9PL. A quadratic equation relating the water content (w) at which tillage with tines was done with the proportion (P8) of pores larger than 8 mm is

$$P8 = 1.35 - 0.43\left(\frac{w}{PL}\right) + 0.18\left(\frac{w}{PL}\right)^2 \qquad (81)$$

The above equation was combined separately with other equations that relate the porosity in pores larger than 8 mm with daily temperature range (R) at the 5 cm depth in tilled soil (Chapter 6), temperature gradient (G) between the 5 and 10 cm depths in tilled soil (Chapter 6), and the mean water content (wt) in tilled soil (Chapter 7).

The equation that relates daily temperature range (R) with porosity in pores larger than 8 mm (η_8), and that which relates daily temperature range with water content at which the soil is tilled with a tined implement are respectively

$$R = 45\eta_8 + 5.6, \ ^{o}C \quad \text{and} \qquad (82)$$

$$R = 45\eta_L \cdot \left[1.35 - 0.43\left(\frac{w}{PL}\right) + 0.18\left(\frac{w}{PL}\right)^2\right] + 5.6, \ ^{o}C, \qquad (83)$$

where η_L is the linear macro-porosity.

The equation that relates the daily maximum tilth temperature gradient (G) and porosity in pores larger than 8 mm, and that which relates the former with the water content at tillage are respectively

$$G = 1.38\eta_8 + 0.03, \ ^{o}C\ cm^{-1}, \quad \text{and} \qquad (84)$$

$$G = 1.38\eta_L \cdot \left[1.35 - 0.43\left(\frac{w}{PL}\right) + 0.18\left(\frac{w}{PL}\right)^2\right] + 0.03, \ ^{o}C\ cm^{-1}, \qquad (85)$$

The equation that relates mean tilth water content (wt) and porosity (η_8) in pores larger than 8 mm, and that which relates the former with the water content at tillage (w) are respectively

$$wt = -4.96\eta_8 + 14.96, \%, \text{ and} \qquad (86)$$

$$wt = -4.96\eta_L.\left[1.35 - 0.43(\frac{w}{PL}) + 0.18(\frac{w}{PL})^2\right] + 14.96, \% \qquad (87)$$

With the above equations, the water content at which tillage was done was related with the resultant water content in tilled soil (in the absence of rainfall), the daily temperature range at the 5 cm depth in tilled soil, and the daily maximum tilth temperature gradient. The results are presented in Table 59. The primary data from which the Table was derived were from tillage experiments sited on Red Brown Earth Loams.

It is found that tillage at about 0.9PL led to greatest water conservation in the resultant tilth, least daily temperature range at the 5 cm depth in tilled soil, and least maximum daily temperature gradient in the tilth.

This is because tillage at water content slightly below the plastic limit produced more aggregates and pores smaller than 8 mm than tillage at smaller or greater water contents. Tillage at a water content slightly below the plastic limit therefore led to comparatively reduced evaporation (Chapter 7) and reduced heat transfer by convection of atmospheric air.

Depending on the critical factor of crop establishment in a micro-climate, the seed bed physical condition could be controlled using the kind of findings in this research.

The recommendations on tillage practises are based on the proportion of aggregates and pores smaller than 8 mm and at least 1 mm in diameter. That water loss from the tilth, and that convective

Table 59. Effects of water content at tillage, w(%), on mean tilth water content, wt(%), daily temperature range, R(^{o}C), and maximum daily tilth temperature gradient, G (^{o}C cm^{-1}).

w(%)	wt(%)	R(^{o}C)	G(^{o}C cm^{-1})
10.7	12.25	30.2	1.06
12.6	12.29	29.8	0.77
15.8	12.35	29.3	0.77
17.0	12.36	29.2	0.76
18.3	12.38	28.0	0.76
25.2	12.00	28.9	0.84

transport of air into the soil and increased vertical temperature gradient (C hapter 6) are due mostly to the presence of voids larger than 8 mm justify the use of the above criterion.

The objective establishment of a criterion for recommending tillage practises, the investigations of tilth structures produced by tillage (Chapters 4 and 5), and the examination of the effects of structural features on soil water, temperature, and their distribution are covered by this research as components of a 'whole'. The components seem to be well knitted in the 'whole', and the 'whole' is based on the physics of the seed bed.

The present suggestion concerning the criterion for recommending tillage methods for seed beds is consistent with the statements of Russell (1961, 1973) and Greenland (1971) that the best physical conditions for a seed bed occur when aggregates are 1-5 mm in diameter; these aggregates allow air and water to move, and yet retain adequate water (Greenland, 1971). In general (Russell, 1973) aggregates larger than 5 to 10 mm are too large for a good seed bed. By the presence of structural elements smaller than 8 mm seedlings and roots growth should not be hindered (Cooke and Williams, 1972).

It is possible to mobilise the general physical condition of the seed bed to the advantage of the seedling as a result of this kind of research which has attempted to serve the following needs:

(1) testing of a new method of quantifying the internal structure of tilled soil in the field;

(2) characterisation of tilth structures produced by different tillage systems, resulting from different cropping practises, due to different initial soil water contents; and as a result of the effect of rainfall on the tilth structure produced; and

(3) identification of approaches to land preparation by reduced tillage, seed bed water conservation, control of heat distribution in tilled soil, and crop establishment.

By serving the above functions, this research fulfilled its major objectives by

(1) applying a new method of measuring the *in situ* structure of tilled soil on field investigations; and

(2) bridging the gap between theoretical expertise and agricultural practise.

9.4 Suggestions for further work

Some suggestions for further research on seed bed structure and physical conditions are now stated.

Possible slight modifications of the new method used to measure tilth structure in this research have already been stated (9.1). Tillage approaches to increase the proportion of small aggregates and pores have been suggested. However, further tillage experiments are needed to test the validity of these findings on soils of different textures. The significance of increased seed bed water content due to tillage practises that produced more small aggregates and pores in relation to seed germination, seedling establishment, and possibly crop yield in arid agriculture needs to be confirmed by field experiments. These attempts could help to minimise the adverse effect of drought on crop yield.

Additional work on the structures produced by multiple implement passes could investigate the phenomenon of tilth 'mellowing'. Mellowing is the cracking-up and softening of a tilled soil under the action of weather. This is thought to be a most important process in the reclamation of damaged or 'difficult' soils (Greenland, 1977). The proper use of mellowing could greatly improve the efficiency of tillage for seed bed preparation.

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APPENDIX I

Appendix I for Chapter 1 contains data on the internal structures of tilled soils in tillage trials carried out in 1976 and 1977. The appendix is divided into Sections A, B, and C which contain primary structural data of differently tilled soils, primary structural data for different levels within tilled soils, and measurements carried out on tillage implements respectively.

The structural data are made up wholly or partly by (a) probabilities P(0) of a 0 following 16 possible four element precursors, (b) the occurrence probabilities for the 16 precursors (Ui), (c) aggregate and pore size distributions, (d) proportions of small size aggregates and pores, (e) macroporosites, and (f) entropies. The data were derived from raw data of linear distributions of aggregates and pores on sections cut through impregnated tilth block samples.

Glossary for tillage implements: In the following, D, MB, Sc, T, RC, CD stand for disc plough, mouldboard plough, tines with wide points (or scarifier), tines with narrow points, rotary cultivator, and combine drill (with narrow points) respectively.

Small letters a, b, c, d, ..., are used to represent replicates, or separate sections cut through tilth block sample(s) collected from plot(s) having a given treatment.

Blank spaces indicate data were not available.

An asterisk (*) indicates that a precursor had no occurrences.

SECTION A

Appendix Table 1. Structures of differently tilled plots. Values of P(0) are the probabilities of a 0 following sixteen possible precursors - (1976).

Precursor	P(0) for Plots (A)							
	D	D+Sc	D+CD	MB	MB+Sc	MB+CD	Sc	RC
0000	0.931	0.600	0.886	0.867	0.895	0.880	0.861	0.722
0001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0010	*	*	*	*	*	*	*	*
0011	0.000	0.000	0.000	0.000	0.000	0.100	0.000	0.091
0100	*	*	*	*	*	*	1.000	*
0101	*	*	*	*	*	*	*	*
0110	*	*	*	*	*	1.000	*	1.000
0111	0.214	0.000	0.000	0.000	0.250	0.111	0.000	0.000
1000	0.546	0.750	1.000	0.556	0.800	0.889	1.000	0.667
1001	0.000	0.000	*	*	0.000	0.000	0.000	0.000
1010	*	*	*	*	*	*	1.000	*
1011	0.000	0.000	*	*	*	*	0.000	*
1100	0.917	0.727	1.000	1.000	0.833	0.500	0.750	0.546
1101	0.000	0.000	*	*	*	*	0.667	*
1110	0.857	0.917	1.000	1.000	1.000	1.000	0.571	1.000
1111	0.026	0.021	0.023	0.044	0.020	0.049	0.032	0.046

Precursor	P(0) for Plots (B)							
0000	0.796	0.714	0.458	0.981	0.881	0.375	0.769	0.600
0001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0010	*	*	*	*	*	*	*	*
0011	0.143	0.143	0.059	0.000	0.000	0.182	0.000	0.000
0100	*	*	*	*	*	*	*	*
0101	*	*	*	*	*	*	*	*
0110	0.000	0.000	1.000	*	*	0.500	*	*
0111	0.000	0.000	0.000	0.000	0.000	0.000	0.111	0.000
1000	0.818	0.800	0.867	0.500	0.800	0.833	0.600	1.000
1001	0.000	0.000	0.000	*	0.000	0.000	0.000	*
1010	*	*	*	*	*	*	*	*
1011	0.000	0.000	0.000	*	0.000	0.000	0.000	*
1100	0.786	0.714	0.882	1.000	0.923	0.546	0.667	1.000
1101	0.000	0.000	0.000	*	0.000	0.000	0.000	*
1110	1.000	0.875	0.842	1.000	0.813	1.000	0.833	1.000
1111	0.030	0.014	0.042	0.018	0.036	0.019	0.034	0.015

Appendix Table 2. Structures of differently tilled plots. Values of P(0) are the probabilities of a 0 following sixteen possible precursors - (1977).

Precursor	P(0) for Plots							
	D		D+D		D+D+D		D+D+D+D	
	a	b	a	b	a	b	a	b
0000	0.935	0.909	0.821	0.813	0.854	0.880	0.869	0.897
0001	0.167	0.000	0.121	0.000	0.077	0.053	0.067	0.152
0010	1.000	*	1.000	*	0.667	1.000	1.000	1.000
0011	0.118	0.182	0.367	0.191	0.053	0.074	0.097	0.300
0100	1.000	*	1.000	*	1.000	1.000	0.667	0.714
0101	*	*	*	*	0.000	*	*	*
0110	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
0111	0.118	0.091	0.095	0.222	0.050	0.000	0.107	0.087
1000	1.000	0.889	0.818	0.722	0.846	1.000	0.750	0.818
1001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.500
1010	*	*	*	*	*	*	1.000	*
1011	0.000	0.000	0.000	0.000	0.000	0.000	*	0.000
1100	0.867	0.818	0.967	0.905	0.949	0.731	0.929	0.933
1101	0.000	0.000	0.000	0.000	0.000	0.000	1.000	1.000
1110	0.867	0.818	0.905	0.944	0.925	0.960	0.962	0.913
1111	0.040	0.051	0.076	0.143	0.162	0.063	0.093	0.167
	D+D		D+T+T		D+T+T+T		T	
0000	0.901	0.875	0.953	0.855	0.935	0.692	0.915	0.926
0001	0.091	0.000	0.125	0.000	0.154	0.182	0.000	0.000
0010	1.000	*	1.000	*	1.000	0.750	*	*
0011	0.000	0.071	0.143	0.310	0.091	0.240	0.100	0.000
0100	0.000	*	1.000	*	1.000	0.667	*	*
0101	*	*	*	*	*	1.000	*	*
0110	*	1.000	1.000	1.000	1.000	0.625	1.000	*
0111	0.129	0.267	0.063	0.100	0.000	0.158	0.100	0.000
1000	0.818	0.923	1.000	0.964	0.926	0.727	0.889	1.000
1001	0.000	0.000	*	*	*	0.000	0.000	0.000
1010	1.000	*	*	*	*	1.000	*	*
1011	0.000	0.000	0.000	*	*	1.000	0.000	0.000
1100	0.917	0.929	1.000	1.000	1.000	0.783	0.900	0.769
1101	0.286	0.000	0.000	*	*	0.500	0.000	0.000
1110	0.774	0.867	0.750	1.000	1.000	0.947	0.900	0.929
1111	0.070	0.058	0.061	0.050	0.108	0.115	0.045	0.038

Appendix Table 2 *(continued)*.

Precursor	P(0) for Plots T+T a	T+T b	T+T+T a	T+T+T b	D+Sc a	D+Sc b	D+Sc+Sc a	D+Sc+Sc b
0000	0.905	0.943	0.839	0.907	0.791	0.872	0.908	0.907
0001	0.107	0.000	0.031	0.240	0.250	0.333	0.000	0.000
0010	1.000	*	1.000	0.333	0.500	0.667	*	*
0011	0.222	0.167	0.294	0.350	0.100	0.000	0.125	0.294
0100	0.333	*	1.000	1.000	1.000	1.000	*	1.000
0101	*	*	*	0.500	0.333	0.000	*	*
0110	1.000	1.000	1.000	1.000	1.000	*	1.000	0.600
0111	0.143	0.083	0.208	0.200	0.226	0.046	0.143	0.143
1000	0.786	0.667	0.719	0.783	0.750	0.889	0.750	1.000
1001	0.000	*	0.250	0.000	0.000	*	*	0.000
1010	*	*	*	1.000	0.500	*	*	1.000
1011	*	0.000	*	0.000	0.000	0.000	*	0.000
1100	1.000	1.000	0.882	0.950	0.813	1.000	1.000	0.667
1101	*	0.000	*	*	0.500	0.000	*	0.500
1110	1.000	0.833	1.000	1.000	0.879	0.636	1.000	0.857
1111	0.092	0.030	0.084	0.043	0.107	0.063	0.033	0.033

Precursor	D+Sc+Sc+Sc a	D+Sc+Sc+Sc b	Sc a	Sc b	Sc+Sc a	Sc+Sc b	Sc+Sc+Sc a	Sc+Sc+Sc b
0000	0.878	0.815	0.813	0.917	0.886	0.936	0.870	0.755
0001	0.000	0.600	0.071	0.000	0.000	0.333	0.065	0.067
0010	*	1.000	1.000	*	*	1.000	1.000	1.000
0011	0.125	0.167	0.077	0.000	0.000	0.000	0.129	0.235
0100	*	0.667	1.000	*	*	0.000	1.000	1.000
0101	*	*	*	*	*	*	*	*
0110	0.000	1.000	1.000	*	*	*	1.000	1.000
0111	0.111	0.000	0.167	0.000	0.167	0.000	0.370	0.154
1000	1.000	1.000	0.923	0.800	0.917	0.667	0.897	0.800
1001	0.000	0.000	*	*	0.000	0.000	0.000	0.250
1010	*	*	*	*	*	*	*	*
1011	0.000	*	*	0.800	0.000	*	*	*
1100	0.625	0.500	1.000	1.000	0.923	1.000	0.931	0.765
1101	0.000	*	*	0.000	0.000	*	*	*
1110	0.889	1.000	1.000	0.833	0.929	1.000	1.000	1.000
1111	0.065	0.034	0.061	0.028	0.027	0.017	0.077	0.076

Appendix Table 3. Structures of differently tilled plots. Values of Ui are the occurrence probabilities for sixteen possible precursors - (1976)**

Precursor	Ui for Plots							
	D	D+Sc	D+CD	MB	MB+Sc	MB+CD	Sc	RC
0000	0.095	0.023	0.066	0.154	0.133	0.107	0.071	0.05
0001	0.019	0.010	0.023	0.022	0.019	0.015	0.016	0.02
0010	0	0	0	0	0	0	0	0
0011	0.022	0.014	0.024	0.022	0.021	0.028	0.022	0.026
0100	0	0	0	0	0	0	0.002	0
0101	0	0	0	0	0	0	0	0.001
0110	0.0016	0.001	0.0007	0	0	0.004	0.027	0.025
0111	0.024	0.016	0.026	0.022	0.023	0.026	0.016	0.02
1000	0.019	0.01	0.023	0.022	0.019	0.015	0.0057	0.0059
1001	0.003	0.004	0.0014	0	0.0025	0.014	0.002	0
1010	0	0	0	0	0	0	0.005	0
1011	0.003	0.0027	0.002	0	0.0022	0.002	0.02	0.026
1100	0.02	0.014	0.024	0.022	0.021	0.028	0.007	0
1101	0.003	0.0027	0.002	0	0.0022	0.002	0.027	0.025
1110	0.024	0.016	0.026	0.022	0.023	0.026	0.027	0.025
1111	0.763	0.885	0.782	0.714	0.733	0.732	0.777	0.801

** Means for two replicates.

Appendix Table 4. Structures of differently tilled plots. Values of Ui are the occurrence probabilities for sixteen possible precursors - (1977)**.

	Ui for Plots							
Precursor	D	D+D	D+D+D	D+D+D+D	D+T	D+T+T	D+T+T+T	T
0000	0.310	0.267	0.291	0.363	0.249	0.341	0.254	0.248
0001	0.025	0.06	0.042	0.054	0.032	0.033	0.057	0.021
0010	0.002	0.0036	0.0024	0.008	0.001	0.0021	0.009	0
0011	0.027	0.06	0.048	0.052	0.036	0.031	0.055	0.025
0100	0.002	0.0036	0.0024	0.008	0.002	0.002	0.011	0
0101	0	0	0.0002	0.0008	0	0	0.001	0
0110	0.004	0.017	0.003	0.01	0.0013	0.007	0.011	0.001
0111	0.027	0.047	0.048	0.044	0.041	0.028	0.046	0.026
1000	0.025	0.06	0.042	0.054	0.032	0.033	0.057	0.021
1001	0.004	0.004	0.008	0.006	0.005	0	0.008	0.004
1010	0	0	0.0002	0.0012	0.001	0	0.003	0
1011	0.004	0.0036	0.003	0.0019	0.006	0.003	0.002	0.002
1100	0.027	0.06	0.048	0.052	0.035	0.03	0.054	0.025
1101	0.004	0.0036	0.003	0.002	0.007	0.003	0.003	0.002
1110	0.027	0.047	0.048	0.044	0.041	0.028	0.046	0.026
1111	0.512	0.362	0.411	0.299	0.511	0.457	0.382	0.598

	T+T	T+T+T	D+Sc	D+Sc+Sc	D+Sc+Sc+Sc	Sc	Sc+Sc	Sc+Sc+Sc
0000	0.410	0.294	0.209	0.223	0.153	0.199	0.146	0.233
0001	0.032	0.050	0.043	0.024	0.023	0.031	0.016	0.051
0010	0.002	0.007	0.013	0	0.007	0.001	0.003	0.004
0011	0.031	0.046	0.034	0.028	0.033	0.03	0.017	0.055
0100	0.0017	0.006	0.009	0.001	0.007	0.001	0.003	0.004
0101	0	0.002	0.007	0	0	0	0	0
0110	0.006	0.015	0.002	0.006	0.005	0.003	0	0.01
0111	0.027	0.033	0.047	0.024	0.033	0.029	0.018	0.045
1000	0.032	0.05	0.043	0.024	0.023	0.031	0.016	0.051
1001	0.001	0.004	0.003	0.004	0.017	0	0.003	0.008
1010	0	0.001	0.004	0.001	0	0	0	0
1011	0.002	0.001	0.015	0.001	0.004	0.002	0.0006	0
1100	0.031	0.048	0.037	0.027	0.033	0.030	0.017	0.055
1101	0.002	0	0.011	0.003	0.004	0.002	0.0006	0
1110	0.027	0.033	0.047	0.024	0.033	0.029	0.018	0.045
1111	0.396	0.41	0.476	0.611	0.624	0.61	0.741	0.436

** Means for two replicates.

Appendix Table 5. Macroporosities of tilths produced by different implements. Measurements were performed within the top 5 cm.

Year	Implements	D	D+Sc	D+CD	MB	MB+Sc	MB+CD	Sc	RC
1976	a	0.18	0.073	0.156	0.221	0.183	0.137	0.145	0.126
	b	0.141	0.055	0.127	0.218	0.180	0.102	0.12	0.115

Year	Implements	D	D+D	D+D+D	D+D+D+D	D+T	D+T+T	D+T+T+T	T
	a	0.457	0.443	0.488	0.468	0.351	0.489	0.505	0.314
	b	0.336	0.483	0.395	0.619	0.366	0.394	0.381	0.333

1977

Year	Implements	T+T	T+T+T	D+Sc	D+Sc+Sc	D+Sc+Sc+Sc	Sc	Sc+Sc	Sc+Sc+Sc
	a	0.532	0.418	0.388	0.297	0.291	0.358	0.20	0.398
	b	0.49	0.482	0.335	0.298	0.307	0.243	0.197	0.40

SECTION B

Appendix Table 6. Structures at different levels (from below) of tilled soils produced at 12.6% water content. Values of P(0) are the probabilities of a 0 following sixteen possible precursors**.

