INFLUENCE OF SOIL SURFACE MANAGEMENT ON PROFILE MOISTURE STORAGE, DEEP PERCOLATION AND SOLUTE MOVEMENT OF AN ALFISOL

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CERTIFICATE

This is to certify that the thesis entitled **"INFLUENCE OF SOIL SURFACE MANAGEMENT ON PROFILE MOISTURE STORAGE, DEEP PERCOLATION AND SOLUTE MOVEMENT OF AN ALFISOL"** submitted in partial fulfilment of the requirements for the degree of **DOCTOR OF PHILOSOPHY IN AGRICULTURE** of the **ACHARYA. N. G. RANGA AGRICULTURAL UNIVERSITY**, Hyderabad is a record of the bonafide research work carried out by **Ms. M Nivedita** under my guidance and supervision. The subject of the thesis has been approved by the Student's Advisory Committee.

No part of the thesis has been submitted for any other degree or diploma. The published part has been fully acknowledged. All assistance and help received during the course of the investigations have been duly acknowledged by the author of the thesis.

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NIVEDITA MAHENDRAKER

DECLARATION

I, M. Nivedita, hereby declare that the thesis entitled "**INFLUENCE OF SOIL SURFACE MANAGEMENT ON PROFILE MOISTURE STORAGE, DEEP PERCOLATION AND SOLUTE MOVEMENT OF AN ALFISOL**" submitted to Acharya N G Ranga Agricultural University for the degree of Doctor of Philosophy in Agriculture is the result of original research work done by me It is further declared that the thesis or any part thereof has not been published earlier in any manner

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ABSTRACT

In developing surface management techniques to reduce soil structural problems and enhance profile moisture storage, thereby decreasing deep percolation losses and modifying solute movement, tillage, residues, conditioners and surface roughness are important considerations. Experiments were conducted in the rainy season of 1995 and 1996 to evaluate the performance of scoops, crop residues, polyvinyl alcohol (PVA) and revegetation treatments in comparison with an untreated control under crop and fallow conditions. The impact on profile moisture storage, deep percolation and solute movement, in a randomised complete split plot design, were monitored. Bromide was used as a tracer to study the solute movement under the different surface management techniques. Revegetation treatment recorded the highest moisture storage in the soil profile and the least water flux at 2.00 m depth than PVA, crop residue, scoop and control treatment in that order. The most rapid bromide flux was observed in the revegetation plots at all the depths than in PVA and crop residue treatment. Bromide flux was least in the control treatment at all depths with scoop treatment showing higher bromide flux. Between the sub treatments, fallow treatments have shown the higher profile moisture storage and lower deep percolation losses of water than the crop treatments. The solute movement (bromide flux) was higher in the fallow than the crop sub treatment in all the main treatments. It can be speculated that the higher profile moisture storage and bromide flux and reduced deep percolation losses in the revegetation, PVA and crop residue treatments, in that order, results from an alteration in soil aggregation and aggregate stability. This has been accompanied by changes in porosity, pore size distribution, pore geometry and soil structure. Scoop treatment has also shown higher moisture storage and lower deep percolation losses than control because of surface roughness which enhances aggregation and aggregate stability. The pearl millet crop also yielded better in the revegetation plots followed by PVA, crop residue, scoop and control plots. Various surface management techniques can therefore be adopted for improving the soil structure which enhance the moisture storage capacity of the soil and reduce deep percolation losses. However, it would also increase solute movement, and possibly increase leaching loss of nutrients.

INTRODUCTION

CHAPTER I

INTRODUCTION

In order to maintain and increase food production, farmers have to deal with soil chemical and biological fertility which includes problems with nitrogen and phosphorus nutrition, problems with other nutrients, as well as biological problems. They also must deal with physical aspects of soil fertility which include infiltration, water retention and proper soil structure for adequacy of seedling emergence and root penetration. All of these physical properties pose problems to farmers. Infiltration, if poor, reduces the quantity of water available to the crop, potentially reduces the recharge of ground water, increases runoff which might increase erosion and have other downstream effects. Water retention, if it is reduced, means less water available to crops, more frequent water stress during growth cycles, poor growth of crop canopy and roots. Poor soil structure can lead to seedling emergence problems due to crusting, the consequences of which are uneven stand with less yield, need for re-sowing which adds to cost (for purchase of seeds), and reduced yield due to late sowing (for example when drought occurs during grain filling), less nitrogen available to re-seeded crop, weeds which are unaffected get advantage, intercrops are out of synchrony. Root penetration problems also occur due to hardpans which give increased drought frequency, less available water for crops. One major consequence may be a reduction in the range of crops that can be grown, or only a single crop instead of double crop.

An understanding of the various physical factors which affect crop growth such as water retention, water infiltration, soil structure, deep percolation losses of water, nutrient movement etc. is imperative to manage them for better production. There is knowledge of these physical processes from research in different parts of the world on different soil types, from which we can conclude that a well-structured soil has lower production risk. This is less researched in soils of the Semi-Arid Tropics (SAT) in developing countries. Therefore it is desirable to learn more about these physical processes in the Indian SAT Alfisols.

Alfisols are an important soil order, occupying 59.6 million hectares in India (Venkateswarlu, 1987). Alfisols are well-drained soils possessing low water storage capacity. The main reason for low water storage capacity is the structural instability of these soils. The lack of structural development is due to low content of fine clay particles, presence of clay minerals of low activity (e.g. kaolin) and relatively low amounts of organic matter within the soil matrix. Clay content plays an important role for improving aggregation in soils as clays are involved in binding with the organic matter and improving the structure of the soil. Poor soil structure is mainly because of a tendency of these soils to slake and rapidly seal the surface following rainfall and to crust with subsequent drying. The structural instability of Alfisols often leads to consolidation of a considerable depth of soil profile or slumping of the plough layer which adversely affects seedling establishment and water infiltration into the soil profile. Because infiltration is affected by crusting and sealing, solute movement will also be affected. The unstable structure of these soils enhances the tendency to develop surface seals that reduce infiltration and profile recharge even under moderate rainfall.

A rainfall of 700-1000 mm (the range received in much of the SAT) is sufficient for crops like millet, sorghum, groundnut, provided the rain water can fully penetrate and be stored in the soil. Most of the deep Alfisols in the semi-arid regions have an effective soil moisture storage capacity. The critical factor to be considered here is the degree to which the surface condition allows the rain water to penetrate into the soil. Since most Alfisols are prone to sealing i.e. formation of a thin layer (1-5 mm) at the soil surface which is dense and hard without any pores, rain water cannot penetrate into the soil. When this happens, most of the rain water is lost due to runoff. As a result the water storage potential of the soil is not being used to its maximum. This would affect both deep percolation and solute movement within the soil profile. A good structure for plant growth requires the presence of pores for the storage of water available to plants, pores for transmission of water and air and pores in which roots can grow. In Alfisols due to formation of surface seals which cause blocking of the pores as a result of dispersion and settling of clay between and within the soil particles, the water holding capacity of the soil decreases which in turn reduces the water storage capacity of these soils. Therefore a good distribution of pores throughout a soil is vitally important for crop growth since pores determine the structural improvement of soils and porosity, pore geometry and pore size distribution which are important for water, air and nutrients to circulate in the soil.

Soil structure is an important physical characteristic of the soil which influences various soil-plant-water relationships. The structural characteristics of the soil have a major impact on crop growth and transport of water and agricultural chemicals. Soil structure is defined as the organization of primary particles into aggregates and arrangement of pores between and within the aggregates. Alteration in soil structure can be observed as a result of surface management, since it influences the pore geometry, pore size distribution, bulk density etc, which are important indices of soil structure. Soil structural stability can be measured for several purposes, one of which is to assess new management practices in terms of their impact on structural stability. Soil structure needs to be stable for a range of agricultural reasons. In an unstable soil structure as is the case of SAT Alfisols seedbeds can collapse and crusts can form on the surface which impede shoot emergence. Surface management affects soil structure which in turn influences the pore geometry, pore size distribution, bulk density, soil aeration, deep percolation, solute movement, soil water storage, rainfall infiltration, erosion and runoff. Surface management of the soils may retard degradation of soil physical properties and improve the soil considerably. An insight into the influence of structure on soil processes can be gained from an examination of soil water behavior in the same soil manipulated to produce different structures.

A challenge for sustainable agriculture is to identify those management practices which are most efficient in forming stable soil structure and incorporating them in the management system thereby improving productivity. Soil management practices should aim at increasing surface storage by increasing the infiltration capacity. Due to sealing, water that would normally infiltrate into the soil will be lost to runoff during rainstorm because the direct impact of raindrops can break down aggregates which block pores that would normally conduct water. The overall effect of sealing is reduction in porosity and permeability of soil surface. Remedial action for sealing-prone soils involves repeated tillage operations, increasing organic matter, mulching etc. as these operations will increase water penetration into the soil. But these methods are difficult in the SAT Alfisols because the organic matter would get oxidized quickly during the hot dry season and continuous tillage is not always possible. Application of artificial soil conditioners may be a solution to reduce sealing.

Tillage, which leaves crop residue on the surface (zero or minimum tillage), limits runoff by preventing direct impact of raindrops. Generally systems which leave substantial amounts of residue on the surface are termed conservation tillage. Thus, soil surface management can profoundly effect infiltration and evaporation leading to increased soil water storage as well as deep percolation (beyond 2 m depth) and solute movement. It is necessary to improve and protect the structure of the soil surface to promote infiltration and suppress evaporation through either tillage operations or mulching or application of natural or synthetic conditioners. If depressions are created in these soils then they would enhance the infiltration of rain water into the soil profile, since these depressions are generally more stable and act as receiving basins for water storage. Such depressions (termed as scoops or pits) enhance rainfall acceptance by the soil thereby increasing the water storage in the soil profile.

Research is still in progress to determine the most feasible method for improving moisture storage in soil profile through increased infiltration by surface modification of soil structure and its effects on the deep percolation of water and losses of nutrients due to leaching along with water. Not many reports are available on the effect of zero tillage, large inputs of residue (mulching), use of pits to store water on surface and use of soil conditioners for improving the profile water storage capacity, deep percolation and solute movement in Alfisols. The present investigation aims at the following objectives :

1. To study the effect of soil surface management on profile water storage of an Alfisol.
2. To study the effect of soil surface management on deep percolation of an Alfisol.
3. To study the effect of soil surface management on solute movement of an Alfisol.

REVIEW OF LITERATURE

CHAPTER II

REVIEW OF LITERATURE

Alfisols are the third most important soil order in the world and cover a large area of potentially arable and grazeable land. The loamy sand texture of the top soil, predominance of kaolinite clay minerals and very low concentrations of organic matter make these soils structurally unstable. Structural instability in these soils can lead to crusting and surface sealing. Soil structure is defined in terms of spatial distribution of solids and voids at macroscopic and microscopic level. Surface management of these soils alters the pore geometry and thereby changes the soil structure. Changes can occur within a growing season. The associated changes in porosity and pore-size distribution give important data on soil structure, because pores determine various physical properties important to plants. The natural complexity of pore size distribution, pore shape and the relative position of the aggregates and pores play an important role in determining soil structural changes due to surface management. Change in soil structure can affect many of the soil properties such as porosity, pore size distribution, aggregation, root growth, seedling emergence, microbial activity, soil water status, rainfall infiltration, deep percolation, solute movement, erosion and runoff. Change in soil structure due to surface management can be direct through cultivation or indirect due to exposure to raindrop impact.

Good soil structure is just as important for sustained agricultural production as are adequate water and nutrients. A soil with open structure is dominated by large pores, drains rapidly and may dry out after rains before seedlings are properly established. The problem in this case is that water holding capacity is small in such a soil. On the other hand, a soil without large pores and many small pores suffers from lack of aeration, and easily becomes waterlogged. A good distribution of pore sizes throughout a soil is vitally important for proper growth of the crops. Within the soil crumb, structure formed due to aggregation a whole range of pore sizes exits, allowing air to penetrate and water to be retained and leaving passages through which roots can grow (Page, 1983). Soils with exceptionally good structure have very high hydraulic conductivity and thus have the potential to transport water and solutes beyond the rooting zone. In recent times increasing interest has developed in substances able to improve soil physical properties, particularly structure, such as organic and inorganic soil conditioners.

Rainfall plays an important role in affecting the soil structure in red soils of the SAT regions. If we consider structure as comprising of individual aggregates in a continuum of void space, then rainfall, will result in increasing the number of isolated voids in the soil matrix continuum. Breakdown of aggregates can occur due to raindrop impact and by percolating water. This leads to closure and isolation of the pores caused by the settling of the detached materials. High rainfall intensity results in decreasing the macroporosity of the soil and also changes the form of the structure. Changes in the structural features produced as a result of surface management may be relatively transient but they have a marked effect on many of the soil properties (Hamblin, 1982). It is not necessary to review the whole literature on this topic. Instead this review will focus on the way soil structure can be improved by surface management, and its relationships with moisture storage, deep percolation and solute movement.

2.1 Tillage and its effect on soil physical properties

2.1.1 Tillage and its effect on soil structure

The usual objective of tillage is to manipulate a soil to change its structure, strength or position in order to improve conditions for crop production. The direct mechanical action of tillage affects the soil space and can thereby strongly influence soil transmission properties and root growth. Tillage also increases the microbial activity by improved aeration, better distribution of bacterial and fungal hyphae and exposure of previously occluded organic matter to microbial attack. All these changes lead to a decrease in soil structural stability due to decrease in organic matter content by increased microbial activity (Gibbs and Reid, 1988). Tillage practices also influence many soil physical properties, structural stability being one of them. Structural stability in turn has an impact on a wide range of processes that influence rain water infiltration, moisture storage and transport of agro-chemicals.

Soil structure is very sensitive to human activity and the increasing intensity of cultivation on arable land leads to deterioration of soil structure (Watts *et al.*, 1996a). Various tillage practices over a period of years lead to deterioration of soil physical properties including soil structure. Intensive cultivation and monoculture cause deterioration of soil structure (Ketcheson, 1980). Similarly, cultivation of crops on land, previously in grass also leads to rapid deterioration of soil structural stability due to tillage, traffic and loss of soil organic matter. Structural deterioration also resulted in decreasing the crop yields considerably (Doyle and Hamlyn, 1960). This indicates that a stable soil structure is important to maintain the agricultural productivity.

Soil structure is influenced not only by tillage practices but also by water content, wetting, drying, roots and microbial biomass (Utomo and Dexter, 1982). The magnitude of influence of other factors on soil structure is determined by climatic conditions. Perfect *et al.* (1990a) have observed that the influence of climatic conditions on the aggregate stability, an index of soil structure, may be as large as or even larger than the variations caused by change in the tillage practices. In general, wet aggregate stability increased showing fluctuations in soil structural stability due to different cropping systems.

Change in cropping system also increases the response of soil structural stability to drying (Caron *et al.*,1992). Soil structural stability thus benefits from drying as it increases soil cohesion by favoring particle-to-particle contact, bond formation and adsorption of inorganic and organic compounds with a subsequent increase in stability. Increase in soil structural stability due to drying is important as it leaves the soil surface aggregates less vulnerable to the disruptive action of raindrops. Similar observations were made by Caron and Kay (1992) wherein stability of aggregates was found to increase on drying. This is of agronomic importance because it implies that a management-induced decrease in the moisture content of the soil could improve the stability of the aggregates. Management practices which enhance the particle to particle bonding will increase the stability of aggregates. Increase in structural stability will in turn reduce clay dispersion and the susceptibility of the soil to surface sealing.

Aggregate size distribution, an index of soil structure, is a dynamic property and it shows changes due to tillage practices as well as climate (Kay and Dexter, 1990). Large aggregates are more sensitive to moisture content and management practices. Dispersible clay was used as an index to study the influence of management practices on soil structural stability. An increase in mechanically dispersible clay with decreasing aggregate stability and increasing specific aggregate surface area was observed. Wet aggregate stability and dispersible clay both are strongly influenced by water content (Rasiah *et al.*, 1992). There was a linear decrease in wet aggregate stability with increasing water content and linear increase in dispersible clay with increasing water content. Wet aggregate stability was also found to increase with increase in clay and organic matter content. These studies provide an example of how Dispersible Clay (DC) can be used as an index of structural stability. Elsewhere Dispersible Clay was found to be a function of total clay content, organic matter content and moisture content at the time of sampling, all of which effect soil structure (Perfect *et al.*, 1990a; Pojasok and Kay, 1990).

Soil structural stability is the result of complex interactions between biological, chemical and physical factors. Alteration of structural stability can be achieved by manipulation of these factors. Stability will also depend on the management practices since it affects the quantity and characteristics of organic matter in the soil. Change in management practices influences both the surface area of aggregates exposed and the dispersibility of the clay. The presence of roots and microbial hyphae also stabilize the aggregates against breakdown. Cultivation sometimes speeds up the decomposition of these roots and cause the aggregates to become unstable (Tisdall and Oades, 1980). Different management practices will decrease the stability of macro aggregates.

Tillage affects the soil structural stability mainly through its influence on soil moisture (Kay, 1990; Perfect *et al.*, 1990b). Accumulation of organic matter occurs in soils where tillage is reduced to a minimum (zero-tillage). In a study conducted by Carter (1996) an increase in the microbial biomass was observed in soils subjected to zero tillage which resulted in greater stability of aggregates. Zero tillage offers environmental benefits over conventional tillage systems as it enhances organic matter accumulation on the surface and cause associated improvement in physical condition of surface soil. Oleschko *et al.* (1996) observed that cultivation has a significant impact on air dry aggregates, bulk density as well as soil microstructure and thus influences the soil structure.

2.1.2 Tillage and its effect on profile water storage

Tillage has a significant effect on soil water as it influences infiltration, runoff, evaporation and precipitation storage. Increase in water storage in soil profile stems from increased water infiltration (Dao, 1993). Zero tillage increases the water storage capacity of the soil thereby increasing the available water for crop growth (Larney and Lindwall, 1995). In their ten-year study, it was observed that maintenance of stubble on the surface enhanced the capacity to store soil water reserves under zero tillage but not under conventional tillage. The precipitation storage efficiency during fallow was found to be greater under minimum tillage than conventional cultivation. Greater infiltration and lower surface evaporation are the advantages associated with the soil structure created by non-inverting tillage (reduced tillage).

Tillage accompanied by crop residue management is important for recharging the soil profile to the maximum extent. Reduced tillage is an effective practice for improving soil water retention. Efficient soil water storage requires prevention of water use by weeds, which can be controlled mechanically or chemically. However, mechanical weed control hastens the evaporation of soil water by inverting the surface soil and exposing moist soil. Tillage also buries crop residues, which when retained on the surface as mulch, conserve soil water by reducing runoff and by retarding evaporation (Lopez *et al.*, 1996). On the other hand, mechanical disruption breaks the surface seals on Alfisols, improving infiltration, and induces surface roughness, providing temporary storage of runoff water. Radford *et al.* (1992) studied the impact of zero tillage with stubble mulch on soil water retention and found that zero tillage gave highest yields during dry years and stubble retention also increased the soil water content.

Rapid infiltration of rain water in the undisturbed soils compared to ploughed soils was observed, consequently water storage was higher under dry conditions in the direct-drilled soil (i.e. undisturbed soils) compared to ploughed soils (Goss *et al.*, 1978). Greater water content in the undisturbed soils is attributed to smaller volume of untilled soil occupied by pores which drain readily under gravity and also to mulch of plant debris left on the soil surface. Similar observations were made by Lafond *et al.* (1992) wherein zero and minimum tillage increased the profile water storage compared to conventional tillage. Jones *et al.* (1968) and Blevins *et al.* (1971) showed that minimum tillage resulted in higher soil water contents than conventional tillage practices, with residues of grasses and cereal crops being beneficial for increasing soil water contents. Other factors contributing to higher water contents were greater water infiltration and lower evaporation resulting from crop residues maintained on the soil surfaces by the minimum tillage cropping practices.

Volumetric water content is usually greater in soils maintained under no-tillage than under conventional tillage systems. Blevins *et al.* (1971) attributed this increased water storage to reduced evaporation and greater ability to store water under zero tillage, resulting in greater water reserve. The increased capability to store soil water can be attributed to the rearrangement of the pore size distribution and residue cover. Conservation of the soil water may carry the no-till crop through short drought periods without development of severe moisture stress.

2.1.3 Tillage and its effect on deep percolation and infiltration

A known benefit of cultivation is increased infiltration rates during subsequent irrigation or precipitation. Cultivation results in temporary increase in pore space and leads to improved infiltration which also improves the saturated hydraulic conductivity and would increase the deep percolation (Poletika and Jury, 1994). Cultivation may reduce the flow of water by minimizing the role of the largest pores in the transport processes. One interpretation from this is that manipulation of the top 25 mm of the soil profile produces important changes in the flow pattern that can be measured at depths of 0.3 m and below. This indicates that surface management of soils would definitely affect deep percolation of water.

The surface layer of arable soils that is deformed by surface management practices thus plays a significant role in the behavior of soil water, not only within the top 0-10 cm layer, but also through its influence upon the deeper portions of the soil profile that accommodate plant roots (2 m). Tillage influences the pore geometry of the top soil and in turn affects the soil water behavior and its movement through the soil profile leading to deep percolation. Infiltration of rain water into the soil is a basic and important process controlling directly surface runoff, soil erosion, soil water storage and deep percolation. Infiltration in turn depends on various factors such as surface texture, aggregate stability, bulk density, porosity, surface roughness etc. Knowledge of the disposition of water after it has been applied on the surface is important in determining the amount of water available for crop use and evaporation and the amount lost to deep percolation beyond the root zone. It is important to know how much water passes through the root zone to determine deep percolation, for which the flux of water below the root zone must be known. Water moves through the soil matrix by traveling through macropores and cracks, as it tries to move through the area of least resistance to its flow. The inherent variability of the soil also effects the movement of water and deep percolation beyond the rooting zone. An insight into the influence of structure on soil processes should be gained from an examination of soil water behavior in the same soil manipulated to produce different structures.

Distribution of water down the first 70 cm of the profile reflects the surface soil differences. Ploughed treatments were found to have maximum water content in the deeper layers of the soil profile during the early part of the rainy season. Therefore, it was concluded that differences in surface management treatments will affect the soil and crop water status. As a result of different tillage treatments, differences were observed in pore size distribution, total porosity, and pore geometry which had a considerable effect on measured and observed aspects of water movement and retention not only in the topsoil but at deeper layers also, leading to deep percolation of water (Hamblin and Tennant, 1981). Improvement in aggregate stability resulted in increasing the infiltration rate by 18%. Clay content, silt content, aggregate stability and dispersion coefficient jointly contribute to 87% increase in infiltration which in turn leads to deep percolation (Mathan and Mahendran, 1994).

Infiltration is a consequence of porosity and it also influences porosity by detaching, transporting and relocating soil particles through its mechanical action. Change in porosity leads to change in water movement through the soil profile. In sandy soils the decrease in porosity was less and it was maximum in soils having higher clay content. This invariably leads to decrease in water movement through soil profile and deep percolation (Painuli and Pagliai, 1996). Low water holding capacity of the SAT Alfisols can be attributed to the fact that little water is transmitted to deeper layers of the profile due to poor porosity as a result of seal formation. Gravel was found to play a significant role in causing variability in the saturated hydraulic conductivity of SAT Alfisols (Bonsu and Laryea, 1989). The total porosity is usually low in the gravelly murrum layer therefore, it has a significant impact on the water transmission properties of the soil at deeper layers.

Important aspects of tillage in relation to infiltration are development of surface crusts and stability of surface roughness and plow layer porosity. Tillage increases infiltration when it loosens surface crusts, disrupts dense soil layers or provides surface depressions for temporary storage of water. Unger (1992) observed an increase in infiltration with tillage on soils having low crop residues on the surface. Tillage reduces surface residue, increases surface porosity, surface roughness and weakens soil structure. Tillage creates voids leading to preferential water flow paths through the soil profile increasing the water intake rate. Hence, it may improve permeability of the soils initially but as the season advances it causes slumping and closure of the soil pores thus reducing the permeability. This affects the deep percolation and water movement in the soil profile. Freebairn *et al.* (1989) observed that in the absence of crust, the soil is highly permeable (>200 mm h^{-1}) while in surface crusted soil the permeability is as low as 10 mm h^{-1}.

Lindstrom and Onstad (1984) observed that no-till system forms an undesirable surface condition characterized by high bulk density, high penetration resistance and low hydraulic conductivity thus promoting rapid water runoff. Infiltration rates, however, may be high with a no-till system because the surface is stable and macropores develop that can transport large quantities of water. An effective way to reduce runoff losses is to establish a soil condition with a high infiltration rate which can be maintained even during periods of high-intensity rainstorms.

Primary tillage operations increase infiltration by increasing soil porosity and establishing channels and voids in the surface layer of soil that conduct water into the soil profile. Whereas secondary tillage operations reduce soil porosity to some extent and break the continuity of channels and fill most large voids. Breakdown of soil aggregates occurs due to tillage that reduces soil porosity by filling interaggregate voids. Sealing of surface soil also occurs which leads to a decline in the infiltration rate. The dominant processes for formation of porosity differ between tilled and untilled cropping systems. Tilled cropping system pores are formed by rearrangement of the solid phase by the tillage tools. Pores in the untilled cropping system are formed by biological activity of microorganisms, earthworms and roots. As a result, pore size distribution and pore continuity vary between these two types of surface management (Benjamin, 1993). The no-till management showed greater water movement due to larger pores leading to greater infiltration and deep percolation of rain water.

Rice (1975) in a study observed the diurnal and seasonal soil water uptake and water flux at 120 cm depth. The estimated amount of water lost to deep percolation below 120 cm was 0.15 cm or 22% of the water uptake by crop roots. Warrick *et al.* (1977) observed a decrease in the flux of water at 180 cm depth with time. At t=0, wherein water was pounded on the surface, the mean flux value was 31.9 cm day^{-1} which decreased to 0.40 cm day^{-1} at t=10. There was also a decrease in volumetric water content with time. This indicates that during heavy rains loss of water through deep percolation increases due to increase in water flux at deeper layers of the soil profile leading to deep percolation losses.

The distribution and movement of water within the soil profile are important from the stand point of providing water to plant roots. Stone *et al.* (1973a) calculated the water flux at various depth layers using hydraulic potential gradients and determined the hydraulic conductivity vs soil water content relationships. During the 31 day study period 6.0 cm of water was lost from the 150 cm soil profile by flux below the root zone. This illustrates the importance of considering water loss due to deep percolation or flux below the root zone even in crop situations.

2.1.4 Tillage and its effect on solute movement

Solute movement occurs in the soil during leaching, crop irrigation, reclamation of soils and other similar processes. This movement determines the presence or absence of beneficial or detrimental solutes in the soil profile. The magnitude and degree of variation of solute movement in a soil depends on various soil factors, the most important factor being soil structure. Improvement in soil structure resulting from various tillage practices leads to increased infiltration and water movement into the soil. This in turn influences the movement of solutes within the soil and its loss beyond the root zone. Solute movement mostly relates to the movement of nitrates, which being negatively charged are easily lost due to leaching along with the percolating water. Chloride and bromide are used as tracers to study nitrate movement because they move through soil similar to nitrates. Bromide is more useful as it is seldom encountered in significant concentration in the soil (Bicki and Guo, 1991; Silvertooth *et al.*, 1992). Another factor which effects the solute distribution within a soil profile is the quantity and distribution of rainfall infiltration. Soils having higher hydraulic conductivity result in greater bromide movement through the soil profile to lower depths in high intensity rainfall (Bruce *et al.*, 1985).