Precursor	P(0) for Levels (a)				P(0) for Levels (b)		
	1	2	3	4	3	4	5
0000	0.900	0.848	0.894	0.892	0.871	0.887	0.887
0001	0.182	0.000	0.000	0.000	0.000	0.000	0.000
0010	0.500	*	*	*	*	*	*
0011	0.000	0.083	0.000	0.222	0.222	0.200	0.200
0100	0.000	*	1.000	*	*	*	*
0101	0.500	*	*	*	*	*	*
0110	*	1.000	*	0.667	1.000	1.000	1.000
0111	0.250	0.167	0.182	0.125	0.111	0.125	0.000
1000	0.546	1.000	0.875	1.000	0.889	1.000	1.000
1001	0.000	0.000	0.000	0.000	*	0.000	0.000
1010	0.000	*	1.000	*	*	*	*
1011	0.000	*	0.000	0.500	0.000	*	*
1100	0.846	0.750	0.875	0.875	1.000	0.900	0.727
1101	0.000	*	0.333	0.000	0.000	*	*
1110	0.867	1.000	0.750	0.875	0.778	1.000	1.000
1111	0.153	0.092	0.082	0.073	0.077	0.071	0.085

Precursor	P(0) for Levels (c)					P(0) for Levels (d)		
	1	2	3	4	5	3	4	5
0000	0.731	0.886	0.816	0.891	0.954	0.857	0.868	0.971
0001	0.111	0.000	0.000	0.000	0.000	0.000	0.077	0.000
0010	1.000	0.000	*	*	*	*	0.000	*
0011	0.222	0.111	0.222	0.000	0.200	0.182	0.143	0.000
0100	0.750	1.000	*	*	*	*	0.000	*
0101	*	0.000	0.000	*	*	*	1.000	*
0110	0.667	0.500	1.000	*	1.000	1.000	1.000	*
0111	0.125	0.091	0.000	0.125	0.000	0.300	0.250	0.667
1000	0.778	1.000	1.000	1.000	1.000	0.857	0.714	0.667
1001	0.500	0.167	0.000	0.000	*	0.000	0.000	0.000
1010	1.000	1.000	0.000	*	*	*	1.000	*
1011	0.500	0.250	0.500	*	*	0.500	*	0.000
1100	0.857	0.250	0.750	0.857	1.000	0.636	0.933	0.600
1101	0.333	0.250	0.250	*	*	0.000	*	0.000
1110	0.714	0.700	0.500	1.000	1.000	0.800	1.000	0.833
1111	0.058	0.094	0.084	0.068	0.068	0.113	0.167	0.069

** Tillage was done with one pass of a set of narrow tines.

Appendix Table 6 *(continued)***.

Precursor	a 3	a 4	a 5	b 3	b 4	b 5	c 4	c 5	d 4	d 5
	P(0) for Levels									
0000	0.895	0.933	0.967	0.724	0.810	0.926	0.741	0.889	0.944	0.957
0001	0.000	0.000	0.000	0.000	0.000	0.000	0.125	0.000	0.000	0.000
0010	0.000	*	*	*	1.000	*	0.000	*	*	*
0011	0.077	0.286	0.000	0.455	0.111	0.000	0.000	0.100	0.000	0.286
0100	*	*	*	*	1.000	*	*	0.000	*	*
0101	0.000	*	*	*	*	*	0.500	*	*	*
0110	1.000	0.500	*	0.800	1.000	*	*	1.000	*	1.000
0111	0.154	0.000	0.000	0.143	0.000	0.125	0.200	0.000	0.000	0.000
1000	0.667	0.833	1.000	0.818	0.875	1.000	0.778	0.667	0.833	1.000
1001	0.250	0.000	*	0.000	1.000	*	0.000	0.000	0.000	0.000
1010	*	*	*	*	*	*	0.000	1.000	*	*
1011	0.500	0.000	*	0.000	0.000	*	0.000	*	*	*
1100	0.692	0.857	1.000	0.917	0.875	1.000	0.900	0.750	0.857	0.857
1101	0.000	0.000	*	0.000	0.000	*	*	1.000	*	*
1110	0.917	0.750	1.000	1.000	0.875	1.000	1.000	0.875	1.000	1.000
1111	0.170	0.119	0.106	0.050	0.068	0.077	0.075	0.076	0.083	0.119

** Tillage was done with two passes of a set of tines with narrow points.

*Appendix Table 6 (continued).***

Precursor	a 4	a 5	b 4	b 5	c 4	c 5	d 4	d 5
	P(0) for Levels							
0000	0.791	0.894	0.861	0.907	0.833	0.950	0.877	0.925
0001	0.100	0.000	0.000	0.000	0.000	0.000	0.091	0.000
0010	0.500	*	*	*	*	*	1.000	*
0011	0.200	0.000	0.000	0.125	0.111	0.000	0.182	0.111
0100	1.000	*	*	*	*	*	1.000	*
0101	0.000	*	*	*	0.500	*	*	*
0110	1.000	*	1.000	1.000	1.000	*	1.000	1.000
0111	0.200	0.167	0.000	0.222	0.222	0.000	0.222	0.000
1000	0.889	0.750	0.857	1.000	0.750	0.833	0.818	1.000
1001	0.500	0.000	*	*	*	*	0.000	0.000
1010	1.000	*	*	*	0.000	*	*	*
1011	0.333	0.000	0.500	0.000	0.000	*	1.000	*
1100	0.778	0.800	1.000	1.000	1.000	1.000	0.909	0.778
1101	0.333	0.000	0.000	0.000	1.000	*	0.000	*
1110	0.667	0.909	0.857	0.800	0.889	1.000	0.889	1.000
1111	0.071	0.106	0.056	0.108	0.058	0.107	0.096	0.111

** Tillage was done with three passes of a set of tines with narrow points.

Appendix Table 6 *(continued)***

Precursor	P(0) for Levels a 4	a 5	b 4	b 5	c 4	c 5	d 4	d 5
0000	0.840	0.960	0.805	0.939	0.841	0.919	0.786	0.906
0001	0.000	0.000	0.111	0.000	0.000	0.000	0.200	0.167
0010	1.000	*	1.000	*	1.000	*	1.000	0.000
0011	0.167	0.143	0.125	0.250	0.000	0.167	0.000	0.000
0100	1.000	*	1.000	*	0.000	*	0.500	*
0101	*	*	*	*	*	*	*	0.000
0110	1.000	1.000	0.000	1.000	*	1.000	*	*
0111	0.000	0.500	0.125	0.000	0.000	0.400	0.000	0.000
1000	0.727	0.875	0.900	1.000	1.000	1.000	0.900	0.833
1001	1.000	*	*	*	0.333	0.000	0.000	*
1010	*	*	*	*	*	*	*	*
1011	*	*	0.000	*	0.000	*	0.000	0.000
1100	0.909	1.000	1.000	1.000	0.778	0.857	1.000	1.000
1101	*	*	0.000	*	0.000	*	0.000	*
1110	1.000	1.000	1.000	1.000	0.900	1.000	0.889	1.000
1111	0.104	0.167	0.090	0.034	0.110	0.041	0.099	0.057

** Tillage was done with four passes of a set of tines with narrow points.

Appendix Table 7. Structures at different levels (from below) of tilled soils produced at 25.2% water content. Values of P(0) are the probabilities of a 0 following sixteen possible precursors**.

Precursor	P(0) for Levels								
	a			b		c		d	
	3	4	5	4	5	4	5	4	5
0000	0.800	0.899	0.907	0.769	0.837	0.650	0.844	0.830	0.954
0001	0.214	0.125	0.125	0.250	0.091	0.000	0.000	0.222	0.000
0010	1.000	0.000	1.000	1.000	1.000	*	*	1.000	*
0011	0.385	0.111	0.125	0.267	0.286	0.000	0.111	0.125	0.167
0100	0.750	*	1.000	0.500	1.000	*	*	1.000	*
0101	0.000	0.000	*	*	*	*	*	*	*
0110	0.600	1.000	1.000	0.600	1.000	*	1.000	0.500	1.000
0111	0.300	0.111	0.143	0.250	0.000	0.100	0.111	0.429	0.000
1000	0.500	0.875	0.875	0.500	0.600	0.875	1.000	0.889	1.000
1001	0.000	0.000	0.500	0.250	0.000	*	0.000	0.000	*
1010	0.500	*	*	1.000	*	*	*	*	*
1011	0.000	0.000	*	0.500	*	0.000	0.000	1.000	*
1100	0.917	0.800	0.750	0.643	0.692	1.000	0.750	0.875	1.000
1101	0.667	0.000	*	0.333	*	0.000	0.000	0.000	*
1110	0.900	0.900	1.000	0.917	1.000	0.800	0.875	1.000	1.000
1111	0.106	0.139	0.088	0.143	0.118	0.067	0.071	0.044	0.172

** Tillage was done with one pass of a set of tines with narrow points.

Appendix Table 7 *(continued)***.

Precursor	P(0) for Levels a 4	a 5	b 3	b 4	c 4	c 5	d 4	d 5
0000	0.667	0.647	0.706	0.850	0.684	0.720	0.875	0.952
0001	0.222	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0010	0.500	*	*	*	1.000	*	*	*
0011	0.250	0.111	0.250	0.000	0.300	0.100	0.100	0.000
0100	1.000	*	1.000	*	1.000	*	*	*
0101	1.000	*	*	*	0.000	*	*	*
0110	1.000	1.000	0.600	*	0.667	1.000	1.000	*
0111	0.167	0.000	0.111	0.125	0.300	0.000	0.333	0.167
1000	0.667	1.000	0.625	1.000	0.600	1.000	0.833	0.750
1001	0.000	0.000	0.000	0.000	1.000	0.000	0.000	0.000
1010	1.000	*	1.000	*	0.500	*	*	*
1011	*	*	1.000	0.000	0.000	*	*	0.000
1100	0.875	0.778	0.667	0.875	0.889	0.700	0.600	0.000
1101	*	*	0.333	0.000	0.500	*	*	0.000
1110	1.000	1.000	0.900	0.889	0.700	1.000	1.000	0.833
1111	0.054	0.100	0.167	0.138	0.137	0.156	0.096	0.100

** Tillage was done with two passes of a set of tines with narrow points.

Appendix Table 7 *(continued)***.

Precursor	P(0) for Levels a 3	a 4	b 4	b 5
0000	0.790	0.862	0.800	0.853
0001	0.000	0.250	0.083	0.000
0010	*	1.000	1.000	*
0011	0.111	0.143	0.000	0.167
0100	1.000	0.667	0.000	*
0101	0.000	*	*	*
0110	1.000	1.000	*	1.000
0111	0.100	0.000	0.071	0.100
1000	0.571	1.000	0.833	0.917
1001	0.000	0.500	0.000	*
1010	0.500	*	*	*
1011	0.000	*	0.000	*
1100	0.750	0.857	0.923	1.000
1101	0.667	*	0.000	*
1110	0.700	1.000	1.000	1.000
1111	0.088	0.057	0.191	0.177

** Tillage was done with three passes of a set of tines with narrow points.

Appendix Table 8. Structures at different levels (from below) of tilled soils produced at 12.6% water content. Values of Ui are the occurrence probabilities for sixteen possible precursors**.

Precursor	Ui for Levels (a)				Ui for Levels (b)		
	1	2	3	4	3	4	5
0000	0.266	0.267	0.282	0.336	0.274	0.328	0.277
0001	0.049	0.041	0.034	0.034	0.o4	0.039	0.033
0010	0.007	0	0.002	0	0	0	0
0011	0.055	0.054	0.036	0.039	0.04	0.043	0.046
0100	0.006	0	0.002	0	0	0	0
0101	0.006	0	0.002	0	0	0	0
0110	0	0.004	0	0.013	0.0088	0.0086	0.0088
0111	0.069	0.05	0.048	0.035	0.04	0.035	0.038
1000	0.049	0.041	0.034	0.034	0.04	0.039	0.033
1001	0.013	0.014	0.004	0.005	0	0.004	0.013
1010	0.006	0	0.002	0.086	0.088	0	0
1011	0.014	0	0.011	0.009	0.008	0	0
1100	0.056	0.054	0.036	0.039	0.04	0.043	0.046
1101	0.013	0	0.011	0.009	0.008	0	0
1110	0.069	0.05	0.048	0.035	0.04	0.035	0.038
1111	0.322	0.426	0.446	0.414	0.46	0.425	0.467

Precursor	Ui for Levels (c)					Ui for Levels (b)		
	1	2	3	4	5	3	4	5
0000	0.134	0.176	0.191	0.323	0.551	0.246	0.321	0.458
0001	0.046	0.018	0.033	0.033	0.026	0.041	0.063	0.016
0010	0.015	0.005	0	0	0	0	0.005	0
0011	0.041	0.043	0.043	0.038	0.026	0.064	0.068	0.024
0100	0.016	0.005	0	0	0	0	0.005	0
0101	0.002	0.005	0.005	0	0	0	0.005	0
0110	0.015	0.01	0.02	0	0.005	0.018	0.009	0
0111	0.038	0.054	0.043	0.038	0.02	0.058	0.058	0.029
1000	0.046	0.018	0.033	0.033	0.026	0.041	0.063	0.016
1001	0.01	0.031	0.01	0.005	0	0.023	0.009	0.0088
1010	0.003	0.005	0.005	0	0	0	0.005	0.044
1011	0.012	0.02	0.02	0	0	0.012	0	0.004
1100	0.041	0.043	0.043	0.038	0.026	0.064	0.068	0.024
1101	0.013	0.02	0.020	0	0	0.012	0	0.004
1110	0.038	0.054	0.043	0.038	0.02	0.058	0.058	0.029
1111	0.529	0.492	0.487	0.452	0.301	0.363	0.263	0.387

** Tillage was done with one pass of a set of tines with narrow points.

Appendix Table 8 (continued).**

Precursor	Ui for Levels a 2	a 4	a 5	b 3	b 4	b 5	c 4	c 5	d 4	d 5
0000	0.297	0.384	0.625	0.132	0.192	0.449	0.136	0.191	0.244	0.385
0001	0.047	0.031	0.023	0.047	0.039	0.033	0.045	0.032	0.067	0.029
0010	0.003	0	0	0	0.004	0	0.0027	0.0026	0.005	0
0011	0.065	0.036	0.023	0.052	0.039	0.033	0.048	0.045	0.078	0.034
0100	0.003	0	0	0	0.005	0	0.0026	0.0025	0.005	0
0101	0.003	0	0	0	0	0	0.0079	0.0026	0.052	0
0110	0.01	0.01	0	0.023	0.005	0	0	0.005	0.025	0
0111	0.063	0.043	0.023	0.033	0.039	0.033	0.051	0.043	0.058	0.034
1000	0.047	0.031	0.023	0.047	0.039	0.033	0.045	0.032	0.067	0.029
1001	0.021	0.005	0	0.004	0.005	0	0.005	0.016	0.016	0.005
1010	0.003	0	0	0.047	0.046	0	0.008	0.003	0.05	0
1011	0.008	0.018	0	0.005	0.005	0	0.003	0.003	0.005	0
1100	0.065	0.036	0.023	0.052	0.039	0.033	0.049	0.045	0.078	0.034
1101	0.008	0.018	0	0.005	0.005	0	0.0025	0.0025	0.005	0
1110	0.063	0.043	0.023	0.033	0.039	0.033	0.051	0.043	0.058	0.034
1111	0.298	0.345	0.237	0.567	0.544	0.35	0.543	0.534	0.289	0.414

** Tillage was done with two passes of a set of tines with narrow points.

Appendix Table 8 *(continued).***

Precursor	Ui for Levels							
	a		b		c		d	
	4	5	4	5	4	5	4	5
0000	0.197	0.303	0.20	0.41	0.182	0.558	0.338	0.43
0001	0.044	0.039	0.032	0.038	0.04	0.03	0.051	0.032
0010	0.009	0	0	0	0	0	0.005	0
0011	0.044	0.049	0.032	0.038	0.04	0.03	0.051	0.042
0100	0.009	0	0	0	0	0	0.005	0
0101	0.005	0	0	0	0.009	0	0	0
0110	0.014	0	0.0046	0.0044	0.004	0	0.014	0.005
0111	0.044	0.053	0.035	0.043	0.04	0.03	0.042	0.037
1000	0.044	0.039	0.032	0.038	0.04	0.03	0.051	0.032
1001	0.009	0.009	0	0	0	0	0.005	0
1010	0.005	0.005	0.07	0.09	0.009	0	0	0
1011	0.014	0.005	0.007	0.009	0.004	0	0.005	0
1100	0.044	0.049	0.032	0.038	0.04	0.03	0.051	0.042
1101	0.014	0.005	0.007	0.009	0.004	0	0.005	0
1110	0.044	0.053	0.035	0.043	0.04	0.03	0.042	0.037
1111	0.461	0.396	0.582	0.33	0.544	0.262	0.338	0.333

** Tillage was done with three passes of a set of tines with narrow points.

Appendix Table 8 (continued)**.

Precursor	Ui for Levels a 4	a 5	b 4	b 5	c 4	c 5	d 4	d 5
0000	0.245	0.687	0.227	0.37	0.232	0.337	0.206	0.270
0001	0.054	0.035	0.052	0.023	0.037	0.027	0.049	0.031
0010	0.005	0	0.005	0	0.005	0	0.010	0.003
0011	0.054	0.035	0.047	0.023	0.048	0.032	0.044	0.028
0100	0.005	0	0.005	0	0.005	0	0.01	0.003
0101	0	0	0	0	0	0	0	0.003
0110	0.009	0.005	0.0058	0.0057	0	0.005	0	0
0111	0.045	0.03	0.047	0.017	0.053	0.027	0.049	0.031
1000	0.054	0.035	0.052	0.023	0.037	0.027	0.049	0.031
1001	0.005	0	0	0	0.016	0.005	0.005	0
1010	0	0	0	0	0	0	0.052	0.003
1011	0	0	0.006	0	0.005	0	0.005	0.003
1100	0.054	0.035	0.047	0.023	0.048	0.032	0.044	0.028
1101	0	0	0.006	0	0.005	0	0.005	0.003
1110	0.045	0.03	0.047	0.017	0.053	0.027	0.049	0.031
1111	0.427	0.109	0.454	0.50	0.457	0.481	0.473	0.536

** Tillage was done with four passes of a set of tines with narrow points.

Appendix Table 9. Structures at different levels (from below) of tilled soils produced at 25.2% water content. Values of Ui are the occurrence probabilities for sixteen precursors.**

Precursor	Ui for Levels								
	a			b		c		d	
	3	4	5	4	5	4	5	4	5
0000	0.179	0.345	0.383	0.133	0.217	0.10	0.227	0.24	0.649
0001	0.071	0.04	0.041	0.061	0.054	0.039	0.033	0.046	0.033
0010	0.018	0.003	0.01	0.028	0.005	0	0	0.01	0
0011	0.064	0.048	0.041	0.074	0.069	0.039	0.043	0.041	0.033
0100	0.018	0.003	0.01	0.028	0.005	0	0	0.01	0
0101	0.008	0.003	0	0.003	0.051	0	0	0	0
0110	0.026	0.005	0.005	0.026	0.02	0	0.005	0.01	0.005
0111	0.051	0.05	0.036	0.061	0.048	0.049	0.043	0.036	0.028
1000	0.071	0.04	0.041	0.061	0.054	0.039	0.033	0.046	0.033
1001	0.01	0.01	0.01	0.041	0.02	0	0.01	0.005	0
1010	0.008	0.003	0	0.003	0	0	0	0	0
1011	0.013	0.008	0	0.013	0	0.01	0.005	0.005	0
1100	0.064	0.048	0.041	0.074	0.069	0.039	0.043	0.041	0.033
1101	0.013	0.008	0	0.013	0	0.01	0.005	0.005	0
1110	0.051	0.05	0.036	0.061	0.048	0.049	0.043	0.036	0.028
1111	0.337	0.339	0.347	0.321	0.39	0.625	0.508	0.469	0.16

** Tillage was done with one pass of a set of tines with narrow points.

Appendix Table 9 *(continued)***.

Precursor	Ui for Levels							
	a		b		c		d	
	4	5	3	4	4	5	4	5
0000	0.118	0.13	0.122	0.277	0.13	0.177	0.266	0.432
0001	0.059	0.046	0.058	0.045	0.069	0.049	0.04	0.027
0010	0.013	0	0.003	0	0.01	0	0	0
0011	0.053	0.06	0.081	0.051	0.065	0.071	0.067	0.034
0100	0.013	0	0.003	0	0.01	0	0	0
0101	0.006	0	0.003	0	0.01	0	0	0
0110	0.014	0.007	0.003	0	0.021	0.007	0.007	0
0111	0.039	0.053	0.064	0.058	0.069	0.064	0.06	0.041
1000	0.059	0.046	0.058	0.045	0.069	0.049	0.04	0.027
1001	0.007	0.014	0.027	0.007	0.007	0.021	0.027	0.007
1010	0.007	0	0.003	0	0.01	0	0	0
1011	0	0	0.017	0.007	0.024	0	0	0.007
1100	0.05	0.06	0.081	0.051	0.065	0.071	0.067	0.034
1101	0	0	0.017	0.007	0.024	0	0	0.007
1110	0.039	0.053	0.064	0.058	0.069	0.064	0.06	0.041
1111	0.522	0.532	0.363	0.394	0.349	0.427	0.368	0.342

** Tillage was done with two passes of a set of tines with narrow points.

Appendix Table 9 *(continued)**.*

Precursor	Ui for Levels a 3	a 4	b 4	b 5
0000	0.10	0.284	0.256	0.383
0001	0.037	0.039	0.061	0.061
0010	0.003	0.015	0.005	0
0011	0.045	0.034	0.067	0.061
0100	0.003	0.015	0.005	0
0101	0.008	0	0	0
0110	0.005	0.005	0	0.01
0111	0.053	0.029	0.069	0.051
1000	0.037	0.039	0.061	0.061
1001	0.011	0.01	0.01	0
1010	0.008	0	0	0
1011	0.013	0	0.003	0
1100	0.045	0.034	0.067	0.061
1101	0.013	0	0.003	0
1110	0.053	0.029	0.069	0.051
1111	0.569	0.467	0.325	0.26

** Tillage was done with three passes of a set of tines with narrow points.

Appendix Table 10. Aggregate size distributions at different levels (from below) in tilths produced at 12.6% water content as expressed by the proportion larger than X mm.

Replicate	Level	X: 1	2	4	8	16	32	64	Mean aggregate size
a**	1	0.84	0.84	0.53	0.26	0.07	0.004	0.00	6.6
	2	1.00	0.92	0.68	0.46	0.20	0.04	0.002	10.8
	3	0.92	0.92	0.68	0.47	0.23	0.05	0.003	11.4
	4	1.00	0.73	0.59	0.44	0.24	0.07	0.006	11.5
b**	3	1.00	0.82	0.67	0.48	0.26	0.07	0.006	12.0
	4	1.00	0.80	0.65	0.48	0.267	0.08	0.008	12.6
	5	1.00	0.81	0.74	0.53	0.272	0.07	0.005	12.9
c**	1	0.75	0.54	0.44	0.34	0.20	0.07	0.009	9.7
	2	0.86	0.72	0.59	0.39	0.17	0.033	0.001	9.2
	3	0.93	0.63	0.57	0.40	0.19	0.04	0.002	9.6
	4	1.00	1.00	0.80	0.59	0.32	0.10	0.008	14.8
	5	1.00	0.80	0.75	0.56	0.32	0.10	0.011	14.6
d**	3	1.00	0.77	0.48	0.30	0.11	0.02	0.00	7.5
	4	0.88	0.76	0.47	0.23	0.05	0.003	0.00	6.0
	5	1.00	1.00	0.93	0.68	0.37	0.11	0.01	16.5
a***	3	0.93	0.81	0.56	0.26	0.05	0.002	0.00	6.6
	4	1.00	0.81	0.71	0.41	0.14	0.02	0.00	9.2
	5	1.00	1.00	0.90	0.60	0.27	0.05	0.002	13.3
b***	3	1.00	0.58	0.48	0.39	0.26	0.11	0.02	12.7
	4	0.91	0.81	0.75	0.56	0.31	0.09	0.01	13.9
	5	1.00	1.00	0.80	0.56	0.28	0.07	0.004	13.5
c***	4	0.83	0.83	0.61	0.45	0.24	0.07	0.006	11.5
	5	0.90	0.81	0.74	0.53	0.27	0.072	0.005	12.8
d***	4	0.94	0.66	0.49	0.22	0.04	0.002	0.00	5.9
	5	1.00	1.00	0.92	0.65	0.32	0.08	0.01	15.0

** Tillage was done with one pass of a set of tines with narrow points.

*** Tillage was done with two passes of a set of tines with narrow points.

Appendix Table 10 *(continued)*.

Replicate	Level	X (mm) 1	2	4	8	16	32	64	Mean aggregate size
a**	4	0.81	0.61	0.45	0.33	0.18	0.05	0.004	8.8
	5	1.00	1.00	0.73	0.46	0.18	0.03	0.006	10.4
b**	4	1.00	0.88	0.83	0.65	0.40	0.15	0.02	17.6
	5	1.00	0.90	0.64	0.42	0.18	0.03	0.001	10.0
c**	4	0.83	0.75	0.55	0.43	0.27	0.10	0.01	12.7
	5	1.00	1.00	0.89	0.54	0.20	0.03	0.001	11.7
d**	4	0.92	0.69	0.49	0.33	0.15	0.028	0.001	8.2
	5	1.00	0.89	0.79	0.49	0.19	0.029	0.001	11.0
a***	4	0.92	0.76	0.68	0.44	0.18	0.03	0.001	9.9
	5	1.00	0.87	0.39	0.21	0.06	0.004	0.00	6.0
b***	4	0.91	0.81	0.64	0.44	0.21	0.05	0.002	10.5
	5	1.00	0.75	0.72	0.63	0.48	0.27	0.09	24.7
c***	4	0.91	0.91	0.80	0.49	0.19	0.027	0.001	10.7
	5	1.00	0.85	0.52	0.45	0.34	0.19	0.06	17.9
d***	4	0.83	0.83	0.74	0.48	0.20	0.03	0.001	10.6
	5	0.86	0.86	0.81	0.64	0.40	0.16	0.024	17.7

** Tillage was done with three passes of a set of tines with narrow points.

*** Tillage was done with four passes of a set of tines with narrow points.

Appendix Table 11. Aggregate size distributions at different levels (from below) in tilths produced at 25.2% water content as expressed by the proportion larger than X mm**.

Number of passes	Replicate	Level	X: 1	2	4	8	16	32	64	$\bar{D}$
1	a	3	0.75	0.50	0.31	0.20	0.08	0.014	0.00	5.5
		4	0.92	0.83	0.65	0.37	0.12	0.012	0.00	8.4
		5	0.80	0.70	0.55	0.38	0.18	0.04	0.002	9.3
	b	4	0.74	0.52	0.34	0.18	0.05	0.005	0.00	5.0
		5	0.93	0.66	0.57	0.34	0.12	0.014	0.0002	7.9
	c	4	1.00	1.00	0.83	0.62	0.35	0.11	0.01	15.7
		5	1.00	0.89	0.73	0.53	0.29	0.08	0.007	13.4
	d	4	0.82	0.64	0.35	0.29	0.20	0.10	0.024	10.8
		5	1.00	0.85	0.70	0.33	0.07	0.004	0.00	7.8
2	a	4	0.73	0.53	0.41	0.32	0.19	0.07	0.009	9.5
		5	1.00	0.89	0.80	0.52	0.23	0.04	0.001	11.8
	b	3	0.94	0.61	0.46	0.23	0.06	0.003	0.00	6.0
		4	1.00	1.00	0.77	0.44	0.14	0.02	0.0002	9.8
	c	4	0.81	0.63	0.38	0.21	0.06	0.006	0.00	5.6
		5	1.00	0.90	0.77	0.40	0.11	0.008	0.00	9.0
	d	4	1.00	0.89	0.52	0.33	0.14	0.02	0.007	8.4
		5	1.00	1.00	0.75	0.49	0.21	0.04	0.001	11.3
3	a	3	0.85	0.77	0.64	0.45	0.22	0.06	0.003	10.9
		4	0.70	0.59	0.56	0.43	0.26	0.092	0.012	11.8
	b	4	0.93	0.93	0.69	0.28	0.05	0.001	0.00	7.2
		5	1.00	0.83	0.62	0.28	0.06	0.002	0.00	7.1

** Tillage was done using different number of passes of a set of tines with narrow points.

$\bar{D}$ = Mean aggregate size.

Appendix Table 12. Pore size distributions at different levels (from below) in tilths produced at 12.6% water content as expressed by the proportion larger than X mm.

Replicate	Level	X: 1	2	4	8	16	32	65	$\bar{\delta}$	Macro-porosity
	1	0.76	0.60	0.29	0.19	0.08	0.015	0.00	24.6	0.46
a**	2	1.00	0.75	0.64	0.33	0.09	0.006	0.00	7.7	0.42
	3	0.74	0.66	0.52	0.33	0.13	0.02	0.0006	7.8	0.41
	4	0.82	0.72	0.65	0.42	0.18	0.03	0.001	9.6	0.46
	3	0.82	0.82	0.63	0.37	0.12	0.013	0.00	8.3	0.40
b**	4	1.00	0.90	0.79	0.48	0.17	0.02	0.00	10.5	0.45
	5	1.00	0.71	0.63	0.38	0.14	0.02	0.00	8.7	0.40
	1	0.79	0.65	0.37	0.11	0.01	0.00	0.00	4.3	0.308
	2	0.66	0.24	0.22	0.14	0.06	0.01	0.00	4.3	0.316
c**	3	0.63	0.48	0.40	0.19	0.04	0.002	0.00	4.9	0.337
	4	1.00	0.87	0.78	0.51	0.21	0.04	0.001	11.3	0.434
	5	1.00	1.00	0.95	0.79	0.54	0.25	0.06	24.6	0.628
	3	0.85	0.54	0.40	0.21	0.06	0.005	0.00	5.6	0.428
d**	4	0.94	0.82	0.50	0.27	0.08	0.008	0.0001	7.7	0.533
	5	0.85	0.54	0.38	0.34	0.28	0.19	0.09	7.8	0.53
	3	0.87	0.63	0.36	0.23	0.10	0.02	0.00	6.3	0.489
a***	4	0.67	0.57	0.44	0.34	0.19	0.06	0.007	9.4	0.504
	5	1.00	1.00	0.96	0.83	0.62	0.34	0.10	30.3	0.694
	3	0.92	0.84	0.48	0.12	0.008	0.00	0.00	5.1	0.287
b***	4	1.00	0.89	0.56	0.15	0.01	0.001	0.00	6.7	0.324
	5	1.00	1.00	0.93	0.68	0.37	0.11	0.01	16.4	0.549
	4	0.83	0.74	0.43	0.13	0.01	0.00	0.00	4.8	0.294
c***	5	0.90	0.60	0.36	0.22	0.09	0.01	0.0003	6.1	0.223
d***	4	0.94	0.77	0.46	0.18	0.03	0.001	0.00	5.5	0.483
	5	1.00	0.85	0.65	0.50	0.30	0.11	0.014	14.0	0.483

** Tillage was done with one pass of a set of tines with narrow points.

*** Tillage was done with two passes of a set of tines with narrow points.

$\bar{\delta}$ = Mean pore size.

Appendix Table 12 *(continued)*

Replicate	Level	X (mm) 1	2	4	8	16	32	64	$\overline{\delta}$	Macro-porosity
a**	4	0.74	0.61	0.44	0.18	0.03	0.001	0.00	5.1	0.366
	5	0.91	0.74	0.51	0.34	0.15	0.027	0.001	8.3	0.445
b**	4	0.83	0.82	0.61	0.33	0.10	0.01	0.00	7.7	0.304
	5	0.81	0.81	0.73	0.50	0.23	0.05	0.002	11.3	0.533
c**	4	0.75	0.75	0.47	0.23	0.05	0.003	0.00	5.9	0.317
	5	1.00	1.00	0.81	0.67	0.46	0.22	0.05	21.6	0.648
d**	4	0.92	0.85	0.61	0.36	0.13	0.015	0.00	8.4	0.505
	5	1.00	0.78	0.72	0.53	0.28	0.08	0.007	13.1	0.546
a***	4	1.00	0.92	0.56	0.28	0.07	0.004	0.00	7.1	0.416
	5	1.00	1.00	0.83	0.69	0.48	0.24	0.06	22.8	0.591
b***	4	0.90	0.90	0.64	0.26	0.04	0.001	0.00	6.7	0.389
	5	1.00	1.00	0.94	0.73	0.44	0.159	0.021	19.3	0.438
c***	4	0.91	0.64	0.54	0.27	0.07	0.004	0.00	6.6	0.380
	5	1.00	0.85	0.78	0.56	0.28	0.07	0.01	13.3	0.428
d***	4	0.91	0.83	0.58	0.22	0.03	0.001	0.00	6.2	0.369
	5	0.86	0.86	0.65	0.44	0.20	0.04	0.002	10.3	0.367

** Tillage was done with three passes of a set of tines with narrow points.

*** Tillage was done with four passes of a set of tines with narrow points.

Appendix Table 13. Pore size distributions at different levels (from below) in tilths produced at 25.2% water content as expressed by the proportion larger than X mm**.

Number of passes	Replicate	Level	X 1	2	4	8	16	32	64	$\bar{\delta}$	Macro-porosity
1	a	3	0.80	0.70	0.28	0.11	0.02	0.001	0.00	4.3	0.434
		4	0.83	0.67	0.52	0.34	0.15	0.03	0.001	8.3	0.495
		5	1.00	0.80	0.63	0.43	0.20	0.04	0.002	10.3	0.526
	b	4	0.87	0.52	0.20	0.07	0.01	0.00	0.00	3.5	0.413
		5	1.00	0.72	0.38	0.20	0.05	0.004	0.00	5.7	0.420
	c	4	0.80	0.80	0.46	0.08	0.003	0.00	0.00	4.6	0.227
		5	0.89	0.68	0.58	0.31	0.09	0.007	0.00	7.3	0.352
	d	4	0.91	0.82	0.60	0.29	0.06	0.003	0.00	7.0	0.393
		5	1.00	1.00	0.95	0.77	0.51	0.22	0.04	23.0	0.470
2	a	4	0.91	0.82	0.36	0.07	0.003	0.00	0.00	4.4	0.310
		5	1.00	0.76	0.49	0.09	0.003	0.00	0.00	4.9	0.300
	b	3	0.81	0.55	0.24	0.06	0.004	0.00	0.00	3.5	0.370
		4	0.88	0.76	0.64	0.32	0.08	0.005	0.00	7.4	0.432
	c	4	0.69	0.63	0.26	0.06	0.003	0.00	0.00	3.5	0.384
		5	1.00	0.70	0.50	0.14	0.01	0.0001	0.00	5.2	0.367
	d	4	1.00	0.60	0.44	0.26	0.09	0.01	0.00	6.6	0.439
		5	0.83	0.67	0.48	0.39	0.27	0.12	0.026	13.0	0.534
3	a	3	0.69	0.54	0.24	0.09	0.01	0.00	0.00	3.7	0.252
		4	1.00	0.80	0.69	0.38	0.12	0.01	0.00	6.8	0.421
	b	4	0.97	0.83	0.55	0.23	0.04	0.001	0.00	6.2	0.463
		5	1.00	1.00	0.78	0.41	0.12	0.01	0.0001	9.2	0.566

** Tillage was done using different number of passes of a set of tines with narrow points.

$\bar{\delta}$ = Mean pore size.

Appendix Table 14. Proportions****of small size aggregates at different levels (from below) in tilths produced at 12.6% water content.

Replicate	Level	Size (mm) 1	2	3	4	5	6	7	8	9	Total 1-5	Total 1-9
a**	1	0.15	0.00	0.22	0.10	0.08	0.07	0.06	0.05	0.04	0.556	0.776
	2	0.00	0.08	0.16	0.07	0.07	0.06	0.05	0.05	0.04	0.379	0.585
	3	0.09	0.00	0.17	0.06	0.06	0.05	0.05	0.05	0.04	0.373	0.561
	4	0.00	0.27	0.09	0.05	0.04	0.04	0.04	0.03	0.03	0.452	0.59
b**	3	0.00	0.18	0.09	0.06	0.05	0.05	0.04	0.04	0.04	0.381	0.552
	4	0.00	0.20	0.10	0.05	0.04	0.04	0.04	0.04	0.04	0.396	0.55
	5	0.00	0.19	0.00	0.07	0.06	0.06	0.05	0.05	0.04	0.316	0.512
c**	1	0.25	0.21	0.07	0.03	0.03	0.03	0.02	0.02	0.02	0.592	0.686
	2	0.14	0.14	0.07	0.07	0.06	0.05	0.05	0.04	0.04	0.468	0.648
	3	0.07	0.30	0.00	0.06	0.05	0.05	0.04	0.04	0.04	0.477	0.64
	4	0.00	0.00	0.13	0.06	0.06	0.06	0.05	0.05	0.04	0.256	0.453
	5	0.00	0.20	0.00	0.05	0.05	0.05	0.04	0.04	0.04	0.305	0.475
d**	3	0.00	0.23	0.23	0.06	0.05	0.05	0.04	0.04	0.03	0.577	0.738
	4	0.12	0.12	0.19	0.10	0.08	0.07	0.06	0.05	0.04	0.605	0.810
	5	0.00	0.00	0.00	0.07	0.07	0.06	0.06	0.06	0.05	0.143	0.372
a***	3	0.07	0.13	0.13	0.12	0.10	0.08	0.07	0.06	0.05	0.541	0.789
	4	0.00	0.19	0.00	0.10	0.09	0.08	0.07	0.06	0.05	0.382	0.64
	5	0.00	0.00	0.00	0.10	0.09	0.08	0.07	0.06	0.06	0.194	0.466
b***	3	0.00	0.42	0.08	0.03	0.02	0.02	0.02	0.02	0.02	0.55	0.631
	4	0.10	0.10	0.00	0.06	0.05	0.05	0.07	0.04	0.04	0.30	0.483
	5	0.00	0.00	0.13	0.07	0.07	0.06	0.06	0.05	0.05	0.271	0.484
c***	4	0.17	0.00	0.17	0.05	0.05	0.04	0.04	0.04	0.03	0.433	0.585
	5	0.10	0.10	0.00	0.07	0.06	0.06	0.05	0.05	0.04	0.316	0.51
d***	4	0.06	0.29	0.06	0.11	0.09	0.07	0.06	0.05	0.04	0.60	0.821
	5	0.00	0.00	0.00	0.08	0.08	0.07	0.06	0.06	0.05	0.159	0.406

** Tillage was done with one pass of a set of tines with narrow points.

*** Tillage was done with two passes of a set of tines with narrow points.

**** Truncated figures.

Appendix Table 14 *(continued)*.

Replicate	Level	Size (mm) 1	2	3	4	5	6	7	8	9	Total 1-5	Total 1-9
a**	4	0.19	0.19	0.13	0.04	0.03	0.03	0.03	0.03	0.03	0.588	0.70
	5	0.00	0.00	0.17	0.09	0.08	0.07	0.07	0.06	0.05	0.347	0.59
b**	4	0.00	0.12	0.00	0.05	0.05	0.05	0.04	0.04	0.04	0.221	0.391
	5	0.00	0.10	0.19	0.07	0.07	0.06	0.05	0.05	0.04	0.424	0.626
c**	4	0.17	0.08	0.17	0.03	0.03	0.03	0.03	0.03	0.03	0.483	0.593
	5	0.00	0.00	0.00	0.12	0.10	0.10	0.08	0.07	0.06	0.216	0.517
d**	4	0.07	0.23	0.15	0.05	0.05	0.04	0.04	0.04	0.03	0.561	0.71
	5	0.00	0.11	0.00	0.10	0.09	0.08	0.07	0.06	0.06	0.298	0.562
a***	4	0.08	0.16	0.00	0.08	0.07	0.06	0.06	0.05	0.05	0.39	0.61
	5	0.00	0.13	0.40	0.07	0.06	0.05	0.04	0.04	0.03	0.66	0.82
b***	4	0.10	0.10	0.10	0.06	0.06	0.05	0.05	0.04	0.04	0.418	0.601
	5	0.00	0.25	0.00	0.03	0.03	0.02	0.02	0.02	0.02	0.301	0.392
c***	4	0.09	0.00	0.00	0.10	0.09	0.08	0.07	0.06	0.06	0.287	0.562
	5	0.00	0.15	0.31	0.02	0.02	0.02	0.02	0.02	0.02	0.562	0.568
d***	4	0.17	0.00	0.00	0.09	0.08	0.07	0.06	0.06	0.05	0.337	0.573
	5	0.14	0.00	0.00	0.05	0.05	0.04	0.04	0.04	0.04	0.238	0.40

Appendix Table 15. Proportions of small size aggregates at different levels (from below) in tilths produced at 25.2% water content. Tillage was done with one to three passes of a set of tines with narrow points.

Replicate	Level	Size (mm) 1	2	3	4	5	6	7	8	9	Total 1-5	Total 1-9
a**	3	0.25	0.25	0.15	0.04	0.03	0.03	0.03	0.02	0.02	0.72	0.84
	4	0.08	0.08	0.09	0.10	0.07	0.06	0.06	0.05	0.05	0.43	0.73
	5	0.20	0.10	0.10	0.05	0.05	0.04	0.04	0.04	0.04	0.50	0.66
b**	4	0.26	0.22	0.13	0.06	0.05	0.04	0.04	0.03	0.03	0.71	0.85
	5	0.07	0.28	0.00	0.08	0.07	0.06	0.05	0.05	0.04	0.43	0.70
c**	4	0.00	0.00	0.11	0.06	0.06	0.05	0.05	0.05	0.04	0.23	0.42
	5	0.00	0.11	0.11	0.06	0.05	0.05	0.05	0.04	0.04	0.32	0.51
d**	4	0.18	0.18	0.24	0.02	0.02	0.01	0.01	0.01	0.01	0.67	0.70
	5	0.00	0.15	0.00	0.15	0.12	0.10	0.08	0.07	0.06	0.42	0.66
a***	4	0.27	0.19	0.10	0.03	0.02	0.02	0.02	0.02	0.02	0.61	0.68
	5	0.00	0.11	0.00	0.09	0.08	0.07	0.06	0.06	0.05	0.27	0.51
b***	3	0.06	0.32	0.06	0.09	0.07	0.06	0.05	0.04	0.04	0.61	0.81
	4	0.00	0.00	0.12	0.12	0.10	0.09	0.08	0.07	0.06	0.33	0.59
c***	4	0.19	0.19	0.19	0.06	0.05	0.04	0.04	0.03	0.03	0.67	0.82
	5	0.00	0.10	0.00	0.14	0.12	0.10	0.08	0.07	0.06	0.35	0.66
d***	4	0.00	0.11	0.32	0.06	0.05	0.05	0.04	0.04	0.03	0.53	0.70
	5	0.00	0.00	0.17	0.00	0.08	0.07	0.06	0.05	0.04	0.33	0.55
a****	3	0.15	0.08	0.07	0.06	0.05	0.05	0.04	0.04	0.04	0.41	0.59
	4	0.30	0.11	0.00	0.04	0.03	0.03	0.03	0.03	0.03	0.47	0.60
b****	4	0.07	0.00	0.07	0.17	0.14	0.11	0.09	0.07	0.06	0.45	0.77
	5	0.00	0.17	0.08	0.13	0.11	0.09	0.07	0.06	0.04	0.49	0.75

** Tillage was done by one pass of implement.

*** Tillage was done by two passes of implement.

**** Tillage was done by three passes of implement.

Appendix Table 16. Proportions**** of small size pores at different levels (from below) in tilths produced at 12.6% water content.