The principal mechanisms of solute transfer in the soil are convection (transportation by the moving liquid phase) and diffusion. The convective transfer of solutes can be studied most conveniently in the absence of interfering chemical processes. Different tillage practices result in increased infiltration rate of water, decreased water evaporation and surface runoff and increased water content in the soil profile (Beven and Germann, 1982). Increased infiltration and permeability of soils under different tillage will also increase the potential for groundwater contamination from movement of agricultural chemicals through the soil beyond the root zone. Rapid movement of agro-chemicals and nitrates below the root zone has been attributed to macropore flow which occurs following high intensity storms. Infiltration of water in no-till soils is attributed to the movement of water through large, surface-connected, continuous voids.

Studies on solute movement through the soil profile, as stated earlier, employ tracers such as chloride (Cl^-) and bromide (Br^-) anions to evaluate water and chemical movement. The depth of penetration of the tracer in the soil profile and its concentration at various depths is used as a measure to determine the effect of surface management on the movement of solutes in the soil profile as was used in our study also. This approach relies upon the concept of flow of solutes along with water within the soil profile. Usually bromide is preferred over chloride as an indicator of nitrate movement in the soil because its native concentration in soils is very low and thus movements of even small amounts may be detected (Smith and Davis, 1974). Observations made by Onken *et al.* (1977) also indicate that nitrate and bromide move similarly in soils under field conditions. But Smith and Davis (1974) observed that the movement of bromide relative to that of nitrate is identical in the subsoils and variable in surface soils. Differences in the apparent relative movement of the two anions is attributed to microbial activity involving nitrates on the surface. In fact, this is a case of convection with reaction (for nitrates), compared with convection alone (for bromide). Convection with reaction (this time chemical) is the usual case with divalent anions (e.g. SO_4^{-2}) or trivalent (e.g. PO_4^{-3}). Even then bromide has utility for following potential path of nitrate movement through soils.

Tyler and Thomas (1977) observed greater losses of nitrate nitrogen and chloride, used as a tracer of nitrate ion, under the no-tillage system compared to conventional tillage. Concentration of nitrate and chloride ions in the leachate indicates that these mobile, surface applied anions can be washed much deeper into the soil along with water moving through soil cracks and channels after intense rains. The loss of nitrate nitrogen was greater under no-tillage than under conventional tillage.

Similarly under high intensity rainfall greater bromide movement occurred in the soil profile managed under continuous long-term no till compared to other tillage techniques namely mouldboard plow, chisel plow, disk plow and para-till. These reports indicate that bromide movement in the soil involves an interaction between tillage system and rainfall intensity. Greater bromide movement in the no-till management was attributed to higher hydraulic conductivity and macropore continuity observed in this system (Bicki and Guo, 1991).

Water and nutrient movement through field soils is of great importance in relation to plant uptake and the potential pollution of subsurface ground water. Being negatively charged, nitrates are more readily lost due to leaching within the soil profile and the presence of large soil pores between structural units will also influence ion movement of nitrates and chlorides. This indicates that improvement in aggregation due to surface management will lead to increased solute movement through the soil profile. Both nitrates and chlorides moved vertically with water through the soil profile (Shuford *et al.*, 1977). This is not the case always, the anions can also move laterally in duplex soils.

Deeper and more rapid movement of bromide is usually observed in the non-tilled soil compared to tilled soil. The exception would be when a deeper layer limits the flow. The difference in solute movement in the tilled and non-tilled soil can be attributed to the improved soil structure in the non-tilled surface soil (Fleming and Butters, 1995). Tillage practices directly affect the soil water movement and leaching characteristics of the soil by disturbing the macropores in the upper 30 cm of the soil profile. No till maintained a lower nitrate level in the upper 0-30 cm layer after two rains compared to the moldboard ploughed plots which can be attributed to the movement of nitrates beyond 30 cm in the no till soil (Kanwar *et al.*, 1985).

Water tends to infiltrate the soil at a greater rate under conservation tillage than flow-tillage due to maintenance of vertical macropores sequence from microbial activity, decayed root channel cracks etc. in conservation tillage. This indicates that the movement of agro-chemicals through soil is affected by soil tillage practices. Rapid movement of agrochemicals through soil macropores has been identified as the major pathway. Starr and Glotfelty (1990) observed movement of bromide is vitally important for having a good water-holding capacity as well as proper aeration, both being essential requirements of the crops. Scientists have long sought for an effective substitute for organic matter in the shape of synthetic materials which can be used to improve soil structure. The use of synthetic polymers for increasing the stability of soil aggregates has prompted a number of investigations on their effect in stabilizing the aggregates and influencing the various soil physical and chemical properties. These studies have provided basic information on the type of synthetic soil conditioner which can be used to stabilize the existing soil aggregates thereby improving the soil structure (Stefanson, 1973). Soil conditioners have potential importance in the arid and semi arid regions of the world where there is an awareness of implication of soil erosion and inefficient water use. Soil conditioning implies improvement of soil's physical properties, thus permitting more effective utilization of soil and water resources. Such materials can favorably modify soil water relationships especially retention and transmissions.

Change in soil structure is observed due to fluctuation in the levels of organic stabilizing constituents. Among biological amendments which influence the stability of aggregates, organic matter is one of the most important constituents. Growing of grasses will also lead to structural improvement as a result of physical enmeshment of roots and hyphae. The effect of live grass on stability of aggregates may also be due to release of organic matter into the soil because of presence of decomposing roots and living roots (Tisdall and Oades, 1979). The increase in stability is partly due to polysaccharides and partly due to organic polymers bound to the surface of clay particles. Structural stability is effected differently by different management practices.

The root exudates effect the structural stability due to chelation with iron and aluminium which are involved in mineral-metal-organic matter linkage. Root exudates also increase the wet aggregate stability and decrease dispersible clay content (Pojasok and Kay, 1990). Different materials in the rhizosphere thus can have different effects on structural stability. The rhizosphere of actively growing roots contains lipids, enzymes, cellular material from the root and microbial biomass, all of which act as stabilizing materials and increase the stability of aggregates. Soil structural stability is strongly influenced by the content of organic matter (Chaney and Swift, 1984). Soil carbohydrates are the organic constituents which are most closely involved in aggregation (Sparling and Cheshire, 1985). They are more closely related with aggregate stability than the total soil organic matter content.

Haynes and Francis (1993) observed higher content of sugars of microbial origin in the carbohydrate fraction which is involved in aggregate stability. In another study Ball et al. (1996) observed higher concentration of organic carbon and carbohydrates near the surface in zero tillage soils but these were uniformly distributed with depth in the ploughed soil. Zero tilled soil had greater structural stability compared to ploughed soil indicating a positive correlation with total carbon and total carbohydrates. From this study it can be concluded that greater stability of the soil in zero tillage is mainly due to presence of large amount of carbohydrates on the surface. Carter (1992) also observed a significant increase in the mean weight diameter and aggregation index (indices of soil structural stability) of soils having high organic carbon and microbial biomass. These studies indicate that structural stability increases with increase in organic matter and microbial biomass.

Organic material released by roots stabilizes the aggregates providing a source of energy for microorganisms in the rhizosphere which in turn produce aggregate stabilizing materials. Part of increase in structural stability is due to polysaccharides and part to organic polymers bound to the surface of clay particles by polyvalent cations (Tisdall and Oades, 1979). Filamentous fungi are also capable of binding particles of soil into stable aggregates because particles of soil adhere to the mucilage on the surface of the hyphae.

Soil organic matter improves soil resistance to deformation therefore, even a small change in organic matter can influence the stability of aggregates to a great extent. Carter (1992) observed that increase in the level of soil organic matter resulted in increasing the aggregate stability. A linear relationship was observed between organic carbon and mean weight diameter (MWD), an index of soil structure.

Application of aggregating agents like organic matter, $Fe(OH)_3$, $CaCO_3$ resulted in increasing the aggregation due to flocculation as well as bridging with cations to form organometallic complexes. Cations of Fe and Ca help to stabilize aggregates and also improve the bulk density and hydraulic conductivity of the soil. Bulk density decreased due to increase in aggregation and porosity which resulted in increased hydraulic conductivity (Sarma and Das, 1996).

Mechanism of formation of soil aggregates is one of the most important phases of the soil-structure problem and the stability of aggregates is a major factor involved in forming and preserving good structural relationships in soil. Reuhewein and Ward (1981) observed that synthetic polyelectrolytes provide an excellent means of stabilizing aggregation in soils. Synthetic polymers not only improve soil structure but also the soil permeability. PVA is a common polymer used experimentally for soil structural improvement. It is a linear uncharged polymer formed by the hydrolysis of polyvinyl acetate. Application of PVA leads to considerably improved aggregate stability in soil systems. PVA gets adsorbed on clays like gibbsite and geothite and forms aggregation resulting in good structure (Kavanagh *et al.*, 1976). Similar observations were made by other investigators such as Greenland, (1963), Emerson and Raupach (1964), and Williams *et al.* (1966).

2.2.2 Soil amendments and their effect on profile water storage

Soil conditioning implies improvement of the soil's physical properties, thus permitting more effective utilization of soil and water resources. Soluble conditioners undergo physico-chemical reactions with soil constituents, especially the clay fraction. Upon drying, an insoluble irreversible matrix is formed which results in improved aggregation, porosity and hydraulic conductivity. Nimah *et al.* (1983) observed that applications of conditioners to the soil resulted in improving aggregation, decreasing bulk density and improving porosity. These factors contribute to an improvement in permeability which increases the movement of water through the soil profile thus leading to increased profile water storage.

Abbott and McKenzie (1986) observed that application of gypsum on soil surface improves the structure of some hard-setting soils thereby increasing the soil water storage. Doyle *et al.* (1980) also observed an improvement in drainage due to application of gypsum this resulted in increased crop establishment thereby reducing the risk of soil compaction. Doyle and Hamlyn (1960) reported an increase in water stable aggregate and porosity by application of VAMA, a synthetic soil conditioner. This in turn resulted in increasing the profile water storage and yield of crops. Application of VAMA increased the yields significantly particularly in soils whose physical properties showed greatest improvement due to VAMA.

Sen *et al.* (1995) observed that application of synthetic conditioners suppressed evaporation due to change in transmissivity of the surface soil as a result of stabilization of aggregates and thus resulted in increasing the profile water storage. Polyelectrolyte soil conditioners increase the supply of available water to the plants. Use of these synthetic conditioners enhances the infiltration of rain water into the soil and encourages deeper plant root penetration thus enabling plants to extract water from a greater volume of soil. They also increase the profile water storage capacity of the soil due to enhanced infiltration (Peters *et al.*, 1953).

Williams *et al.* (1966) used poly(vinyl alcohol) (PVA) and determined its effect on soil aggregation, because it was thought that an uncharged polymer would be able to penetrate more readily into the negatively charged porous structure of soil aggregates than would either a negatively or a positively charged polymer. PVA adsorption is more if size of aggregating particles is small inducing greater aggregate stability. Natural neutral polymers are responsible for greater stabilizing of soil aggregates. PVA is one such uncharged synthetic organic polymer involved in the stabilization of soil aggregation. The attachment between polymer and clay surface is probably by hydrogen bonding between the hydroxyl groups of PVA and oxygen on the clay surface (Emerson, 1956). This would lead to increased infiltration and increased water storage in the soil profile. Stefanson (1973) also observed that application of PVA to the soil enhances the stability of pores and prevents the blocking of these pores by detached soil materials. Thus PVA has been shown as an effective stabilizer of surface soils. It enhanced the capacity of the soils to absorb rainfall and decreased runoff, thereby increasing the water storage capacity of the soil.

The stability of aggregates can be increased by use of synthetic soil conditioners such as poly (vinyl alcohol) (PVA) which offers a rapid means of stabilizing aggregates near the surface of the soil against various mechanisms of disruptions. Oades (1976) observed that application of PVA stabilized the surface structure and prevented crust formation. Rainfall infiltration was improved in soils treated with PVA. Increased infiltration also led to an increase in water storage and about 12% increase in water available to wheat crop was observed. Botha *et al.*, (1981) also observed that incorporation of PVA in fine sandy soils resulted in formation of stable aggregates. PVA enhances the aggregation of soil particles and the stability of aggregates as a result it improves rain water movement into the soil.

Application of Hygromull (a urea formaldehyde soil conditioner) improved the hydraulic conductivity by increasing the porosity of clay soils whereas Agrosil LR (conditioner) decreased the hydraulic conductivity of sandy soils and improved the aggregation in these soils which lead to an increase in water storage (Nimah *et al.*, 1983). Painuli and Pagliai (1990) observed that polyvinyl alcohol and dextran (soil conditioners) improved the soil structure considerably and soils treated with these conditioners produced numerous fine cracks, smaller clods and imparted greater stability against water which is important in agriculture. Profile water storage was enhanced due to increase in rain water infiltration as a result of improved aggregation in soils treated with PVA and dextran.

In another study conducted by Painuli *et al.* (1990) an increase in the porosity was observed due to PVA application. PVA was more efficient in improving the continuity of the pore system than dextran, consequently it also increased rain water infiltration and water storage. PVA and dextran also increased the water retention against gravity. Application of soil conditioner (Krilium) resulted in a marked increase in the yield of cauliflower due to improvement in soil structural stability which also resulted in increasing the available water through improved infiltration (Low, 1973).

Botha *et al.* (1981) observed that PVA improved soil aggregation without altering other soil physical properties. Most effective method of application was in solution form to a wet soil which gave a better degree of aggregation. The permeable film of soil conditioner, in addition to stabilising the soil, was found to reduce runoff and thus increase water infiltration and water storage capacity of the soil. PVA enhances the stabilization of soil thus increasing the rate of emergence of wheat seedlings (Stefanson, 1974).

Application of PVA improved the pore space by improving aggregation thus resulting in improved rainfall infiltration and water storage in the soil. Application of PVA was also found to change the specific surface area and pore size distribution due to adsorption by aggregates, this results in strengthening the aggregates and prevents their breakdown due to external disruptive forces (Williams *et al.*, 1967a). Increasing the amount of PVA adsorbed on clay surfaces results in increasing the tensile strength of aggregates (Williams *et al.*, 1967b). But as water content increased there was a decrease in the tensile strength of aggregates of the soil-PVA complexes.

Hemyari and Nofziger (1981) observed that application of super slurper, (hydrolyzed starch polyacrylonitrile graft copolymer commonly called "super slurper") a soil conditioner, decreased the crust strength and increased water infiltration and retention. Loamy sand and sandy loam soils treated with super slurper retained more water than the untreated soil. Infiltration rate was also reduced for clay loam and loamy sand soils treated with 0.4% super slurper.

Conserving rainfall in the soil profile is very important for growing successful crop in the SAT regions. Aujla and Cheema (1983) observed that use of evaporation retardants, straw mulch, herbicide as well as tillage are useful in conserving more soil moisture in the 180 cm deep soil profile. These moisture conservation practices improved plant stand, profile water use and yield of rainfed chickpea. Polythene and straw mulch showed greatest increase in profile water storage leading to higher yields compared to the other treatments. Tillage which forms a fine mulch of soil particles was very effective in maintaining soil moisture.

2.2.3 Soil amendments and their effect on deep percolation and infiltration

One of the undesired important consequence of modern farming is the deterioration of soil structure. The response to crops to water and fertilizer is much less in structurally deteriorated soils. In recent times the emphasis is on maintaining a good soil structure and the use of conditioners is one promising approach in order to attain this objective. Pores ranging from 0.5 to 50 μm diameter are the storage pores, and pores ranging from 50-500 μm are transmission pores. Painuli *et al.* (1990 observed an increase in the elongated, transmission pores in soils treated with PVA and dext PVA and dextran also improved other physical properties of the soil such as hydraulic condu water retention, porosity, pore shape, pore size distribution and pore continuity. These parameters are fundamental in maintaining a good soil structure and consequently they regulate the water movement in the soil. Improvement in water movement also increases the deep percolation losses of water beyond the rooting zone.

Treatment of soils with conditioner resulted in 1.5 to 3 fold increase in soil-water diffusivity over the whole range of volumetric water contents as was observed by Kijne (1967). Rate of movement of wetting front also increased as a result of treatment with soil conditioners. Both Krilium and PVA have a stabilizing influence on the soil structure which in turn improves the water conducting qualities of the soil. A higher rate of infiltration was observed in PVA treated soils compared to Krilium. This indicates that PVA treatment is more effective in stabilizing the soil particles and the pores between them compared to Krilium. Therefore, PVA due to its mode of attachment, is found most effective in influencing the water conducting properties of soils.

PVA application increases cracking and hence the movement of water into the soil profile in clay soils is also increased. The addition of these neutral organic conditioners, modify the wettability of the soil and therefore the interactions with water are also enhanced leading to improved transport of water in the soil profile. Both PVA and dextran enhance the stability of soil structural aggregates against water by resisting crusting. This results in improved infiltration and deep percolation losses of water which are also enhanced (Painuli and Pagliai, 1990).

2.2.4 Soil amendments and their effect on solute movement

Bromide is usually present in soils at very low concentration (Bowman, 1984) and is not subject to chemical and biological transformation. Therefore, movement of bromide in soils has been used widely to evaluate nitrate mobility because of the similarity of nitrate and bromide mobility (Jones and Schuab, 1993; Silvertooth *et al.*, 1992). Clays and other soluble and insoluble products eluviate from the surface soil to lower layers in the soil profile and thus effect the movement of solutes since they block the pores.

In mechanized agriculture, particularly in developed countries, use of heavy machinery in fields changes the soil pore geometry and pore size distribution which in turn influences solute movement. Bulk density and pore size distribution influence both water and bromide transport through the soils. Movement of bromide is more rapid through uniform-sized and larger pores which may occur in soils treated with conditioners (Smith *et al.*, 1995). Very little literature is available on the study of the effect of conditioners on solute movement. Most of the work on conditioners relates to improvement in structural stability and its effect on water movement, hydraulic conductivity, infiltration etc. and therefore work on the effect of conditioners on solute movement is less. Much information on the effect of tillage practices on solute movement is available as can be observed from the literature reviewed in section 2.1.3.

2.3 Crop residue and its effect on soil physical properties

2.3.1 Crop residue and its effect on soil structure

Crop residues at the soil surface will protect the soil from excessive radiation and rainfall energy, retain infiltration capacity by retarding the formation of surface seal from the impact of rainfall and provide a conduit during saturated conditions where water can be conducted into and through the soil. However incorporation of crop residues is not as effective as leaving the residue on the surface where it decomposes less rapidly and continues to replenish the cementing products for a longer period (Dubey *et al.*, 1995). Skidmore *et al.* (1986) observed that incorporation of residue had less influence on soil physical properties and did not affect the wet aggregate stability and porosity as compared to surface maintenance of residue.

Straw management tends to have a greater impact on soil properties than does tillage management. Straw management has been reported to influence aggregate stability thus enhancing the water infiltration into the soil (Sharratt, 1996). Black (1973) reported a decrease in bulk density as the amount of straw applied on soil surface increased. The decrease in bulk density is an indication of improved soil structural features. This is because bulk density influences porosity which in turn is effected by soil structural arrangement. Edwards *et al.* (1988) also observed that presence of macropores created by earthworms in the no-till soils, where the surface residue has been retained, results in improving the soil structure by enhancing the structural stability and aggregation. This also leads to sustained high infiltration rates due to improved soil structure as the macropores are important channels for rapidly infiltrating water.

2.3.2 Crop residue and its effect on profile water storage

Maintaining crop residue on the surface is an effective method of conserving moisture and it also improves infiltration and reduces runoff. Organic debris left on the surface of the soil due to crop residue also has many physical, chemical and biological effects which are beneficial to crops (Duley and Russel, 1939). Lafond *et al.* (1992) in their studies observed that maintenance of residue at the soil surface improved water infiltration and reduced evaporation thereby increasing water storage in the soil profile. Placing of wheat straw beneath the surface was also found to reduce the water loss and thus enhance water stored in the soil profile but the effect was only for a short duration (Sembiring *et al.*, 1995).

Continuous stubble retention was found to increase the soil water content and soil water extraction during crop growth thus increasing dry matter production and soil water accumulation during fallow and reducing runoff (Radford *et al.*, 1992). Smika and Unger (1986) stated that additional water for crop use can be provided by increasing infiltration and reducing evaporation by using residue management practices. Surface residues enhance infiltration and decrease runoff. It affects not only infiltration and redistribution of water but also deep percolation. Because infiltration is increased more water will be stored in the soil, provided the soil has the capacity to store the additional water. Otherwise, the excess water is lost through deep percolation and runoff.

Tanaka (1985) observed that management of residue on the soil surface can reduce evaporation by decreasing air movement immediately above the soil, changing albedo and insulating the soil surface thereby increasing soil water storage during fallow. Surface residue can be maintained by reducing mechanical tillage and adopting chemical fallow, i.e. use of herbicides to control weeds. This results in greater portion of the residue being maintained above the soil surface and therefore enhances the water storage capacity than stubble - mulch fallow (Fenster and Peterson, 1979; Good and Smika, 1978).

Unger (1978) reported that maintaining straw mulch on the surface increased the water storage and also increased the yield of sorghum. These results indicate that presence of straw mulch increases water storage during fallow compared with no residues. In another study Unger (1976) reported an increase in the amount of water accumulated in soils with increase in the rate of surface residue and water application. Maintenance of mulch on the soil surface increases the soil profile water storage for the subsequent wheat crop as was observed by Dubey *et al.* (1995). Mulching also increased the yield of wheat crop, and mulch application left more residual water in the soil during the post monsoon period.

Decreased water loss is a consequence of a reduction in the turbulent transfer of water vapor to the atmosphere, decreased capillary continuity, capillary flow and water-holding capacity of soil surface layers. Any kind of layer or profile discontinuity will decrease water movement, and elimination of tillage enhances precipitation storage (Dao, 1993). In areas where soils have low water-holding capacity, additional water for crop use can be provided by increasing infiltration and reducing evaporation. Stubble management of surface soil can reduce runoff and retard flow across the surface. This results in increasing infiltration, and more water is stored in the soil, provided the soil has the capacity to store the additional water.

2.3.3 Crop residue and its effect on deep percolation and infiltration

Crop residues retained on the soil surface enhances infiltration by dissipating raindrop energy, thus minimizing aggregate dispersion and surface sealing, and retarding surface water flow, thus providing more time for infiltration. Surface management and crop residue management practices alter the pattern of water entry into the soil. As these practices yield different soil surface roughness, surface residue distribution, organic carbon concentration, aggregate-size distribution and aggregate stability, they will in turn influence water infiltration and deep percolation (Unger, 1992).

Infiltration was higher in the more porous no-till soil surface than ploughed soil surface, and remained unchanged throughout the season thus reducing the potential for runoff losses of water because of maintenance of residue on the surface in the no till soil. In the no-till soil, reduction in soil seal and crust formation enhanced water infiltration resulting in increased volumetric-water holding capacity and precipitation storage. It also leads to increased infiltration and finally deep percolation of water (Dao, 1993).

Pikul *et al.* (1990) also observed that a para-plowed stubble mulch treatment had less decrease in macroporosity and more water infiltration and storage in the soil profile than a chiseled stubble mulch treatment. This indicates that maintenance of stubble mulch improved the water storage in the soil profile by improving the surface soil structure and infiltration and reduced the runoff.

2.3.4 Crop residue and its effect on solute movement

Soil surface aggregates and macropores which are influenced by surface residue have the potential to greatly influence the transport of surface-applied agricultural chemicals in soil and to groundwater. The flow of water through soil is often considered as bulk movement which can be described by Darcy's law (Nielsen and Bigger, 1961). For the purpose of defining movement of solutes dissolved in this water, which may not move with the water front, it is important to measure such movement using tracers. The tracer movement through the soil also gives information regarding the movement of water. Day and Forsythe (1957) concluded that the movement of dissolved solutes in the soil moisture stream cannot be determined adequately from the average fluid velocity. Hydrodynamic dispersion is also an important process through which solutes move and which should be taken into account when dealing with solute movement.

Heathman *et al.* (1995) observed that presence of macropores in residue-covered soils allowed bromide ions to move down below the main wetting front. This was explained as formation of aggregates on the surface due to surface residue which increased the amount of bromide transferred to the macropore flow. These studies suggest that promoting surface soil aggregation will cause leaching of surface-applied agricultural chemicals especially where surface runoff is not a problem such as under no-till or where residues cover the surface and in soils with high infiltration capacity.

Results of experiments conducted by Thomas *et al.* (1973) show that a large proportion of nitrate was lost from the top 90 cm of soil under mulch treatment (killed-sod mulch plot) but that no nitrate was lost from the conventionally-tilled soil. The loss of nitrate was attributed to lower evaporation from the mulched soil causing deeper penetration of water and nitrates through larger pores in the wetter, mulched soil. Hence rainfall resulted in removing nearly half of the nitrate from the mulched soil due to deep penetration compared to conventionally tilled soil.

Similarly Watts and Hall (1996) observed greater herbicide loss due to leaching in mulch tillage than conventional tillage. Therefore, any management of the surface which enhances surface roughness and increases infiltration, as is the case in mulched soils, will decrease runoff losses of chemicals and increase the movement of such chemicals through the soil profile.

There is strong relationship between surface management practices and the abundance of macropores which influence the infiltration capacity of the soil. Germann *et al.* (1984) observed that bromide had moved deeper into soil profile, along with water, in soils having a very good macropore system, as in a non-ploughed soil with surface mulch. Kissel *et al.* (1973) also observed rapid movement of chlorides through large connected pores which can be observed in soils subjected to minimum tillage having surface residue. In a soil with good structure, the large pores play a major role in conducting the percolating soil water and solutes.

Mulching with killed-sod resulted in removing essentially all of the chloride and nitrate from the 90 cm soil profile. These results suggest that nitrate losses are commonly due to leaching in mulched soils whereas, in conventionally tilled soil the loss of nitrate was only half of that of mulched treatment. This indicates that improved infiltration due to mulching can lead to greater solute movement and leaching losses of nitrates (McMohan and Thomas, 1976).

2.4 Surface roughness and its effect on soil physical properties

2.4.1 Surface roughness and its effect on profile water storage, deep percolation and infiltration

Surface roughness is a means of improving in-situ soil and water conservation. It can affect the soil physical properties and have a direct bearing on infiltration of rain water and its storage in the soil profile. Changes in soil physical properties that occur as a result of surface roughness include the improvement in the intake capacity of the soil and reduced runoff, both of which increase the moisture storage in the soil profile. However, quantitative information on the effect of surface roughness on soil physical properties such as water movement, solute movement, deep percolation, infiltration etc., is scarce.

An important means to increase surface roughness is by making scoops or pits. Scoops (pitting), or shallow pits made in the soil, store most of the rain in the depressions thus reducing runoff and soil loss. For example, scoops reduced seasonal runoff by 67% (ICRISAT, 1991) thus increasing water storage in the soil. Scoops were also found to increase crop yields significantly compared to flat cultivation which can be attributed to the additional water stored in the soil profile. Scoops were found to be more stable during high intensity rainfall compared to tied ridges.

Soil structure has a marked influence on the amount of water that infiltrates into a soil profile. This is important in Alfisols where the surface is prone to sealing and crusting. Pathak and Laryea (1991) observed that scoops were effective in reducing runoff and increasing infiltration and the scoops were found to have greater stability than tied ridges. A decrease in the scoop capacity occurred as the season progressed, the decrease being more in bare soil than in cropped soil. Studies on scoops and their effect on profile water storage, deep percolation and solute movement are very few. Mostly the studies relate to runoff and soil loss and do not refer to the amount of water stored in the soil profile.

Surface roughness can also be used as a means to improve the profile water storage of the soil and increase the infiltration leading to deep percolation. Pathak and Laryea (1995) used scoops as a means of improving the profile water storage. The main effect came from the increased time for water to infiltrate into the soil. This led to increased storage of water in the soil profile and also to deep percolation of water below the root zone. The main advantage of scoops over flat cultivation occurred during early part of the crop growing season. This was due to the soil being more prone to surface crusting and sealing because of sparse vegetation cover during this period, this being more evident in the flat cultivation.

2.4.2 Surface roughness and its effect on solute movement

The distribution and movement of water within the soil profile are important from the standpoint of solute transport and providing water to plant roots. Surface roughness improves infiltration leading to deep percolation of water, which is important in determining the depth to which solutes will move in the soil. Studies on the processes involved in water and solute movement due to deep percolation as a result surface roughness is important because of contamination of groundwater by nitrates and pesticides and off-site pollution of the environment due to erosion. With downward flow of water in the soil as a result of surface roughness, there can be an associated downward movement of water-soluble chemicals. The flow of water transports salts into the root zone (Kanwar *et al.*, 1985).

Ahuja *et al.* (1983) observed that increasing surface roughness will also increase the amount of a mobile soil chemical released to runoff. Increasing surface roughness also delayed runoff and increased infiltration by 2.5 times compared with the control, and yet the bromide concentration in runoff was high indicating that surface roughness can also increase the loss of chemicals through runoff. This indicates that increasing surface roughness enhances the macropores and results in greater leaching losses and solute movement compared to the no-till system. Granovsky *et al.* (1993) also observed that the no-till treatment transmitted larger volumes of water and chemicals indicating greater solute movement in these soils. This is attributed to the development of a stable macropore network in the no-till soil due to uninterrupted earthworm and microbial activity and the waterflow through these macropores is a possible mechanism for accelerated transport of chemicals (Thomas and Phillips, 1979).

2.5 Crop effect on profile water storage, deep percolation and infiltration

Another factor which is important in determining water content in soil profile is the role of the plant canopy in redistribution of rain water. Plants may act as "reverse umbrellas" which intercept the falling water and direct it inwards to the stem or trunk (Clothier, 1988). Plants may also create and maintain many of the large, continuous macropores that are easily exploited by free surface water. All agricultural crops are involved in directing water to the soil surface.

Zhai *et al.* (1990) observed that soil water recharge from rainfall was distributed systematically because of canopy interception and subsequent stemflow. Soil water content in no-tilled soil was higher than in conventional tilled soils. Surface recharge of soil water was less in the no-tilled soil compared to conventional tilled soil due to storage and flow of water in deeper layers, which leads to greater deep percolation in no tilled soils than in conventional tilled soils.

Surface sealing by raindrop impact plays an important role in controlling infiltration and water movement through soil profile. Surface sealing is prevented by complete crop and residue cover which increases intake rate leading to deep percolation. Fertility level is also important in determining the infiltration because it leads to additional crop cover and bio-mass production (Zuzel *et al.*, 1990).

Stone *et al.* (1973a) in a 31-day study observed that 35% of total water was lost due to flux loss from the root zone. In their studies they emphasized the importance of considering flux below the root zone when attempting to determine evaporation losses. Van Bavel *et al.*, (1968) also have discussed the magnitudes of deep profile water movement and the error involved when this movement is not considered in plant water use studies. The amount of water moving into or out of the root zone was greatly influenced by the amount of water added on the surface. The presence of a crop also influences the amount of water lost to deep percolation. The less frequent the application of water, then the less water was lost due to deep drainage from the soil profile (LaRue *et al.*, 1968).

MATERIALS AND METHODS

CHAPTER III

MATERIALS AND METHODS

3.1 Experimental site

The experiment was conducted during 1995 and 1996 rainy season (*kharif*) at the International Crops Research Institute for the Semi Arid Tropics (ICRISAT). The site is located at 18° N 78° E in Patancheru village, 26 km northwest of Hyderabad at an altitude of 545 m above sea level (ICRISAT, 1985).

3.2 Climate

ICRISAT is located in the Semi Arid Tropical belt characterised by a short rainy season (3-4 months) and prolonged dry weather (8-9 months) (ICRISAT, 1989). There are three distinct seasons which characterise the environment. The rainy season (*kharif*) begins in June and extends into early October. The post rainy winter season (*rabi*) follows from middle of October to January, and that is followed by the hot dry summer season from February to June when the rains begin again. The average annual rainfall is 760 mm of which >80% falls during the rainy season.

3.2.1 Weather conditions during the experimental period

In the 1995 rainy season, 1108 mm of rainfall was received which is 46 % above the long term average (ICRISAT, 1995). The rainfall was higher in 1996, enough to result in crop lodging. Meteorological data pertaining to rainfall, minimum and maximum temperature, relative humidity and pan evaporation recorded during the period of the experiment are presented in Figure 1 and Appendix I.

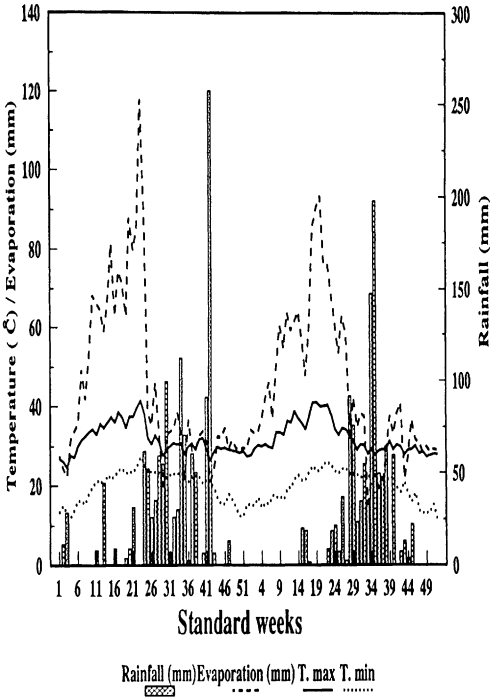

Figure 1. Rainfall, evaporation and temperature data during the experimental period.

3.3 Soil

The experiment was conducted on a deep Alfisol located in the ICRISAT watershed area (RW3-C). These Alfisols are reddish-brown soils derived from granite-gneiss and which belong to mixed isohyperthermic family of Udic Rhodustalfs (Soil Survey Staff, 1975). Texture of the soil is sandy clay loam to sandy loam and they occur mostly on flat gently undulating uplands. The dominant clay mineral is kaolinite with varying proportions of 2:1 clay minerals and sesqui-oxides. Alfisols are well drained soils with moderate permeability. These soils have medium available water holding capacity with granite and weathered rock fragments occurring commonly at lower depth in the profile.

3.4 Layout of the Experiment

The four main treatments in the experimental field were :

Control	Normal cultivation (first control) .
Scoops	As for control but pitting (size of the scoops were approximately 30 x 30 cm and 15 cm deep, (5555 pits ha^{-1} (app.)). The pits were made by labourers using traditional hand tools after sowing.
Crop residue	As for control and with application of unchopped pearl millet straw @ 5 t ha^{-1} placed on the surface after sowing.
Polyvinyl alcohol	As for control and with polyvinyl alcohol (a soil conditioner which improves the soil structure) applied @ 100 kg ha^{-1} (25%) by power sprayer after sowing (PVA).

Revegetation area   Revegetation plots where the soil was not disturbed for the last 30 years (second control) (Reveg).

The sub-treatments were :

Cropped (pearl millet was sown) (C).

Fallow (kept bare) (F).

The treatments were repeated during 1996 rainy season (*kharif*) on the same field. The experiment consisted of the five main treatments each with two sub-treatments and three replications. The four imposed main treatments were laid out in a simple split plot design. The imposed main treatments (control, crop residue, scoops and polyvinyl alcohol) were located together, whereas the revegetation area treatment was 2 km away. The experiment aims to study the influence of methods of surface management of soil on profile moisture, deep percolation and solute movement. These methods are compared with a control treatment in which the soil had not been disturbed for the last 30 years (Revegetation plot). No field operations were done on the revegetation plot except for sowing which was done manually.

Each main plot size was 15 X 20 m, divided equally into two subplots. At 5 m away from the lower bund a microplot was created by inserting an aluminium wall (10 X 5 m for each subplot) to 20 cm deep with 5 cm above soil surface. In this area potassium bromide (KBr) was sprayed at 134 kg ha^{-1} (50% concentration) bromide for the solute movement studies. The layout of the experiment is presented in Figure 2.

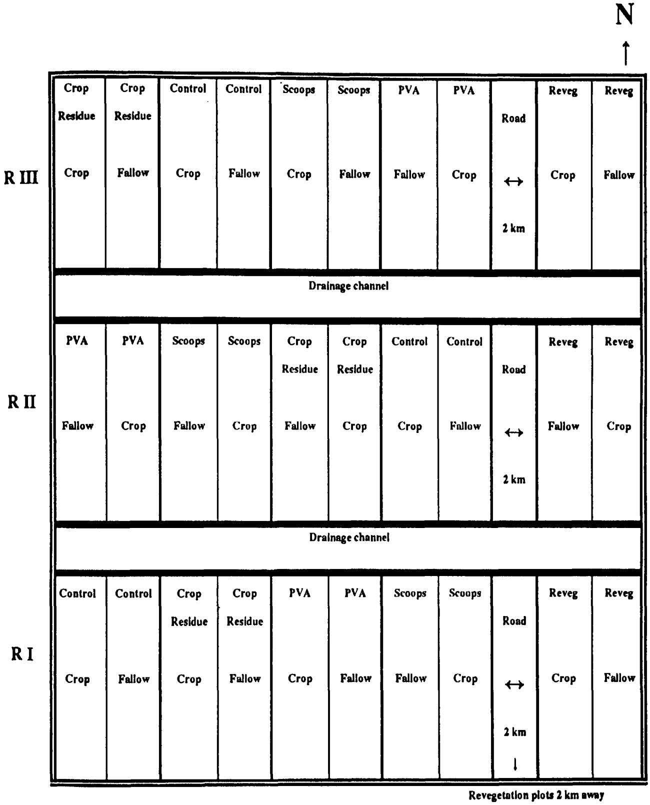

Figure 2. Layout of the experimental field.

3.5 Influence of different rates of PVA application on profile soil moisture of an Alfisol

The pilot study conducted during the 1994 post rainy season was to determine the rate of application of polyvinyl alcohol (PVA) soil conditioner to be used as one of the treatments in the main experiment during 1995 and 1996 rainy seasons. In this experiment, the effect of different rates of PVA on water storage in soil profile under simulated rainfall condition was studied. Infiltration of rain water and its storage in the soil was taken as a measure of the improvement in soil structure by application of PVA. The experiment had six treatments, PVA at 0, 25, 50, 100, 150 and 200 kg ha^{-1} and three replications. A nozzle type of rainfall simulator developed at ICRISAT (Thomas and El-Swaify, 1989) was used to create rainfall of 60 mm h^{-1} intensity. This intensity of rainfall was chosen as it is a rate known to destroy the soil structure in this type of red soil. It is also close to the maximum average intensity of rainfall on the red soils at ICRISAT which was 58.7 ± 4.5 mm h^{-1} during the past decade.

3.6 Field operations

The experimental field had been fallow for the past 6 years. The field was prepared using bullock-drawn cultivator (during both seasons) so as not to disturb unduly the soil structure. Weeds were controlled by spraying glyphosate immediately after sowing. All the other plant protection operations were carried manually.

Table 1: Physical and chemical characteristics of the Alfisol soil profile at the experimental site.

Properties	Depth of soil (cm)								
	0-15	15-30	30-45	45-60	60-90	90-120	120-150	150-180	180-210
I PHYSICAL									
1) Particle size analysis									
a) Sand (%)	85.6	74.3	57.2	58.1	59.1	57.1	63.9	67.9	75.9
b) Silt (%)	5.7	4.5	8.4	9.3	8.9	11.4	12.7	13.9	12.4
c) Clay (%)	6.3	19.7	33.9	30.9	26.8	26.6	20.5	13.5	9.9
2) Bulk density (Mg m^{-3})	1.62	1.70	1.58	1.52	1.56	1.65	1.65	1.55	1.68
3) Particle Density Mg m^{-3})	2.65	-	-	-	-	-	-	-	-
4) Total Porosity (%)	37.2	-	-	-	-	-	-	-	-
5) Wet aggregate analysis		-	-	-	-	-	-	-	-
a) MWD (mm)	25.6	-	-	-	-	-	-	-	-
b) GMD (mm)	0.19	-	-	-	-	-	-	-	-
6) Sorptivity (mm $h^{-1/2}$)	44.6	-	-	-	-	-	-	-	-
7) Hydraulic conductivity (mm h^{-1})	98.8	-	-	-	-	-	-	-	-
8) Steady-state flow rate		-	-	-	-	-	-	-	-
(mm h^{-1})	172.1	-	-	-	-	-	-	-	-
9) Mean pore size (mm)	0.32	-	-	-	-	-	-	-	-
II CHEMICAL									
1) pH	6.5	6.6	6.5	6.2	6.6	7.1	7.2	7.4	7.5
2) EC (dS m^{-1})	0.07	0.06	0.07	0.07	0.07	0.08	0.08	0.11	0.10
3) Organic carbon (%)	0.77	0.76	0.66	0.60	0.57	0.54	0.45	0.31	0.27
4) Total N (mg kg^{-1})	750.8	734.6	647.2	590.4	535.9	515.7	410.8	301.7	812.6
5) Available N (mg kg^{-1})	166	164	160	148	126	94	87	85	80
6) Available P (mg kg^{-1})	4.9	3.1	1.0	0.51	0.1	0.06	0.04	-	-
7) Available K (mg kg^{-1})	95.0	86.3	70.0	62.5	82.5	76.3	78.7	65.4	60.0
8) Exchangeable Ca (C.mol kg^{-1})	1.70	2.29	4.19	3.66	4.06	5.04	5.73	6.70	7.07
9) Exchangeable Mg (C.mol kg^{-1})	0.53	0.84	1.38	1.64	2.26	2.23	2.63	3.36	2.92
10) Exchangeable Na (C.mol kg^{-1})	0.16	0.17	0.20	0.20	0.24	0.20	0.19	0.23	0.22
11) CEC (cmol (p^+) kg^{-1})	10.0	13.0	14.0	11.0	9.0	8.0	7.0	7.0	7.0

3.7 Characterization of the experimental soil

Composite soil samples were collected at random from the field from depths up to 2.10 m prior to conducting the experiment. These samples were analysed for their physical properties viz. particle size analysis, bulk density, particle density, total porosity, wet aggregate analysis, hydraulic conductivity, sorptivity, steady state flow rate, mean pore size and chemical properties viz pH, EC, CEC, organic carbon, total nitrogen, available phosphorus and potassium, exchangeable calcium, magnesium and sodium. In any study based on soil structure, estimates of these above components is essential to determine the chemical and physical stability of the soil. These results are presented in Table 1 and Figure 3.

3.7.1 Soil physical properties

Soil physical properties were measured using the composite soil samples collected initially and after the experiment. Since our study deals with soil structural improvement and its influence on soil properties, this aspect was given more importance. Soil structure refers to the physical constitution of soil material as expressed by size, shape and arrangement of soil particles and voids. Measurement of soil structure is complex and there is no simple, definitive measure of it. Fundamental soil properties such as texture, total porosity, density etc provide the most useful indices of soil structure and are used here.

3.7.1.1 Particle size analysis

Mechanical composition of the soil was determined using the Bouyoucos hydrometer method (Bouyoucos, 1962) for soil depth from 0 to 2.10 m at 0.15 m depth increments upto 0.60 m and at 0.30 m depth increment upto 2.10 m, and the sand, silt and clay percentages were calculated.

3.7.1.2 Bulk density

Bulk density was determined before starting the experiment and again at the end of experiment during both the seasons by core sample method (Dakshinamurthy and Gupta, 1967) and expressed as Mg m^{-3}. Bulk density was also measured upto 2.10 m at 0.15 m depth increment for calibration of the neutron moisture meter, the bulk density values are as follows 1.62, 1.70, 1.58, 1.52, 1.56, 1.66, 1.65, 1.65, 1.66, 1.61, 1.53, 1.61, 1.67 and 1.70 Mg m^{-3} for the various depths.

3.7.1.3 Particle density

Particle density was determined using pycnometer by the procedure given by Blake and Hartge (1982) and is found to be 2.65 Mg m^{-3}.

3.7.1.4 Total porosity

Total porosity of top soil layer (0-15 cm) was determined both before and after the experiment by using the equation :

$$f = 1 - (\rho_b / \rho_p) \tag{1}$$

where, f = Total porosity

ρ_b = Bulk density (Mg m^{-3})

ρ_p = Particle density (Mg m^{-3})

3.7.1.5 Moisture characteristics of the soil

The plot of moisture content versus moisture potential is termed the moisture characteristic of the soil. The moisture content at pressures 0.033, 0.1, 0.2, 0.33, 0.5. 1.0. 1.2 and 1.5 MPa was determined, before starting the experiment, for soil depths 0 to 210 cm at 15 cm increments using a pressure plate apparatus at a constant room temperature 23±2 °C. The results are presented in Figure 3.

3.7.1.6 Wet aggregate analysis

Stability of soil aggregates is also an important index of soil structure. Aggregates are groups of primary particles that cohere to each other strongly. A stable aggregate is one which does not disintegrate under the influence of disruptive forces. The different size aggregates were determined before and after the experiment during both the seasons by following Yoder's procedure (1936) modified as suggested by Kemper and Rosenau (1982). The Mean Weight Diameter (MWD) and Geometric Mean diameter (GMD) were calculated and expressed as mm.

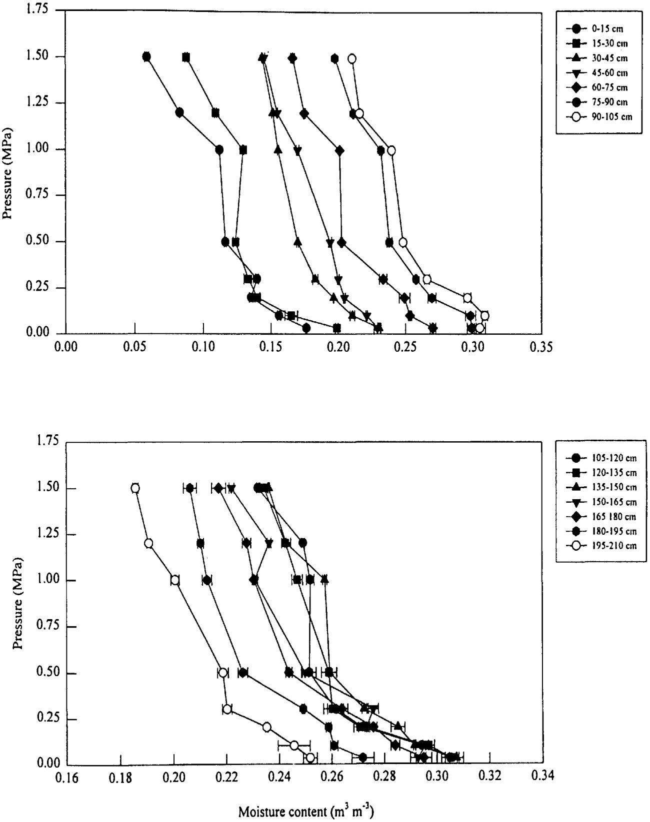

Figure 3. Moisture characteristic curves of the experimental soil at different depths.

3.7.1.7 Surface hydraulic properties

The disc permeameter (White *et al.*, 1989) was used to measure in-situ surface hydraulic properties of the experimental soil. It enables rapid measurement of hydraulic conductivity, sorptivity, steady-state flow rate and characteristic mean pore size with minimal soil disturbance. The main advantage of disc permeameter is that one can apply water to soil at different tensions, usually between 1 and 15 cm of water. This way, the contribution of various pore sizes (ranging from 3.0 mm to 0.2 mm) to water flow into the soil can be determined. Another advantage is that it can be placed directly on a soil surface with minimum disturbance. This makes it useful for investigating the changes in the surface structure of soils due to management.

3.7.1.7.1 Description of disc permeameter

The disc is made of clear polycarbonate sheet. The bottom of the disc is milled to form a shallow reservoir, which is enclosed by a water supply membrane, i.e a fine mesh nylon screen (63 μm Nytal). The membrane is supported by a steel mesh backing and two or more layers of supporting material, Vylene. The Vylene and Nytal are attached to the disc with silicon sealant and a screw clamp. A graduated and calibrated water reservoir of clear polycarbonate tubing is attached to the disc. The reservoir is filled by placing a vacuum on the one-way valve or stopcock at the top of the reservoir. There is a bubble tower attached to the side made of same material which provides the pathway for air entering the reservoir as infiltration proceeds. The height of water in the bubble tower is used to control supply potential. The bubble tower has a small diameter tube for air to enter the tower from the outside and an identical tube to supply air from the tower to the reservoir. The water potential at the membrane surface is varied by altering the water level in the bubble tower.

3.7.1.7.2 Principle of operation

When a source of water, such as a wet circular disc, is placed on the soil surface, the initial stages of the flow into the soil are dominated by the soil's capillary properties. As time progresses both the geometry of water source and the force of gravity influence flow rate. A time is reached where the flow rate from the source becomes steady. This steady-state flow rate is governed by capillarity, gravity, the size of the disc and the pressure at which water is supplied to the soil surface.

In this technique, we make use of both the initial and steady-state flow rates to separate the capillarity and gravity contributions to soil-water flow. In addition, by selecting the water supply pressure we can determine the sizes of pore sequences or fissures which participate in the flow process.

3.7.1.7.3 Procedure for measuring the sorptivity

Prepare the site at which observations are to be recorded by making a contact layer usually by applying sand. Place a rubber ring of 3 mm thickness on the surface, fill it with sand which is smoothed across the top of the ring, then remove the ring carefully. Place the disc permeameter filled with water on the sand and begin timing as soon as the bubbling begins. Record the scale reading and time as often as possible during early stages of infiltration. Continue taking the readings until the flow rate becomes constant. At the completion of infiltration remove the disc and scrape aside the sand and sample top 2-3 mm of soil with spatula for moisture content. The method for calculation of various soil hydraulic properties is presented in Appendix III.

3.7.2 Soil chemical analysis

3.7.2.1 Soil reaction (pH)

The procedure as described by McLean (1982) was followed to determine the pH in 1:2.5 soil water suspension and a Systronix pH meter (model 335) with combined electrode.

3.7.2.2 Electrical conductivity (EC)

The method as described by Richards *et al.* (1954) was used to determine the electrical conductivity of the soil in 1:2.5 soil to water extract using an electrical conductivity meter (Elico Model EM 88) and expressed in dS m^{-1}. Conductivity of the saturation extract indicates the salt content of the soil, which is important to determine the chemical stability of soil structure.

3.7.2.3 Organic carbon

The organic carbon content of the soil was estimated both before and after the experiment as per the procedure given by Nelson and Sommers (1982) and expressed in percentage.

3.7.2.4 Total Nitrogen

The procedure given by Bremner and Mulvaney (1982) was used to determine total N and it was expressed in terms of mg kg^{-1}.

3.7.2.5 Available phosphorus

Olsen & Sommers (1982) procedure was used to determine P using Olsen's reagent and it was expressed in mg kg^{-1}.

3.7.2.6 Available Potassium

The procedure given by Knudsen *et al.* (1982) was followed to determine available potassium content of the soil and was expressed in mg kg^{-1}.

3.7.2.7 Exchangeable sodium, calcium and magnesium

Exchangeable sodium, calcium and magnesium of the soil samples were determined as described by Thomas (1982) and the results expressed in C.mol kg^{-1} of soil.

3.8 Package of practices of pearl millet

3.8.1 Crop

Pearl millet crop variety WC C 75 was used in the study. The plants were medium tall in height (190-210 cm) with two to four tillers. In general the variety is vigorous, thick-stemmed and leafy. The variety flowers in 52 to 55 days and matures in 85 to 90 days. Heads are medium (22-28 cm) semi-cylindrical, slightly tapering and compact having perfect seed setting. Seeds are bold and plump having slate grey colour. It has good resistance to downy mildew and has low susceptibility to ergot.

3.8.2 Sowing and fertilizer application

Sowing was done (on 7th July 1995 and 6th July 1996) manually, furrows were opened at 30 cm spacing and seeds were placed at 15 cm apart, and the furrows closed. Fertilizer was applied as bands along the seed beds 5cm away from the seed rows at the rate of 40 kg N and 20 kg P per ha. Nitrogen was applied along the crop rows in split application. Fifteen to 20 days after sowing, the rows were thinned to an inter-plant spacing of 15 cm and gaps were filled in order to ensure a uniform plant stand, after which the second split of N was applied.

3.8.3 Interculture and plant protection operation

Weeds were controlled by spraying glyphosate. Hand weeding was not done so as not to disturb the soil surface. There was no pest infestation, hence no plant protection measures were needed.

3.9 Observations and measurements

Observations made during the experiment include soil moisture content, bromide in soil samples from the KBr-treated area and moisture potential readings during the crop growth season. Other measurements such as scoop capacity, light interception readings were taken at 15-20 days interval during the crop growth period. Precautions were taken to prevent the impact of treading on the plots by making small pathways along which to move within the plots for taking readings and samples.

3.9.1 Soil moisture content

The soil moisture of the profile was measured as described by Gardner (1982) using the neutron probe moisture meter (Troxler Model 4302 Soil Moisture Gauge). The neutron probe equipment consists of a source of fast neutrons (Americium-Beryllium), a detector for thermalized neutrons, and a scaler for registering the counts. Access tubes made of aluminium were installed in the soil to 2.25 m depth leaving 10 cm above soil surface. The top of the tubes was stoppered. The probe was placed over the access tube and initial standard counts were taken while the probe was in the shield. Then, the probe was lowered into the tube to the desired depth and readings taken for 30 seconds. Readings were taken at every 15 cm interval. The probe was calibrated and the calibration curve (Appendix II) was used to calculate the volumetric moisture content from the count ratio. Count ratio is the ratio of the observed count and the standard count. Gravimetric moisture samples were also collected from the top 0-15 cm to get the surface moisture readings.

3.9.2 Soil moisture potential

Moisture potential was determined at depths of 1.80, 1.95 and 2.10 m using the procedure described by Cassell and Klute (1982). Tensiometers were installed in the fields to the specified depths, filled with deaerated water and closed with a septum stopper. The SMS Tensiometer, which consists of a digital read out transducer connected to a needle, was used to measure the tension in millibars. The needle attached to the transducer is penetrated into the septum stopper of the tensiometer and the output is recorded from the digital read out. The potential readings at 1.80 and 2.10 m were used to calculate the water flux in a vertical one-dimensional soil system at 1.95 m depth using Darcy's equation as follows :

$$K(dH/dz) \qquad (2)$$

where j_w is soil water flux (L/T), H is the hydraulic head (L), K is a proportionality factor called the hydraulic conductivity (L/T), and z is vertical distance or depth (L).