Replicate	Level	Size (mm) 1	2	3	4	5	6	7	8	9	Total 1-5	Total 1-9
a**	1	0.24	0.16	0.27	0.03	0.03	0.03	0.02	0.02	0.02	0.737	0.827
	2	0.00	0.25	0.00	0.11	0.10	0.08	0.07	0.06	0.05	0.461	0.722
	3	0.26	0.08	0.08	0.06	0.06	0.05	0.04	0.04	0.04	0.539	0.706
	4	0.18	0.10	0.00	0.07	0.07	0.06	0.05	0.05	0.04	0.418	0.621
b**	3	0.18	0.00	0.09	0.09	0.08	0.07	0.06	0.05	0.05	0.449	0.683
	4	0.00	0.10	0.00	0.11	0.09	0.08	0.07	0.07	0.06	0.30	0.579
	5	0.00	0.29	0.00	0.09	0.08	0.07	0.06	0.05	0.05	0.447	0.667
c**	1	0.21	0.15	0.14	0.14	0.10	0.07	0.05	0.04	0.03	0.732	0.924
	2	0.35	0.42	0.00	0.03	0.02	0.02	0.02	0.02	0.01	0.81	0.878
	3	0.37	0.15	0.00	0.08	0.07	0.06	0.05	0.04	0.03	0.67	0.845
	4	0.00	0.13	0.00	0.09	0.08	0.07	0.06	0.06	0.05	0.30	0.547
	5	0.00	0.00	0.00	0.05	0.04	0.04	0.04	0.04	0.04	0.09	0.247
d**	3	0.15	0.31	0.08	0.07	0.06	0.05	0.04	0.04	0.03	0.67	0.83
	4	0.06	0.12	0.24	0.08	0.07	0.06	0.05	0.04	0.04	0.57	0.76
	5	0.15	0.31	0.15	0.01	0.01	0.01	0.01	0.01	0.01	0.63	0.668
a***	3	0.13	0.27	0.20	0.04	0.04	0.03	0.03	0.03	0.03	0.024	0.678
	4	0.33	0.10	0.10	0.03	0.03	0.03	0.03	0.02	0.02	0.023	0.549
	5	0.00	0.00	0.00	0.04	0.03	0.03	0.03	0.03	0.03	0.072	0.201
b***	3	0.08	0.08	0.16	0.20	0.14	0.10	0.07	0.05	0.04	0.656	0.912
	4	0.01	0.10	0.10	0.13	0.11	0.09	0.07	0.06	0.05	0.54	0.81
	5	0.00	0.00	0.00	0.08	0.07	0.06	0.06	0.06	0.05	0.144	0.373
c***	4	0.17	0.09	0.17	0.15	0.11	0.08	0.06	0.05	0.03	0.683	0.904
	5	0.10	0.30	0.20	0.05	0.04	0.04	0.03	0.03	0.03	0.682	0.80
d***	4	0.06	0.18	0.18	0.13	0.10	0.08	0.06	0.05	0.04	0.634	0.859
	5	0.00	0.15	0.15	0.04	0.04	0.04	0.04	0.03	0.03	0.391	0.529

** Tillage was done with one pass of a set of tines with narrow points.
*** Tillage was done with two passes of a set of tines with narrow points.
**** Truncated figures.

Appendix Table 16 *(continued).*

Replicate	Level	Size (mm) 1	2	3	4	5	6	7	8	9	Total 1-5	Total 1-9
a**	4	0.26	0.13	0.07	0.11	0.09	0.07	0.06	0.05	0.04	0.65	0.857
	5	0.09	0.17	0.17	0.06	0.05	0.05	0.04	0.04	0.03	0.54	0.699
b**	4	0.18	0.00	0.12	0.10	0.09	0.07	0.06	0.05	0.05	0.478	0.715
	5	0.19	0.00	0.00	0.08	0.07	0.06	0.06	0.05	0.05	0.334	0.549
c**	4	0.25	0.00	0.19	0.09	0.08	0.07	0.05	0.05	0.04	0.61	0.81
	5	0.00	0.00	0.15	0.04	0.04	0.04	0.03	0.03	0.03	0.23	0.36
d**	4	0.08	0.08	0.15	0.09	0.08	0.07	0.06	0.05	0.04	0.468	0.686
	5	0.00	0.22	0.00	0.06	0.05	0.05	0.05	0.04	0.04	0.335	0.513
a***	4	0.00	0.08	0.25	0.11	0.09	0.08	0.06	0.05	0.05	0.53	0.766
	5	0.00	0.00	0.13	0.04	0.04	0.04	0.03	0.03	0.03	0.207	0.337
b***	4	0.10	0.00	0.10	0.17	0.13	0.10	0.08	0.07	0.05	0.492	0.797
	5	0.00	0.00	0.00	0.06	0.06	0.05	0.05	0.05	0.05	0.12	0.318
c***	4	0.09	0.27	0.00	0.10	0.09	0.07	0.06	0.05	0.04	0.549	0.776
	5	0.00	0.15	0.00	0.07	0.06	0.06	0.05	0.05	0.05	0.285	0.490
d***	4	0.09	0.09	0.08	0.16	0.13	0.10	0.08	0.06	0.05	0.541	0.825
	5	0.14	0.00	0.14	0.07	0.06	0.06	0.05	0.05	0.04	0.414	0.61

Appendix Table 17. Proportions of small size pores at different levels (from below) in tilths produced at 25.2% water content. Tillage was done with one to three passes of a set of tines with narrow points.

Replicate	Level	Size (mm) 1	2	3	4	5	6	7	8	9	Total 1-5	Total 1-9
a**	3	0.20	0.10	0.35	0.07	0.06	0.04	0.04	0.03	0.02	0.78	0.91
	4	0.17	0.17	0.08	0.06	0.05	0.05	0.04	0.04	0.03	0.53	0.69
	5	0.00	0.20	0.10	0.07	0.06	0.05	0.05	0.04	0.04	0.42	0.55
b**	4	0.13	0.35	0.26	0.06	0.05	0.04	0.03	0.02	0.02	0.85	0.95
	5	0.00	0.28	0.28	0.07	0.06	0.05	0.04	0.04	0.03	0.68	0.84
c**	4	0.20	0.00	0.10	0.25	0.16	0.10	0.07	0.04	0.03	0.71	0.79
	5	0.11	0.21	0.00	0.10	0.09	0.07	0.06	0.05	0.05	0.51	0.74
d**	4	0.09	0.09	0.09	0.12	0.10	0.09	0.07	0.06	0.05	0.50	0.77
	5	0.00	0.00	0.00	0.05	0.05	0.05	0.04	0.04	0.04	0.10	0.23
a***	4	0.09	0.09	0.27	0.18	0.12	0.08	0.05	0.04	0.02	0.75	0.94
	5	0.00	0.24	0.00	0.27	0.17	0.11	0.07	0.05	0.03	0.68	0.94
b***	3	0.19	0.26	0.21	0.10	0.07	0.05	0.04	0.03	0.02	0.83	0.96
	4	0.12	0.12	0.00	0.12	0.10	0.09	0.07	0.06	0.05	0.46	0.73
c***	4	0.31	0.06	0.25	0.12	0.08	0.06	0.04	0.03	0.02	0.82	0.96
	5	0.00	0.30	0.00	0.20	0.14	0.10	0.07	0.05	0.04	0.64	0.91
d***	4	0.00	0.40	0.10	0.06	0.05	0.05	0.04	0.04	0.03	0.61	0.77
	5	0.17	0.17	0.17	0.02	0.02	0.02	0.02	0.02	0.02	0.55	0.64
a****	3	0.31	0.15	0.23	0.06	0.05	0.04	0.03	0.03	0.02	0.81	0.93
	4	0.00	0.20	0.00	0.11	0.10	0.08	0.07	0.06	0.05	0.41	0.67
b****	4	0.03	0.14	0.14	0.14	0.11	0.09	0.07	0.06	0.05	0.56	0.82
	5	0.00	0.00	0.08	0.13	0.11	0.10	0.08	0.07	0.06	0.33	0.65

** Tillage was done by one pass of the implement.

*** Tillage was done by two passes of the implement.

**** Tillage was done by three passes of the implement.

Appendix Table 18. Entropies (H) at different levels within tilths produced at different water contents (w%) by tillage with different number of passes of a set of tines with narrow points.

No. of passes	Level	W = 12.6%				W = 25.2%			
		a	b	c	d	a	b	c	d
1	1	0.551		0.512					
	2	0.452		0.501					
	3	0.442	0.433	0.482	0.564	0.641			
	4	0.431	0.392	0.367	0.54	0.511	0.723	0.40	0.427
	5		0.40	0.275	0.277	0.452	0.539	0.43	0.297
2	3	0.559	0.418			0.652			
	4	0.431	0.312	0.451	0.332	0.485	0.487	0.657	0.494
	5	0.247	0.328	0.409	0.316	0.444		0.513	0.380
3	3					0.506			
	4	0.540	0.344	0.400	0.503	0.412	0.528		
	5	0.463	0.432	0.305	0.387		0.494		
4	3								
	4	0.463	0.461	0.447	0.471				
	5	0.307	0.249	0.317	0.331				

SECTION C

Appendix Table 19. Measurements of the characteristics of tillage implements used for producing different tilth structures. Measurements in mm.

Characteristic	Designation of Implement						
	MB	D	Sc	CD	T(A)	T(B)	RC
Frame length			3200	3290	3200	1500	1600
Frame clearance	295	590	457	457	457	457	700
Number of rows			5	4	5	4	
Row spacing			495	410	495	360	
Number of units	3	14(in pairs)					
Mouldboard dimension	280(H)x1035(L)						
Disc diameter		510					
Disc spacing (within pairs)		185					
Coulter diameter	310						
Number of tines			21	32	21	18	
Mouldboard/Tine spacing	412		435	245	435	300	
Tine width			195	105	67	65	
Tine length			175	95	194	120	
Tine arrangement			2,5,3,5,6	8,8,8,8	2,5,3,5,6	4,4,5,5	
Number of blades (rotary)							36
Number of discs (rotary)							7
Maximum number of blades on disc (rotary)							6
Minimum number of blades on disc (rotary)							3
Effective spacing (in soil)*	412	147	109	61	109	75	240

T(A),T(B) Two sets of tines with narrow points were used. T(B) was used at the Waite Institute and T(A) at the Mortlock Station.

L Length

H Height

* Assuming 45° angle of frame travel.

APPENDIX II

Appendix II goes with Chapter 5 which deals with factors affecting the internal structure of tilled soil before and after its production by tillage.

Section A of the Appendix contains structural data (probabilities P(0) for sixteen precursors and occurrence probabilities for precursors) of tilths produced by tillage at different soil water contents.

Section B contains structural data of differently tilled plots in Spring and Summer. The Winter data are in Appendix I and Chapter I. The data expected to be in this section were used to trace seasonal changes in the internal structure of tilled soils. The Winter, Spring, and Summer data were collected on 7th July, 1976, 11th October, 1976, and 10th January, 1977, respectively.

Section C is constituted by structural data (aggregate and pore size distributions, macroporosities, and entropies) of different tilled permanent rotation plots collected in 1976 and 1977.

Glossary

BL = Barley crop

$\bar{D}$ = Mean aggregate size

η_L = Macroporosity

D, Sc, CD, MB, and RC = Disc plough, scarifier, combine drill, mouldboard plough, and rotary cultivator respectively.

P = Pasture

W = Wheat

F = Fallow

CW = Continuous wheat

(W) = Any letter in parenthesis indicates the last crop grown on or treatment given to a permanent rotation crop.

* = A precursor had no occurrences.

SECTION A

Appendix Table 20. Internal structures of plots tilled at different water contents. Values of P(0) are the probabilities of a 0 following sixteen possible precursors (replicate a).

Precursor	P(0) for Water Content (%)					
	10.7%	12.6%	15.8%	17.0%	18.3%	25.2%
0000	0.930	0.892	0.906	0.820	0.818	0.907
0001	0.037	0.000	0.056	0.000	0.000	0.125
0010	1.000	*	1.000	1.000	*	1.000
0011	0.035	0.222	0.368	0.200	0.071	0.125
0100	0.000	*	1.000	1.000	*	1.000
0101	*	*	*	*	*	*
0110	1.000	0.667	1.000	0.667	1.000	1.000
0111	0.067	0.125	0.125	0.125	0.033	0.143
1000	0.630	1.000	0.750	0.786	0.923	0.875
1001	0.000	0.000	0.000	0.333	0.000	0.500
1010	*	*	*	*	*	*
1011	0.000	0.500	0.000	0.000	0.000	*
1100	0.931	0.875	0.882	0.813	0.929	0.750
1101	0.000	0.000	0.000	0.000	0.000	*
1110	0.933	0.875	0.714	0.824	0.867	1.000
1111	0.092	0.073	0.037	0.117	0.099	0.088

Appendix Table 20 *(continued)*. (b).

Precursor	P(0) for Water Content (%)					
	10.7%	12.6%	15.8%	17.0%	18.3%	25.2%
0000	0.934	0.887	0.903	0.934	0.853	0.837
0001	0.083	0.000	0.083	0.083	0.097	0.091
0010	1.000	*	1.000	1.000	1.000	1.000
0011	0.313	0.200	0.214	0.313	0.207	0.286
0100	1.000	*	1.000	1.000	0.667	1.000
0101	*	*	*	*	*	*
0110	1.000	1.000	1.000	1.000	0.667	1.000
0111	0.250	0.125	0.182	0.250	0.120	0.000
1000	0.692	1.000	1.000	0.692	1.000	0.600
1001	0.000	0.000	0.400	0.000	0.000	0.000
1010	*	*	*	*	*	*
1011	0.000	*	*	0.000	0.000	*
1100	0.706	0.900	0.643	0.707	1.000	0.692
1101	0.000	*	*	0.000	0.000	*
1110	1.000	1.000	1.000	1.000	1.000	1.000
1111	0.114	0.071	0.107	0.114	0.128	0.118

Appendix Table 20 *(continued).* (c).

Precursor	P(0) for Water Content (%) 10.7%	12.6%	15.8%	17.0%	18.3%	25.2%
0000	0.887	0.891	0.882	0.917	0.933	0.650
0001	0.111	0.000	0.870	0.091	0.000	0.000
0010	1.000	*	1.000	1.000	1.000	*
0011	0.167	0.000	0.136	0.333	0.000	0.000
0100	0.000	*	1.000	0.250	1.000	*
0101	*	*	*	*	*	*
0110	1.000	*	1.000	0.833	*	*
0111	0.000	0.125	0.238	0.273	0.200	0.100
1000	0.722	1.000	0.913	0.727	1.000	0.875
1001	0.000	0.000	0.000	0.000	1.000	*
1010	*	*	*	1.000	*	*
1011	*	*	0.000	0.500	0.000	0.000
1100	0.750	0.875	0.955	0.769	0.889	1.000
1101	*	*	0.000	0.500	0.000	0.000
1110	1.000	1.000	0.905	0.727	0.900	0.800
1111	0.048	0.068	0.059	0.078	0.080	0.067

Appendix Table 20 *(continued).* (d).

Precursor	P(0) for Water Content (%)					
	10.7%	12.6%	15.8%	17.0%	18.3%	25.2%
0000	0.914	0.868	0.936	0.810	0.926	0.830
0001	0.000	0.077	0.125	0.077	0.000	0.222
0010	*	0.000	1.000	1.000	*	1.000
0011	0.182	0.143	0.000	0.231	0.000	0.125
0100	*	0.000	1.000	1.000	*	1.000
0101	*	1.000	*	*	*	*
0110	0.500	1.000	1.000	0.750	*	0.500
0111	0.200	0.250	0.192	0.364	0.417	0.429
1000	0.900	0.714	0.875	0.923	0.900	0.889
1001	*	0.000	0.000	0.000	0.000	0.000
1010	*	1.000	*	*	*	*
1011	0.000	*	0.500	0.500	*	1.000
1100	1.000	0.933	0.583	0.923	0.909	0.875
1101	0.000	*	0.000	0.000	*	0.000
1110	1.000	1.000	0.846	0.909	1.000	1.000
1111	0.048	0.167	0.097	0.090	0.065	0.044

Appendix Table 21. Internal structures of plots tilled at different water contents. Values of Ui are the occurrence probabilities of sixteen possible precursors (means).

Precursor	Ui for Water Content (%)					
	10.7%	12.6%	15.8%	17.0%	18.3%	25.2%
0000	0.298	0.327	0.333	0.303	0.344	0.235
0001	0.030	0.042	0.035	0.046	0.042	0.045
0010	0.001	0.001	0.004	0.005	0.002	0.006
0011	0.003	0.047	0.041	0.054	0.044	0.048
0100	0.001	0.001	0.004	0.005	0.002	0.006
0101	0.00	0.001	0.00	0.001	0.00	0.00
0110	0.003	0.008	0.008	0.017	0.002	0.001
0111	0.031	0.042	0.037	0.046	0.044	0.041
1000	0.030	0.042	0.035	0.046	0.042	0.045
1001	0.004	0.006	0.009	0.013	0.003	0.009
1010	0.00	0.001	0.00	0.001	0.00	0.00
1011	0.002	0.002	0.005	0.009	0.003	0.004
1100	0.003	0.047	0.041	0.054	0.044	0.048
1101	0.002	0.002	0.005	0.009	0.003	0.004
1110	0.031	0.042	0.037	0.046	0.044	0.042
1111	0.502	0.389	0.406	0.350	0.381	0.458

SECTION B

The part of the primary structural data expected to be in this section is in the first section of Appendix I and first section of Chapter 1. The data are from tilth block samples collected in July 1976 from plots tilled with D, D+Sc, D+CD, MB, MB+Sc, MB+CD, Sc and RC.

Appendix Table 22. Internal structures of differently tilled plots (Spring data). Values of P(0) are the probabilities of a 0 following sixteen possible precursors (replicate a).

Precursor	P(0) for Plot									
	D	D+Sc	D+CD	D+CD+BL	MB	MB+Sc	MB+CD	MB+CD+BL	Sc	RC
0000	0.741	0.941	0.936	0.902	0.925	0.865	0.917	0.923	0.924	0.894
0001	0.056	0.000	0.000	0.000	0.083	0.000	0.000	0.000	0.000	0.000
0010	1.000	*	1.000	*	1.000	*	*	*	*	1.000
0011	0.048	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.143	0.000
0100	1.000	*	1.000	*	1.000	*	*	*	*	1.000
0101	*	*	*	*	*	*	*	*	*	*
0110	1.000	*	*	*	*	*	*	*	1.000	*
0111	0.000	0.118	0.000	0.143	0.182	0.000	0.059	0.000	0.000	0.111
1000	0.833	0.615	1.000	0.833	1.000	0.833	1.000	1.000	0.833	0.800
1001	0.000	0.000	0.200	0.000	*	*	0.000	0.000	0.000	0.400
1010	*	*	*	*	*	*	*	*	*	*
1011	*	0.000	*	0.000	*	*	*	*	0.000	*
1100	0.810	0.722	0.643	0.923	1.000	1.000	0.824	0.824	0.857	0.722
1101	*	0.000	*	0.000	*	*	*	*	0.000	*
1110	1.000	0.947	1.000	0.929	1.000	1.000	1.000	1.000	0.857	1.000
1111	0.045	0.040	0.035	0.021	0.022	0.020	0.044	0.048	0.034	0.030

Appendix Table 22 *(continued)*. (Replicate b).

Precursor	P(0) for Plot									
	D	D+Sc	D+CD	D+CD+BL	MB	MB+Sc	MB+CD	MB+CD+BL	Sc	RC
0000	0.940	0.930	0.972	0.867	0.767	0.931	0.846	0.907	0.923	0.813
0001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0010	*	1.000	*	*	1.000	*	1.000	*	*	*
0011	0.000	0.077	0.000	0.000	0.200	0.000	0.100	0.000	0.000	0.000
0100	*	1.000	*	*	1.000	*	1.000	*	*	*
0101	*	*	*	*	*	*	*	*	*	*
0110	*	0.500	*	*	1.000	*	1.000	*	*	*
0111	0.000	0.077	0.000	0.000	0.000	0.083	0.105	0.000	0.000	0.111
1000	0.909	0.667	1.000	1.000	0.933	0.765	0.778	1.000	1.000	0.944
1001	0.000	0.200	0.000	*	1.000	0.000	0.500	0.000	0.000	*
1010	*	*	*	*	*	*	*	*	*	*
1011	*	0.750	0.000	*	*	0.000	0.000	*	0.000	*
1100	0.917	0.615	0.857	1.000	0.933	0.739	0.778	0.833	0.889	1.000
1101	*	0.000	0.000	*	*	0.000	0.667	*	0.000	*
1110	1.000	0.846	0.778	1.000	1.000	0.958	0.834	1.000	0.900	1.000
1111	0.028	0.026	0.024	0.020	0.025	0.051	0.036	0.026	0.021	0.029

Appendix Table 23. Internal structures of tilled plots (Summer data). Values of P(0) are the probabilities of a 0 following sixteen possible precursors (replicate a).

Precursor	P(0) for Plot									
	D	D+Sc	D+CD	D+CD+BL	MB	MB+Sc	MB+CD	MB+CD+BL	Sc	RC
0000	0.891	0.444	0.866	0.805	0.833	0.973	0.864	0.682	0.654	0.869
0001	0.000	0.000	0.000	0.044	0.000	0.000	0.000	0.000	0.000	0.000
0010	*	*	*	1.000	*	*	*	*	*	*
0011	0.167	0.000	0.000	0.200	0.000	0.000	0.000	0.000	0.000	0.125
0100	*	*	*	1.000	*	*	*	*	*	1.000
0101	*	*	*	*	*	*	*	*	*	*
0110	1.000	*	*	1.000	*	*	*	*	*	1.000
0111	*	0.000	0.000	0.136	0.000	0.000	0.000	0.000	0.000	0.083
1000	1.000	0.833	0.900	0.652	0.700	1.000	1.000	0.636	0.692	0.722
1001	0.000	0.000	0.000	0.000	0.000	*	0.000	*	0.000	0.000
1010	*	*	*	*	*	*	*	*	*	1.000
1011	*	0.000	*	0.333	*	*	0.000	0.000	0.000	0.000
1100	0.500	0.600	0.833	0.880	0.909	1.000	0.444	1.000	0.722	0.772
1101	*	0.000	*	0.000	*	*	0.000	0.000	0.000	0.333
1110	1.000	0.909	1.000	0.864	1.000	1.000	0.947	0.917	0.900	0.864
1111	0.026	0.018	0.018	0.042	0.016	0.016	0.036	0.020	0.031	0.044

Appendix Table 23 *(continued)*. (replicate b).

Precursor	P(0) for Plot									
	D	D+Sc	D+CD	D+CD+BL	MB	MB+Sc	MB+CD	MB+CD+BL	Sc	RC
0000	0.874	0.828	0.846	0.893	0.723	0.718	0.720	0.500	0.333	0.522
0001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0010	*	*	*	*	*	*	*	*	*	*
0011	0.000	0.000	0.059	0.000	0.000	0.050	0.000	0.063	0.000	0.160
0100	*	*	*	*	*	*	*	*	*	*
0101	*	*	*	*	*	*	*	*	*	*
0110	*	*	1.000	*	*	1.000	*	1.000	*	1.000
0111	0.000	0.000	0.053	0.000	0.000	0.046	0.000	0.000	0.154	0.083
1000	1.000	1.000	0.769	0.750	0.929	1.000	1.000	0.700	1.000	0.647
1001	*	*	0.000	0.000	*	*	0.000	0.000	0.000	0.000
1010	*	*	*	*	*	*	*	*	*	*
1011	0.000	*	0.000	0.000	*	0.000	*	0.000	0.000	0.000
1100	1.000	1.000	0.765	0.308	1.000	1.000	0.778	0.625	0.500	0.739
1101	0.000	*	0.000	0.000	*	0.000	*	0.000	0.000	0.000
1110	0.750	1.000	0.842	0.813	1.000	0.850	1.000	0.750	0.308	0.864
1111	0.031	0.017	0.035	0.028	0.025	0.038	0.015	0.035	0.015	0.038

Appendix Table 24. Internal structures of differently tilled plots (Spring data). Values of Ui are the occurrence probabilities for sixteen possible precursors (means).

Precursor	Ui for Plot									
	D	D+Sc	D+CD	D+CD+BL	MB	MB+Sc	MB+CD	MB+CD+BL	Sc	RC
0000	0.131	0.166	0.278	0.129	0.136	0.171	0.185	0.229	0.193	0.127
0001	0.024	0.017	0.013	0.016	0.022	0.022	0.025	0.019	0.016	0.021
0010	0.0007	0.0008	0.0004	0.00	0.002	0.00	0.001	0.00	0.00	0.0001
0011	0.027	0.024	0.016	0.017	0.021	0.025	0.029	0.023	0.018	0.025
0100	0.0007	0.0008	0.0004	0.00	0.002	0.00	0.003	0.00	0.00	0.0001
0101	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0110	0.0006	0.002	0.00	0.00	0.002	0.00	0.001	0.00	0.001	0.00
0111	0.026	0.025	0.019	0.017	0.019	0.026	0.028	0.023	0.019	0.025
1000	0.024	0.017	0.013	0.016	0.022	0.022	0.025	0.019	0.016	0.021
1001	0.0036	0.008	0.004	0.0003	0.0007	0.003	0.005	0.004	0.002	0.003
1010	0.00	0.00	0.00	0.00	0.00	0.00	0.002	0.00	0.00	0.00
1011	0.00	0.004	0.002	0.0003	0.00	0.0005	0.0008	0.00	0.012	0.00
1100	0.027	0.024	0.016	0.017	0.021	0.025	0.027	0.023	0.018	0.025
1101	0.00	0.004	0.002	0.0006	0.00	0.0005	0.002	0.00	0.002	0.00
1110	0.026	0.025	0.019	0.017	0.019	0.026	0.028	0.023	0.019	0.025
1111	0.709	0.684	0.681	0.769	0.737	0.680	0.640	0.634	0.691	0.728

Appendix Table 25. Internal structures of differently tilled plots (Summer data). Values of Ui are the occurrence probabilities for sixteen possible precursors (means).

Precursor	P(0) for Plot									
	D	D+Sc	D+CD	D+CD+BL	MB	MB+Sc	MB+CD	MB+CD+BL	Sc	FC
0000	0.132	0.030	0.095	0.077	0.061	0.128	0.061	0.027	0.014	0.058
0001	0.015	0.012	0.016	0.017	0.017	0.020	0.013	0.016	0.008	0.026
0010	0.000	0.000	0.000	0.0004	0.000	0.000	0.000	0.000	0.000	0.000
0011	0.021	0.015	0.021	0.027	0.018	0.020	0.021	0.020	0.013	0.034
0100	0.000	0.000	0.000	0.0004	0.000	0.000	0.000	0.000	0.000	0.0007
0101	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0110	0.002	0.000	0.0006	0.003	0.000	0.0005	0.000	0.0006	0.000	0.005
0111	0.022	0.016	0.021	0.028	0.018	0.021	0.021	0.024	0.022	0.033
1000	0.015	0.012	0.016	0.017	0.017	0.020	0.013	0.016	0.008	0.026
1001	0.005	0.003	0.004	0.011	0.0008	0.000	0.008	0.004	0.005	0.008
1010	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.0007
1011	0.003	0.0009	0.002	0.005	0.000	0.002	0.0006	0.004	0.009	0.004
1100	0.021	0.015	0.021	0.027	0.018	0.020	0.021	0.020	0.013	0.033
1101	0.003	0.0009	0.002	0.005	0.000	0.002	0.0006	0.004	0.009	0.004
1110	0.022	0.016	0.022	0.028	0.018	0.021	0.021	0.024	0.022	0.033
1111	0.741	0.800	0.780	0.754	0.834	0.749	0.820	0.840	0.878	0.734

Appendix Table 26. Aggregate size distributions in differently tilled plots (Spring data) as expressed by the proportion larger than X mm (means).

X	Proportion									
	D	D+Sc	D+CD	D+CD+BL	MB	MB+Sc	MB+CD	MB+CD+BL	Sc	RC
1	0.96	0.97	0.98	1.00	0.93	1.00	0.91	1.00	1.00	0.99
2	0.95	0.89	0.98	1.00	0.84	1.00	0.87	1.00	0.94	0.99
4	0.92	0.78	0.95	0.91	0.74	0.92	0.76	0.96	0.91	0.86
8	0.79	0.68	0.84	0.83	0.68	0.80	0.65	0.83	0.81	0.76
16	0.58	0.52	0.66	0.70	0.56	0.59	0.47	0.61	0.65	0.60
32	0.32	0.30	0.40	0.50	0.39	0.33	0.24	0.34	0.41	0.37
64	0.096	0.104	0.153	0.254	0.18	0.10	0.066	0.10	0.17	0.14
$\overline{D}$	28.7	27.2	35.6	47.2	35.8	29.6	22.7	30.0	36.4	32.5

Appendix Table 27. Pore size distributions in differently tilled plots (Spring data) as expressed by the proportion larger than X mm (means).

X	Proportion									
	D	D+Sc	D+CD	D+CD+BL	MB	MB+Sc	MB+CD	MB+CD+BL	Sc	RC
1	1.00	0.87	0.89	0.97	1.00	0.98	0.93	1.00	0.89	1.00
2	0.87	0.59	0.67	0.93	0.97	0.85	0.76	0.83	0.77	0.86
4	0.64	0.35	0.64	0.75	0.79	0.61	0.60	0.76	0.66	0.64
8	0.32	0.27	0.53	0.46	0.41	0.40	0.36	0.53	0.48	0.34
16	0.08	0.16	0.37	0.17	0.11	0.17	0.13	0.26	0.25	0.097
32	0.005	0.056	0.172	0.025	0.007	0.03	0.018	0.063	0.072	0.008
64	0.00	0.007	0.038	0.0005	0.00	0.001	0.0003	0.004	0.006	0.00
n_L	0.21	0.235	0.326	0.179	0.202	0.243	0.271	0.295	0.248	0.198
$\overline{\delta}$	7.6	8.4	17.2	10.3	9.1	9.5	8.4	12.6	12.0	8.0

Appendix Table 28. Aggregate size distributions in differently tilled plots (Summer data) as expressed by the proportion larger than X mm (means).

X	Proportion D	D+Sc	D+CD	D+CD+BL	MB	MB+Sc	MB+CD	MB+CD+BL	Sc	RC
1	1.00	1.00	1.00	0.99	1.00	1.00	1.00	1.00	1.00	0.98
2	0.93	1.00	0.97	0.88	1.00	0.98	1.00	0.97	1.00	0.85
4	0.90	0.98	0.92	0.79	0.98	0.93	0.97	0.95	0.90	0.75
8	0.80	0.91	0.83	0.69	0.90	0.83	0.88	0.84	0.82	0.64
16	0.63	0.79	0.66	0.52	0.76	0.67	0.71	0.67	0.68	0.45
32	0.39	0.59	0.43	0.29	0.54	0.43	0.47	0.43	0.47	0.23
64	0.15	0.33	0.18	0.09	0.27	0.18	0.20	0.17	0.22	0.06
$\bar{D}$	34.9	58.6	38.0	26.3	50.6	38.3	41.5	37.7	43.1	21.9

Appendix Table 29. Pore size distributions in differently tilled plots (Summer data) as expressed by the proportion larger than X mm (means).

X	Proportion D	D+Sc	D+CD	D+CD+BL	MB	MB+Sc	MB+CD	MB+CD+BL	Sc	RC
1	0.88	0.95	0.92	0.86	1.00	0.93	0.97	0.84	0.60	0.88
2	0.66	0.76	0.74	0.51	0.96	0.93	0.60	0.68	0.37	0.67
4	0.59	0.44	0.53	0.31	0.61	0.78	0.47	0.27	0.15	0.32
8	0.36	0.07	0.28	0.16	0.22	0.40	0.19	0.03	0.009	0.075
16	0.13	0.002	0.08	0.04	0.03	0.11	0.029	0.0005	0.00	0.004
32	0.018	0.00	0.007	0.003	0.0005	0.007	0.0007	0.00	0.00	0.00
64	0.0003	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
η_L	0.191	0.073	0.154	0.153	0.113	0.188	0.116	0.088	0.06	0.157
$\bar{\delta}$	8.2	4.6	6.9	4.8	6.5	8.9	5.4	3.6	2.6	4.1

Appendix Table 30. Proportions of small size aggregates in differently tilled plots.

Size (mm)	D	D+Sc	D+CD	D+CD+BL	MB	MB+Sc	MB+CD	MB+CD+BL	Sc	RC
	Proportion for Plot (Spring)									
1	0.024	0.028	0.022	0.00	0.071	0.00	0.09	0.00	0.00	0.006
2	0.023	0.083	0.00	0.00	0.093	0.00	0.044	0.00	0.064	0.00
3	0.00	0.087	0.00	0.072	0.076	0.042	0.071	0.00	0.00	0.11
4	0.035	0.027	0.029	0.02	0.018	0.035	0.032	0.037	0.026	0.027
5	0.034	0.026	0.029	0.019	0.017	0.033	0.031	0.036	0.026	0.026
6	0.033	0.025	0.028	0.019	0.017	0.032	0.029	0.034	0.025	0.025
7	0.032	0.024	0.027	0.018	0.016	0.031	0.028	0.033	0.024	0.024
8	0.03	0.023	0.026	0.018	0.016	0.030	0.027	0.032	0.023	0.024
Total 1-5	0.116	0.251	0.080	0.111	0.275	0.110	0.268	0.073	0.116	0.169
Total 1-8	0.211	0.323	0.161	0.166	0.324	0.203	0.352	0.172	0.188	0.242
	Proportion for Plot (Summer)									
1	0.00	0.00	0.00	0.011	0.00	0.00	0.00	0.00	0.00	0.019
2	0.074	0.00	0.028	0.11	0.00	0.023	0.00	0.027	0.00	0.126
3	0.00	0.00	0.026	0.06	0.00	0.023	0.00	0.00	0.077	0.071
4	0.027	0.018	0.026	0.029	0.021	0.026	0.026	0.027	0.021	0.032
5	0.026	0.018	0.025	0.028	0.021	0.025	0.025	0.027	0.021	0.031
6	0.025	0.017	0.024	0.027	0.02	0.024	0.025	0.026	0.02	0.03
7	0.025	0.017	0.024	0.026	0.02	0.024	0.024	0.025	0.02	0.03
8	0.024	0.017	0.023	0.025	0.019	0.023	0.023	0.024	0.02	0.027
Total 1-5	0.127	0.036	0.105	0.238	0.042	0.097	0.051	0.081	0.119	0.279
Total 1-8	0.201	0.087	0.176	0.316	0.101	0.168	0.123	0.156	0.179	0.366

Appendix Table 31. Proportions of small size pores in differently tilled plots.

Size (mm)	Proportion for Plot (Spring)									
	D	D+Sc	D+CD	D+CD+BL	MB	MB+Sc	MB+CD	MB+CD+BL	Sc	RC
1	0.00	0.133	0.109	0.035	0.00	0.021	0.072	0.00	0.113	0.00
2	0.133	0.278	0.217	0.037	0.031	0.127	0.167	0.171	0.113	0.138
3	0.112	0.212	0.00	0.077	0.032	0.171	0.085	0.00	0.064	0.11
4	0.12	0.024	0.031	0.098	0.144	0.069	0.08	0.071	0.054	0.11
5	0.101	0.023	0.03	0.087	0.122	0.621	0.071	0.065	0.05	0.094
6	0.085	0.021	0.028	0.077	0.103	0.056	0.062	0.059	0.046	0.08
7	0.071	0.02	0.027	0.068	0.087	0.05	0.055	0.054	0.043	0.068
8	0.06	0.019	0.026	0.06	0.074	0.045	0.048	0.049	0.039	0.058
Total 1-5	0.466	0.67	0.387	0.334	0.329	0.45	0.474	0.307	0.394	0.452
Total 1-8	0.682	0.73	0.468	0.539	0.593	0.601	0.639	0.469	0.522	0.658
	Proportion for Plot (Summer)									
1	0.116	0.055	0.077	0.142	0.00	0.073	0.026	0.162	0.396	0.116
2	0.221	0.189	0.186	0.344	0.045	0.00	0.378	0.157	0.235	0.211
3	0.00	0.063	0.122	0.154	0.177	0.00	0.00	0.226	0.057	0.212
4	0.078	0.252	0.089	0.055	0.173	0.143	0.124	0.187	0.158	0.14
5	0.069	0.161	0.076	0.046	0.134	0.121	0.098	0.11	0.078	0.098
6	0.061	0.102	0.065	0.039	0.105	0.102	0.078	0.065	0.039	0.068
7	0.053	0.065	0.056	0.033	0.081	0.086	0.062	0.039	0.019	0.047
8	0.047	0.041	0.048	0.028	0.063	0.073	0.049	0.023	0.009	0.033
Total 1-5	0.484	0.72	0.55	0.741	0.529	0.337	0.626	0.842	0 924	0.777
Total 1-8	0.645	0.918	0.719	0.841	0.778	0.598	0.815	0.969	0.991	0.925

Appendix Table 32. Entropies (H) in differently tilled plots.

Plot	H (Spring)			H (Summer)		
	Replicates		Mean	Replicates		Mean
D	0.319	0.207	0.263	0.232	0.242	0.237
D+Sc	0.266	0.242	0.254	0.303	0.155	0.229
D+CD	0.253	0.189	0.221	0.172	0.284	0.228
D+CD+BL	0.206	0.179	0.193	0.360	0.208	0.284
MB	0.217	0.230	0.224	0.153	0.200	0.177
MB+Sc	0.180	0.320	0.250	0.132	0.287	0.210
MB+CD	0.276	0.328	0.302	0.251	0.136	0.194
MB+CD+BL	0.296	0.215	0.256	0.172	0.261	0.216
Sc	0.272	0.187	0.229	0.238	0.136	0.187
RC	0.264	0.245	0.255	0.351	0.312	0.331

SECTION C

Appendix Table 33. Internal structures of tilled rotation plots (1976 - replicate a). Values of P(0) are the probabilities of a 0 following sixteen possible precursors.

Precursor	P(0) for Plot							
	WF(W)	WF(W)	WF(W)	WF(W)	WPF(F)	WPPF(F)	WPP(P)	CW(W)
0000	0.905	0.657	0.754	0.640	0.796	0.827	0.783	0.565
0001	0.000	0.000	0.000	0.167	0.286	0.000	0.105	0.000
0010	*	*	1.000	1.000	0.571	*	1.000	*
0011	0.000	0.125	0.100	0.118	0.177	0.067	0.167	0.000
0100	*	*	1.000	0.000	1.000	*	1.000	*
0101	*	*	*	*	0.333	*	0.000	*
0110	*	1.000	0.600	1.000	0.800	1.000	0.750	*
0111	0.063	0.250	0.177	0.111	0.143	0.069	0.167	0.063
1000	0.667	0.857	0.800	0.750	0.563	0.667	0.684	0.727
1001	0.000	0.000	0.071	0.000	0.333	0.000	0.000	0.000
1010	*	*	*	*	1.000	*	0.000	*
1011	0.000	0.000	0.222	0.000	1.000	0.000	0.000	0.000
1100	0.429	0.875	0.500	0.706	0.850	0.900	0.944	0.846
1101	0.000	0.000	0.000	0.000	1.000	0.000	0.500	0.000
1110	0.875	0.875	0.781	0.833	1.000	0.966	0.889	0.929
1111	0.052	0.043	0.054	0.027	0.071	0.087	0.042	0.021

Appendix Table 33 *(continued)*. 1976 replicate b.

Precursor	P(0) for Plot							
	WF(F)	WF(F)	WF(F)	WF(F)	WPF(F)	WPPF(F)	WPP(P)	CW(W)
0000	0.772	0.805	0.841	0.909	0.798	0.871	0.760	0.615
0001	0.044	0.067	0.000	0.000	0.087	0.000	0.100	0.000
0010	1.000	1.000	*	*	1.000	*	1.000	1.000
0011	0.290	0.238	0.000	0.000	0.136	0.071	0.167	0.044
0100	1.000	1.000	*	*	1.000	*	1.000	0.000
0101	*	*	*	*	*	*	*	*
0110	0.889	1.000	*	*	1.000	1.000	0.750	1.000
0111	0.136	0.056	0.063	0.000	0.000	0.143	0.044	0.000
1000	0.913	0.533	0.714	0.667	1.000	0.696	0.600	0.895
1001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.143
1010	1.000	*	*	*	*	*	*	*
1011	*	0.500	0.000	0.000	*	0.000	0.100	*
1100	0.690	0.667	0.778	0.333	0.950	0.821	0.500	0.760
1101	1.000	0.000	0.000	0.000	*	0.000	0.000	*
1110	0.955	0.778	0.563	0.643	1.000	0.929	0.625	1.000
1111	0.089	0.050	0.052	0.041	0.115	0.067	0.059	0.040

Appendix Table 33 (continued) - 1977 replicate a.

Precursor	P(0) for Plot									
	WF(F)	WF(F)	WF(F)	WF(F)	WPF(F)	WPF(F)	WPPF(F)	WPPF(F)	WPP(F)	CW(W)
0000	0.892	0.916	0.931	0.7877	0.941	0.846	0.902	0.927	0.922	0.917
0001	0.000	0.222	0.000	0.000	0.000	0.000	0.000	0.000	0.182	0.000
0010	*	1.000	*	*	*	*	*	*	1.000	*
0011	0.037	0.125	0.000	0.235	0.000	0.000	0.091	0.000	0.000	0.182
0100	*	0.500	*	*	*	*	*	*	1.000	*
0101	*	*	*	*	*	*	*	*	*	*
0110	1.000	1.000	*	1.000	*	*	1.000	*	*	1.000
0111	0.231	0.000	0.167	0.000	0.000	0.000	0.046	0.000	0.000	0.083
1000	1.000	0.778	1.000	0.867	1.000	0.947	1.000	1.000	0.769	0.727
1001	0.000	0.000	*	*	0.000	0.000	0.000	0.000	0.000	*
1010	*	*	*	*	*	*	*	*	*	*
1011	*	*	*	*	0.000	*	0.000	*	*	0.000
1100	0.920	1.000	1.000	1.000	0.857	0.950	0.909	0.875	0.917	1.000
1101	*	*	*	*	0.000	*	0.000	*	*	0.000
1110	1.000	1.000	1.000	1.000	0.923	1.000	0.909	1.000	1.000	0.786
1111	0.087	0.044	0.023	0.029	0.036	0.042	0.054	0.035	0.034	0.030

Appendix Table 33 (continued) - 1977 replicate b.

Precursor	P(0) for Plot									
	WF(W)	WF(W)	WF(W)	WF(W)	WPF(F)	WPF(F)	WPPF(P)	WPPF(F)	WPP(P)	CW(W)
0000	0.819	0.911	0.857	0.932	0.882	0.897	0.927	0.844	0.829	0.953
0001	0.129	0.040	0.167	0.000	0.000	0.000	0.000	0.000	0.067	0.000
0010	1.000	1.000	1.000	*	*	*	*	*	1.000	*
0011	0.067	0.280	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0100	1.000	1.000	1.000	*	*	*	*	*	1.000	*
0101	*	*	*	*	*	*	*	*	*	*
0110	1.000	1.000	*	*	*	*	*	*	*	*
0111	0.000	0.111	0.059	0.125	0.115	0.036	0.000	0.000	0.000	0.000
1000	0.903	0.783	1.000	0.857	0.909	0.810	0.875	0.938	0.933	1.000
1001	0.000	0.000	*	0.000	0.000	0.000	*	*	0.000	*
1010	*	*	*	*	*	*	*	*	*	*
1011	0.000	*	0.000	*	0.000	0.000	*	*	0.000	0.000
1100	0.900	0.880	1.000	0.875	0.880	0.875	1.000	1.000	0.933	1.000
1101	0.000	*	*	*	0.000	0.000	*	*	0.000	0.000
1110	0.966	1.000	1.000	1.000	0.893	0.923	1.000	1.000	0.882	0.750
1111	0.076	0.044	0.039	0.044	0.061	0.067	0.097	0.050	0.049	0.018

Appendix Table 34. Internal structures of tilled rotation plots. Mean values of occurrence probabilities (Ui) for sixteen possible four element precursors.