3.9.3 Hydraulic conductivity

The hydraulic conductivity was measured at 1.95 m depth using the constant head method as described by Klute and Dirksen (1982). The estimation of hydraulic conductivity at this depth was essential to measure the water flux at that depth using the Darcy's equation as given in equation (3) above. The water flux was used to measure the deep percolation losses of water beyond 2.00 m under different surface management practices and also to measure the cumulative water loss from the top 2.00 m soil profile.

3.9.4 Bromide estimation

Soil samples were collected (on 3, 13, 16, 35, 47, 55, 67, and 72 DAS in 1995 and 7, 12, 19, 32, 35, 42, 48, 55, and 73 DAS in 1996) from depths to 2.10 m at 15 cm intervals, the day after rainfall of more than 10 mm was recorded, from the area where bromide was sprayed at 134 kg ha^{-1} (50%). The samples were dried at 105 °C in the oven, sieved through 2 mm seive and analysed for bromide concentration by the procedure given by Adriano and Doner (1982). The PHM 85 precision pHmeter (Radiometer A/S, Copenhagen, Denmark) with a radiometer Br^- electrode (Type F 1022 Br^-) was used to determine the bromide concentration in the soil sample. The bromide selectrode is a solid-state membrane electrode whose sensing element is a single crystal of pure silver bromide (AgBr). Calomel electrode (Type K 711) was used with double salt bridge as a reference electrode. The procedure given by Bruce et al (1985) was used to extract bromide. To 50 g of soil sample 50 ml of 0.5M calcium nitrate was added, stirred and allowed to stand overnight. The extract was then filtered and the bromide was determined using the ion selective electrode.

3.9.5 Scoop capacity

The capacity of the scoops in the scoop treatment was measured as volume of water held per scoop. To measure this, the scoop was covered with polythene sheet and the hollow filled with water. Care was taken so that there was no air space. The water from the polythene sheet was then transfered to a bucket and the volume of the water was measured. The results are depicted in Figure 5. The capacity of the scoops decreased drastically from 13.20 lit (app.) to 6.40 lit within 10 days after sowing and later decreased slowly as the season proceeded. The scoop capacity was higher in the cropped sub treatment than in fallow at harvest. The reason may be attributed to the protection provided by the crop cover from the direct impact of rainfall.

3.9.6 Light interception by pearl millet

The interception of photosynthetically active radiation (PAR) readings were taken for determining the growth of the pearl millet canopy under different treatments. For taking the PAR, a battery operated linear PAR ceptometer (Model PAR-80) was used. This has 80 independent sensors located in a weatherproof enclosure at one centimeter intervals in combination with an integral data logger. The instrument measures the PAR in the 400 to 700 nm waveband, which represents the portion of the spectrum which plants use for photosynthesis. To take the readings, level the probe in a position above the canopy to collect the above-canopy readings of PAR. This serves as a reference or standard count for the amount of light entering the canopy. Standard counts were taken at the begining of each data set or any time during the measurement process when the level of total available PAR changes (cloudy condition). The probe is then levelled below the canopy to take below-canopy readings. Total of 6 measurements were taken at different locations in each of the cropped sub treatment.

3.10 Yield of pearl millet

To determine the influence of various surface management practices on the crop growth the yield of the pearl millet crop was recorded. The yield data of millet was collected at harvest (crop harvested on 4th November in 1995 and 2nd November in 1996) from the cropped sub treatment of the experiment. Yield data was collected from an area of 4 m^2 in three replications within each of the cropped sub treatment. Both the grain and straw yield of the pearl millet were recorded.

3.11 Statistical analysis

The experimental data were analysed statistically by analysis of variance as given by Gomez and Gomez (1984) using Split-plot Randomised Design. Statistical significance was tested by F value at 0.05 level of probability. The revegetation treatment (second control) was compared with the other four treatment using the paired t-test. The results were depicted in tabular form and also by graphical representation with standard error and critical difference.

RESULTS

CHAPTER IV

RESULTS

The various soil structural parameters namely bulk density, porosity, aggregate stability, sorptivity, steady state flow rate, hydraulic conductivity, characteristic mean pore size, organic carbon etc. were found to be significantly influenced by the different surface management practices both under crop and fallow sub treatments, the results for which are presented in Tables 2 to 12. Figures 6 to 13 present the effect of various surface management practices on profile water storage, deep percolation losses and solute movement.

4.1 Influence of soil surface management on soil structural parameters

4.1.1 Bulk Density

Bulk density in the 0-15 cm layer of the soil was found to be significantly influenced by surface management of the Alfisols both under crop and fallow situation. The bulk density before starting the experiment was 1.62 ± 0.013 Mg m^{-3}. In both the cropped and fallow treatments, increase in bulk density was observed significantly in the control (1.69 and 1.73 Mg m^{-3} in 1995 and 1996) as well as scoop treatment (1.67 and 1.72 Mg m^{-3} in 1995 and 1996). There was also increase in bulk density from one season to the next indicating that bulk density increased due to cultivation. Similar trend of increase in bulk density due to cultivation was observed in the revegetation areas. The results are presented in Table 2.

In the crop residue and PVA treatments decrease in bulk density from the initial value was observed. Maximum decrease was observed in the PVA fallow treatment where the bulk density decreased from 1.62 to 1.58 Mg m^{-3} in 1995 and 1.60 Mg m^{-3} in 1996. Crop residue fallow treatment also showed a decrease of 1.60 Mg m^{-3} in 1995 from 1.62 Mg m^{-3} but in 1996 the bulk density increased to 1.63 Mg m^{-3}. There was increase in bulk density during the second year of the experiment in all the treatments. When comparing between the main treatments, revegetation treatment showed least increase in bulk density with cultivation followed by PVA and crop residue treatment. Control as well as scoop treatments showed highest increase in bulk density. Among the sub treatments, fallow showed lower bulk density compared to cropped sub-treatment in all the main treatments.

4.1.2 Porosity

Significant differences in the porosity were also observed between the treatments. Porosity was highest in the revegetation treatment (Table 3). Cultivation led to a decrease in porosity since lower porosity readings were obtained during the 1996 cropping season in all the treatments. Porosity at the beginning of the experiment was 0.37 ± 0.005. Decrease in porosity was observed in the control and scoop main treatments in the cropped sub treatment, whereas fallow sub treatment did not show any change in porosity during the first season but it decreased in the second year to 0.35 and 0.36 in the fallow sub treatment of control and scoop main treatment, respectively.

Porosity increased in the crop residue, PVA and revegetation treatments. In the revegetation treatment, porosity increased to 0.41 during the end of second season in the fallow treatment and

Table 2. Influence of soil surface management on bulk density (Mg m^{-3}) of surface (0-15 cm) layer of the Alfisol.

	1995			1996		
Treatments	Crop	Fallow	Mean	Crop	Fallow	Mean
Control	1.72	1.67	1.69	1.74	1.72	1.73
Scoop	1.68	1.67	1.67	1.73	1.71	1.72
Crop Residue	1.62	1.60	1.61	1.64	1.63	1.63
PVA	1.60	1.58	1.59	1.63	1.60	1.61
Revegetation	1.59	1.56	1.57	1.61	1.60	1.60
Mean	1.66	1.63		1.69	1.66	
Statistical Data	Main Treatment	Sub Treatment	Interaction Effect	Main Treatment	Sub Treatment	Interaction Effect
S.Em (±)	0.005	0.003	0.006	0.006	0.005	0.008
CD (0.05)	0.017	0.009	0.019	0.020	0.016	0.024

Table 3. Influence of soil surface management on porosity of surface layer (0-15 cm) of the Alfisol.

	1995			1996		
Treatments	Crop	Fallow	Mean	Crop	Fallow	Mean
Control	0.35	0.37	0.36	0.34	0.35	0.34
Scoop	0.36	0.38	0.37	0.35	0.36	0.35
Crop Residue	0.39	0.40	0.39	0.38	0.39	0.38
PVA	0.41	0.42	0.41	0.39	0.40	0.39
Revegetation	0.41	0.43	0.42	0.40	0.41	0.40
Mean	0.38	0.40		0.37	0.38	
Statistical Data	Main Treatment	Sub Treatment	Interaction Effect	Main Treatment	Sub Treatment	Interaction Effect
S.Em (±)	0.001	0.001	0.002	0.003	0.002	0.004
CD (0.05)	0.003	0.003	0.006	0.009	0.006	0.011

0.40 in the cropped treatment. PVA treatment also showed an average porosity of 0.40 at the end of both the seasons. In all the main treatments the fallow sub-treatment had higher porosity than the cropped sub treatment. Of the main treatments, porosity was highest in the revegetation treatment with PVA and crop residue treatments showing lower porosity. All the four treatments were compared with the revegetation treatment using the paired t-test, the revegetation plots showed significantly better and higher porosity readings compared to the other four treatments.

4.1.3 Organic carbon

The organic carbon content was also determined at 0-5, 5-10 and 10-20 cm layer of the soil, the data for which are presented in Tables 4, 5 and 6 respectively. Organic carbon was significantly higher in the revegetation treatments which had remained uncultivated for the last 30 years and hence had resulted in accumulation of the organic carbon. Crop residue and PVA treatments have shown lower organic carbon values than revegetation treatment. Crop residue treatment showed higher organic carbon content than PVA treatment which may be due to presence of millet straw on the surface which must have undergone humification thereby increasing the organic carbon content of the surface layer. Organic carbon is also involved in improving the soil structure, through its binding action on the soil particles leading to the formation of soil aggregates. Organic carbon content was found to be higher in the crop sub treatment than the fallow sub treatment in all the main treatments. There was a decrease in the organic carbon content in 1996 in all the treatments except crop residue where it remained constant or increased. Decrease in the organic carbon content was also observed with depth (Tables 4, 5 and 6).

Table 4. Influence of soil surface management on organic carbon (%) of 0 - 5 cm soil layer of the Alfisol.

	1995			1996		
Treatments	Crop	Fallow	Mean	Crop	Fallow	Mean
Control	0.217	0.187	0.202	0.205	0.177	0.191
Scoop	0.225	0.202	0.213	0.215	0.195	0.205
Crop Residue	0.285	0.295	0.290	0.273	0.264	0.268
PVA	0.235	0.210	0.222	0.215	0.207	0.211
Revegetation	0.965	0.817	0.891	0.954	0.807	0.881
Mean	0.386	0.342		0.342	0.330	
Statistical Data	Main Treatment	Sub Treatment	Interaction Effect	Main Treatment	Sub Treatment	Interaction Effect
S.Em (±)	0.003	0.005	0.002	0.006	0.007	0.002
CD (0.05)	0.009	0.015	0.005	0.018	0.021	0.005

Table 5. Influence of soil surface management on organic carbon (%) of 5 - 10 cm soil layer of the Alfisol.

	1995			1996		
Treatments	Crop	Fallow	Mean	Crop	Fallow	Mean
Control	0.187	0.142	0.165	0.175	0.140	0.157
Scoop	0.195	0.180	0.187	0.187	0.175	0.181
Crop Residue	0.262	0.247	0.255	0.256	0.240	0.248
PVA	0.217	0.210	0.214	0.207	0.205	0.206
Revegetation	0.840	0.727	0.784	0.802	0.705	0.754
Mean	0.340	0.311		0.325	0.293	
Statistical Data	Main Treatment	Sub Treatment	Interaction Effect	Main Treatment	Sub Treatment	Interaction Effect
S.Em (±)	0.006	0.007	0.005	0.003	0.005	0.005
CD (0.05)	0.017	0.021	0.014	0.009	0.014	0.015

Table 6. Influence of soil surface management on organic carbon (%) of 10 - 20 cm soil layer of the Alfisol.

	1995			1996		
Treatments	Crop	Fallow	Mean	Crop	Fallow	Mean
Control	0.187	0.157	0.172	0.175	0.155	0.165
Scoop	0.217	0.187	0.202	0.207	0.175	0.191
Crop Residue	0.255	0.227	0.241	0.257	0.225	0.241
PVA	0.247	0.232	0.240	0.237	0.227	0.232
Revegetation	0.622	0.555	0.589	0.612	0.550	0.581
Mean	0.306	0.272		0.298	0.266	
Statistical Data	Main Treatment	Sub Treatment	Interaction Effect	Main Treatment	Sub Treatment	Interaction Effect
S.Em (±)	0.006	0.007	0.004	0.002	0.006	0.007
CD (0.05)	0.017	0.020	0.012	0.007	0.017	0.021

4.1.4 Aggregate stability

Assessment of soil structural improvement was also made by measuring the aggregate stability parameters namely mean weight diameter (MWD) and geometric mean diameter (GMD). The results of MWD and GMD are presented in Table 7 and 8, respectively. There was significant effect of surface management on MWD and GMD.

The MWD before starting the experiment was 25.6 ± 0.07 mm. There was increase in the MWD in all the treatments except control treatment which showed a decrease in MWD at an average of 2.85 ± 0.45 mm (Table 7). Highest MWD was observed in the revegetation and PVA treatment with crop residue treatment showing next lower value. The scoop treatment did not show much increase in the MWD. The t-test comparision showed that the revegetation treatment has significantly higher MWD than the other treatments during both the years, except PVA treatment which shows non significant differences in the MWD with revegetation. The fallow sub treatments showed significantly higher MWD compared to the cropped sub treatment indicating that fallow improves aggregate stability. Among the various main treatments the revegetation treatment showed highest MWD values of 39.4 mm higher than the PVA treatment. Control treatment had the lowest MWD of 22.4 mm in 1995 which increased by 0.93 mm during 1996. All the treatments showed increase in MWD during the second season though the increase was very small and almost negligible. Revegetation fallow treatment showed the highest MWD of 40.4 mm during 1996.

The GMD data presented in Table 8 also showed similar trend as the MWD. The initial GMD before starting the experiment was 0.19 ± 0.075 mm. There was increase in GMD in all the treatments except control treatment. Highest GMD of 0.51 mm was recorded in the revegetation fallow treatment during 1996. GMD also increased from one season to the next mainly in the crop sub treatment, even though the increase was not very high. Of all the treatments revegetation treatment showed highest increase in GMD than PVA and crop residue treatments. Fallow sub treatment showed significantly higher GMD values in all the main treatments than the cropped sub treatment. The t-test comparision of the revegetation treatment with the other treatments was significant indicating that the revegetation fallow treatment has the highest GMD values higher than the revegetation crop treatment. The results of the GMD suggests that aggregate stability increases during fallowing, and cropping causes the deterioration of aggregates. Consequently, fallowing is important to maintain the soil structure for better crop growth.

4.1.5 Surface hydraulic properties

Disc permeameter was used to measure the in-situ hydraulic properties such as sorptivity, hydraulic conductivity, steady-state flow rate, macroscopic capillary length and characteristic pore size with minimum soil disturbances. The results for these measurements on the soil surface are presented in Tables 9 to 12.

Table 7. Influence of soil surface management on MWD (mm) of surface layer of the Alfisol.

	1995			1996		
Treatments	Crop	Fallow	Mean	Crop	Fallow	Mean
Control	21.7	23.1	22.4	22.6	24.1	23.4
Scoop	26.3	27.8	27.1	26.7	27.9	27.3
Crop residue	29.5	31.9	31.7	28.3	30.9	31.6
PVA	31.9	32.3	33.1	31.9	33.4	32.2
Revegetation	38.0	40.2	39.1	37.3	40.4	38.9
Mean	29.5	31.1		29.4	31.4	
Statistical Data	Main Treatment	Sub Treatment	Interaction Effect	Main Treatment	Sub Treatment	Interaction Effect
S.Em (±)	1.01	0.53	1.26	1.09	0.51	1.30
CD (0.05)	3.01	1.59	3.78	3.27	1.53	3.90

Table 8. Influence of soil surface management on GMD (mm) of surface layer of the Alfisol.

	1995			1996		
Treatments	Crop	Fallow	Mean	Crop	Fallow	Mean
Control	0.071	0.143	0.107	0.104	0.170	0.137
Scoop	0.243	0.268	0.256	0.246	0.235	0.241
Crop residue	0.299	0.311	0.320	0.282	0.300	0.316
PVA	0.320	0.351	0.336	0.326	0.349	0.338
Revegetation	0.457	0.506	0.482	0.439	0.497	0.468
Mean	0.278	0.316		0.280	0.310	
Statistical Data	Main Treatment	Sub Treatment	Interaction Effect	Main Treatment	Sub Treatment	Interaction Effect
S.Em (±)	0.008	0.005	0.011	0.003	0.007	0.011
CD (0.05)	0.024	0.015	0.033	0.009	0.021	0.033

4.1.5.1 Sorptivity

The sorptivity data for 1995 and 1996 are presented in Table 9. Initial sorptivity before starting the experiment was 44.6 ± 1.71 mm $h^{-1/2}$. Sorptivity decreased significantly in control and scoop treatment but increased in the other treatments. Sorptivity was found to decrease from one season to the next. Highest sorptivity was recorded in the revegetation fallow treatment than in PVA fallow treatment. Among the sub treatments, fallow showed significantly higher sorptivity values than cropped. The main treatments also showed significant differences in which revegetation treatment had higher sorptivity than the PVA and crop residue treatments. PVA and crop residue treatments did not show significant differences in sorptivity. Similarly sorptivity was higher in scoops treatment but was not significantly different from control treatment. Sorptivity decreased in 1996 in all the treatments.

4.1.5.2 Steady-state flow rate

The steady-state flow rate is obtained during the last part of the infiltration processes at which stage the time required for infiltration becomes nearly constant. Table 10 presents the data for the steady-state flow rate during 1995 and 1996. The initial steady-state flow rate was 172.1 ± 4.21 mm h^{-1}. There was a decrease in the steady-state flow rate in the control treatment whereas it increased in the other treatments. In the scoop treatment the steady state flow rate did not show much increase. Infiltration rate was strongly related to inputs of organic materials, such that revegetation treatment has shown infiltration rate higher than PVA > crop residue > scoop which has shown infiltration rate not significantly different from control treatment.

Table 9. Influence of soil surface management on sorptivity (mm $h^{-1/2}$) of surface layer of the Alfisol.

	1995			1996		
Treatments	Crop	Fallow	Mean	Crop	Fallow	Mean
Control	35.5	39.5	37.5	32.3	37.4	34.8
Scoop	40.7	48.3	44.5	39.9	46.6	43.3
Crop residue	64.1	73.8	69.0	60.1	71.6	65.8
PVA	90.3	100.0	95.1	87.0	97.3	92.2
Revegetation	111.5	129.8	120.7	108.0	123.9	115.9
Mean	68.4	97.3		65.4	75.3	
Statistical Data	Main Treatment	Sub Treatment	Interaction Effect	Main Treatment	Sub Treatment	Interaction Effect
S.Em (±)	2.94	3.85	2.04	3.64	2.39	3.39
CD (0.05)	8.82	11.55	6.12	10.92	7.17	10.17

Table 10. Influence of soil surface management on steady-state flow rate (mm h^{-1}) of surface layer of the Alfisol.

	1995			1996		
Treatments	Crop	Fallow	Mean	Crop	Fallow	Mean
Control	165	170	167	162	168	165
Scoop	175	181	178	168	172	170
Crop residue	204	219	211	198	213	205
PVA	240	251	246	236	246	241
Revegetation	276	288	282	270	280	275
Mean	212	222		207	216	
Statistical Data	Main Treatment	Sub Treatment	Interaction Effect	Main Treatment	Sub Treatment	Interaction Effect
S.Em (±)	1.93	1.74	3.54	4.29	1.57	4.58
CD (0.05)	5.79	5.22	10.62	12.87	4.71	13.74

The steady-state flow rate did not vary much in 1996. Similarly cropping and fallowing also did not make much difference on infiltration rate. Though fallow sub treatment showed significantly higher steady state flow rate compared to crop with the highest steady state flow rate observed in the revegetation fallow treatment during 1995. The results suggests that manipulation of the surface soil significantly influences the steady state flow rate due to improvement in soil structural features.

4.1.5.3 Hydraulic Conductivity

Surface hydraulic conductivity of the soil at the potential at which the measurement was being made (-10 mm) was calculated from equation (4) (White *et al.*, 1989) presented in Appendix III. The data for hydraulic conductivity during 1995 and 1996 presented in Table 11 suggests that improving the soil structure, due to surface management, improves the hydraulic conductivity. The initial hydraulic conductivity was 98.8 ± 2.8 mm h^{-1}, which has increased in all the treatments except the control treatment. Scoop and control treatment did not show significant differences in hydraulic conductivity. Of the sub treatments, fallow plots had higher hydraulic conductivity than cropped plots in all the treatments. Revegetation treatment showed the highest hydraulic conductivity than PVA and crop residue treatment, among the main treatments. Hydraulic conductivity was slightly but consistently less in 1996 than in 1995.

4.1.5.4 Characteristic mean pore size (λ_m)

The initial characteristic mean pore size was 0.32 ± 0.02 mm which decreased to 0.20 and 0.21 mm in the control crop and control fallow plots (Table 12). It increased in all other treatments, except for the treatment with the scoops. In this treatment it decreased in 1995 and then remained constant in the fallow sub treatment. Highest mean pore size of 2.85 mm was observed in the revegetation fallow during 1995. Among the main treatments mean pore size (λ_m) was significantly higher in the revegetation treatment, and the PVA and crop residue treatments were also high. Control and scoop treatments had the lowest mean pore size. Among the sub treatments fallow showed significantly higher λ_m compared to crop. There was a small significant decrease in the mean pore size from one season to the next.

4.2 Influence of different rates of PVA application on soil moisture

The results of the pilot study conducted to determine the rate of PVA to be used are presented in Figure 4 and Table 13 and 14. The moisture content is highest in the soil profile where PVA was applied at the rate of 200 kg ha^{-1} (Figure 4). Table 13 presents the initial and final moisture content (cm^3 cm^{-3}) at different depths in the six treatments and Table 14 presents the moisture storage in millimeters for the top 1.50 m soil profile for different treatments. The highest amount of moisture of 130 mm was stored in the 200 kg ha^{-1} treatment (Table 14). But there was no significant difference between the three treatments i.e. 100, 150 and 200 kg ha^{-1} of PVA, in the amount of moisture stored in the top 1.50 m profile (Table 14). So also the profile moisture curves of the 100, 150 and 200 kg ha^{-1} treatments are close to each other indicating that they have nearly similar moisture profiles which are not significantly different (Figure 4).

Table 11. Influence of soil surface management on hydraulic conductivity (mm h^{-1}) of surface layer of the Alfisol.

	1995			1996		
Treatments	Crop	Fallow	Mean	Crop	Fallow	Mean
Control	92	95	94	90	91	91
Scoop	99	102	101	95	98	97
Crop residue	121	127	124	119	123	121
PVA	140	147	143	134	140	137
Revegetation	153	159	156	148	154	151
Mean	121	126		117	121	
Statistical Data	Main Treatment	Sub Treatment	Interaction Effect	Main Treatment	Sub Treatment	Interaction Effect
S.Em (±)	2.56	1.19	3.27	2.27	2.71	2.48
CD (0.05)	7.52	3.37	9.43	6.89	8.12	7.47

Table 12. Influence of soil surface management on characteristic mean pore size (λ_m) (mm)of surface layer of the Alfisol.

	1995			1996		
Treatments	Crop	Fallow	Mean	Crop	Fallow	Mean
Control	0.23	0.25	0.24	0.20	0.22	0.21
Scoop	0.31	0.37	0.34	0.27	0.32	0.29
Crop residue	0.71	0.74	0.73	0.64	0.70	0.67
PVA	0.92	1.37	1.15	0.89	1.04	0.97
Revegetation	2.14	2.85	2.49	1.96	2.57	2.27
Mean	0.86	1.12		0.79	0.97	
Statistical Data	Main Treatment	Sub Treatment	Interaction Effect	Main Treatment	Sub Treatment	Interaction Effect
S.Em (±)	0.003	0.003	0.003	0.004	0.007	0.006
CD (0.05)	0.009	0.009	0.009	0.012	0.021	0.018

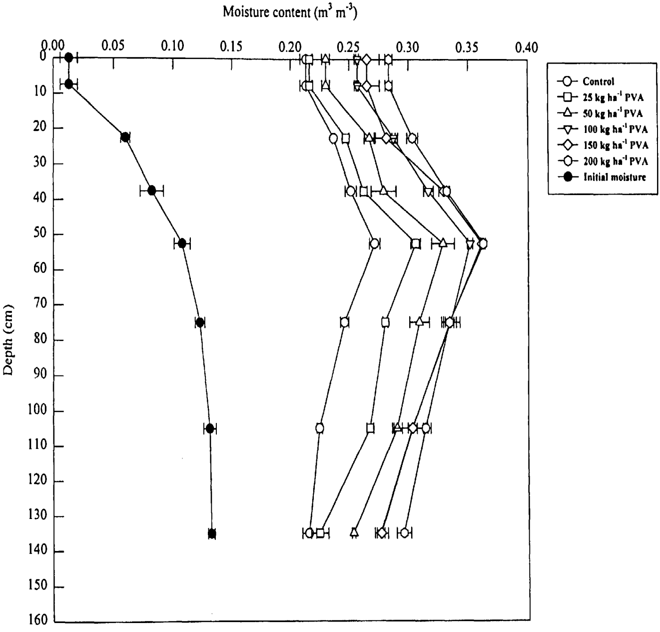

Figure 4. Moisture content of an Alfisol soil profile after application of different rates of PVA.

Table 13. Initial and final profile moisture content ($cm^3\ cm^{-3}$) in different treatments of an Alfisol.

Treatments	Depth (cm)	0-15	15-30	30-45	45-60	60-90	90-120	120-150
Control	Initial	0.079	0.148	0.227	0.294	0.242	0.201	0.202
	Final	0.213	0.237	0.231	0.311	0.246	0.224	0.215
25 kg ha^{-1} PVA	Initial	0.117	0.142	0.172	0.200	0.248	0.223	0.213
	Final	0.256	0.257	0.282	0.316	0.270	0.257	0.254
50 kg ha^{-1} PVA	Initial	0.064	0.145	0.172	0.242	0.216	0.193	0.192
	Final	0.250	0.277	0.299	0.304	0.289	0.250	0.215
100 kg ha^{-1} PVA	Initial	0.069	0.142	0.192	0.260	0.249	0.195	0.199
	Final	0.257	0.288	0.317	0.351	0.315	0.243	0.226
150 kg ha^{-1} PVA	Initial	0.074	0.138	0.223	0.231	0.245	0.225	0.198
	Final	0.255	0.271	0.329	0.361	0.323	0.292	0.216
200 kg ha^{-1} PVA	Initial	0.085	0.134	0.244	0.237	0.224	0.214	0.208
	Final	0.284	0.303	0.332	0.363	0.324	0.284	0.225
S.Em (±)	Initial	0.004	0.003	0.009	0.010	0.003	0.006	0.004
	Final	0.007	0.006	0.006	0.005	0.007	0.007	0.006
CD (0.05)	Initial	0.012	0.009	0.026	0.031	0.009	0.018	0.012
	Final	0.021	0.018	0.018	0.016	0.021	0.021	0.018

From the results of the pilot study, we conclude that the best treatment which can be used in the main experiment is the 100 kg ha^{-1} PVA application as it does not differ significantly from the 150 and 200 kg ha^{-1} treatments and would also be economical. Therefore based on these results we have used the PVA application at the rate of 100 kg ha^{-1} in the main experiments during 1995 and 1996 as one of the treatments. In Figure 4 for the sake of simplicity and easy understanding the averages of the initial moisture content (cm^3 cm^{-3}) of all the treatments were taken and presented as a single curve along with the standard error (SE) bars.