Precursor	Ui for Plots (1976)					Ui for Plots (1977)				
	WF	WPF	WPPF	WPP	CW	WF	WPF	WPPF	WPP	CW
0000	0.063	0.222	0.182	0.076	0.039	0.26	0.224	0.284	0.182	0.197
0001	0.023	0.057	0.04	0.027	0.02	0.031	0.027	0.030	0.026	0.015
0010	0.0009	0.012	0.00	0.003	0.0004	0.002	0.00	0.00	0.003	0.00
0011	0.036	0.051	0.047	0.033	0.025	0.031	0.03	0.031	0.025	0.015
0100	0.002	0.011	0.00	0.003	0.0004	0.002	0.00	0.00	0.003	0.00
0101	0.00	0.002	0.00	0.0027	0.00	0.00	0.00	0.00	0.00	0.00
0110	0.006	0.010	0.003	0.006	0.0005	0.003	0.00	0.0007	0.00	0.001
0111	0.04	0.043	0.046	0.038	0.025	0.028	0.032	0.031	0.027	0.018
1000	0.023	0.057	0.04	0.027	0.02	0.031	0.027	0.03	0.026	0.015
1001	0.014	0.005	0.007	0.009	0.005	0.002	0.003	0.0017	0.002	0.00
1010	0.001	0.0018	0.00	0.0027	0.00	0.00	0.00	0.00	0.00	0.00
1011	0.010	0.0016	0.002	0.011	0.0009	0.0001	0.002	0.0007	0.0016	0.004
1100	0.035	0.052	0.047	0.033	0.025	0.031	0.03	0.031	0.025	0.015
1101	0.011	0.001	0.002	0.011	0.0009	0.0001	0.002	0.0007	0.0016	0.004
1110	0.04	0.043	0.046	0.038	0.025	0.028	0.032	0.031	0.027	0.018
1111	0.696	0.430	0.536	0.680	0.813	0.55	0.592	0.527	0.650	0.70

Appendix Table 35. Internal structures of tilled rotation plots that were under fallow (COF), pasture (COP), and wheat (COW) in previous season. Mean values of P(0) are the probabilities of a 0 following sixteen possible precursors.

Precursor	P(0) - 1977			P(0) - 1976	
	COF	COP	COW	COF	COW
0000	0.904	0.884	0.898	0.824	0.665
0001	0.028	0.041	0.056	0.071	0.021
0010	1.000	1.000	1.000	0.893	1.000
0011	0.081	0.000	0.088	0.119	0.083
0100	0.500	1.000	1.000	0.875	0.250
0101	*	*	*	0.333	*
0110	1.000	*	1.000	0.791	0.825
0111	0.055	0.025	0.063	0.08	0.091
1000	0.949	0.872	0.878	0.634	0.79
1001	0.000	0.000	0.000	0.056	0.045
1010	*	*	*	1.000	*
1011	0.000	0.000	0.000	0.375	0.028
1100	0.939	0.934	0.943	0.793	0.715
1101	0.000	0.000	0.000	0.417	0.00
1110	0.979	0.950	0.917	0.894	0.903
1111	0.043	0.060	0.042	0.076	0.037

Appendix Table 36. Internal structures of tilled rotation plots that were under fallow (COF), pasture (COP), and wheat (COW) in previous season. Mean values of occurrence probabilities (Ui) for sixteen possible four element precursors.

Precursor	Ui - 1977			Ui - 1976	
	COF	COP	COW	COF	COW
0000	0.261	0.238	0.231	0.15	0.051
0001	0.026	0.032	0.027	0.042	0.022
0010	0.0007	0.0013	0.0015	0.004	0.0009
0011	0.028	0.033	0.027	0.048	0.030
0100	0.0007	0.0013	0.0015	0.006	0.0009
0101	0.00	0.00	0.00	0.0004	0.00
0110	0.002	0.00	0.002	0.007	0.003
0111	0.026	0.034	0.027	0.045	0.031
1000	0.026	0.032	0.027	0.042	0.022
1001	0.002	0.002	0.002	0.01	0.009
1010	0.00	0.00	0.00	0.003	0.00
1011	0.0005	0.0017	0.002	0.004	0.003
1100	0.028	0.033	0.027	0.046	0.03
1101	0.0005	0.002	0.002	0.006	0.003
1110	0.026	0.034	0.027	0.045	0.031
1111	0.572	0.557	0.597	0.544	0.762

Appendix Table 37. Aggregate size distributions in tilths of permanent rotation plots as expressed by the proportion larger than X mm.

X	Proportion - 1976				
	WF	WPF	WPPF	WPP	CW
1	0.95	0.80	1.00	0.89	0.99
2	0.83	0.65	0.93	0.77	0.96
4	0.70	0.55	0.77	0.65	0.91
8	0.57	0.37	0.56	0.53	0.80
16	0.38	0.17	0.29	0.35	0.63
32	0.16	0.04	0.08	0.16	0.39
64	0.031	0.002	0.006	0.03	0.14
Mean aggregate size	17.3	9.0	13.8	16.4	34.1
	Proportion - 1977				
1	0.93	1.00	1.00	0.89	1.00
2	0.85	1.00	0.98	0.89	0.93
4	0.74	0.91	0.91	0.85	0.87
8	0.61	0.74	0.71	0.72	0.79
16	0.41	0.48	0.44	0.52	0.65
32	0.19	0.20	0.17	0.26	0.44
64	0.041	0.037	0.02	0.069	0.20
Mean aggregate size	19.3	21.5	19.4	24.5	40.00

Appendix Table 38. Pore size distributions in tilths of permanent rotation plots as expressed by the proportion larger than X mm.

X	WF	WPF	WPPF	WPP	CW
	Proportion - 1976				
1	0.77	0.95	0.95	0.73	0.97
2	0.48	0.87	0.82	0.54	0.76
4	0.23	0.54	0.47	0.27	0.37
8	0.08	0.22	0.25	0.10	0.04
16	0.01	0.036	0.066	0.12	0.001
32	0.0002	0.001	0.004	0.0002	0.00
64	0.00	0.00	0.00	0.00	0.00
Macroporosity	0.171	0.408	0.319	0.188	0.111
Mean pore size	3.6	6.2	6.5	3.8	4.2
	Proportion - 1977				
1	0.99	0.93	0.98	0.95	0.78
2	0.94	0.83	0.93	0.88	0.78
4	0.75	0.68	0.79	0.66	0.63
8	0.47	0.43	0.52	0.39	0.48
16	0.19	0.17	0.22	0.13	0.28
32	0.03	0.027	0.04	0.016	0.096
64	0.001	0.001	0.0014	0.0002	0.011
Macroporosity	0.357	0.313	0.377	0.267	0.245
Mean pore size	10.7	9.8	11.7	8.9	13.0

Appendix Table 39. Proportion of small size aggregates in tilths of permanent rotation plots.

Plot	Size (1976) mm 1	2	3	4	5	6	7	8	Total 1-5	Total 1-8
WF	0.048	0.121	0.088	0.038	0.036	0.034	0.032	0.031	0.331	0.428
WPF	0.202	0.146	0.046	0.056	0.051	0.046	0.042	0.038	0.501	0.627
WPPF	0.00	0.066	0.099	0.064	0.059	0.055	0.051	0.047	0.288	0.441
WPP	0.11	0.123	0.081	0.034	0.033	0.031	0.029	0.028	0.381	0.469
CW	0.014	0.021	0.030	0.028	0.027	0.026	0.026	0.025	0.12	0.197
					Size (1977) mm					
WF	0.066	0.087	0.074	0.036	0.035	0.033	0.032	0.03	0.298	0.393
WPF	0.00	0.00	0.038	0.05	0.047	0.045	0.043	0.04	0.135	0.263
WPPF	0.00	0.023	0.011	0.057	0.054	0.051	0.048	0.045	0.145	0.289
WPP	0.11	0.00	0.00	0.037	0.035	0.034	0.032	0.031	0.182	0.279
CW	0.00	0.071	0.039	0.021	0.021	0.02	0.02	0.019	0.152	0.212

Appendix Table 40. Macroporosities in tilths of permanent rotation plots.

Year	Plot WF(W)	WF(W)	WF(W)	WF(W)	WPF(P)	WPF(P)	WPPF(P)	WPPF(P)	WPP(P)	CW(W)
1977	0.341	0.397	0.296	0.366	0.31	0.343	0.423	0.391	0.254	0.259
1976	0.353	0.184	0.134	0.094					0.148	0.149
	WF(F)	WF(F)	WF(F)	WF(F)	WPF(F)	WPF(F)	WPPF(F)	WPPF(P)	WPP(P)	CW(W)
1977	0.499	0.369	0.333	0.271	0.356	0.236	0.37	0.324	0.281	0.23
1976	0.169	0.181	0.168	0.089	0.448	0.368	0.328	0.311	0.229	0.074

Appendix Table 41. Entropies (H) in tilths of permanent rotation plots (1977).

Plot WF(W)	WF(W)	WF(W)	WF(W)	WPF(F)	WPF(P)	WPPF(P)	WPPF(P)	WPP(P)	CW(W)
0.43	0.352	0.297	0.291	0.372	0.369	0.347	0.309	0.327	0.162
WF(F)	WF(F)	WF(F)	WF(F)	WPF(F)	WPF(F)	WPPF(F)	WPPF(F)	WPP(P)	CW(W)
0.401	0.327	0.208	0.269	0.244	0.283	0.334	0.246	0.259	0.253

APPENDIX III

Appendix III goes mainly with Chapter 6. It contains temperature (°C) at depths (5 and 10 cm) within differently tilled plots. The temperatures were collected in July 1976 (Winter) for eight days, October 1976 (Spring) for five days, and January 1977 (Summer) for three days. The data for the three periods are placed in three tables respectively. Each of the temperatures is a mean for three replicates.

Glossary

Plots that were tilled with disc plough, disc plough followed by scarifier, disc plough followed by combine drill, mouldboard plough, mouldboard plough followed by scarifier, mouldboard plough followed by combine drill, scarifier, and rotary cultivator are designated by D, D+Sc, D+CD, MB, MB+Sc, MB+CD, Sc, and RC respectively.

Tt	=	Temperature in tilled soil (°C)
Ta	=	Air temperature (°C)
N.A.	=	Data that are not available
BL	=	Barley crop

Appendix Table 42. Temperatures (Tt°C) in differently tilled plots in winter.

Plot	Depth (cm)	Time (July 7th)					Time (July 8th)					
		0900	1200	1500	1800	2100	0600	0900	1200	1500	1800	2400
D	5	5.5	11.4	13.0	10.5	7.6	3.5	9.9	14.4	14.4	8.4	5.7
	10	6.8	10.3	11.6	10.3	8.7	5.9	8.5	11.9	13.0	9.5	7.8
D+Sc	5	6.0	11.1	12.6	9.8	7.6	4.6	8.9	13.5	13.6	8.6	6.2
	10	6.7	9.4	10.8	9.7	8.4	5.9	7.7	10.7	11.5	9.1	7.6
D+CD	5	5.9	11.6	12.8	10.3	6.8	3.5	8.9	14.0	13.7	8.5	5.0
	10	6.3	9.4	10.8	10.1	7.5	5.8	7.5	10.6	11.8	9.4	7.8
MB	5	6.3	11.0	17.6	10.6	8.0	4.3	7.5	12.6	12.8	10.1	6.5
	10	7.0	9.8	11.0	10.3	8.9	6.1	7.7	10.9	11.9	10.3	8.3
MB+Sc	5	7.3	12.9	14.3	9.7	6.7	2.9	9.4	16.0	16.8	9.2	6.5
	10	6.5	9.3	10.9	10.1	8.4	5.5	6.6	10.2	11.8	10.1	7.7
MB+CD	5	6.3	11.4	12.7	9.7	7.1	3.6	7.4	13.3	14.3	10.1	7.4
	10	6.9	10.1	11.5	9.8	8.3	5.7	7.1	10.8	11.2	9.9	N.A.
Sc	5	7.3	11.2	11.8	9.4	7.2	5.0	7.9	12.1	13.3	9.6	5.9
	10	7.7	9.7	10.8	9.5	8.1	6.1	7.7	12.1	12.1	10.0	8.0
RC	5	7.4	11.7	12.8	9.2	7.3	4.9	7.1	13.3	14.1	10.3	5.7
	10	7.1	11.1	12.2	9.3	7.6	5.4	7.0	11.9	13.4	10.3	6.5
Mean		6.6	10.6	12.3	9.8	7.7	4.8	7.9	12.3	13.1	9.5	6.8
Ta		12.5	17.9	18.0	14.0	13.0	4.5	6.0	17.5	18.0	16.5	6.5
Tt-Ta		-5.9	-6.9	-5.7	-4.2	-5.3	0.3	1.9	-5.2	-4.9	-7.0	0.3

Appendix Table 42 *(continued).*

Plot	Depth (cm)	Time (July 9th) 0600	0900	1200	1500	1800	Time (July 10th) 0600	0900	1200	1500	1800
D	5	2.9	5.6	12.7	13.8	8.3	3.2	5.7	13.2	14.0	11.2
	10	5.5	6.5	11.0	12.1	9.2	5.6	6.6	11.3	12.3	10.9
D+Sc	5	4.1	6.1	12.3	12.6	8.4	4.3	6.1	12.4	13.2	10.5
	10	5.7	6.4	10.1	11.2	9.2	5.7	6.5	10.6	11.5	10.3
D+CD	5	N.A.	N.A.	12.5	13.4	8.5	2.6	N.A.	12.9	16.8	10.9
	10	N.A.	N.A.	10.0	11.4	-9.5	5.0	N.A.	9.8	8.4	10.7
MB	5	3.8	5.9	11.5	13.3	10.3	3.6	5.9	11.4	13.4	11.6
	10	5.7	6.8	10.1	11.3	10.7	6.0	6.6	10.0	11.5	11.0
MB+Sc	5	1.8	7.7	15.2	14.9	9.4	2.9	7.7	14.7	14.7	11.8
	10	5.8	5.9	9.4	11.4	10.7	5.1	6.0	9.1	11.2	10.6
MB+CD	5	3.9	8.0	11.8	14.0	10.3	3.4	6.4	9.9	11.5	11.7
	10	6.3	7.0	9.2	13.7	10.1	4.8	6.5	8.6	10.1	11.0
Sc	5	4.3	7.9	10.3	11.4	9.6	3.9	7.5	10.3	12.0	N.A.
	10	5.8	6.8	9.4	10.8	9.8	5.6	7.8	9.3	11.0	N.A.
RC	5	4.3	7.9	11.7	13.0	10.5	4.2	7.8	14.4	15.8	11.2
	10	4.9	6.8	10.5	12.4	10.3	5.1	7.7	12.1	14.3	11.0
Mean		4.6	6.8	11.1	12.5	9.6	4.4	6.7	11.2	12.5	11.0
Ta		3.5	7.0	17.0	18.5	16.0	N.A.	N.A.	17.0	18.0	14.5
Tt-Ta		1.1	-0.2	-5.9	-6.0	-6.4			-5.8	-5.5	-3.5

Appendix Table 42 (continued).

Plot	Depth (cm)	Time (July 12th)					Time (July 13th)				
		0600	0900	1200	1500	1800	0600	0900	1200	1500	1800
D	5	6.8	8.2	11.5	12.0	9.9	2.4	4.5	9.7	11.5	9.7
	10	8.1	8.5	10.4	10.6	10.3	5.0	6.0	8.9	10.6	9.9
D+Sc	5	7.4	8.0	11.1	10.9	9.6	3.4	4.8	9.2	11.0	9.2
	10	8.2	8.1	10.2	10.6	9.8	5.2	5.7	8.1	9.8	9.8
D+CD	5	6.7	N.A.	N.A.	11.8	9.4	3.3	4.3	10.0	11.8	9.4
	10	8.0	N.A.	N.A.	10.8	10.3	5.3	5.7	8.1	10.0	10.0
MB	5	7.3	N.A.	10.6	11.7	10.1	3.0	3.5	8.6	11.1	10.2
	10	8.1	N.A.	10.3	10.7	10.1	5.4	5.5	8.2	9.8	9.7
MB+Sc	5	6.3	8.5	12.6	12.1	9.2	1.3	3.5	9.6	12.4	10.1
	10	7.5	7.5	9.8	11.0	9.6	4.3	4.7	7.7	9.7	9.3
MB+CD	5	7.1	N.A.	11.3	11.8	9.7	2.6	2.8	9.5	11.6	9.9
	10	7.9	N.A.	10.2	11.1	10.1	5.9	5.8	9.3	9.4	9.7
Sc	5	7.2	N.A.	10.7	10.9	8.7	3.0	4.4	11.3	11.1	8.6
	10	7.7	N.A.	9.7	10.5	9.4	4.8	5.1	9.6	9.5	9.0
RC	5	7.2	7.7	11.1	11.5	9.5	3.2	4.1	9.3	10.7	9.1
	10	7.4	7.8	10.9	11.6	9.9	3.9	5.2	9.2	9.6	9.4
Mean		7.4	8.0	10.7	11.2	9.7	3.8	4.6	9.1	10.6	9.5
Ta		8.0	9.5	12.0	13.0	10.5	N.A.	N.A.	11.0	13.0	12.5
Tt-Ta		-0.6	-1.5	-1.3	-1.8	-0.8			-1.9	-2.4	-3.0

Appendix Table 42 *(continued)*.

Plot	Depth (cm)	Time (July 14th) 0600	0900	1200	1500	1800	Time (July 15th) 0600	0900	1200	1500	1800
D	5	5.9	6.9	8.7	9.7	9.0	5.9	6.7	8.7	10.4	9.2
	10	6.4	7.3	8.5	9.6	9.3	7.3	7.5	8.8	9.9	9.5
D+Sc	5	5.9	6.8	8.6	9.8	8.8	6.5	7.0	9.0	9.9	9.1
	10	6.6	7.2	8.0	9.3	9.0	7.2	7.5	8.6	9.5	9.2
D+CD	5	6.2	6.2	9.0	10.3	N.A.	6.1	6.8	9.3	10.1	9.1
	10	6.3	7.2	8.2	9.4	N.A.	7.3	7.5	8.7	9.6	9.3
MB	5	5.4	6.8	8.5	9.8	9.1	6.6	7.0	8.9	10.2	9.4
	10	6.5	6.7	8.3	9.3	9.1	7.3	7.4	8.5	9.5	9.4
MB+Sc	5	5.4	7.1	9.2	10.9	8.4	5.5	6.7	9.3	10.6	9.1
	10	6.6	6.8	8.2	9.2	8.9	7.0	7.1	8.4	9.5	9.1
MB+CD	5	5.5	6.6	8.8	10.2	9.1	6.1	6.8	9.1	10.1	9.1
	10	6.4	6.9	8.6	9.4	9.1	7.2	7.4	8.4	9.7	9.3
Sc	5	6.0	7.0	8.5	11.8	8.1	6.5	6.8	8.8	9.4	9.3
	10	6.8	7.4	8.1	8.9	8.6	7.0	7.1	8.4	9.2	9.0
RC	5	5.1	6.7	8.7	9.9	8.7	6.6	6.8	9.0	9.8	8.8
	10	6.3	6.9	8.4	9.4	8.7	6.9	7.1	9.1	9.8	8.9
Mean		6.0	6.9	8.5	9.8	8.8	6.6	7.0	8.8	9.8	9.1
Ta		7.5	8.5	11.5	13.6	11.0	8.5	8.5	10.5	11.0	10.0
Tt-Ta		-1.5	-1.6	-3.0	-3.8	-2.2	1.9	-1.5	-1.7	-1.2	-0.9

Appendix Table 43. Temperatures ($Tt^{o}C$) in differently tilled plots in Spring.

Plot	Depth (cm)	Time (October 18th) 1800	2100	(October 19th) 0300	0600	0900	(October 20th) 1200	1500	1800
D	5	13.3	11.3	7.8	6.7	11.0	16.8	16.5	16.0
	10	13.5	11.5	8.5	7.3	10.2	15.5	16.3	15.8
D+Sc	5	13.7	10.6	7.3	6.3	10.4	17.6	18.1	16.7
	10	13.4	12.5	8.3	7.3	9.5	14.4	15.8	15.4
D+CD	5	13.3	9.4	6.1	5.3	11.0	18.2	17.3	16.4
	10	13.3	12.0	8.7	7.5	9.6	14.7	15.8	15.5
D+CD+BL	5	12.9	11.8	8.6	7.9	10.4	15.6	14.6	14.2
	10	13.5	12.6	9.5	8.5	10.5	14.3	14.3	14.2
MB	5	13.1	9.5	6.8	5.9	12.1	1w.6	-7.4	16.1
	10	13.0	10.9	7.5	6.6	9.9	17.3	16.1	15.8
MB+Sc	5	12.9	9.5	6.6	5.6	11.8	18.7	17.8	16.4
	10	13.1	12.9	8.0	7.1	9.3	14.2	15.5	15.1
MB+CD	5	12.9	9.2	6.4	5.6	10.7	20.5	18.5	16.8
	10	13.1	11.5	9.0	7.5	8.1	15.2	16.7	16.0
MB+CD+BL	5	13.0	10.7	7.7	6.7	10.7	20.8	17.1	15.8
	10	13.6	11.1	8.1	7.1	10.4	16.0	16.4	15.3
Sc	5	12.7	10.4	7.1	6.3	10.9	17.2	16.3	15.3
	10	12.8	12.0	8.4	7.8	10.8	16.5	16.1	15.2
RC	5	12.2	10.0	7.2	6.3	12.1	18.1	17.2	15.9
	10	12.8	11.1	8.0	7.0	11.1	17.6	16.9	16.1
Mean		13.1	11.0	7.8	6.8	10.6	17.0	16.7	15.8
Ta		N.A.	N.A.	9.5	8.5	10.5	17.5	18.5	18.5
Tt-Ta				-1.7	-1.7	0.1	-0.5	-1.8	-2.7

Appendix Table 43 (*continued*).

Plot	Depth (cm)	Time (October 21st) 0600	0900	1200	1500	1800	Time (October 22nd) 0600	0900	1200	1500	1800
D	5	10.4	14.6	20.7	20.1	17.5	11.0	15.8	18.7	19.6	17.0
	10	11.0	13.8	18.3	19.6	17.8	11.6	14.4	17.0	18.9	17.7
D+Sc	5	10.2	14.1	19.2	22.4	18.2	10.9	15.2	18.6	21.1	18.9
	10	10.5	12.8	16.7	18.5	17.7	11.4	13.9	16.1	18.5	17.5
D+CD	5	9.5	15.3	20.-	21.8	17.8	9.9	15.4	19.3	20.8	18.1
	10	10.9	12.9	17.2	19.4	17.6	11.7	13.7	16.3	18.4	17.6
D+CD+BL	5	10.6	13.3	17.3	16.2	14.6	10.6	13.3	15.7	16.3	14.6
	10	10.8	13.3	16.5	16.7	15.0	11.2	13.3	15.6	16.4	15.1
MB	5	10.1	16.9	22.5	21.8	17.8	10.3	15.5	20.4	21.0	17.8
	10	10.4	13.8	18.5	19.4	17.5	10.9	13.5	17.1	18.7	17.4
MB+Sc	5	9.7	15.7	21.9	22.9	18.0	9.9	15.2	19.9	21.7	18.0
	10	10.4	12.7	16.4	18.8	17.5	11.1	13.0	15.8	18.0	17.4
MB+CD	5	10.1	15.9	20.6	21.5	18.0	10.4	14.9	19.5	20.7	17.8
	10	11.2	13.2	16.6	19.3	17.8	11.9	13.1	16.0	18.0	17.5
MB+CD+BL	5	10.6	13.7	19.2	16.8	14.9	10.2	13.0	16.4	17.1	15.3
	10	10.6	13.6	15.8	15.7	15.2	10.4	12.9	15.9	16.8	15.0
Sc	5	10.3	15.0	18.1	19.6	16.8	10.7	13.8	18.0	19.4	17.1
	10	10.8	14.3	17.8	19.1	16.8	11.4	13.8	17.1	18.7	16.9
RC	5	10.4	15.9	19.6	20.9	16.9	10.7	14.9	19.1	20.1	17.5
	10	10.8	15.0	17.8	18.9	16.8	11.4	13.9	17.6	18.7	17.4
Mean		10.5	14.3	18.6	19.5	17.0	10.9	14.1	17.6	19.0	17.1
Ta		13.0	15.0	18.0	19.0	18.0	12.0	14.0	16.5	18.0	17.5
Tt-Ta		-2.5	-0.7	0.6	0.5	-1.0	-1.1	0.1	1.1	1.0	-0.4

Appendix Table 43 *(continued).*

Plot	Depth (cm)	Time (October 23rd)				
		0600	0900	1200	1500	1800
D	5	11.2	17.9	22.4	20.8	17.4
	10	11.9	15.5	19.7	20.7	18.3
D+Sc	5	11.1	16.4	21.7	23.2	19.1
	10	11.6	14.5	18.2	20.9	18.4
D+CD	5	10.2	16.5	22.2	23.5	18.2
	10	12.0	14.6	18.8	20.7	18.2
D+CD+BL	5	10.7	13.7	18.3	17.2	14.8
	10	11.3	13.8	18.0	18.0	15.7
MB	5	10.7	18.1	24.6	23.1	17.7
	10	11.2	15.0	21.2	21.1	17.9
MB+Sc	5	10.5	17.0	24.6	24.7	17.8
	10	11.4	13.2	18.5	20.8	18.3
MB+CD	5	10.7	16.5	22.7	23.6	17.7
	10	12.1	14.0	18.5	20.5	18.3
MB+CD+BL	5	10.3	13.4	21.7	19.1	15.5
	10	10.5	12.7	17.5	17.7	15.3
Sc	5	11.1	15.1	21.3	21.9	17.2
	10	11.6	14.7	20.0	20.9	17.3
RC	5	11.1	16.0	22.0	22.9	17.5
	10	11.7	15.2	20.3	20.8	17.6
Mean		11.2	15.2	20.6	21.1	17.4
Ta		11.5	13.0	17.5	19.0	17.0
Tt-Ta		-0.3	2.2	3.1	2.1	0.4

Appendix Table 44. Temperatures (Tt°C) in differently tilled plots in Summer.

Plot	Depth (cm)	Time (January 10th)			Time (January 11th)					
		1500	1800	2100	0300	0600	0900	1200	1500	1800
D	5	41.7	32.9	30.0	16.9	19.3	33.1	41.9	44.0	33.6
	10	38.4	32.8	30.9	19.5	21.9	30.2	34.4	37.9	33.8
D+Sc	5	41.7	32.4	28.7	16.2	17.8	33.8	43.1	41.6	35.9
	10	41.1	32.8	29.0	16.2	19.4	32.4	43.2	44.1	36.4
D+CD	5	42.8	33.8	30.2	16.8	19.3	30.6	41.0	43.9	36.9
	10	37.4	32.9	30.9	19.6	22.4	29.5	36.0	38.4	34.0
D+CD+BL	5	39.1	33.7	31.0	19.1	22.2	32.4	43.1	39.6	33.0
	10	38.9	34.8	32.3	20.4	23.1	28.7	40.6	39.8	34.0
MB	5	40.6	33.3	28.9	17.5	19.8	33.0	42.8	43.0	32.9
	10	36.8	34.1	30.8	18.7	21.0	26.6	33.8	37.4	34.2
MB+Sc	5	40.0	34.2	28.7	16.3	19.7	32.6	44.0	42.9	33.9
	10	37.6	34.3	30.7	19.3	21.7	27.8	36.6	39.1	34.6
MB+CD	5	37.5	34.1	29.6	18.7	21.5	29.3	38.6	39.9	32.8
	10	37.0	33.8	30.5	19.0	21.9	27.3	36.6	39.5	33.9
MB+CD+BL	5	39.4	36.1	31.3	18.7	21.7	28.5	41.7	43.6	36.6
	10	36.7	34.3	32.1	21.0	23.7	26.0	37.1	39.5	35.7
Sc	5	37.9	33.7	28.6	19.2	21.7	29.0	44.3	39.4	32.3
	10	37.6	34.1	28.6	17.7	21.7	27.1	37.2	40.6	32.2
RC	5	38.4	34.4	28.1	17.8	20.8	28.0	38.8	40.8	32.6
	10	37.9	33.9	28.3	18.7	23.1	28.2	42.2	41.1	31.8
Mean		39.0	33.9	30.0	18.4	21.2	29.7	39.9	40.8	34.4
Ta		34.5	28.5	21.0	18.0	16.0	23.0	28.0	30.0	28.5
Tt-Ta		4.5	5.4	9.0	0.4	5.2	6.7	11.9	10.8	5.9

Appendix Table 44 *(continued)*.

Plot	Depth (cm)	Time (January 12th) 0600	0900	1200	1500	1800	Time (January 13th) 0600	0900	1200	1500	1800
D	5	18.1	31.6	37.5	42.3	34.2	20.0	34.3	43.1	35.1	30.2
	10	20.4	28.2	33.0	39.0	34.3	21.8	30.5	36.5	34.0	30.4
D+Sc	5	17.5	34.6	42.7	43.5	36.6	19.3	37.1	45.4	35.7	27.4
	10	17.7	32.3	39.7	45.6	36.9	19.5	34.1	42.6	34.9	27.9
D+CD	5	17.8	31.3	38.2	45.2	37.6	19.6	32.3	41.8	37.1	29.3
	10	20.9	29.2	33.4	38.5	34.4	22.4	30.3	36.1	34.5	29.9
D+CD+BL	5	21.1	30.2	37.2	45.5	33.2	22.3	34.1	43.9	36.5	33.5
	10	21.9	28.4	35.1	38.5	33.6	23.0	30.5	41.5	37.0	32.0
MB	5	18.1	33.0	40.1	45.5	34.3	20.0	34.4	44.8	37.5	28.3
	10	19.8	26.4	31.4	37.4	34.8	21.4	29.9	34.1	35.3	29.5
MB+Sc	5	18.1	33.8	41.7	41.6	34.7	20.0	34.5	43.6	37.1	28.3
	10	20.3	27.9	34.3	39.1	34.9	21.7	29.1	36.6	34.9	29.6
MB+CD	5	20.3	29.9	36.2	46.5	33.1	21.6	30.4	38.4	35.3	28.5
	10	20.4	27.0	34.1	40.2	34.3	21.9	28.0	36.0	34.4	28.9
MB+CD+BL	5	20.8	30.6	44.8	44.6	36.3	22.2	32.2	43.8	37.8	29.4
	10	22.8	26.2	33.7	38.0	35.9	23.9	27.3	35.8	34.0	30.2
Sc	5	20.5	30.4	41.7	47.2	32.9	21.8	30.9	38.8	35.7	28.1
	10	20.5	27.4	37.6	41.1	32.9	21.9	20.2	36.2	36.3	28.5
RC	5	19.8	29.0	38.3	41.8	32.5	21.2	29.4	38.9	35.9	27.7
	10	20.8	30.5	38.3	40.7	32.7	22.1	31.0	39.5	35.7	28.5
Mean		19.9	29.9	37.5	42.1	34.5	21.4	31.0	39.9	35.7	29.3
Ta		16.0	19.0	24.0	29.5	29.0	18.0	23.5	31.0	32.5	25.5
Tt-Ta		3.9	10.9	13.5	12.6	5.5	3.4	7.5	8.9	3.2	3.8

APPENDIX IV

Appendix IV goes mainly with Chapter 7. It contains water contents (% dry weight basis) at depths (5 and 10 cm) within differently tilled plots. The samples for the water content measurements were collected in July 1976 (Winter) for eight days, and in October 1976 (Spring) for five days. Each of the measurements is a mean of two replicates. The data for the two periods are in two tables.

Glossary

Plots that were tilled with disc plough, disc plough followed by scarifier, disc plough followed by combine drill, mouldboard plough, mouldboard plough followed by scarifier, mouldboard plough followed by combine drill, scarifier, and rotary cultivator are designated by D, D+Sc, D+CD, MB, MB+Sc, MB+CD, Sc and RC respectively.

BL = Barley crop.

Appendix Table 45. Water contents in differently tilled plots in Winter (%).

Plot	Depth (cm)	Time (July 7th) 0900	1500	2100	Time (July 8th) 1200	1500	2400	Time (July 9th) 1200	1500
D	5	11.83	10.13	6.55	14.48	6.20	7.39	13.58	6.33
	10	13.30	10.58	12.31	20.23	12.44	15.90	15.81	14.08
D+Sc	5	17.08	8.88	9.88	12.20	9.25	14.74	18.79	6.79
	10	15.90	15.90	16.66	17.62	15.10	20.19	21.32	20.06
D+CD	5	17.14	8.08	13.39	10.14	8.64	13.39	11.63	4.43
	10	17.19	11.74	11.10	12.21	12.62	14.44	14.07	13.48
MB	5	15.96	10.42	12.34	15.15	11.80	16.50	13.28	7.06
	10	14.37	13.50	15.57	17.50	15.61	16.59	14.36	18.06
MB+Sc	5	15.26	9.48	7.99	12.61	10.01	13.10	18.62	8.54
	10	19.26	12.66	15.77	14.40	12.44	14.67	17.26	16.05
MB+CD	5	11.92	11.72	10.91	13.69	9.12	12.27	13.79	11.26
	10	14.21	10.48	17.64	17.89	13.61	19.21	17.15	16.37
Sc	5	23.45	11.37	11.89	16.74	10.43	16.68	15.18	4.54
	10	24.76	14.39	18.43	19.17	16.80	21.11	17.72	12.84
RC	5	16.99	9.96	10.56	11.39	8.88	8.58	8.74	11.50
	10	22.12	13.64	14.63	17.09	14.41	16.53	15.93	19.09
Mean	5 cm	16.68	10.01	10.44	13.30	9.29	12.80	14.20	7.56
Mean	10 cm	17.64	12.86	15.27	17.03	14.13	17.33	16.70	16.25
Mean		17.16	11.43	12.89	15.15	11.71	15.10	15.48	11.90

Appendix Table 45 *(continued).*

Plot	Depth (cm)	Time (July 10th) 0900	1200	1500	Time (July 12th) 0600	0900	1200	1800	Time (July 13th) 0600	0900	1200	1500
D	5	7.57	12.70	8.03	12.80	11.30	8.70	3.85	12.73	15.90	12.35	10.94
	10	15.47	14.20	15.71	17.48	12.80	11.93	9.81	16.57	9.38	16.76	16.45
D+Sc	5	12.30	12.71	13.65	11.24	11.45	10.94	3.08	7.51	16.62	11.95	15.88
	10	25.13	16.86	17.65	19.78	16.28	16.71	13.84	18.38	18.08	19.67	13.76
D+CD	5	10.41	10.60	13.87	7.94	9.72	4.93	4.71	10.98	11.52	15.96	13.84
	10	12.78	15.65	14.50	13.79	14.23	11.60	11.85	16.31	15.22	16.85	16.54
MB	5	9.45	11.98	13.69	10.97	11.38	9.64	7.57	11.45	13.88	15.99	15.11
	10	17.42	18.26	23.95	18.00	22.53	15.83	16.23	20.23	18.29	19.85	18.54
MB+Sc	5	11.22	12.18	13.79	9.55	9.72	6.17	6.22	10.02	10.93	11.08	6.63
	10	15.49	17.71	17.00	19.10	14.62	14.66	12.64	15.09	19.86	16.41	14.49
MB+CD	5	11.39	16.07	10.04	8.79	12.26	9.04	5.72	13.48	14.14	18.63	11.39
	10	16.02	11.68	17.34	14.15	16.29	14.74	12.86	16.73	16.13	19.00	17.88
Sc	5	8.35	15.38	10.65	8.36	9.29	8.81	8.10	13.40	11.35	19.18	14.44
	10	15.48	20.77	15.21	15.36	14.62	18.11	17.84	18.28	20.27	22.62	21.54
RC	5	8.29	8.62	10.64	11.06	8.54	6.52	8.57	12.18	15.93	14.53	11.66
	10	16.34	16.76	23.84	18.88	10.45	14.80	17.93	17.64	20.61	19.84	20.27
Mean 5 cm		9.87	12.53	11.80	10.09	10.50	8.09	5.98	11.47	13.78	14.86	12.44
Mean 10 cm		16.77	16.49	18.14	17.07	15.23	14.80	14.13	17.40	17.23	18.88	17.43
Mean		13.32	14.51	14.97	13.58	12.85	11.45	10.07	14.44	15.51	16.92	14.83

Appendix Table 45 *(continued).*

Plot	Depth (cm)	Time (July 14th) 0600	0900	1200	1800	Time (July 15th) 0600	0900	1200	1500
D	5	26.32	7.61	5.00	2.30	11.34	11.30	9.92	7.09
	10	27.38	15.75	8.16	8.20	16.72	14.95	11.70	9.59
D+Sc	5	27.17	10.70	5.42	4.09	16.33	13.22	13.20	14.13
	10	29.38	16.07	10.83	9.60	17.27	16.99	15.66	15.18
D+CD	5	18.04	9.49	5.25	4.12	9.54	10.73	7.73	9.01
	10	23.82	14.30	9.10	8.18	13.98	13.47	11.70	12.98
MB	5	21.14	12.71	5.01	3.42	12.90	13.55	12.34	10.83
	10	19.23	14.70	10.89	8.99	17.14	19.96	14.99	15.24
MB+Sc	5	22.44	12.74	2.92	2.00	14.06	9.77	10.27	7.24
	10	23.63	14.24	9.35	5.23	13.48	14.22	13.44	14.20
MB+CD	5	17.56	12.40	9.28	2.41	12.46	10.59	9.83	11.57
	10	19.37	17.72	10.70	7.34	17.72	14.47	14.54	17.91
Sc	5	30.74	12.35	5.34	2.80	13.14	16.11	13.98	13.21
	10	32.20	22.89	11.41	7.63	16.96	20.01	13.98	18.88
RC	5	23.61	11.67	8.71	2.17	13.84	14.09	8.33	9.13
	10	32.49	16.70	15.94	7.93	19.36	18.22	17.29	14.58
Mean	5 cm	23.38	11.21	5.87	2.92	12.95	12.42	10.70	10.28
Mean	10 cm	25.94	16.55	10.80	7.89	16.58	16.54	14.16	14.86
Mean		24.66	13.88	8.34	5.41	14.74	14.48	12.43	12.57

Appendix Table 46. Water contents in differently tilled plots in Spring (%).

Plot	Depth (cm)	October 18th	October 19th			October 20th			October 21st		October 22nd	
		1800	0600	1200	1800	0600	1200	1800	0600	1200	1200	1800
D	5	11.66	22.12	13.46	8.27	15.13	14.37	12.28	13.07	13.94	13.66	12.96
	10	15.98	24.00	15.13	11.83	17.28	17.28	16.35	15.03	15.68	16.01	15.92
D+Sc	5	12.28	20.54	13.49	9.31	12.93	14.83	14.38	16.31	15.78	15.91	14.09
	10	14.54	23.13	19.19	13.53	15.20	17.97	17.01	17.81	18.42	19.44	17.48
D+CD	5	7.92	21.14	13.10	11.29	13.50	14.02	13.97	14.36	11.64	15.56	12.75
	10	15.00	22.84	14.98	12.29	15.11	16.81	16.29	15.57	14.20	16.38	14.51
D+CD+BL	5	15.85	22.56	16.80	10.67	14.87	15.75	12.10	13.69	14.78	17.22	12.14
	10	17.16	23.30	19.09	12.50	16.66	17.76	14.80	14.04	16.12	16.96	11.69
MB	5	10.38	18.80	12.40	9.50	13.91	15.66	11.98	13.57	15.06	14.50	14.99
	10	15.04	22 45	17.22	14.32	17.69	18.87	14.94	15.51	18.91	16.55	17.58
MB+Sc	5	12.17	20.66	14.88	8.79	14.64	15.30	14.43	14.76	15.59	14.29	15.46
	10	16.15	24.03	16.45	12.83	18.44	18.27	16.90	18.14	12.96	18.20	19.05
MB+CD	5	11.44	20.85	15.19	10.22	13.50	16.19	13.93	13.60	15.46	14.79	16.10
	10	15.03	23.15	17.86	14.45	17.63	17.91	15.88	16.35	18.09	19.03	18.98
MB+CD+BL	5	17.27	25.34	15.54	13.05	17.34	17.45	17.41	15.28	15.70	17.07	13.79
	10	17.33	25.44	15.97	13.23	17.18	18.77	18.70	18.36	17.08	18.39	14.48
Sc	5	12.60	21.77	14.98	10.43	15.39	16.30	17.30	17.94	16.36	15.82	18.06
	10	15.20	22.01	15.67	12.63	16.11	18.87	17.30	17.36	17.37	18.28	18.70
RC	5	13.75	24.10	17.18	13.27	17.22	17.33	18.03	18.00	19.56	16.16	16.79
	10	15.92	26.89	18.44	14.93	18.18	20.00	20.26	20.80	21.21	19.57	20.15
Mean 5 cm		12.53	21.79	14.70	10.48	14.14	15.72	14.58	15.06	15.39	15.50	14.71
Mean 10 cm		15.74	23.72	17.00	13.25	16.95	18.23	16.84	16.90	17.00	17.88	16.65
Mean		14.14	22.76	15.86	11.87	15.90	16.98	15.71	15.98	16.20	16.69	15.69

APPENDIX V

Appendix V for Chapter 8 contains primary data (in tables) of changes in water content in soil columns subjected to applied temperature gradients, and data of temperatures in columns of soil aggregates (7.0 - 4.0 mm) also subjected to applied temperature gradients. The above two sets of data are placed in Sections A and B respectively.

Glossary

A	=	Mean value for hot end (soil inside hot water jacket alone (2 sections)
B	=	Mean value for hot end (heat source) and column within 2 cm from hot end (3 sections)
C	=	Mean value for hot end (heat source) and column within 4 cm from hot end (4 sections)
D	=	Mean value for hot end (heat source) and column within 6 cm from hot end (5 sections)
A	=	Approximate value
CH	=	Soil column held vertically with hot end at the top
HC	=	Soil column held vertically with cold end at the top
w(%)	=	Initial soil water content (dry weight basis).

SECTION A

Appendix Table 47. Changes in water contents of soil columns within mean temperature gradient of 1.4°C cm^{-1} for different time durations (hr).