4.3 Scoop capacity

The capacity of the scoops (one of the treatments in the main experiment) was measured and the data are presented in Figure 5 and Table 15. The scoop capacity was the same in both the sub treatments at the start of the experiment. There was a decrease in the capacity of the scoops as the season advanced in both years (Figure 5). The decrease in the scoop capacity was more in the fallow sub treatment than in the crop sub treatment. The protection from the direct impact of rainfall that the crop canopy provides to the pits slows the process of filling of the pits by slumping of the soil. In the crop sub treatment the decrease in scoop capacity was moderate (a scoop of 6.47 cm^3 at the beginning of the season was reduced to 3.97 cm^3 at harvest in 1995). In contrast, the decrease in scoop capacity in the fallow sub treatment was relatively high (a scoop of 5.79 cm^3 at the beginning of the season was reduced to 2.93 cm^3 at harvest in 1995). Increase in rainfall intensity resulted in a further decrease in storage capacity of the scoops.

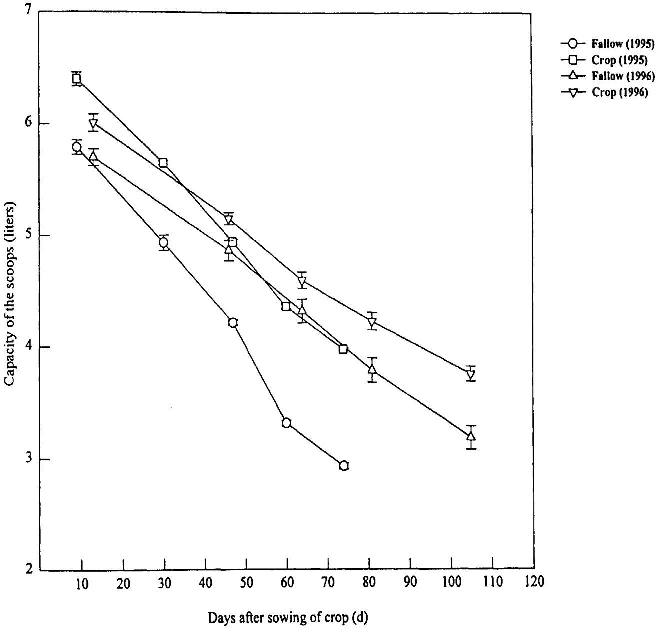

Figure 5. Capacity of the scoops made in scoop treatment during the experimental period.

Table 14. Moisture stored in the top 1.50 m depth of the Alfisol soil profile as affected by different rates of PVA.

S. No.	Treatments	Moisture stored in the soil profile (mm)
1.	Control (no PVA applied)	44.1
2.	PVA at the rate 25 kg ha^{-1}	61.7
3.	PVA at the rate 50 kg ha^{-1}	102.2
4.	PVA at the rate 100 kg ha^{-1}	125.1
5.	PVA at the rate 150 kg ha^{-1}	128.1
6.	PVA at the rate 200 kg ha^{-1}	130.0
	S.Em (±)	2.7
	CD (0.05)	8.1

Table 15. Capacity of the scoops (liters) during the entire crop growth season in the two sub treatments on the Alfisol.

1995					1996				
DAS	Crop	SE (±)	Fallow	SE (±)	DAS	Crop	SE (±)	Fallow	SE (±)
9	6.40	0.06	5.79	0.07	13	6.01	0.08	5.70	0.04
30	5.65	0.02	4.94	0.07	46	5.15	0.05	4.87	0.02
47	4.94	0.03	4.22	0.02	64	4.60	0.07	4.32	0.05
60	4.36	0.02	3.31	0.03	81	4.23	0.08	3.79	0.03
74	3.97	0.01	2.93	0.03	105	3.75	0.07	3.18	0.02

4.4 Effect of surface management on profile moisture storage

The data for profile moisture storage in the top 2.00 m soil profile in different treatments are presented in Figure 6 and Table 1 in Appendix IV for 1995, and Figure 7 and Table 2 in Appendix IV for 1996. The moisture stored was highest in the no-till revegetation plots during both 1995 and 1996 season (Figures 6 and 7) suggesting that a high amount of moisture is stored in the 2 m soil profile in revegetated soil in which the soil structure is very good. Lower moisture storage in PVA and crop residue treatments were recorded in both years (Figures 6 and 7). In 1995 all the curves in the different treatments are distinctly separate (Figure 6) whereas the curves are very close in 1996 season (Figure 7). The difference can be attributed to the very heavy rains in 1996 during the *kharif* season compared to 1995 (Figure 7). Statistical analysis indicates that the moisture stored in the profile is significantly different in all the treatments.

Control and scoop treatments show nearly identical moisture storage though they are significantly different statistically (Tables 1 and 2 in Appendix IV). In all the main treatments the fallow sub treatments have higher amounts of moisture stored in the profile than in the crop sub treatments. This could be due to part of the moisture being used by the crop for its growth thereby decreasing the amount of moisture stored in the soil profile in the crop sub treatment. Improvement in soil structural parameters during the fallow period may also contribute to higher soil moisture storage in the fallow sub treatment than in crop sub treatment. Fallowing is thus important in improving the water storage capacity of the soil. Of the main treatments, revegetation has shown the highest amount of water storage, with PVA and crop residue next best. Application of PVA

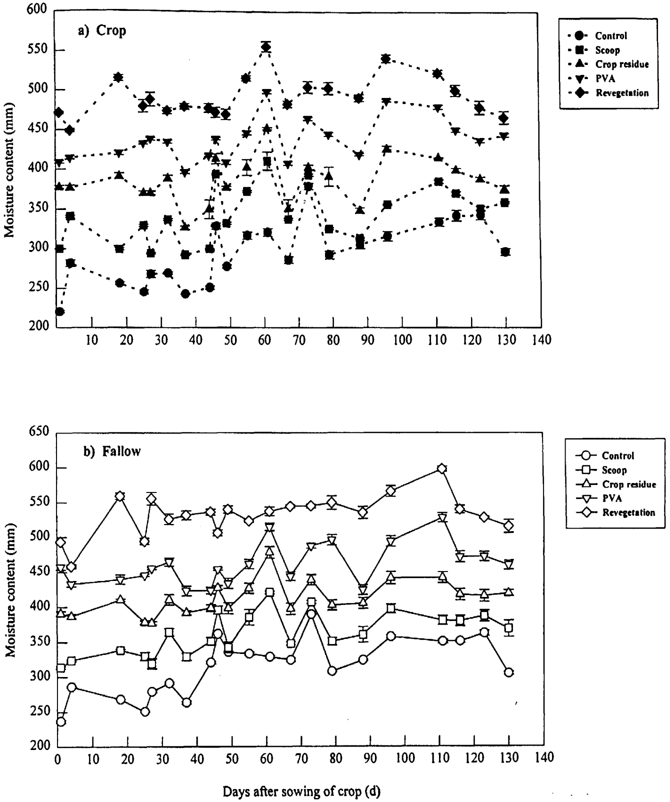

Figure 6. Moisture stored in the top 2.00 m soil profile in different treatments during 1995 season, for (a) cropped and (b) fallow. Error bars (⌶) are seen when the symbol is small.

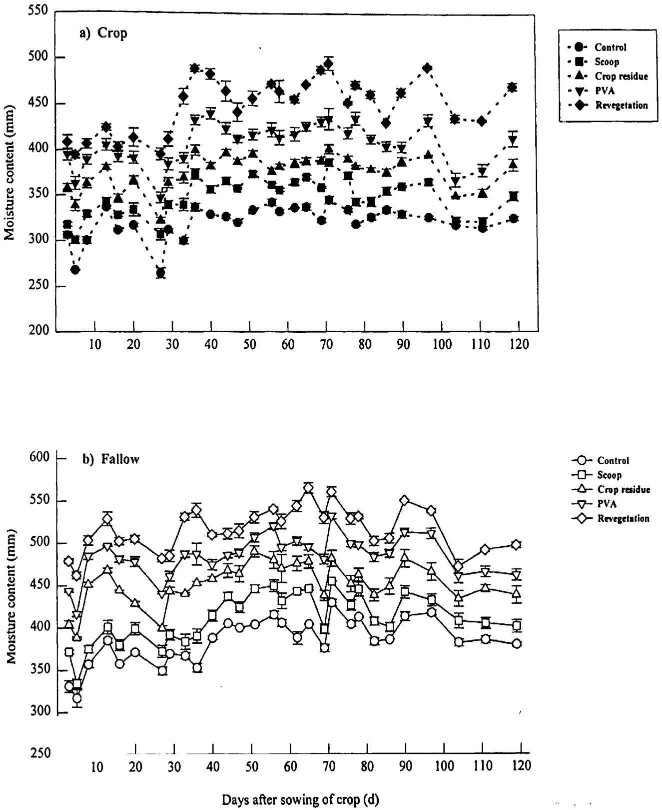

Figure 7. Moisture stored in the top 2.00 m soil profile in different treatments during 1996 season, for a) cropped and b) fallow. Error bars (⌶) are seen when the symbol is small.

increased the amount of water stored in the soil profile. This may be because of improved soil structural condition which has led to higher infiltration of rain water into the soil thereby reducing the runoff losses. In the crop residue treatment, the runoff was reduced because most of the rain water infiltrated into the soil due to the presence of straw mulch on the surface.

Significantly higher moisture storage was observed in the scoop treatment than in the control treatment. Rain water was retained in the scoops thus reducing runoff and allowing more time for the rain water to infiltrate into the soil. The maximum amount of water (598 mm) was stored in the revegetation fallow treatment at 111 days after sowing (DAS) in 1995 because rainfall of 133 mm was received in a seven days period.

During 1996 heavy rainfalls were received, the highest being 95.6 mm at 56 DAS (28^{th} August 1996). The amount of rainfall stored in the revegetation fallow treatment on this day was 540 mm. Another high rainfall of 67 mm was received at 71 DAS (12^{th} Sept. 1996) during which the water storage in the soil profile in revegetation fallow treatment was 560 mm. The moisture storage was highest in the revegetation treatment, whereas PVA and crop residue showed lower water storage in that order throughout the season in both 1995 and 1996 season. In Figure 7 the difference was small but they were significant. Thus even with heavy rainfall conditions it is possible to have better moisture storage where there is well developed soil structure.

4.5 Effect of surface management on deep percolation

The data presented in Table 3 and Table 4 in Appendix IV are the soil water flux data at 1.95 m depth indicating deep percolation losses from different treatments during 1995 and 1996. These data are presented graphically in Figures 8 and 9 for seasons 1995 and 1996. The soil water flux is presented on days when rainfall was received. During both years maximum soil water flux was in the control treatment with scoop treatment showing lower flux values than control treatment. Least soil water flux and deep percolation losses were in the revegetation plots. The percolation losses when there was heavy rain, show that heavy rains increase the deep percolation losses of soil water. In both 1995 and 1996 soil water flux at 1.95 m depth was highest in control treatment with scoop treatment showing lower flux with the curves quite similar. Because of heavy rains in 1996 very good soil water flux curves occurred (Figure 9). The highest soil water flux was at 54 DAS in 1996 when 95.6 mm of rainfall was received (Figure 9). Of the sub treatments, cropping showed higher soil water flux at 1.95 m depth than the fallow. The crop used some water for its growth, but the effect of the crop seemed to be overshadowed by the soil structural effect on soil water flux. Another factor to be considered is that during both years above average rains were received. Therefore, the soil water losses due to deep percolation are higher than normal in all the treatments in both the years as indicated by the soil water flux at 1.95 m depth.

These results are consistent with the moisture storage data. In those treatments where moisture storage is high, the soil water flux is less since most of it is stored in the top 2.00 m of the soil profile, and in the treatments where the moisture storage is low (e.g. control treatments) the soil water flux is high indicating that soil water losses have occurred due to deep percolation. The results

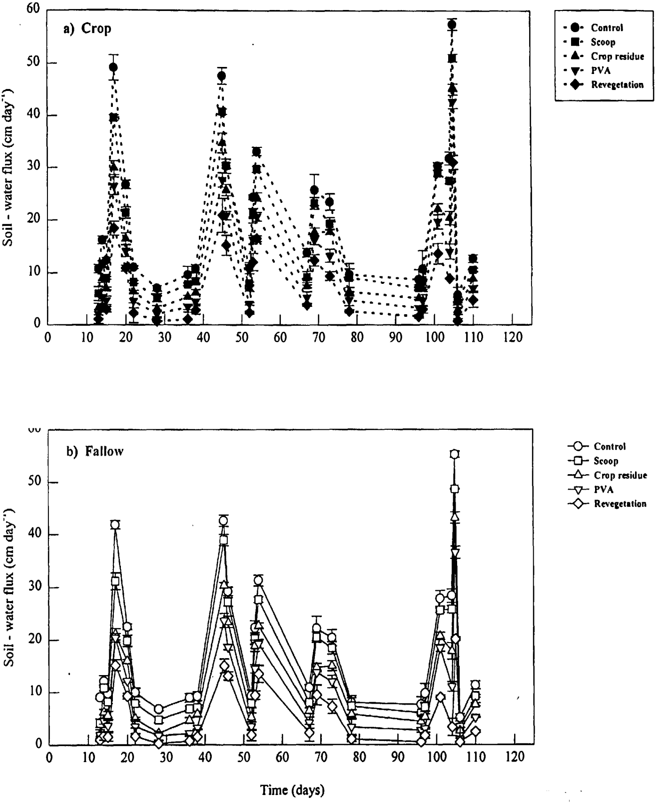

Figure 8. Soil-water flux at 1.95 m depth in different treatments for days when rains were received during 1995 crop growth period indicating deep percolation, for a) cropped and b) fallow. Error bars (⌶) are seen when the symbol is small.

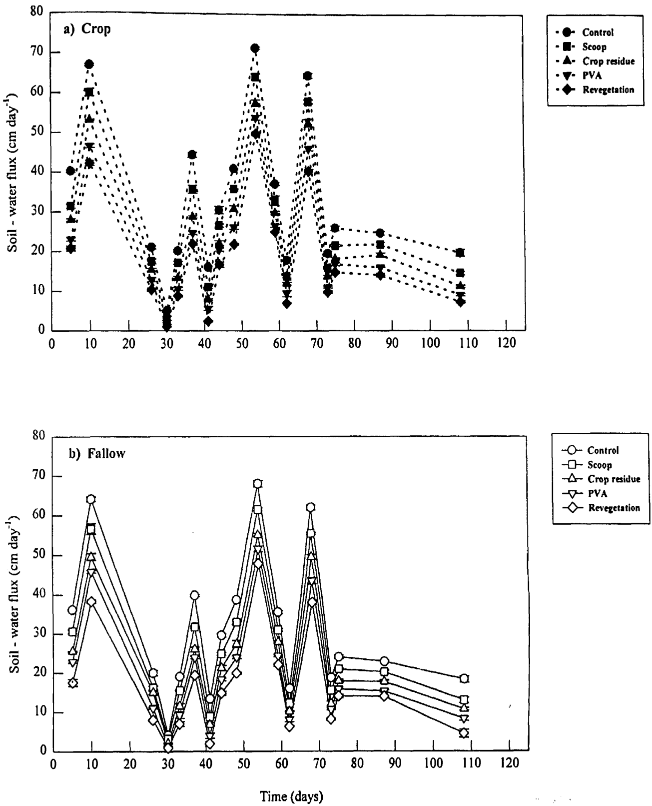

Figure 9. Soil-water flux at 1.95 m depth in different treatments for days when rains were received during 1996 crop growth period indicating deep percolation, for a) cropped and b) fallow. Error bars (I) are seen when the symbol is small.

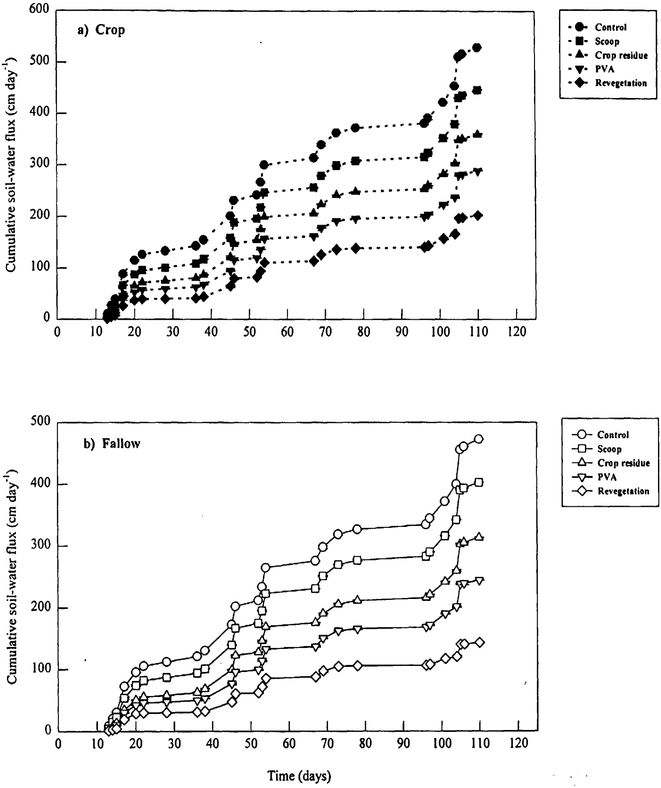

Figure 10. Cumulative soil-water flux by deep percolation from the 1.95 m profile versus time for different treatments in 1995 season, for a) cropped and b) fallow. Error bars (⌶) are seen when the symbol is small.

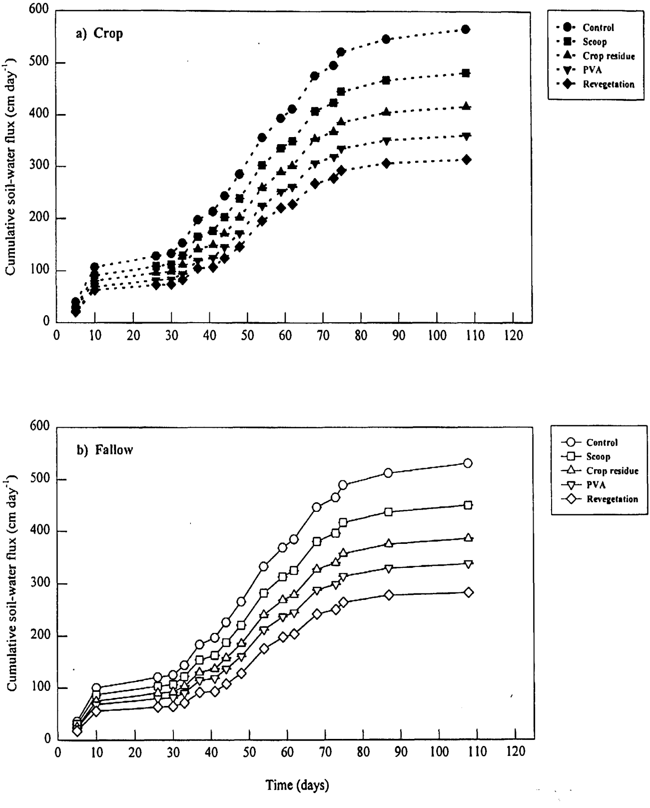

Figure 11. Cumulative soil-water flux by deep percolation from the 1.95 m profile versus time for different treatments in 1996 season, for a) cropped and b) fallow. Error bars (I) are seen when the symbol is small.

indicate that by improving the soil structure it is possible to improve the profile moisture storage and thereby decrease deep percolation losses due to reduced soil water flux. Relatively higher amounts of moisture can be stored in the soil profile and loss due to deep percolation can be reduced considerably. Negative soil water fluxes were also observed during some of the days, indicating the upward movement of water from the 1.95 m depth towards surface. The negative soil water flux occurred when there was a lengthy period without rainfall.

Same data were used to measure the cumulative soil water flux at 1.95 m depth (Figures 10 and 11) for all the treatments. The cumulative soil water flux was highest in the control treatment with the other treatments in the order scoop, crop residue, PVA and revegetation. Both revegetation and PVA treatments have shown the lowest cumulative soil water flux at 1.95 m depth.

Of the sub treatments, fallow has consistently lower cumulative soil water flux at 1.95 m depth than the crop sub treatment. The soil water flux differed significantly in all the treatments during both years. The soil water flux was lower during 1995 than during 1996. This may be due to a deterioration in soil structure after one year of cultivation which may have led to increased soil water flux in 1996. Less water would be stored in the soil profile due to poor structure and hence the soil water flux at 1.95 m depth would increase. These results suggest that cultivation increases the soil water flux thereby reducing the moisture storage capacity of the soil. The cumulative soil water flux was also higher in 1996 than in 1995 in all the treatments.

4.6 Effect of surface management on solute movement

Solute movement was studied using bromide as a tracer, and measuring the bromide flux at different depths in the soil profile to 1.95 m. In this study it was assumed that there was no bromide uptake by the crop and bromide is not toxic to plants (Martin, 1966; Smith and Davis, 1974; Silvertooth *et al.*, 1992). Movement of bromide in the soil profile in different treatments is presented in Figures 12 and 13 (Tables 5 and 6 in Appendix IV). There were significant differences in the bromide flux at different depths in all the treatments. The bromide flux was highest at the surface 0-15 cm layer and it decreased with depth. Least bromide flux was observed at 1.95 m depth which was the lowest depth measured.

The bromide flux is highest in the revegetation treatment where the soil structure was good (Figures 12 and 13). For all the depths the bromide flux was higher in the revegetation treatment than all other treatments. Thus movement of solutes is more in soils where the structure is well developed and hence in such soils there are more chances of nutrient losses. PVA and crop residue treatments also showed relatively higher bromide flux. Bromide flux was least in the control treatment with the scoop treatment showing higher flux. Of the sub treatments, bromide flux was higher in fallow treatment than crop treatment. This was the trend in all the five main treatments. The flux curves are almost linear and the bromide flux decreases with depth (Figures 12 and 13). Flux at 1.95 m depth was minimum indicating that at this depth there is least movement of solutes.

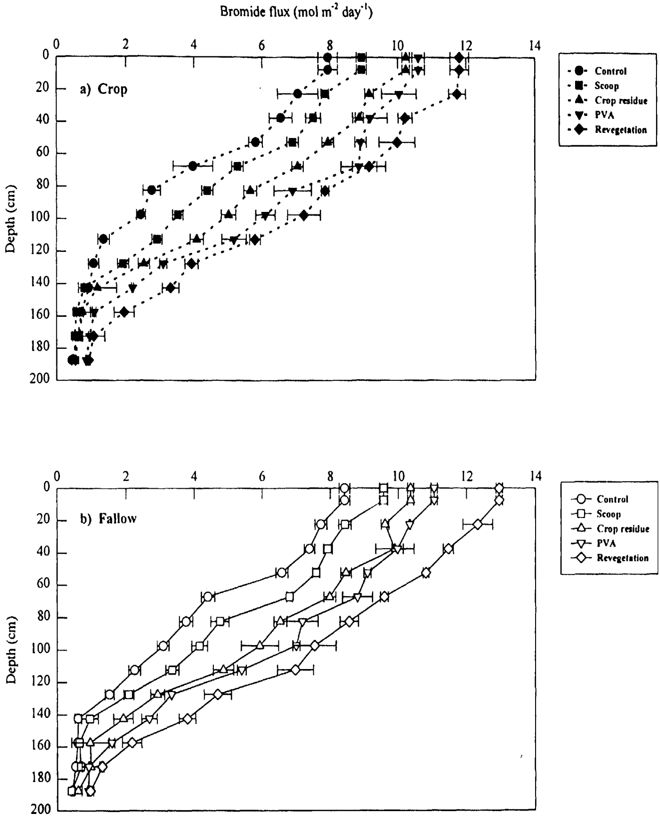

Figure 12. Bromide flux at different depths during 1995 for different treatments, for a) cropped and b) fallow. Error bars (|—|) are seen when the symbol is small.

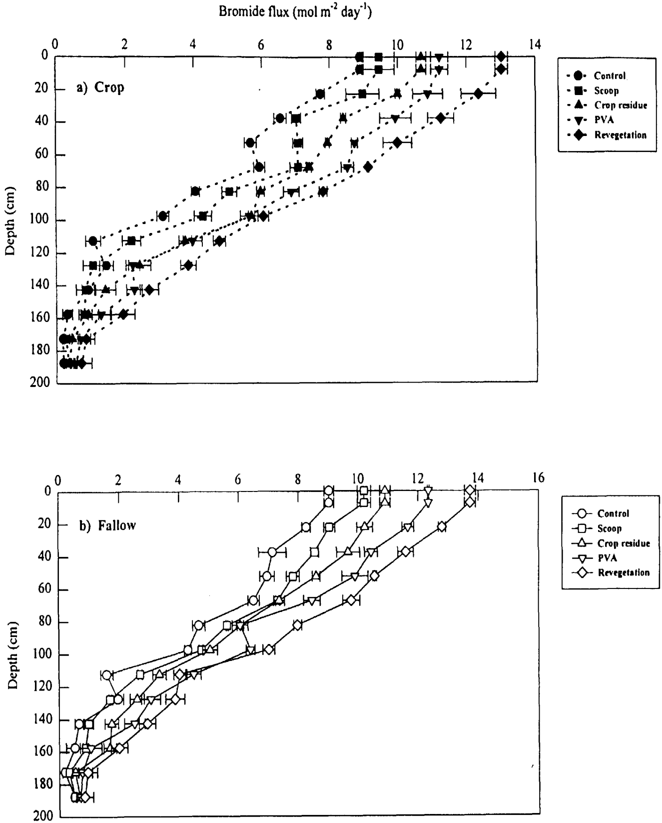

Figure 13. Bromide flux at different depths during 1996 for different treatments, for a) cropped and b) fallow. Error bars (├┤) are seen when the symbol is small.

4.7 Effect of surface management on interception of photosynthetically active radiation (PAR) by the pearl millet crop

Interception of PAR was measured for the crop sub treatment during the crop growth period. Significant differences were observed in interception between all the treatments (Figure 14 and Table 16). In Figure 14 PAR interception increases initially which indicates the development of leaves up to 45 to 55 DAS after which it decreases. The decrease in PAR interception at later stages maybe due to the leaf fall and senescence. This decreases the amount of light that is being absorbed by the crop thereby decreasing photosynthesis. In the initial stages lower PAR interception is due to less number of leaves when the crop is small and the leaves are smaller during that stage. The peaks in the curves in Figure 14 indicate the stage of maximum growth of the crop when it has highest photosynthesis and hence the interception of PAR is also high.

PAR interception was higher in the revegetation treatment than the PVA and crop residue treatments. This indicates that by improving the moisture storage in the soil profile it is possible to improve the crop growth and its light absorption capacity. At all the stages of crop growth the PAR interception was highest for the revegetation treatment. In 1995 there was no significant difference in PAR interception between control and scoop treatments, and between crop residue and PVA treatments, but they were all significantly different from revegetation at 32 DAS (initial stages). At 46 and 60 DAS all the treatments were significantly different whereas at harvest (76 DAS) only crop residue and PVA treatments were not significantly different. In 1996 control and scoop treatments were not significantly different from each other and crop residue, PVA and revegetation treatments

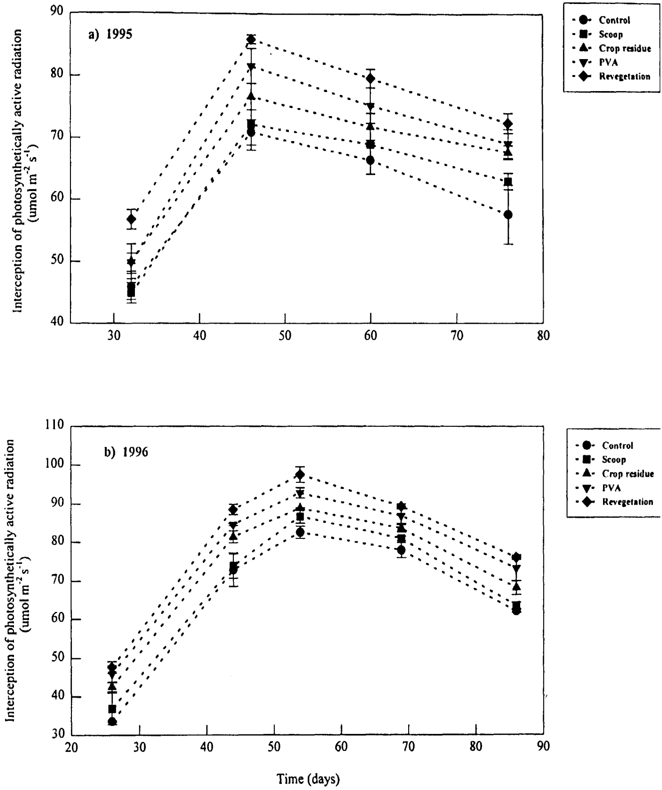

Figure 14. Light interception readings during the crop growth period, for a) 1995 and b) 1996 in the cropped subtreatment. Error bars (I) are seen when the symbol is small.

Table 16. Influence of soil surface management on interception of photosynthetically active radiation (PAR) (μmol m^{-2} s^{-1}) by pearl millet in different treatments of the Alfisol.

Days after sowing	Control	Scoop	Crop residue	PVA	Revegetation plots	S.Em (±)	CD (0.05)
1995	1995						
32	46.0	44.9	50.0	49.9	56.8	1.5	4.5
46	70.9	72.1	76.6	81.6	85.9	1.9	5.7
60	66.3	68.9	71.8	75.2	79.6	2.1	6.3
76	57.6	63.0	67.7	69	72.4	1.8	5.4
1996	1996						
26	33.6	36.9	42.6	45.9	47.6	1.9	5.5
44	72.8	73.8	81.3	84.5	88.5	1.1	3.0
54	82.4	86.6	88.8	92.8	97.5	0.7	2.1
69	77.8	81.0	83.5	86.9	89.3	1.7	5.1
80	62.0	63.4	68.1	73.2	76.0	1.3	3.9

were not significantly different at initial stages (26 and 44 DAS). All the treatments were significantly different at 54 DAS. Of all the treatments, revegetation treatment has shown the highest PAR interception at all the stages than the PVA and crop residue treatments. Control and scoop treatments have shown nearly similar PAR interception.

4.8 Effect of surface management on yields of pearl millet crop

Straw and grain yield were also taken as an index to determine the effect of surface management of soil on the pearl millet performance. Of all the treatments, revegetation treatment has the highest grain yield of millet and this is significantly different from all the other treatments. The data for grain yield of pearl millet crop are presented in Table 17. There was significant difference between the millet yields in all the treatments. Control treatment showed the lowest grain yield of millet with the scoop treatment showing next higher yields.

The pearl millet straw yields showed a similar trend as the grain yields (Table 17) with highest straw yield in the revegetation treatment than the PVA and crop residue treatments showing lower straw yields in that order. Lowest straw yields were in control and scoop treatments. The yields were lower in 1996 than in 1995. This may be attributed to the heavy rains in 1996 which caused the crop to lodge which reduced the millet yields considerably.

Table 17. Influence of soil surface management on pearl millet yields (kg ha^{-1}) of the Alfisol.

	1995		1996	
Treatments	Grain yield	Straw yield	Grain yield	Straw yield
Control	1200	2080	1020	1920
Scoop	1450	2500	1230	2190
Crop residue	2020	3170	1700	2560
PVA	2490	3300	2160	2930
Revegetation	3090	3580	2400	3100
S.Em (±)	44.3	66.6	46.2	86.7
CD (0.05)	132.3	199.8	139.1	260.1

DISCUSSION

CHAPTER V

DISCUSSION

In the results reported in the previous chapter, it was shown that various types of soil surface management affected soil structure, which in turn affected soil properties such as profile moisture storage, deep percolation and solute movement. In this chapter, I will consider the implications of these results and draw conclusions.

5.1 Soil surface management in relation to soil structure

Agricultural management practices have their greatest impact on the structural stability at the level of macroaggregates and macropores (Tisdall and Oades, 1980). Materials responsible for bonding soil particles together may be inorganic or organic in nature. Recovery of soil structural stability when external forces are removed or reduced can contribute to recovery of the structural form. The impact of management practices on structural characteristics can be managed through various surface management practices such as use of crop residue, soil conditioners, surface roughness etc.

Soil measurements made in the experiment reported here for an Alfisol indicate that different surface management practices result in soil surface conditions that differ with respect to bulk density, porosity, aggregate stability, organic carbon percentages, surface roughness, etc., all of which are related to soil structure which influences the profile moisture storage, deep percolation losses and solute movement. Surface management practices are recognised for their value in protecting the soil surface against the impact of falling raindrops thereby minimising aggregate breakdown and surface sealing in the weakly-structured red soils.

Most of the soil physical parameters measured were found to be influenced by the surface management practices tested. An increase in the Mean Weight Diameter (MWD) and Geometric Mean Diameter (GMD), two of the parameters of aggregate stability, was observed in the crop residue treatment over control treatment. Similarly, increase in the aggregate stability and GMD was observed by Skidmore *et al* (1986) by application of residue on the surface. The increase in aggregation was attributed to increased organic matter content of the plots. The MWD and GMD was higher in the PVA treatment than in crop residue treatment which may be due to the strong interparticle bonding as a result of improved contact between PVA molecules and soil particles (Williams *et al.*, 1966) Therefore, there is an increase in the stability of PVA treated aggregates showing greater resistance to frequent disruption. Tables 7 and 8 present the MWD and GMD data from which it is clear that the soil aggregation is better in PVA treated plots compared to crop residue, scoop and control treatment (Kavanagh, 1976, Botha *et al.*, 1981). The revegetation treatment shows higher aggregate stability among all the treatments which can be related to its undisturbed condition for the past 30 years. Soil aggregate stability is an important factor which influences the moisture content of the soil. In all the treatments surface management has affected the soil structure, thereby effecting rainfall acceptance and moisture storage capacity of the soil. Scoop treatment has shown greater stability of aggregates than control treatment, this can be attributed to improvement in surface roughness of the soil (Benjamin, 1993).

A reduction in the MWD and GMD was observed in cropped plots compared to fallow. The results were in confirmation with Utomo and Dexter (1982) who observed a decrease in the stability of aggregates by tillage operation. Different surface management techniques such as tillage, application of conditioners, surface roughness or mulching would cause a change in the stability of aggregates and may increase or decrease the aggregate stability depending upon the type of management techniques adopted. Application of conditioner or residue increases the stability of the aggregates, but tillage results in weakening of the aggregates.

The revegetation soil has shown the highest degree of aggregate stability which was maintained nearly constant during both 1995 and 1996. Carter (1992) also recorded higher MWD values in the direct drilling tillage (revegetation). The MWD and GMD of the revegetation treatment was the highest. Aggregate stability was reduced in the control treatment suggesting that cultivation without any surface management practices leads to a decrease in aggregation. Both the indices of aggregate stability, i.e MWD and GMD, decreased in control and scoop treatment. These results suggest that agricultural practices cause breakdown of aggregates thereby leading to deterioration of soil structure. MWD decreased by 3.92 mm in control crop treatment and 2.02 mm in control fallow treatment from the initial MWD value of 25.65 mm. GMD also showed a reduction of 0.119 mm in control crop (highest decrease) and 0.047 mm in control fallow treatment from the initial GMD value of 0.190 mm. From these results, it is clear that fallowing shows greater degree of aggregate stability compared to cropping.

In the crop sub treatment the aggregates get weakened due to growth of the roots even though in some cases fine roots and hyphae may act as binding agents for formation of aggregates, but their effect on stability of aggregates is very less. The crop sub treatment shows lower aggregate stability, lower porosity and lower MWD and GMD values. Of all the crop sub treatments, PVA crop treatment has shown greater stability than crop residue crop treatment. Least stability of aggregates was observed in the control crop treatment. Tisdall and Oades (1979) have shown that stabilization of aggregates is related to the root length. Therefore, crops help to improve aggregation to some extent but there is no build-up of stable aggregates in the crop area. However, in the fallow sub treatment there is a build-up of the aggregates leading to better soil structure. This may be related to the better soil structure, aggregation and stability of aggregates in the fallow sub treatment compared to crop sub treatment.

Revegetation treatment has shown higher organic carbon percentage than other treatments at all the depths. Beare *et al.* (1994) have also shown that no-tillage management has higher organic carbon content than conventional tillage. The differences in organic carbon content in the different treatments may be attributed to differences in the assimilation and decomposition of the organic matter in all the treatments. In PVA-treated soils the formation and stabilization of aggregates occurs due to application of the conditioner so even though the organic carbon is lower it has shown better moisture storage capacity than crop residue treatment. In crop residue treatment higher organic carbon is related to the humification of straw applied on the surface. Repeated cultivation of soils enhances the decomposition of the organic matter thereby changing the composition of the residual organic matter which increases the dispersibility of clay (Oades, 1984). Humification of the native organic matter may have been more rapid in the PVA applied treatment, therefore the organic carbon content was higher in the PVA treated soils than in control or scoop treatment and was nearly similar to crop residue treatment. Crop residue treatment has shown higher organic carbon percentage than PVA treatment. Doyle and Hamlyn (1960) have made similar observation using VAMA as conditioner.

Decrease in stability of aggregates was associated with a decrease in percentage organic carbon. The revegetation plots have shown the highest stability of aggregates; they also had the highest percentage of total organic carbon (Tables 4, 5 and 6). In the revegetation, non-cultivated soils, plant materials are continually being added to the soil thus resulting in higher organic carbon content. In all the main treatments the crop sub treatment has shown higher organic carbon percentage than fallow, at the three depths. This may be because plant materials are being added to the soil surface in the cropped sub treatment. Lack of cultivation (fallow) is just as important, if not more important than organic inputs alone. Uncultivated fallows normally increase the organic carbon (Doran and Smith, 1987). In the fallow sub treatment minimal amount of plant material are being added and more of the organic material is being oxidised. Therefore, the organic carbon content is less in all the fallow sub treatments. In the crop residue treatment higher organic carbon is due to the presence of surface mulch which on decomposition adds extra organic matter to the soil thereby increasing the organic carbon.

Higher organic carbon was recorded when there was direct drilling (no-till) than when there was conventional cultivation (Ball *et al.*, 1996). The greater stability of soil structure in the revegetation treatment, as can be observed from most of the soil structural parameters, is also due to presence of large amounts of organic carbon. Similarly the organic carbon also causes a lowering of the bulk density since organic matter is considered as an important determinant of soil bulk density. The surface soils of the revegetation plots accumulate organic carbon as a result of humification therefore higher levels of organic carbon were observed in this treatment. Carter (1992) also observed higher organic carbon in the no-till (direct drilled) soil than with conventional ploughing. This he attributed to the decomposition and accumulation of organic matter at the soil surface. In the crop residue treatment due to application of straw mulch the organic carbon is higher compared to PVA treatment. In the crop residue treatment, organic carbon content is higher than the other treatments, but it is lower than in the revegetation treatment. This may be because the crop residue cover was only for one year in that treatment whereas in the revegetation the plant material was retained for the past 30 years.

The organic carbon percentage was lower in 1996 than 1995 season. The soil was cultivated for one year which resulted in increasing the microbial activity thereby leading to oxidisation and decomposition of the organic matter, thus decreasing the organic carbon content during the second year of the experiment. The extra stability of aggregates in the revegetation plots not attributed to total carbon may be due to the distribution and type of organic matter and presence of microbial biomass. The organic colloids and mineral particles are more intimately associated in the revegetation soils (Low, 1973). One year of cultivation of a soil of this type decreases the stability of the soil aggregates considerably by physical disruption of the aggregates and exposing the soil particles on the surface to further physical disruption by raindrop impact. The resistance to external physical disruption was also higher in the aggregates of the revegetation plots which can be one of the reasons for their greater stability. Similarly, the aggregates in the PVA treated soils, due to the application of the conditioner, have also shown greater resistance to the external disruptive forces by the formation of stable aggregates.

Porosity, an important soil structural parameter, was also influenced by the surface management techniques. Increase in porosity was observed in the soils subjected to PVA and crop residue treatment. The increase in porosity in the PVA treatment may be related to formation of strong and stable aggregates which increase the pore spaces between the soil particles thereby increasing the porosity. Similar increase in porosity was observed by Doyle and Hamlyn (1960) by application of VAMA, a soil conditioner. Porosity is a function of aggregate size and stability therefore it can safely be stated that application of soil conditioner PVA has resulted in increased aggregation and higher porosity. Similarly crop residue cover also increases aggregation, therefore porosity in crop residue treatment was also higher than control treatment but lower than PVA treatment. In control and scoop treatments there was a decrease in porosity from the initial porosity. This is consistent with cultivation causing breakdown of aggregates and therefore reduced porosity. Highest porosity was recorded in the revegetation plots where the soil had not been disturbed for the past 30 years. Cultivation of the soil leads to a decrease in porosity, and there was decrease in the porosity in the second year of cultivation. Within one year, porosity decreased by 0.01 in the revegetation crop treatment and by 0.02 in the revegetation fallow treatment. In all other treatments there was a decrease in porosity in 1996. PVA-treated soils also showed decrease in porosity which suggests that application of conditioners under cultivation will also cause a change in porosity.

Changes in bulk density is one of the foremost parameter studied wherever soil structural changes are involved. There was significant impact of different surface management practices on bulk density. The lowest bulk density (1.56 Mg m^{-3}) was recorded in the revegetation fallow treatment. Bulk density of crop residue treatment was lower than scoop treatment but higher than the PVA treatment. Maintenance of straw on the surface would lead to lowering in the bulk density (Table 2). Application of conditioner PVA has also resulted in decreasing the bulk density which means that mulching and conditioner application are two best means which can be adopted to improve the soil structure in terms of bulk density. The lowest bulk density was recorded in the revegetation treatment and these results are consistent with the findings of Oleschko *et al.*, (1996). In their studies also they have observed that the no-till soil has shown lower bulk density than the cultivated soils. Highest bulk density was recorded in the control crop treatment with scoops treatment showing lower bulk density. These results suggest that surface roughness reduces the bulk density to some extent. Bulk density increased during second year of the experiment as a consequence of one year of tillage. The bulk density in 1996 was higher in all the treatments than in 1995 (Table 2). Chan and Heenan (1996) also observed that cultivation of the soils results in increasing the bulk density.

The different structure modifying ability of the various surface management techniques could be related to the effectiveness with which aggregates are formed and the stability of these aggregates as well as the method of formation of the aggregates either by binding action with conditioners as in the case of PVA, or by the microbial action and production of organic matter as in case of crop residue or by the formation of aggregates due to surface roughness as in the case of scoops or due to no-till management as in the case of revegetation treatment.

Some of the other important soil structural parameters include sorptivity, steady state flow rate (infiltration), hydraulic conductivity and characteristic mean pore size. All these parameters were found to be influenced by surface management techniques. These parameters are influenced by change in porosity and aggregate stability, therefore any change in these two soil factors would affect these surface hydraulic properties.

Revegetation treatment has shown the highest sorptivity (130 mm $h^{-1/2}$ in fallow sub treatment) than PVA, crop residue, scoop and control treatment in that order. Higher sorptivity in the revegetation treatment is due to better porosity, higher mean pore size and greater aggregate stability. PVA-treated soils also have shown relatively higher sorptivity because of greater aggregation, better pore size distribution and aggregate stability than crop residue treatment. PVA, being a conditioner, is adsorbed on the soil particles, improving aggregation and leading to higher sorptivity. Scoop treatment, due to surface roughness, has better aggregation, therefore, it has shown higher sorptivity than control treatment, where the soil structure collapses easily. Sorptivity was higher in the fallow sub treatment than the crop. Better aggregation and porosity, as well as higher aggregate stability and mean pore size in the fallow sub treatment, are consistent with the higher sorptivity in the fallow than cropped sub treatment.

Surface hydraulic conductivity was also found to be influenced by the different surface management practices. Hydraulic conductivity was greater in the revegetation treatment both in cropped and fallow sub treatment than the other treatments. Sharratt (1996) also has recorded higher hydraulic conductivity readings in the no-tillage soil compared to conventional tilled soil. These differences in hydraulic conductivity in all the treatments can be related to structural differences as all the management techniques were found to influence soil structure considerably. Higher hydraulic conductivity in the revegetation treatment may be related to better soil structure in this soil.

Cultivation has led to deterioration in soil structure which resulted in the decrease in hydraulic conductivity between 1996 and 1995 (Table 11). Between crop residue and PVA treatments the latter has shown better hydraulic conductivity (Skidmore *et al.*, 1986). The differences in hydraulic conductivity may be related not only to soil structure. Other mechanisms are also operative such as organic carbon content, porosity, aggregate stability, aggregate size distribution, mean pore size etc., all of which are influenced by the various surface management practices and therefore would affect hydraulic conductivity. Skidmore *et al.* (1986) recorded an increase in the hydraulic conductivity by maintaining a surface cover. Incorporation of crop residue is not as effective as leaving the residue on the surface where it decomposes less rapidly and continues to replenish the cementing products for a longer period. PVA treatment has recorded higher hydraulic conductivity which may be due to greater aggregate stability and higher mean pore size produced by PVA than crop residue treatment (Stefanson, 1973). The soil aggregates from the PVA plots were more stable than aggregates from crop residue plots. These factors may be involved in increasing the hydraulic conductivity in the PVA treatment compared to crop residue treatment.

The mean pore size in the revegetation plots was highest with PVA and crop residue treatment showing lower values (Table 12). Because of the larger mean pore size it is to be expected for such soils to admit water readily, have adequate oxygen diffusion and allow rapid root development. The revegetation soil is characterised by a system of continuous wide pores stretching from the surface to the depth of rooting. Pores of > 50 μm are required to allow water to drain freely and pores of 0.50 to 50 μm are required for water storage in the soil to be used by the plants, which are present adequately in the revegetation plots. Similar type of pore size distribution can be observed in the PVA treatment which shows the next highest mean pore size. Scoop treatment have shown higher characteristic mean pore size because of surface roughness than control treatment which causes collapse of the seedbed.

The characteristic mean pore size decreased in 1996 in all the treatments, which may be due to degradation of the soil structure as a result of cultivation. The mean pore size was always higher in the fallow sub treatment which can be attributed to better aggregation and greater continuity of the pores in fallow than cropped sub treatment. Higher infiltration and more stable aggregates are generally associated with fallow soil conditions and are essential requirements for a good tilth. These may be the reasons why the characteristic mean pore size was always higher in the fallow sub treatment in all the main treatments compared to the crop sub treatment.

5.2 Rate of application of polyvinyl alcohol (PVA) on profile soil moisture of an Alfisol

Increase in the rate of application of PVA resulted in increasing the amount of moisture stored in the soil profile (Figure 4). In the control treatment on application of rainfall by the simulator relatively higher runoff was recorded compared to the PVA treated soils. The soil in the control treatment collapsed immediately after receiving rainfall of 60 mm h^{-1} intensity but the soils which were treated with PVA remained stable maintaining aggregation on the surface. The PVA treated soils were also seen to be more porous compared to control which on receiving rainfall became smooth and compact in nature. Oades (1976) also observed that the PVA treated soils (red brown sandy loam type) were highly porous and aggregated compared with untreated soils.

This increase in aggregation in the PVA-treated soils resulted in high amount of moisture storage in the soil profile in all treatments of the PVA-treated soils over control. The higher profile moisture storage can be attributed to the improvement in the soil structure due to application of conditioner PVA to the soil surface. PVA gets sorbed on the soil particles and results in binding the particles together thereby increasing stability of aggregates. There is also a linear increase in the moisture storage capacity of the Alfisol soil in the top 1.50 m soil profile (Table 11). Stefanson (1973) has also recorded an increase in the rainfall acceptance with increase in application rate of PVA. In his studies he found that the optimum application rate of PVA was 30 to 60 kg ha^{-1}, which compares with Blavia *et al.* (1971) who found it to be 70 to 100 kg ha^{-1} PVA. In the present study also PVA at the rate of 100 kg ha^{-1} was found desirable for use in the main experiment as one of the main treatments since it has shown highest moisture storage in the soil profile which is not significantly different from the 150 and 200 kg ha^{-1} rate of PVA application. PVA stabilises the large pores in the soil and prevents the blocking of these pores by detached soil materials thereby increasing rainfall infiltration and its storage in the soil. PVA has a very high degree of effectiveness in improving aggregation and stability of aggregates. Based on the results of the pilot experiment PVA at the rate of 100 kg ha^{-1} was used in the main experiment.

5.3 Soil surface management in relation to profile moisture storage

PVA treatment was more effective than crop residue, scoop and control treatments in increasing the profile moisture storage when applied on the surface of the soil. The differences in increasing moisture storage by PVA treatment compared to crop residue treatment may be related to its effect on the soil structural parameters. PVA was found to have a greater impact on all the parameters which affect soil structure compared to crop residue. This resulted in improved moisture storage in the PVA-treated soils compared to crop residue-treated soils. Scoop treatment was found to have a better moisture storage capacity than control treatment. The greater moisture storage by scoop treatment may be attributed to the excess water retained on the surface for a longer period of time in the pits resulting in lesser runoff losses. This also allowed more time for water to infiltrate into the soil leading to higher moisture storage than in control treatment in which the excess water was lost as runoff.

Application of PVA and crop residue on the surface would help to preserve the soil moisture by increasing infiltration and decreasing runoff losses. By using such management practices water conservation can be increased because the potential for increased water storage and decreased runoff is greater due to PVA and crop residue. Higher moisture storage was recorded in the crop residue treatment throughout the growing season than control treatment. Unger (1978) also observed that bare soil without any mulch cover (eg. control fallow treatment) has lower moisture storage capacity compared to mulched soil (eg. crop residue fallow treatment).

Application of PVA increases the time required for runoff to occur which means that most of the rain water is allowed to infiltrate into the soil. Similar observations were made by Oades (1976) wherein there was an increase in the time for runoff and decrease in the volume of runoff by application of PVA, indicating that most of the rainfall had entered into the soil and was stored in the soil profile and very little was lost as runoff. In the crop residue treatment also the infiltration of rain water into the soil was more and runoff was less. In crop residue treatment the decrease in runoff was mainly due to the presence of mulch on the surface which enhanced infiltration and retarted the flow across the surface, whereas in PVA treatment it was due to the formation of stable aggregates and increase in porosity which increased infiltration and reduced runoff. The moisture storage was always higher in the PVA-treated soils. This means that improving the stability of aggregates is superior to mulching for increasing the profile moisture storage. Stabilization of surface structure influences several factors and infiltration of rainfall is one of the most significant among them (Oades, 1976). Increased infiltration leads to greater water storage as was the case in this study. Steady state flow rate (infiltration) was higher in the PVA-treated soils compared to the other treatments except revegetation treatment (Table 10). Scoop treatment had higher water storage than control, but lower than PVA and crop residue treatments. The increase in water storage in the soil profile in the scoops treatment, over control, may be due to greater time available for the water retained in the pits to infiltrate into the soil. Because infiltration is increased more water will be stored in the soil profile provided the soil has the capacity to store the additional water. Increasing the moisture storage capacity of the soil, increases the available water to the crops. These results suggest that by improving the moisture storage capacity of the soil through adoption of surface management techniques, it is possible to fill the soil profile moisture reservoir of the red soils in the SAT conditions.

The soil water use by the millet crop has also influenced the water storage capacity of the soil considerably. Moisture storage in the crop sub treatment in all the main treatments was lower than in fallow. This is related to the water used by the crop for growing (Unger, 1978). The revegetation crop sub treatment has shown higher moisture storage than PVA and crop residue crop sub treatment, even after the crop utilization. Desirable tilth and better soil structure in the revegetation crop treatment compared to the other treatments has resulted in the higher moisture content in this treatment The scoop crop treatment has shown higher moisture storage compared to control crop The presence of standing water in the scoops, which has allowed more water to infiltrate into the soil may be responsible for the higher moisture storage in the scoop crop treatment Additional water stored in the soil profile and effective use of seasonal rainfall on the revegetation, PVA and crop residue treatments resulted in reducing the plant water stress thereby allowing greater response of pearl millet to precipitation

In the fallow sub treatment higher moisture storage than crop sub treatment may be related to the better aggregation and soil structure as well as to absence of crop for using the stored water Fallowing is usually suggested for rejuvenation of the soil structure and to allow the rain water to be stored in the soil so as to replenish the depleted moisture Fallow sub treatment has shown greater efficiency in storing moisture in the soil profile which is comparable with reports in literature (Lopez *et al*, 1996) Greater infiltration is the main advantage associated with fallowing which resulted in higher moisture storage in the fallow sub treatment than the cropped

The various surface management techniques have resulted in different amount of moisture storage in the same red soil These differences are a reflection of the differences in soil structure which occur as a result of application of either a conditioner or straw mulch or surface roughness which affect the soil structural features such as porosity, hydraulic conductivity, sorptivity, mean pore size etc (Chan and Heenan, 1996) Depth of water penetration is a major factor in increasing the soil water storage in the soil profile and this is influenced by soil structural improvement

Revegetation plots have shown the highest moisture storage in the soil profile both in the crop and fallow sub treatments. The highly developed soil structure and aggregation in the revegetation plots may be related to the high moisture storage in this treatment (Watts *et al.*, 1996). Many soil factors are likely to enhance or limit the long term effects of surface management on soil structural condition and in turn on the profile moisture storage capacity of the soil. Revegetation plots (no-till) were very effective in improving the soil water storage capacity. Better moisture storage capacity in the revegetation plots is due to the favourable soil structure and accumulation of organic material on the soil surface over the years which lead to increased infiltration and profile moisture storage. In the revegetation plots there is greater number of continuous minute fissures which enhance infiltration of rain water into the soil. Furthermore large number of earthworms and earthworm casts observed in these plots, produce additional channels for the rapid infiltration of rain water thus increasing the profile moisture storage (Goss *et al.*, 1978). Another contributory factor is the greater stability of the surface soil which reduces the extent to which channels are obstructed by the deposition of colloidal and other fine materials carried downward by rainfall. All these factors contribute to the rapid infiltration of rain water in the undisturbed revegetation plots. These factors vary in their importance depending on the soil type and other soil factors.