Time / Distance (cm) from dry end	3 hr					6 hr				
	Aggregate fraction (mm) in column									
	7.0-4.0	4.0-2.0	2.0-1.0	1.0-0.5	Mixed	7.0-4.0	4.0-2.0	2.0-1.0	1.0-0.5	Mixed
0	-1.78(B)	-2.9(A)	-2.3(B)	-2.3(B)	-2.7(C)	-2.9(B)	-3.4(A)	-3.27(B)	-1.67(B)	-2.63(A)
2	+1.91	+0.33	+1.0	+1.61	+1.82	+3.79	+3.64	+1.65	+0.13	+2.64
4	+1.25	+1.52	+1.61	+1.32	+2.62	+2.25	+2.48	+2.11	+0.64	+2.83
6	+0.66	+2.55	+1.25	+1.18	+1.71	+3.01	+2.19	+2.57	0	+1.71
8	+2.14	+1.05	+0.68	0	+1.54	+1.88	+1.95	+1.6	-0.34	+1.2
10	+0.52	+1.06	+1.08	+0.54	+0.64	+1.01	+2.14	+1.29	-0.51	+1.2
12	+0.82	+0.95	+0.9	-0.16	+0.42	+2.53	+0.95	+0.6	-0.85	+0.1
14	+1.17	+0.28	+0.68	+0.53	+0.74	+0.98	+1.18	0	-0.22	0
16	-0.17	+0.25	+0.46	-0.22	+0.67	+1.29	+0.1	+1.07	-0.65	+0.28
18	+0.24	-0.26	+0.28	+0.76	+0.2	+0.94	+0.47	+0.54	-0.39	+1.0
20	+0.79	-0.1	+0.11	+0.16	+0.23	+0.76	+0.87	+0.28	-0.7	+0.68
22	-0.17	+0.27	0	-0.42	+0.14	1.59	+0.42	+1.45	-0.54	+0.58
24	+0.1	+0.55	+1.72	-0.38	+0.8	+0.6	+1.87	+0.74	-0.65	+0.73
w (%)	13.7	13.51	8.92	10.22	14.1	12.7	13.03	8.35	4.5	9.24
Time	6 hr (CH)					6 hr (HC)				
0	-2.19(B)	-3.39(B)	-3.38(B)	-2.69(B)	-5.45(B)	-3.45(B)	-3.05(B)	-2.88(B)	-3.83(B)	-4.7(B)
2	+3.27	+2.66	+2.14	+0.96	+1.54	+1.93	+1.56	+3.51	+1.7	+1.11
4	+3.98	+2.84	+2.19	+2.04	+2.15	+3.09	+3.43	+3.69	+2.65	+2.73
6	+3.41	+1.88	+1.48	+2.0	+1.01	+1.75	+3.23	+2.56	+1.9	+1.95
8	+2.24	+0.77	+1.73	+1.05	+0.66	+1.15	+0.39	+2.28	+1.83	+0.57
10	+0.89	+2.76	+0.53	+0.46	+0.49	+0.68	+0.38	+1.91	+0.51	+0.39
12	+1.11	+0.37	+1.06	+0.9	+0.33	+0.54	-0.26	+1.17	+0.61	+0.23
14	+0.99	+0.63	0	+0.31	+0.55	+1.26	-0.44	+0.67	+0.49	+0.61
16	+0.69	+0.3	+0.3	0	+0.19	+0.59	0	+0.1	+0.22	+0.1
18	+0.77	0	+0.33	0	-0.44	0	-0.99	+0.2	+0.55	+0.33
20	+1.03	-0.16	-.015	0	-0.4	+0.2	-0.22	+0.16	+0.62	0
22	+1.53	0	-0.22	-0.11	+0.42	+0.18	-0.1	-0.14	+0.52	+0.3
24	+1.68	-0.46	-0.24	-0.94	-0.18	+0.85	+0.28	0	0	+0.19
w (%)	13.12	14.32	8.67	7.0	11.68	9.5	11.13	9.38	11.7	11.82

Appendix Table 47 *(continued).*

Time	9 hr					12 hr				
Distance (cm) from dry end	Aggregate fraction (mm) in column									
	7.0-4.0	4.0-2.0	2.0-1.0	1.0-0.5	Mixed	7.0-4.0	4.0-2.0	2.0-1.0	1.0-0.5	Mixed
0	-5.35(B)	-5.31(B)	-4.0(B)	-4.49(B)	-3.02(B)	-5.58(B)	-6.93(B)	-3.43(B)	-6.61(B)	-7.43(B)
2	+2.19	+1.86	+2.77	+1.68	+2.84	+4.24	+3.3	+1.0	+1.23	+3.52
4	+3.39	+2.71	+4.23	+2.66	+4.04	+4.45	+6.65	+2.04	+3.79	+4.54
6	+2.4	+2.94	+3.94	+2.03	+2.29	+0.35	+3.69	+1.04	+3.7	+3.39
8	+1.18	+2.87	+2.33	+1.4	+2.21	+3.03	+2.87	+0.6	+1.67	+2.2
10	0	+1.9	+1.5	+0.26	+0.97	0	+2.89	-0.74	+3.28	+1.76
12	+2.0	+1.07	+1.24	+1.87	+0.81	+1.46	+1.5	-0.93	+0.61	+0.34
14	+0.98	+1.28	+1.04	+0.58	+0.33	+1.53	+0.99	-1.36	+0.54	+1.35
16	+0.83	+0.56	+0.83	+0.58	+0.31	+0.81	+0.99	-0.33	0	+0.55
18	+0.66	+0.49	+0.67	+0.1	+0.24	+0.77	+0.23	-1.36	-0.4	+0.64
20	+0.52	+0.41	+0.68	+0.1	+0.17	+0.49	+0.65	-0.91	+0.31	+0.31
22	+0.58	+0.19	+1.02	-0.93	+0.14	+2.71	+0.46	-0.92	+0.71	-0.22
24	+0.49	+0.62	+0.75	0	0	+0.81	+0.63	-1.1	+0.16	0
w (%)	10.9	13.8	9.43	7.52	8.9	12.6	13.1	11.6	10.5	12.66

Appendix Table 48. Changes in water contents of soil columns within mean temperature gradient of 1.0°C cm^{-1} for different time durations (hr).

Time / Distance (cm) from dry end	3 hr					6 hr				
	Aggregate fraction (mm) in column									
	7.0-4.0	4.0-2.0	2.0-1.0	1.0-0.5	Mixed	7.0-4.0	4.0-2.0	2.0-1.0	1.0-0.5	Mixed
0	-0.43(B)	-1.43(B)	-0.77(B)	-1.25(B)	-1.29(A)	-0.51(B)	-2.79(B)	-2.96(A)	-4.63(A)	-2.19(B)
2	+2.77	+0.32	+1.61	+1.46	+0.39	+1.55	+0.1	+1.1	+1.19	+1.9
4	+3.18	+0.67	+0.88	+1.28	+1.0	+1.79	+1.0	+2.18	+3.87	+0.84
6	+3.83	+0.55	+0.9	+1.25	-0.44	+1.36	+0.13	+1.52	+3.7	+1.42
8	+0.32	+0.42	+0.69	-0.1	+0.77	-0.58	+0.31	+1.02	+3.15	+0.28
10	-0.11	-0.12	+0.95	-0.12	+0.1	+0.19	+0.13	+1.8	+3.06	+0.17
12	+1.7	+0.58	+0.45	-0.56	-0.67	-0.77	-0.22	+1.06	+2.39	+0.54
14	+0.87	+0.89	+0.45	+0.68	-0.17	-0.38	-1.01	+1.12	+1.15	+0.17
16	+1.88	+0.59	+0.37	+0.1	0	-2.22	+0.1	+1.8	+1.79	+0.79
18	+2.09	+1.23	+0.16	+0.1	+1.6	+0.67	-0.55	+1.4	+0.89	+0.3
20	+1.42	+0.35	+0.21	+0.41	+1.03	-0.15	0	+1.52	+1.49	0
22	+1.08	+0.76	+0.59	+0.35	+1.78	-0.24	-0.37	+0.77	+1.8	+0.94
24	0	0	0	0	+1.49	-0.24	+0.43	+0.76	+1.37	+0.69
w (%)	17.05	11.67	13.84	11.67	12.06	17.65	12.37	8.3	9.15	9.92

Time	6 hr (CH)					6 hr (HC)				
0	-2.25(B)	-0.82(B)	-2.3(B)	-2.52(A)	-2.38(A)	-4.01(B)	-2.05(B)	-1.7(B)	-1.46(B)	-3.74(A)
2	+1.49	+1.19	+2.13	+0.21	+1.19	+0.8	+0.12	+1.11	+4.21	+5.09
4	+1.42	+2.63	+2.44	+2.73	+2.18	+1.87	+0.48	+2.19	+3.56	+4.56
6	0	-0.39	+1.35	+1.28	+3.41	+2.77	-0.25	+1.55	+1.65	+0.19
8	-0.42	-0.24	+0.8	+1.58	+1.42	-1.51	0	+1.8	+0.46	+0.27
10	+0.1	-0.17	+1.23	+1.01	+1.08	-1.65	+0.1	+1.07	+0.27	-0.11
12	-0.34	0	+1.02	+1.87	+1.29	-1.32	+0.1	+1.23	+0.12	+0.17
14	0	-0.66	+0.95	+0.37	+1.6	-1.65	-0.1	+0.71	-0.17	-0.56
16	-0.2	-1.09	+0.76	0	+0.73	-1.85	-0.1	+1.38	0	-1.48
18	0	-0.89	+0.13	+0.53	+0.1	-1.39	+1.0	+1.53	0	-0.9
20	-0.13	0	+0.96	+0.62	+0.67	-2.01	+0.1	+0.77	+1.23	-0.83
22	-0.3	-0.3	+1.44	+0.94	+1.08	-1.47	+0.37	+0.77	+0.3	-1.7
24	-0.39	-0.63	+1.1	+1.02	+1.82	-0.84	+0.37	+0.76	+1.16	-1.45
w (%)	16.62	19.81	8.29	7.36	9.92	17.96	16.76	8.29	7.31	14.91

Appendix Table 48 *(continued)*

Time	9 hr					12 hr				
Distance (mm) from	Aggregate fraction (mm) in column									
dry end	7.0-4.0	4.0-2.0	2.0-1.0	1.0-0.5	Mixed	7.0-4.0	4.0-2.0	2.0-1.0	1.0-0.5	Mixed
0	-2.55(D)	-2.05(B)	-2.49(B)	-3.14(B)	-1.46(C)	-1.11(B)	-3.45(B)	-2.52(B)	-3.08(B)	-2.66(B)
2	+0.1	+2.29	+2.8	+1.62	+0.71	+0.54	+2.31	+1.05	+0.4	+4.09
4	+0.2	+2.81	+1.89	+2.75	+0.83	+1.48	+2.99	+1.43	+0.84	+3.22
6	+0.25	+1.53	+1.71	+2.41	+0.69	+1.13	+3.44	+3.3	+1.15	+1.35
8	-0.29	+1.37	+0.75	+1.46	+0.59	-0.49	+3.01	+1.32	+1.49	+0.78
10	-0.42	+1.81	+0.5	+1.62	+0.13	-0.38	+1.64	+0.26	+0.47	+1.03
12	-0.46	+0.85	+0.28	+1.74	+0.59	-0.92	+1.84	-0.11	+0.64	+0.82
14	-0.54	+1.67	+0.33	+1.2	+0.14	-0.46	+1.5	+0.92	+0.69	+0.92
16	-1.25	-0.44	+0.77	+1.4	+0.21	+0.11	-0.58	+0.54	+0.71	+0.91
18	-1.89	+1.17	+0.83	+1.27	+0.22	+0.19	-0.38	0	+0.54	+0.25
20	-0.92	+0.19	+0.1	+1.1	0	+0.27	+0.75	+0.87	+0.39	+0.72
22	-0.4	+1.92	+0.1	+1.55	+0.69	-0.17	+0.95	+0.31	+0.39	+0.86
24	+0.23	+1.94	+0.65	+0.9	0	+0.1	+1.76	+1.43	+0.29	+0.79
w(%)	17.42	14.53	11.33	11.67	17.3	17.1	12.24	13.1	17.29	8.47

Appendix Table 49. Changes in water contents of soil columns with mean temperature gradient of 0.5°C cm^{-1} for different time durations (hr).

Time	3 hr					6 hr				
Distance (cm) from dry end	Aggregate fraction (mm) in column									
	7.0-4.0	4.0-2.0	2.0-1.0	1.0-0.5	Mixed	7.0-4.0	4.0-2.0	2.0-1.0	1.0-0.5	Mixed
0	-0.6(A)	-1.71(A)	-0.22(A)	-0.47(A)	-0.7(C)	-0.61(C)	-0.94(A)	-0.61(A)	-0.74(A)	-1.16(B)
2	+0.78	+0.46	+0.61	+0.86	+0.11	+0.71	+0.69	+0.71	+1.62	+0.69
4	+1.09	+0.85	+1.75	+1.34	+0.71	+0.29	+0.16	+2.33	+0.25	+1.58
6	+1.43	+0.86	-0.1	+1.6	0	-0.21	+0.57	+1.92	-0.1	-0.1
8	+0.37	-0.17	+0.36	+1.22	+0.1	+1.04	+0.56	+1.56	0	+0.41
10	+0.28	-0.12	+0.45	+1.35	+0.19	+0.47	+0.44	+1.41	-0.15	-2.29
12	0	-0.4	-0.14	+1.38	0	-0.27	+0.17	+0.76	-0.22	-3.17
14	+0.17	+0.69	+0.77	+0.45	+0.32	0	0	+1.07	+1.2	-0.49
16	+0.41	-0.67	+0.45	+1.67	-0.43	+0.35	0	+1.31	+0.59	-0.75
18	-0.39	-0.58	+0.61	+0.68	+0.1	-0.32	0	+0.84	+1.13	+0.3
20	+0.16	-1.11	+1.06	+1.6	-0.39	+0.23	0	+1.3	-0.39	0
22	-1.26	+0.1	+0.78	+1.24	-0.52	+0.59	+0.59	+1.1	+1.04	-0.5
24	-0.35	+0.18	+0.35	+1.18	+0.17	+0.23	+0.45	+1.23	+1.49	+0.34
w(%)	8.72	12.9	10.5	9.04	11.79	10.76	7.06	8.5	9.04	9.88
Time	6 hr (CH)					6 hr (HC)				
0	-0.81(A)	-1.45(A)	-1.27(B)	-1.9(B)	-1.36(B)	-0.33(B)	-0.78(B)	-1.0(A)	-2.0(C)	-1.21(A)
2	+0.56	+1.66	+0.47	+0.79	+0.19	+0.18	+0.16	+0.25	+0.29	+1.15
4	+2.47	+0.7	-2.4	-0.1	+0.17	+1.95	+0.47	+1.21	+0.3	-0.3
6	-0.23	+1.14	-2.34	-0.48	-0.1	+1.75	+0.38	+1.94	-0.79	-0.1
8	-0.37	+0.56	-4.08	-0.1	+0.33	0	+0.6	+0.73	-0.69	-0.21
10	-0.58	-0.21	-0.38	-0.42	-0.15	0	+0.71	+0.1	-1.9	-0.68
12	+0.7	-0.34	-3.43	-0.58	+0.2	+0.38	+0.27	+0.15	-1.03	-0.25
14	+0.64	+0.87	-0.43	-0.7	-0.1	+0.5	0	+0.1	+0.12	+0.15
16	+0.86	+0.63	-1.54	-0.88	-0.93	+1.51	-0.17	0	-0.66	+0.99
18	+0.97	+0.37	-0.53	-0.5	-0.12	+0.71	+0.14	+0.91	-0.51	+0.98
20	+1.05	+0.48	-0.37	+0.1	+0.44	+0.93	0	+0.2	-0.3	+1.11
22	+0.6	+0.77	+0.2	0	-0.35	0	-0.21	+0.71	-0.26	+1.05
24	+1.65	+0.23	-1.14	-0.23	-0.45	0.1	-0.39	-1.03	-0.26	+0.21
w(%)	9.24	12.5	11.54	7.0	8.53	11.38	12.8	9.9	8.35	11.7

Appendix Table 49 *(continued)*

Time Distance (cm) from dry end	9 hr					12 hr				
	Aggregate fractions (mm)									
	7.0-4.0	4.0-2.0	2.0-1.0	1.0-0.5	Mixed	7.0-4.0	4.0-2.0	2.0-1.0	1.0-0.5	Mixed
0	-1.57(A)	-1.25(A)	-1.02(B)	-1.0(A)	-0.3(A)	-1.21(B)	-0.66(B)	-2.45(B)	-2.23(B)	-1.35(A)
2	+0.12	+0.14	-1.51	+0.64	+0.35	+1.92	+2.72	+1.9	+0.47	+0.12
4	-0.13	+0.84	+1.85	+1.77	-0.1	+3.15	+3.35	+1.59	+1.0	+0.17
6	-0.51	+0.45	+1.28	+2.22	+0.14	+2.34	+2.5	+1.56	+0.67	-0.53
8	-0.6	+0.23	+0.72	+1.98	+0.68	+1.31	+1.87	+1.24	+0.27	-0.31
10	+0.49	-0.1	+1.09	+1.06	+0.57	+1.84	+1.83	+1.32	+0.67	+0.17
12	-1.11	-0.35	+0.79	+1.98	+0.87	+1.44	+1.87	+0.91	-0.38	+0.1
14	-0.82	-0.53	+1.34	+0.46	+0.7	+1.83	+1.68	+1.21	+0.27	+0.39
16	-0.71	-0.1	+1.36	+2.08	+1.13	+1.79	+2.2	+0.92	-0.38	-0.16
18	-0.4	-0.19	+1.07	+2.12	+0.79	+2.05	+2.38	+1.34	0.28	0
20	-0.42	-0.34	+1.36	+1.0	+1.43	+1.3	+1.58	+1.67	-0.1	-0.16
22	-0.78	+0.53	+1.51	+1.37	+1.56	+1.66	+1.92	+1.01	+0.45	-0.38
24	-0.44	-0.14	+0.9	+0.94	+1.65	+1.65	+2.36	+1.19	+0.18	0
w (%)	8.4	8.91	12.78	8.63	8.3	13.59	16.55	12.32	6.76	7.49

SECTION B

Appendix Table 50. Temperature in soil columns under different differential temperature (Td°C) and temperature gradient (ΔT°C cm^{-1}).

Td°C	Distance (cm) from dry end	Time (min.) 15	30	60	80	100	120	140	160	170	180	Mean
	0	49.5	51.9	51.9	51.9	52.5	52.5	52.5	52.5	52.5	52.5	52.0
	2	34.2	38.9	41.7	43.6	44.0	44.5	44.5	44.5	44.5	44.5	43.5
44	4	31.9	35.5	39.1	39.7	40.0	40.2	40.5	40.5	40.5	40.5	38.8
	6	27.0	30.0	33.4	34.3	35.0	35.5	35.7	35.7	35.7	36.0	33.8
	8	25.0	27.0	30.0	30.8	31.5	32.0	32.5	32.5	32.5	32.7	30.7
ΔT=1.4	10	23.5	24.6	26.4	27.2	27.9	28.3	28.5	28.8	29.0	30.0	27.4
°C cm^{-1}	12	23.0	23.6	25.0	25.4	26.0	26.5	26.7	26.9	26.9	27.1	25.7
	14	22.2	22.5	23.3	23.5	23.9	24.3	24.7	24.7	24.9	24.9	23.9
	16	22.0	22.0	22.3	22.4	22.8	23.1	23.2	23.4	23.6	31.1	23.6
	18	21.8	22.0	22.2	22.2	22.5	22.7	22.9	22.9	22.9	23.2	22.5
	20	21.5	21.7	21.7	21.7	21.8	22.1	22.1	22.1	22.1	22.1	21.9
	22	21.2	21.2	21.2	21.2	21.2	21.4	21.4	21.4	21.4	21.4	21.3

Td°C	Distance (cm) from dry end	Time (min.) 15	60	80	100	120	140	150	Mean
	0	41.5	42.7	42.7	42.2	43.2	43.2	43.2	42.7
	2	28.6	32.6	33.4	33.9	34.2	34.5	34.8	33.1
30	4	28.0	31.9	32.8	33.5	33.7	33.9	34.1	32.6
	6	25.9	27.0	27.7	28.3	28.8	29.2	29.4	28.0
ΔT=1.0	8	25.0	24.4	25.0	25.3	25.7	26.1	26.1	25.4
°C cm^{-1}	10	23.8	22.9	23.3	23.5	23.6	24.0	24.0	23.6
	12	23.4	22.3	22.3	22.5	22.5	22.7	22.7	22.6
	14	22.4	21.5	21.5	21.6	21.6	21.6	21.6	21.7
	16	21.5	20.9	20.9	21.1	20.9	20.9	20.9	21.0
	18	21.2	20.7	20.7	20.7	20.7	20.7	20.7	20.8
	20	21.0	20.4	20.4	20.4	20.4	20.4	20.4	20.4
	22	21.2	20.5	20.5	20.5	20.5	20.5	20.5	20.5

Appendix Table 50 *(continued)*.

Td°C	Distance (cm) from dry end	Time (min.) 10	30	40	80	120	180	Mean
	0	30.2	32.3	33.0	33.3	33.0	33.2	32.6
	6	21.9	23.4	25.2	25.9	26.1	26.1	24.8
15	12	20.7	20.8	21.4	21.1	20.9	21.0	21.0
ΔT=0.5	18	20.3	20.2	20.3	20.5	20.2	20.2	20.3
$^{o}C\ cm^{-1}$	20	20.2	20.0	19.7	19.7	19.9	19.9	19.9
	24	20.6	20.4	19.9	19.9	20.2	20.1	20.2

Td = Differential temperature between hot water and cold water.

* Soil water contents between 6 to 8%.

APPENDIX VI

This appendix goes with Chapter 9.

Appendix Table 51. Standard deviation of structural probabilities P(0) calculated from values obtained from a data string length of 2,000 elements.

Precursor	Standard deviation of P(0) for diameter 5	10	20	40
0000	0.036	0.028	0.017	0.009
0001	0.027	0.017	0.010	0.000
0010	0.110	0.065	0.0000	*
0011	0.013	0.018	0.011	0.009
0100	0.133	0.327	0.033	0.000
0101	0.140	0.652	*	*
0110	0.062	0.092	0.000	0.000
0111	0.032	0.020	0.014	0.011
1000	0.064	0.052	0.035	0.041
1001	0.048	0.023	0.024	0.000
1010	0.177	0.000	*	*
1011	0.023	0.015	0.000	0.000
1100	0.040	0.024	0.029	0.021
1101	0.030	0.023	0.000	0.000
1110	0.015	0.020	0.034	0.036
1111	0.022	0.011	0.009	0.006