Significant differences in soil water storage resulting from the effect of surface management techniques on structure occurred on nearly every parameter of the soil structure. The untilled treatment (revegetation) provided structure which was very stable to various disruptive forces, whereas in the disturbed treatments (PVA, crop residue, scoop and control) it was less stable and in some cases collapsed, leading to lower moisture storage compared to revegetation treatment. Control treatment showed the greatest collapse in soil structural parameters (Hamblin, 1982). It can be postulated then that the influence of higher organic matter, higher pore size, greater stability, better pore continuity and fissures, have resulted in greater moisture storage in the revegetation treatment as against PVA and crop residue treatments.

Structural differences between revegetation, PVA, crop residue, scoop and control treatments are known to give very different flow rates which in turn influence the profile moisture storage of the red soils (Cassel *et al.*, 1974). The condition of the soil surface, in all these treatments, as a receptor and transmitter of water in liquid and vapour phases thus plays a critical role in affecting the moisture storage capacity and may account for the variations in the moisture storage capacity in all the treatments.

From the results it is evident that while disturbed soil surfaces (PVA, crop residue, scoop, control) initially contained larger number of conducting pores and hence conducted water into the subsoil at a faster rate, this situation is transient. In the undisturbed soil (revegetation) the advantage is at a later stage in relation to the unsaturated water movement (sorptivity and steady state infiltration rate) which are more relevant to water gain and loss. The relative accumulation of organic matter on the surface layer in the revegetation treatments may have been responsible for maintaining greater stability of pore geometry compared to the other four treatments.

In the results presented here there is substantial evidence that differences in porosity, aggregate stability, hydraulic conductivity, sorptivity, characteristic mean pore size and pore geometry arise as a result of adoption of various surface management techniques. These differences have a considerable influence on the measured aspects of water retention and movement not only in the top soil but also at depth. The most pronounced difference occurred between the control treatments and the revegetation treatments. Significant differences in moisture storage was also observed in the other treatments namely PVA, crop residue and scoop (Hamblin and Tennant, 1981). From these results it can be inferred that most of the soil water could be lost through deep drainage in the disturbed treatments as water moves more rapidly within the ploughed profile than in the revegetation treatment. The differences noted in the first year of the experiment, persisted over the second year also.

5.4 Infiltration and deep percolation in relation to soil surface management

Soil water flux (cm day^{-1}) was measured at the depth of 1.95 m using the hydraulic gradient and hydraulic conductivity values. Soil water flux was highest in the control crop treatment with the next lower soil water flux in the control fallow treatment. PVA treatments have shown lower soil water flux whereas crop residue treatment has shown higher soil water flux with revegetation plots showing the least soil water flux. Results from the cumulative soil water flux data (Figures 10 and 11) suggest that control treatment shows the maximum loss of water due to deep percolation at 2.00 m depth. Revegetation and PVA treatments have shown the least loss of water due to deep percolation losses.

Infiltration is an important basic process which controls surface runoff, soil water storage and deep percolation. Soil factors which affect infiltration rate and finally the deep percolation include aggregate stability, hydraulic conductivity, characteristic mean pore size, bulk density, etc. Any change brought about in these factors, due to surface management, would affect the moisture storage and deep percolation losses. In the present study changes in most of the above soil factors due to surface management techniques were observed which resulted in changing the infiltration and thus affecting both profile moisture storage and deep percolation.

In the revegetation plots water moves through the continuous macropores, resulting in sustained high infiltration rates. Most of the rain water which has infiltrated into the soil was stored in the soil profile therefore the water flux at 1.95 m depth was less leading to lower deep percolation losses. Hence the loss of water due to deep drainage was the least in revegetation treatment. In the PVA treatment there was improvement in aggregation due to application of the conditioner which resulted in improving the pore geometry thereby increasing the infiltration and improving the profile moisture storage of the soil thus reducing the deep percolation losses. Therefore the soil water flux at 1.95 m depth is lower in the PVA-treated soils than in crop residue treatment.

For deep drainage to occur it is necessary that the soil profile is fully charged with moisture. Only after the storage capacity of the soil profile has reached saturation would it lead to runoff on the soil surface and deep percolation losses at greater depths within the soil profile. In control and scoop treatment the soil showed lower moisture storage, therefore in these two treatments water flux was the greatest at 1.95 m depth suggesting larger deep percolation losses (Edwards *et al.*, 1988).

Measurements made under field conditions reveal that type of surface management has an influence on infiltration, water storage capacity and hence on deep percolation. Soil measurements made in conjunction with soil water flux at 1.95 m depth indicated that different surface management practices resulted in soil surface conditions that differed with respect to aggregate stability, organic carbon concentration, surface roughness, mean pore size, all of which are related to water infiltration and storage in the soil profile. Surface management techniques also affected the length of time that water had to be applied to attain constant infiltration rates. Aggregate stability had a strong influence on infiltration rate and it may be dominant factor involved in the deep percolation losses.

The different surface management techniques help in protecting the soil surface against the impact of falling raindrops and thereby minimise the breakdown of aggregates and prevent surface sealing, which can reduce infiltration considerably. Scoop treatment had higher infiltration than control treatment and the deep percolation losses were also less, because of higher moisture storage in the soil profile. Greater infiltration in the scoop treatment than in control treatment can be attributed to disruption of surface crust, roughening of the soil surface and presence of surface depressions (pits) to temporarily store water on the surface, thus providing more time for infiltration (Unger, 1992).

Mathan and Mahendran (1994) observed that aggregate stability, bulk density, exchangeable sodium percentage (ESP), porosity are some of the factors which influence infiltration rate and deep percolation losses. Application of PVA enhances the pore geometry, this can be attributed to the physical bonding between soil constituents which increases infiltration and moisture storage thereby decreasing the deep percolation losses. Moreover the addition of such organic compounds can modify the wettability of the soil surface, thereby improving the interaction with water (Painuli and Pagliai, 1990). This results in improved infiltration and water storage thereby decreasing the deep percolation losses. In crop residue treatment the decomposition of the residue results in the production of stable soil aggregates which have a long term effect on increasing infiltration as well as water storage which lowers the deep percolation losses (Chaney and Swift, 1984). In the scoop treatment a major fraction of the rainfall was stored in the depressions, which gets lost as runoff in control treatment. This water stored in the scoops (pits) will have more time to infiltrate into the soil thereby leading to moisture storage, or causing deep percolation losses, depending on the capacity of the soil.

Deep water movement is a significant part of the total water lost due to flux at 1.95 m depth. Flux below the root zone at 1.95 m depth is important in studies related with moisture storage to determine the deep percolation losses. Water flux in all the treatments was higher on days when heavy rains were received whereas flux was less when low rains were received. But at all times flux was highest in the control treatment. Soil water flux was lowest in revegetation treatment with PVA, crop residue and scoop treatments having higher flux in that order.

Of the sub treatments, flux was higher in the crop sub treatment than fallow sub treatment in all the main treatments. The improved pore size distribution, greater number of large size pores and higher moisture storage capacity in the fallow sub treatment maybe related to the lesser deep percolation losses in fallow sub treatment. Lower infiltration, poor soil structure and reduced soil moisture storage capacity may have enhanced the deep percolation losses which has resulted in higher flux at 1.95 m depth in the cropped sub treatment for all the main treatments.

The cumulative soil water flux was also highest in the control treatment. Revegetation treatment has shown the lowest cumulative soil water flux than PVA, crop residue, and scoop treatment in that order, which indicates lesser deep percolation losses in the revegetation treatment than in PVA, crop residue and scoop treatment. The major factors contributing to higher water content and lesser cumulative soil water flux in the revegetation treatment were greater infiltration resulting from better pore size distribution, larger pores, and greater aggregate stability. Surface management techniques change the porosity of the soil surface considerably, thereby influencing the water storage capacity of the soil, which in turn influences the soil water flux causing deep percolation losses.

In the PVA-treated soils the increase in infiltration and profile moisture storage can be attributed to the modification induced by the PVA, to the pore shape, as the increase in elongated pores, which resulted in lesser deep percolation losses than crop residue, scoop and control treatments. In crop residue treatment the beneficial effect was the protection provided to the soil surface covered with mulch against rainfall impact energy and dissipation of the energy. Surface cover also reduces evaporation by preventing the vapour to move to the surface. These factors contribute towards increasing the profile moisture storage thus reducing the deep percolation losses (Aujla and Cheema, 1983).

Soil is a medium where water movement depends not only on the pores but also the interaction occurring between the water and soil matrix. The roughness of the soil particles and the actual pore geometry are important factors to be considered during water movement, but the influence of these factors on water movement is difficult to assess. The adsorption of uncharged polymer molecules like PVA results in lining of the soil pores which stabilizes the aggregates and thereby improve the water flow through the soil. The contact angle would also be decreased leading to better water flow. Therefore, the water storage in PVA-treated soils is higher compared to crop residue-treated soils. PVA, due to its mode of attachment, is most effective in influencing water conducting properties of the soil, thereby affecting deep percolation losses. PVA-treated soils show lower deep percolation losses than crop residue, where the water storage is mainly due to reduced evapotranspiration losses, hence in this treatment the deep percolation losses were more than in PVA treatment. The differences in deep percolation losses between scoop and control treatment may be due to greater roughness and surface storage in the scoop treatment than in the control treatment (Freebairn *et al.*, 1989). Stable porosity due to application of PVA facilitates easy transmission of water through the soils and this leads to increase in infiltration rates. By adopting different surface management techniques there is a possibility to increase the potential for water storage in the soil, thus reducing the deep percolation losses. Water was able to move into the soil profile instead of being lost as surface runoff which resulted in better water storage and lower deep percolation losses by using these surface management techniques (Mannering and Meyer, 1963). Depending on the frequency of rainfall, even small amounts can be effective in keeping the soil surface wet and contribute to the soil water reservoir when appropriate surface management techniques are employed to increase infiltration and reduce deep percolation losses.

In the control treatment soil dries rapidly to depth of tillage whereas in crop residue and PVA treatment this is not the case and in scoop water retained in the depressions will help to replenish the water lost from the tillage layer. Crop residue and PVA treatment extend the time that the surface layer of the soil remains wet, thereby there is improvement in profile water storage and this reduces the deep percolation losses (Aase and Tanaka, 1987).

5.5 Soil surface management in relation to solute movement

As stated in section 5.2 soil surface management increases infiltration rate, decreases surface runoff and enhances water storage in the soil profile. Greater infiltration and permeability of the soils under different surface management conditions would increase the potential for the transport of agricultural chemicals from the surface to deeper layers. Preferential flow of water occurs through macropores under saturated conditions due to movement of water through the large surface connected, continuous pores. Along with water, movement of various agricultural chemicals like nitrogen, herbicides etc. also occurs through the macropore flow. Bromide has been used as a tracer to document the chemical movement through the soil profile subjected to various surface management practices in this study.

Bromide flux was measured as it moved along with water. Dispersion of bromide in the soil probably occurred as a result of the time delay between rainfall and soil sampling. Bromide was detected even at 1.95 m depth in all the treatments during both seasons, which can be attributed to the heavy rainfalls received during both years. Bromide flux in the soil involves an interaction between the surface management techniques adopted and its effect on the soil structural features through either their improvement or deterioration.

Bromide flux was higher in the revegetation plots than in PVA, crop residue, scoop and control treatments. Greater flux of bromide in the revegetation plots may be attributed to the better porosity and infiltration leading to macropore flow (Bicki and Guo, 1991). Bromide flux was lower in the control treatment than in scoop which has shown higher flux, whereas bromide flux was higher in PVA treatment than in crop residue treatment. These results indicate that a substantial potential exists for nitrate leaching through soil profile under different surface management practices to depths below 1.95 m depth as indicated by the bromide flux curves (Figures 12 and 13).

Higher bromide flux is observed at depths 0 - 15 cm and the bromide flux decreases with depth. Potential for leaching of nitrates is more during heavy rainfalls and early in the season, when consumptive use and plant uptake is less. Therefore there is a need to minimise early or presowing application of fertilizer nitrogen and splitting application of nitrogen fertilizer into smaller ones throughout the growing season would minimise the potential of nitrate loss under these surface management conditions, otherwise most of the nitrogen would be lost due to leaching as indicated by the bromide flux data.

Differences in physical characteristics of the soil surface as a result of surface management techniques result in affecting the bromide flux through the soil profile and produce observable differences in bromide movement (Bruce *et al.*, 1985). In soils having better aggregation (eg. revegetation) the bromide flux was found to be higher than in soils having poor aggregation (eg. control). The bromide flux in the revegetation was highest at all depths which can be attributed to the better aggregation, porosity, pore size distribution, pore geometry and higher infiltration rates in this treatment. PVA has also shown higher porosity and stable aggregates which has lead to the next highest bromide flux being in this treatment rather than in crop residue treatment. In control treatment all the soil structural parameters were poor, hence in this treatment the bromide flux was lower than all other treatments including the scoop treatment.

In the revegetation plots which is characterised by the presence of macropores, the bromide flux would have occurred through these macropores. These macropores are a part of the basic soil structure. It is the same in PVA treatment where the soil conditioner resulted in improved aggregation, forming macropores which have led to higher bromide flux than in the crop residue, scoop and control treatments. In the control as well as the scoop treatment, movement of bromide may occur through the fine soil pores, either because macropores are lacking (as in scoops) or because of the presence of a crust (as in control), which did not allow the bromide movement to occur through the macropores that were present. This may be the contributory factor for the lower bromide flux in the control and scoop treatments.

Each of the structures in all the treatments show a significant difference in the bromide flux. This illustrates that management of the soil surface results in different well-defined textural porosity or basic soil structure which exhibits variation in solute (bromide) movement within the soil profile due to changes in the soil structural features. The effect of large continuous pores due to stable aggregation (as observed in the revegetation treatment) was very apparent with bromide movement being highest at all depths in revegetation treatment. Solute flux maybe primarily through the macropores in this treatment. Soil morphological studies emphasize the description of larger pores as individuals, in terms of size, shape and arrangement which are formed as a result of improved aggregation, leading to greater bromide flux (Bouma and Anderson, 1977). However, in control treatment, presence of the finer pores affects the solute (bromide) flux and hence lower flux rates were observed in this treatment.

Leaching losses of nitrates were always higher in the mulch plots (killed sod applied as mulch) as compared to conventionally tilled plots as observed by McMahon and Thomas (1976). This can be attributed to intensive leaching in the mulched plots. Similarly in the present study also bromide flux was higher in the crop residue treatment than in scoop and control treatment. But higher bromide flux was observed in the well aerated PVA-treated soils, which may be related to better water movement through the soil profile, greater aggregation, better porosity, higher hydraulic conductivity and better pore size distribution in this treatment than in crop residue, scoop and control treatment. Scoop treatment has also shown higher bromide flux than control treatment which may be attributed to the improved soil physical characteristics and higher infiltration as a result of surface roughness (Granovsky *et al.*, 1993). High surface roughness will enhance the movement of mobile soil chemicals into the soil profile (Ahuja *et al.*, 1983).

Anions like bromide and nitrate move through the soil along with water flow and hence are lost due to leaching. Mostly anions like bromide and nitrate do not associate with the soil matrix because of the electrical repulsion which prevents the association of bromide and nitrate even with water near the negatively charged soil surface. Hence bromide and nitrate move through the soil along with water. Differences in the movement of bromide through the soil profile in all the treatments may be attributed to the differences in the soil structure as a result of imposing the various surface management practices (Smith and Davis, 1974). In the control treatment, due to tillage effect, the soil aggregates are pulverized. This physical disturbance would eliminate the larger pores creating smaller pores, consequently reducing the bromide flux which is related to the lower flux of bromide at all depths in this treatment. The soil hydraulic properties are significantly influenced by surface management techniques, thereby leading to differences in bromide flux in all the treatments with the highest flux observed in the revegetation treatment with PVA and crop residue showing lower fluxes This study indicates that large connected pores as observed in revegetation and PVA treatments are important pathways for bromide movement and would increase the bromide flux within the soil profile (Kissel *et al* , 1973, Shuford *et al* , 1977)

Connectivity among macropores is also important for bromide flux to occur and the soils in the revegetation treatment have a good network of pores which resulted in higher bromide flux in these soils (Germann *et al* , 1984) Maintenance of crop residue also results in increased bromide flux This is because of two factors Firstly the upward movement of salts is completely stopped because evaporation from the soil surface in the crop residue treatment is nil compared to evaporation from bare soil surface (control treatment) Secondly runoff is reduced and entire rain water moves into the soil thereby moving the bromide along with it which is also the reason for higher bromide flux in scoop treatment than in control treatment In PVA treated soils the macropores formed as a result of aggregation result in the development of a network of pores which allow greater infiltration of rainwater thereby causing bromide to move into the soil profile leading to bromide flux which is higher than in crop residue treatment Most of the water flow occurs in the larger pores in a well aggregated soil (revegetation and PVA treatment) causing bromide to move into the soil profile The results indicate that improving the soil aggregation by no-till management (revegetation plots) or by addition of conditioners (PVA treatment) leads to large losses of solute Mulching of the soil surface (crop residue treatment) would also result in solute losses, but these are lesser compared to other treatments (PVA, revegetation treatments) Control treatment has shown the least loss of solutes as the bromide flux is lowest in this treatment due to crusting problem, but loss in this treatment may occur due to runoff

Water flowing from the large flow channels carry the dissolved bromide deep into the soil profile along with it, showing greater bromide flux near the surface and lesser bromide flux at greater depths In well-structured soils like revegetation plots and PVA-treated plots large amounts of surface applied bromide is lost due to greater and deeper turbulent transfer of bromide in a large number of macropores formed (Tyler and Thomas, 1977)

Pore geometry, pore connectivity, uniformity, pore size distribution and pore shape play an important role in solute movement Soil having higher pore size distribution and lower bulk density (revegetation, PVA treatments) would cause more of the bromide to be eluviated to greater depths In solute transport through soils that are characterized as having greater proportion of larger pores as in revegetation and PVA treatment, a large fraction of the bromide could be transported because bromide concentrates in pore centres and moves with the most rapidly flowing water Because of repulsion of bromide anions from the soil surface very little of these bromide anions maybe entering smaller pores or pores with constricted openings Therefore a small fraction of the bromide would be transported through soil with a smaller proportion of larger pores, as in control and scoop treatment, since smaller amounts of bromide would concentrate in the centres of intermediate and smaller-sized pores which are found in more abundance in the control and scoop treatments Therefore the bromide flux is higher in the revegetation and PVA treatments with crop residue and scoop showing lower bromide flux and control showing the least bromide flux (Smith *et al*, 1995) The volume of water required to remove same amount of bromide from the soils having larger number of large pores (revegetation and PVA treatments) and smaller number of large pores (crop residue, scoop and control treatments) would be greater in soils having less proportion of larger pores

The bromide flux was higher in the fallow sub treatment and lower in the cropped sub treatment among all the main treatments Fallowing improves soil structural features thereby it enhances the water infiltration There is also improvement in porosity, mean pore size, pore size distribution and pore geometry due to fallowing All these factors contribute to higher bromide flux in the fallow sub treatment than in cropped In the crop sub treatment lower bromide flux is recorded which may be attributed to the lower porosity and poor pore geometry Bromide flux depends on the presence of macropores which are found in large numbers in the fallow sub treatment and in lesser numbers in the crop sub treatment This may be attributed to the higher bromide flux in the fallow sub treatment compared to cropped

5.6 Soil surface management in relation to pearl millet growth and yield

The different surface management techniques were observed to have significant influence on pearl millet growth and yield Growth of pearl millet was measured in terms of interception of the photosynthetically active radiation (PAR) Interception of PAR was significantly affected by improvement in soil structure and profile moisture storage capacity Interception of PAR was highest in the revegetation treatment followed by PVA, crop residue, scoop and control The higher PAR interception in the revegetation treatment means that there is better plant growth and leaf development rates due to availability of sufficient moisture at all the stages of the pearl millet crop growth The crop did not face any moisture stress during its growth therefore the leaf development was good which resulted in higher PAR interception Proper development and good growth of the leaves in the revegetation and PVA treatments has resulted in higher PAR interception at all the stages of the crop in these two treatments In control treatment the leaves could not intercept PAR efficiently This resulted in lower PAR interception in control as well as scoop treatment Pearl millet crop did not show significant differences in light interception at initial stages but at maximum growth stage (45 to 55 DAS) there was significant difference in PAR interception during both seasons The differences again disappeared when millet crop reached maturity and harvesting

Soils treated with conditioner resist crusting and also provide a better environment for crop growth and root development by providing very good network of pores in the soil due to aggregation (Painuli and Pagliai, 1990) Higher moisture storage in the soil profile results in increasing the soil water use efficiency of the crop especially in revegetation, PVA and crop residue treatments The higher soil water use resulting from greater infiltration and moisture storage in the soil during the growing season, resulted in better leaf development thereby increasing the light interception ability of the millet crop

Additional water stored in the soil profile in revegetation PVA and crop residue treatments at planting and the more effective use of seasonal rainfall reduced the plant water stress and permitted greater response of pearl millet to precipitation especially during critical stages like booting, flowering and grain filling which had a beneficial affect on the grain yield also In scoop treatment also pearl millet showed better response to the moisture stored in the soil profile thereby showing better leaf development, higher light interception and greater yields compared to control treatment

By adopting different surface management techniques, it is possible to increase the available soil water for plant growth by improving the precipitation storage in the soil This results in decreasing the water stress for the millet crop at critical growth stages It would also help to increase vegetative growth and leaf development thereby increasing light interception and the final yields as this would lead to higher production of photosynthates which are required for pearl millet crop development and growth.

Pearl millet grain and straw yields were also significantly influenced by adopting different surface management techniques. The available soil water at planting and also during the entire crop growth period influence the millet yields considerably. Because of high profile moisture storage the water availability was also good and this has resulted in higher yields in the revegetation and PVA treatment than in crop residue and scoop treatments. In the control treatment the amount of moisture storage in the soil profile was lower and hence water available to the millet crop was less, thereby reducing the crop yields. The greater response of pearl millet to water storage obtained in the revegetation, PVA, and crop residue treatments indicate an additional beneficial effect of these surface management practices through more efficient use of the growing season rainfall.

In this study increased precipitation storage as soil water due to adoption of different surface management techniques results in increasing the available water and also it improved the precipitation use efficiency thereby resulting in production of higher dry matter and greater yields. Due to increase in moisture storage the grain yields were more than doubled in the revegetation and PVA treatments compared to control, during both the seasons. Lower yields during 1996 was due to lodging of the crops as a result of heavy rains.

The differences in the yields among the different treatments can be solely ascribed to the improvement in the soil structural features which have resulted in increased moisture storage in the soil profile Because care was taken to see that all the other factors such as nutrient supply, pest and diseases control etc were similar for all the treatments during both years Therefore any difference in pearl millet performance is attributed to the soil structural improvement and the various favourable influences it has on profile water storage, nutrient status and deep percolation losses

By improving the soil structure there is a chance for better development of the root system and this results in improving the capacity of pearl millet to obtain water from the soil even from greater depths All these factors are responsible for getting higher yields in the revegetation, PVA and crop residue treatments than in scoop and control (Low, 1973, Stefanson, 1974) Significant increase in the yields of tomato with increase in aggregation, total pore space and porosity was observed by Doyle and Hamlyn (1960) In this study also an improvement in soil structural features have resulted in increasing the yields of pearl millet crop

5.7 Conclusions

The results suggest that application of conditioner and crop cover significantly increase all the soil structural parameters relative to control treatment Such surface management-induced changes provide the means to enhance the structural stability of these inherently unstable red soils of SAT in a relatively short time Methods of the study used to quantify the degree of soil structural stability suggest that reduced or minimum tillage (revegetation) can provide the potential for an improved distribution of stable aggregates for optimum transport of air and water However, the low resistance of these red soils to slumping due to heavy rains and their limited potential for regeneration of adequate macroporosity, without any addition of mulch or conditioner or surface roughness, emphasises the need to combine improved surface management techniques, as listed above, which reduce excessive soil compaction and improve aggregation and aggregate stability, if the potential benefits of soil structural stability are to be realised.

The soil structural differences developed as a result of surface management are well characterised by their hydraulic properties as well as by a description of porosity, aggregate stability, pore size distribution etc. All these parameters are involved in improving the profile moisture storage of the soil in different treatments. The value of water stored in the soil for obtaining favourable yields in the red soils of the arid and semi arid regions has long been recognised. The value of surface management by using conditioners, or by crop residues, or surface roughness or no tillage methods to improve profile moisture storage have been only recently realized. The additional water being stored in the soil as a result of surface management has resulted from an increase in water infiltration due to development of favourable soil structure. These practices also help to conserve the limited soil and water resources in the arid and semi arid regions.

Higher water storage in the revegetation soils can be attributed to greater ability to store water under zero tillage compared to conventional tillage, resulting in greater water reserve. This increased capacity to store water is attributed to the rearrangement of the pore size distribution and improved soil structure (Zhai *et al.*, 1990). The influence of surface management techniques on soil water characteristics will depend on the type of surface management technique adopted, climate and soil properties.

The pattern of water flow within a soil profile does not provide sufficient information to describe the physical conditions controlling water flow nor the precise locations in transport volume where the uniform applied fluxes of water were redistributed. Based on the results of deep percolation losses we arrive at the following conclusions: surface management techniques affect the soil structural features such as aggregate stability, mean pore size, porosity and surface roughness, therefore water infiltration is increased. This leads to greater water storage depending on the capacity of the soil. Once the water storage of the soil profile is saturated it leads to deep percolation losses. Surface residues (as in crop residue treatment) were found to increase infiltration. Loosening of the soil by scoops and creating surface roughness is effective in increasing water infiltration into the soil and can be used in areas where residue are limited. Using PVA also enhances infiltration due to development of stable aggregates. The PVA treatment has resulted in higher infiltration and water storage capacity of the soil profile than the other treatments and the soil structural features in this treatment were resembling that of the revegetation plots.

Improvement in soil physical properties as a result of different surface management techniques would lead to better profile moisture storage and thereby reduce the deep percolation losses. There is increase in porosity due to surface management compared to control which led to the observable increase in hydraulic conductivity as well as infiltration rates due to improvement in the water transmitting ability of the soil. This has resulted in improved water storage and reduced deep percolation losses.

The results presented show a dramatic effect of surface management techniques on the movement of a mobile chemical, bromide, in soil. This chemical is transported through the various macropores to deeper layers into the soil profile. These findings have an important implication for interpreting the transport of surface applied fertilizers and herbicides under field conditions. These findings suggest that promoting surface soil structural improvement through surface management techniques would result in leaching of surface-applied agricultural chemicals in general, especially where surface runoff is not a problem like in revegetation, PVA and crop residue treatments. The results show that improving aggregation results in development of a network of pore system which causes leaching of mobile chemicals such as bromide and nitrate through the soil matrix. The bromide flux curves indicate that the flux decreases with depth and it is minimum at 1.95 m depth.

These findings have an important application in selecting the surface management techniques and fertilization application, including timing, depth of placement and form of fertilizers needed to minimize the loss of surface applied chemicals due to solute movement. These results are important to determine the surface management techniques which can be adopted in the red soils of SAT to improve moisture storage and reduce deep nutrient losses through various means like timing, placement, split application etc. for better crop growth.

From this study it can be concluded that use of conditioner like PVA would help to improve the soil structure to induce the status of the revegetation plots. In this study revegetation plots are taken as the second or main control with which the other treatments are compared to check which of the surface management techniques would improve the soil structural features so that it approaches the revegetation treatment. PVA-treated soil was found to improve the soil structure which has resulted in significantly increasing the profile moisture storage over control (cultivated control plots). The use of surface cover not only enhances the organic carbon content of the soil, but also improves the profile moisture storage over control plots, but is less efficient than PVA. Scoops is not preferable as it is not very effective in improving the soil structure and profile moisture storage and requires disturbing the soil. Therefore, among all the treatments PVA treatment improves the soil structural features substantially compared to crop residue and scoop and would outdo these treatments in bringing the soil structure approaching the revegetation plots.

SUMMARY

CHAPTER VI

SUMMARY

Soil structure is an important soil physical aspect which influences not only many other soil properties but also the crop growth and yield. Many surface management techniques can be adopted which affect soil structure through formation as well as stabilization of aggregates. The changes brought about in the soil structural features are reflected in soil physical properties such as porosity, bulk density, aggregate stability, sorptivity, hydraulic conductivity, steady-state flow rate, mean pore size etc. Soil structure is not a static property and changes with water content and other agencies of stress. The formation of aggregates and pores and their stabilization is very important to maintain a good soil structure and to increase productivity of the soils. Stable aggregation and proper pore size distribution determine a good soil tilth. Crusting and sealing are the major constraints related with the red soils of the SAT. These red soils are characterised by lack of structural development due to low content of fine clay particles and poor organic matter in the surface layers. Due to poor structure and unstable aggregation these soils tend to form crusts and thereby adversely affect crop establishment. These soils also have low water retention characteristics as a result the profile moisture storage is also less.

In experiments conducted at ICRISAT Asia Centre during *kharif* season of 1995 and 1996, different surface management techniques were adopted to determine their effect on the soil structure. The treatments include control (normal cultivation), scoops (depressions excavated with hand tools), crop residue at 5 t ha^{-1} on the surface, polyvinyl alcohol (PVA) at 100 kg ha and revegetation (second control) with two sub treatments i.e. cropped (sown with pearl millet) and fallow (kept bare), with three replications in a simple completely randomized split-plot design. It was assumed that by modifying the soil structure, infiltration of rain water into the soil profile may increase. Consequently there is increase in the precipitation storage capacity of the soil. Since any soil has a finite water storage capacity therefore the increased rain water infiltration would then enhance deep percolation losses. As water percolates it will carry dissolved solutes with it thereby leading to movement of solutes beyond the rooting zone. Measurements taken included those related with soil structure such as porosity, bulk density, organic carbon, MWD, GMD, sorptivity, steady-state flow rate, hydraulic conductivity and mean pore size. Moisture content readings were taken at 15 cm depth intervals using the neutron probe moisture metre for determining the moisture storage capacity of the soil. Moisture potential readings were taken from tensiometers installed in the field for determining the soil-water flux and deep percolation losses. For solute movement study, bromide was used as a tracer and soil samples were collected from depths at 15 cm intervals for bromide estimation.

Bulk density, an important soil structural feature, decreased in all the treatments except in control and scoop treatments. Lower bulk density readings indicate an improvement in soil structure as observed in the PVA and crop residue treatments both in the crop and fallow sub treatment. Lowest bulk density was observed in the revegetation plots. PVA-treated plots have reduced bulk density such that it is comparable to revegetation plots indicating that it can be used to improve the soil structure. Fallow sub treatments have shown lower bulk density values than cropped.

Increase in porosity was also observed in all the treatments except control treatment in which porosity decreased. Porosity influences many of the soil hydrological properties through its effect on pore size distribution, pore shape, pore geometry etc., hence it is important in any study involving soil structure improvement. Porosity was highest in the revegetation plots. PVA-treated plots have shown lower porosity values than revegetation plots, but it can be more effectively used to improve the soil structure than crop residue or scoop treatment. Porosity decreased in the control treatment indicating deterioration of soil structure. Porosity values were lower during 1996 than 1995.

Organic carbon which is also an important factor contributing towards soil structural improvement through its binding action on soil particles was also recorded. Highest organic carbon percentage was observed in the revegetation treatment. Crop residue treatment showed higher organic carbon than PVA treatment but lower than the revegetation treatment. The humification of the millet straw resulted in increasing the organic carbon percentage in the crop residue treatment. Control treatment had the lowest organic carbon and the scoop treatment was a little higher in organic carbon than the control. Of the sub treatments, fallow treatments showed lower organic carbon than crop treatments. This is attributed to the addition of organic matter to the soil due to the presence of crop through leaf fall, roots and stubble remaining in the crop treatment.

Results for aggregate stability indicate that the aggregation is better in PVA treatment than crop residue treatment and that the revegetation plots have the highest aggregate stability. Scoop treatment has shown better aggregation than control treatment due to better surface roughness. These results suggest that surface management by various means such as conditioner, mulching, surface roughness etc., help to improve aggregation.

Surface hydraulic properties such as sorptivity, steady state flow rate, hydraulic conductivity and mean pore size were also determined and the results also suggest that application of the conditioner, PVA, is superior to crop residue cover or scoop treatment in improving all the surface hydraulic properties. Higher sorptivity, steady state flow rate, hydraulic conductivity and mean pore size was recorded in the PVA treatment than in crop residue, scoop and control treatments, and hence the PVA-treated plots can be said to improve the soil hydraulic properties. The revegetation plots have shown the highest values for sorptivity, steady state flow rate, hydraulic conductivity and mean pore size. In scoop treatment also all the surface hydraulic properties showed an improvement over control treatment. These results suggest that application of conditioner like PVA is the best means of improving soil structure to get better aggregation and stabilization of the aggregates.

A study was conducted to determine the effect of rate of application of PVA during 1994 post rainy (*rabi*) season. Application of PVA increased the amount of water stored in the soil profile. The rate of 100 kg ha^{-1} was superior to either 50 or 25 kg ha^{-1} and on par with 150 and 200 kg ha^{-1} of PVA application. Based on this study, PVA at the rate of 100 kg ha^{-1} could be used as one of the main treatments in the surface management studies.

Different surface management techniques were studied to determine their effect on moisture storage in the soil profile through soil structure improvement. Of all the treatments, revegetation (no-till) has shown the highest moisture storage. Better infiltration rate, higher hydraulic conductivity, larger pore size and presence of large number of macropores may have resulted in the greater capacity of these soils to store the moisture. PVA treatment has shown better moisture storage than crop residue, the better aggregation and pore geometry may have led to higher moisture storage in this treatment and hence PVA conditioner can be used to improve the moisture storage capacity of the soil. Scoop treatment has also shown higher moisture storage than control treatment, which may be related to the greater surface roughness and longer time of standing water in the pits allowing water to infiltrate fully into the soil and reducing runoff.

Deep percolation losses were higher in the control treatment than the other treatments. This can be attributed to the lower moisture storage in the soil profile in control treatment due to poor pore geometry and lower porosity leading to greater deep percolation and runoff losses. Thus, the amount of moisture entering into the soil and the storage of rain water in the soil profile are both reduced. Deep percolation losses were lesser in the PVA treatment than in crop residue, which is attributed to the higher moisture storage in the PVA treated plots than crop residue plots. This resulted in greater deep percolation losses in the crop residue treatment than in PVA treatment. Revegetation plots have shown the least deep percolation losses because of the higher amount of moisture stored in the profile of these soils due to better porosity and pore size distribution. Fallowing has resulted in higher moisture storage than cropping, in all the main treatments. Therefore deep percolation losses are lower in the fallow than the crop sub treatment. These results suggest that fallowing improves moisture storage capacity of the soil and reduces the deep percolation losses.

Movement of bromide through the soil profile was studied to evaluate the effect of surface management techniques on solute movement within the soil profile. Bromide flux was highest in the revegetation plots with PVA and crop residue treatment showing lower fluxes. At all the depths in the soil profile, bromide flux was higher in the revegetation plots than in PVA and crop residue treatments. PVA treatment has shown higher bromide flux than crop residue treatment which can be attributed to better aggregate stability and higher aggregation in the PVA-treated plots than in crop residue-treated plots. These results are consistent with the idea that bromide moves with the bulk water through the macropores, and since there was a higher porosity and better pore geometry in the revegetation and PVA-treated plots, they have shown the highest bromide flux. Scoop treatment had higher bromide flux than control treatment, due to better surface roughness in the scoop treatments. Of the sub treatments, fallow has shown higher bromide flux at all depths in all the treatments than the crop sub treatments.

Pearl millet growth and performance was also influenced by the various surface management techniques. The highest photosynthetically active radiation (PAR) interception during the crop growth period was in the revegetation plots than in PVA, crop residue, scoop and control treatments in that order. PAR interception increased with growth of pearl millet and was highest at maximum growth stage (i.e 45 to 55 DAS), and decreased at later stages due to senescence of leaves. Significant differences in PAR interception were observed only at 45 to 55 DAS when pearl millet was at its maximum growth. PAR interception affects the formation of photosynthates and hence the growth and development of a crop. Therefore, differences in the PAR interception between the treatments was reflected in the pearl millet yields. Revegetation plots had higher yields than the PVA and crop residue treatments. The reduction in incidence of moisture stress at all the stages in the revegetation, PVA, and crop residue treatments resulted in higher pearl millet yields in these treatments than in the scoop and control treatments. Control treatment was in turn lower yielding than the scoop treatment.

Future research needs

There are a range of surface management techniques available that modify the soil structure. They involve the use of organic inputs, as with conditioner, and crop residues, a combination of organic inputs and lack of disturbance as in no-till management, or surface roughness manipulation to mention a few. A better understanding of the effects of various surface management techniques on soil structure and other soil properties may lead to the development of even better surface management techniques.

Much work has been done on the effect of residue management and tillage on soil properties. There has been much less research on the effect of conditioners on soil physical and chemical properties. One of the important drawbacks is the high cost of the conditioners, which limits their use in the field where it might be required in large amounts. Research on the effect of conditioners on soil structure, aggregation and aggregate stability is available, but there has been little research on the effect of conditioners on moisture storage, deep percolation and solute movement. Literature cited suggests that very little work has been done on the effect of surface roughness on soil properties such as moisture storage and deep percolation and there is little known about the effect of surface roughness on solute movement. Therefore, further research needs to be done on the effect of surface roughness on soil properties such as deep percolation, moisture storage and solute movement. Scoops are also an important means for improving the moisture storage in the soil profile.

Much research has been done on moisture storage and deep percolation losses by using residue cover and zero tillage. But research on the effect of residue cover and zero tillage on solute movement is very less. There is a need to study the effect of residue cover and no-till management on nutrient losses leading to ground water contamination due to leaching of surface applied chemicals. In this study the bromide flux was measured with the assumption that anions move along with the bulk water movement through the soil which can be described by Darcy's law. This description may not be adequate for defining the movement of dissolved anions. It is necessary to measure the tracer concentration distribution moving through a soil-water system so that the mechanism of both anion and water movement is more clearly understood. The distance that anion travels through the soil is determined by the tortuosity of the total path length. The path followed by each ion will vary and depend on the convection, diffusion and chemical processes which occur in different soils.

It may not be possible to produce sufficient crop residue to influence soil structure in the arid and semi-arid regions. Use of PVA is not economical, and making of scoops is time consuming and requires manual labour. Consequently additional research, in searching for new and cheap soil conditioners, or developing new surface roughness techniques, or using the crop residue available more effectively etc., is needed to develop suitable systems for improving profile moisture storage for all soils so that crop production potential will be maintained or improved. Only by adequately conserving the soil and water resources can we be assured that future generations will have adequate resources for producing food. There is a need to develop approaches which are cheap, easily available and can be easily adopted by the farmers to overcome the problems of soil structure in the Alfisols of the SAT regions. Once the soil structural problems such as crusting and sealing have been solved by adopting surface management techniques, it may be possible to increase the yields of crops to meet the demand of the growing population.

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APPENDICES

APPENDIX I

Table 1. Weekly mean meteorological data during the experimentation period.

Standard Weeks	Rainfall (mm)	Evapora. (mm)	Temp. max (°C)	Temp. mini (°C)	RH 7 (%)	RH 14 (%)	Wind Velocity (kmph)	Sunshine (hr)	Solar radiation (Mj m^{-2})
(1995) 1	0.0	27.5	26.9	13.3	87.6	35.4	9.6	8.6	16.1
2	11.4	24.1	26.0	15.1	94.4	55.0	8.4	7.5	13.5
3	28.6	22.2	24.6	13.0	95.7	61.7	7.9	7.3	14.3
4	0.0	31.4	27.6	11.9	92.1	35.3	5.2	10.0	19.1
5	0.0	33.8	27.2	13.9	92.0	42.3	7.9	9.3	17.9
6	0.0	35.6	30.0	16.3	93.0	42.1	7.9	9.9	18.5
7	0.0	49.3	31.6	16.1	81.6	27.4	8.2	10.3	20.1
8	0.0	41.7	32.5	15.4	76.9	26.3	5.7	10.1	19.9
9	0.0	52.6	33.6	18.1	77.7	25.4	7.8	10.0	19.7
10	0.0	68.3	34.3	19.7	76.3	23.3	12.6	10.2	21.3
11	7.8	66.2	33.0	21.0	75.7	32.9	10.6	9.4	19.4
12	0.0	64.5	35.7	21.4	59.6	23.1	7.2	9.6	21.4
13	44.4	58.9	34.8	19.9	72.9	29.0	9.4	9.5	17.6
14	0.0	66.4	36.1	22.7	68.9	26.7	10.2	9.2	20.4
15	0.0	81.4	37.4	21.6	59.7	20.1	11.2	10.7	24.0
16	8.8	62.8	36.1	22.4	67.7	27.3	9.0	9.8	20.7
17	0.0	74.4	38.6	23.9	59.7	22.1	8.6	9.7	24.3
18	0.0	71.6	37.4	24.2	62.0	27.1	9.0	8.8	21.7
19	3.6	62.8	34.6	23.2	67.0	44.0	14.9	6.0	16.8
20	8.8	87.9	37.5	23.4	59.9	30.4	17.2	8.1	22.4
21	31.4	79.7	37.5	23.5	57.9	24.9	9.7	9.4	23.9
22	0.0	85.6	39.7	25.0	51.4	18.7	10.0	11.2	25.3
23	0.0	17.8	41.5	27.4	55.0	18.4	19.3	8.6	23.4
24	61.6	88.2	38.4	25.6	69.0	32.3	13.5	9.4	23.3
25	52.0	38.5	32.2	23.1	82.6	59.0	13.0	3.4	16.6
26	26.0	35.2	30.5	23.5	88.0	73.3	13.6	2.3	13.5
27	35.2	46.1	32.7	23.4	86.0	53.4	12.9	5.5	19.0
28	59.2	33.2	31.1	23.1	89.4	64.3	12.7	2.8	15.7
29	54.8	19.7	27.6	22.7	90.7	78.1	17.2	0.6	10.1
30	99.4	32.8	29.1	22.0	95.3	72.7	12.5	3.8	15.6
31	7.0	33.7	30.1	22.7	91.1	69.0	11.7	4.8	17.7
32	26.2	34.5	30.9	22.9	89.1	62.6	10.1	5.3	17.3
33	30.0	38.7	30.4	22.9	88.9	60.9	10.1	8.0	21.2
34	112.0	32.9	30.7	23.0	94.9	67.3	7.0	5.9	19.6
35	70.4	21.4	28.0	22.6	94.0	79.9	13.4	1.3	11.1
36	2.5	36.7	30.0	21.0	89.9	57.4	12.4	8.0	20.6
37	60.3	28.9	30.7	22.3	95.1	67.1	5.4	5.2	17.0
38	50.1	29.3	29.1	22.5	92.6	75.7	7.4	3.2	13.8
39	0.0	32.7	31.8	22.1	94.1	54.0	5.3	7.7	21.3
40	6.5	33.9	32.1	20.5	94.1	56.0	4.0	7.9	18.5
41	90.6	31.1	29.1	21.7	95.7	65.6	4.9	1.6	12.1
42	257.6	20.9	26.4	21.1	97.6	93.6	8.8	1.0	7.1
43	6.3	23.7	28.5	19.4	94.4	68.9	4.8	6.8	16.1
44	0.0	32.6	29.8	16.6	95.0	47.6	4.9	10.1	20.1
45	0.0	32.2	29.4	15.4	91.9	44.6	5.4	10.3	19.9
46	0.0	34.6	29.6	15.4	90.1	37.4	5.4	9.7	18.6
47	13.0	29.3	29.1	18.0	93.6	54.7	6.3	8.5	15.8
48	0.0	31.6	28.9	16.4	92.0	42.3	6.9	8.6	16.8
49	0.0	29.6	28.7	14.6	92.6	42.1	4.7	9.1	16.0

50	0.0	29.1	28.4	12.4	94.7	32.1	4.9	10.1	17.3
51	0.0	29.6	28.8	12.5	97.0	37.0	5.6	10.0	17.1
52	0.0	29.4	27.4	15.2	93.4	43.3	8.7	9.6	16.2
(1996) 1	0.0	34.1	27.7	15.3	89.9	36.7	10.6	10.1	17.5
2	0.0	33.4	29.3	15.0	92.0	34.3	8.4	9.4	16.8
3	0.0	33.7	30.3	17.0	93.0	35.3	8.0	9.3	16.4
4	0.0	37.0	30.0	14.4	89.7	34.7	5.5	10.1	17.7
5	0.0	42.0	30.5	15.7	87.7	34.1	7.6	9.9	17.5
6	0.0	46.0	29.8	15.4	87.3	30.7	9.3	10.2	18.6
7	0.0	36.9	29.6	17.6	91.7	43.6	8.7	8.1	16.1
8	0.0	49.5	33.6	17.1	87.0	25.6	6.5	10.1	21.4
9	0.0	60.5	33.6	17.2	78.6	26.9	10.3	10.6	22.6
10	0.0	54.6	33.0	16.6	72.6	29.4	7.5	10.2	22.4
11	0.0	63.8	36.4	19.5	61.1	19.9	7.2	10.0	21.7
12	0.0	59.2	36.1	19.5	61.3	20.0	7.7	8.0	20.8
13	0.0	61.4	38.8	21.7	64.1	17.7	6.6	10.1	22.8
14	0.0	64.0	37.0	22.6	77.1	23.4	10.1	9.0	21.7
15	20.0	57.5	35.8	21.3	73.1	27.7	7.9	7.7	20.2
16	18.8	47.8	34.3	21.6	80.7	35.4	8.1	8.6	22.1
17	1.6	59.3	37.6	23.7	70.4	30.0	8.7	9.8	23.1
18	0.0	85.2	40.9	24.9	45.7	21.4	10.9	10.4	25.3
19	0.0	90.6	41.0	23.6	38.1	12.6	11.0	10.8	26.2
20	0.0	93.5	40.0	24.0	36.9	19.3	10.5	11.5	26.7
21	0.0	76.9	40.1	25.6	47.4	21.7	9.8	9.6	23.5
22	8.6	76.8	40.3	25.8	61.7	24.9	12.2	9.2	23.4
23	18.4	32.1	37.9	25.0	67.1	38.0	10.9	5.3	17.1
24	21.6	13.3	34.3	23.6	83.6	50.3	0.0	5.5	18.9
25	7.1	53.4	32.9	23.2	83.0	54.0	21.6	4.6	18.5
26	37.0	63.0	34.6	24.2	72.6	39.0	16.0	6.1	20.2
27	2.4	58.2	34.2	24.1	75.3	42.4	13.6	6.9	20.3
28	91.4	32.7	32.4	22.8	90.2	52.5	10.1	5.0	19.1
29	75.6	42.3	31.5	22.9	88.1	60.4	15.4	5.5	17.7
30	23.5	34.8	29.1	22.7	89.1	70.4	20.3	1.5	13.0
31	34.6	38.2	30.4	22.0	88.7	60.4	19.0	4.8	16.5
32	54.6	37.6	30.3	22.3	87.3	60.9	15.0	4.7	16.7
33	34.8	15.3	28.1	22.4	94.4	82.3	9.9	1.6	12.5
34	147.4	22.0	29.3	22.0	96.3	76.6	5.7	3.1	13.2
35	197.8	22.6	27.9	21.8	95.1	77.0	12.1	2.9	10.6
36	49.4	19.5	28.9	22.2	96.3	77.7	4.8	4.5	14.8
37	47.6	20.3	29.3	22.3	95.1	70.7	3.9	3.4	15.7
38	64.4	28.1	29.1	21.6	93.3	79.0	9.3	5.0	16.4
39	0.0	37.8	31.5	21.8	91.0	54.4	3.8	8.0	21.6
40	59.6	33.1	29.2	22.1	91.9	71.0	11.5	3.3	13.3
41	0.0	38.4	30.4	19.6	89.6	48.4	4.0	7.8	20.6
42	7.3	40.9	30.1	18.5	82.0	47.4	4.0	8.2	16.8
43	13.1	21.7	28.0	21.1	93.6	70.9	7.4	4.5	12.4
44	3.6	27.5	29.1	18.1	90.6	53.1	4.0	7.6	15.6
45	22.4	36.9	29.3	16.0	83.7	41.0	7.3	9.1	18.5
46	0.0	31.8	30.2	18.3	86.3	44.9	3.1	9.7	17.6
47	0.0	31.0	28.3	13.8	86.0	46.3	3.8	8.1	16.3
48	0.0	28.7	28.8	13.2	90.1	41.6	3.6	9.5	14.9
49	0.0	30.0	27.4	13.1	91.4	40.7	3.7	7.7	16.0
50	0.0	28.7	27.8	13.5	78.4	35.3	3.8	6.5	13.4
51	0.0	29.4	28.1	15.4	85.1	45.1	5.9	6.1	13.8
52	0.0	29.0	28.0	11.3	89.3	31.7	3.4	9.5	16.7

APPENDIX II

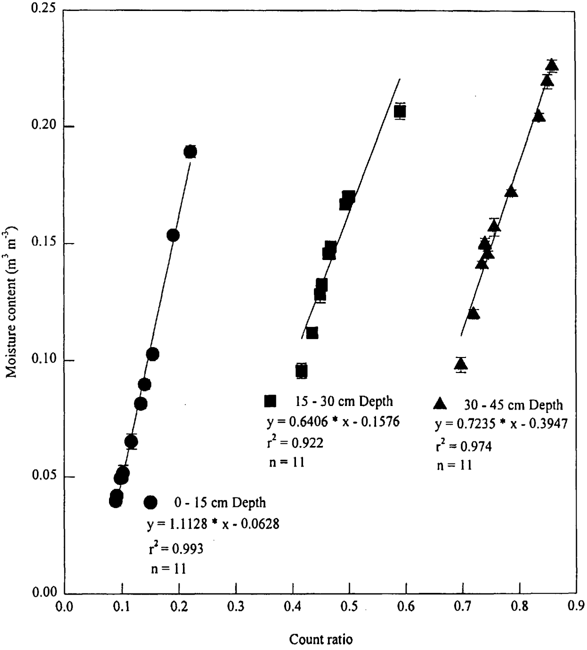

Figure 1. Neutron probe calibration curve for three depths from 0 to 45 cm.

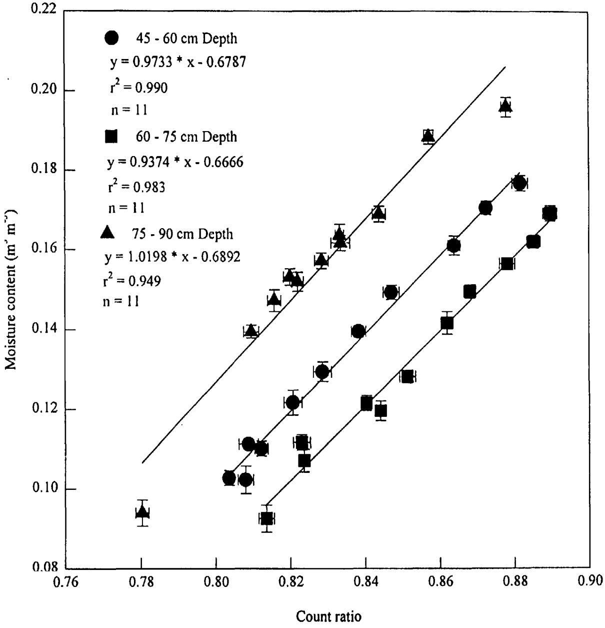

Figure 2. Neutron probe calibration curve for three depths from 45 to 90 cm.

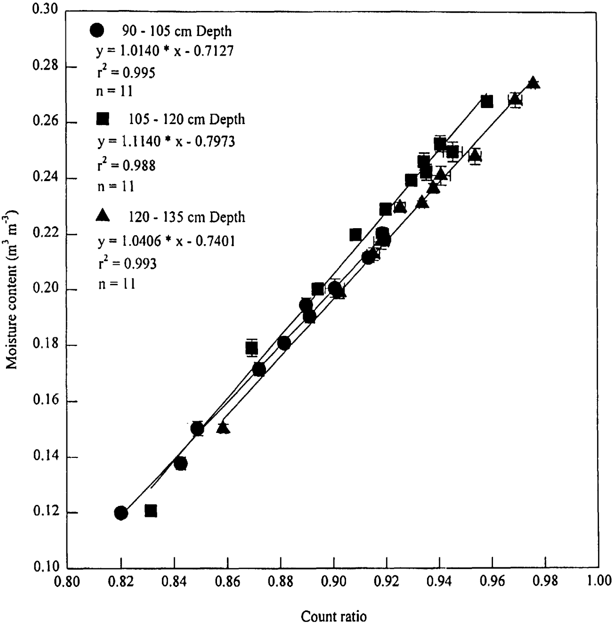

Figure 3. Neutron probe calibration curve for three depths from 90 to 135 cm.

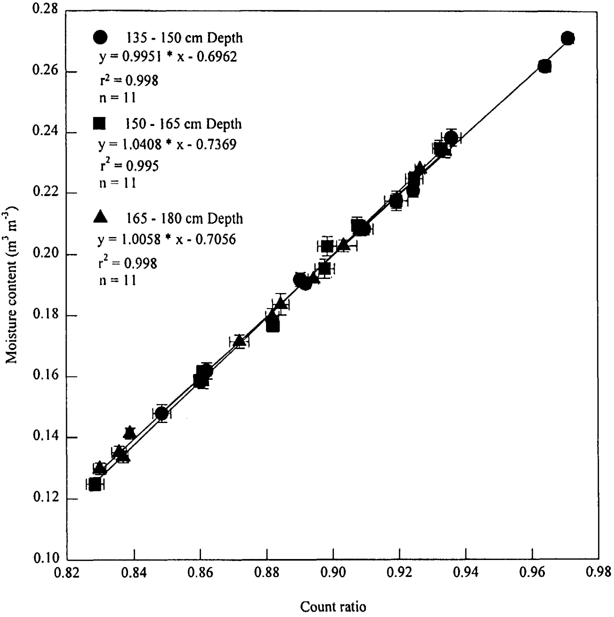

Figure 4. Neutron probe calibration curve for three depths from 135 to 180 cm.

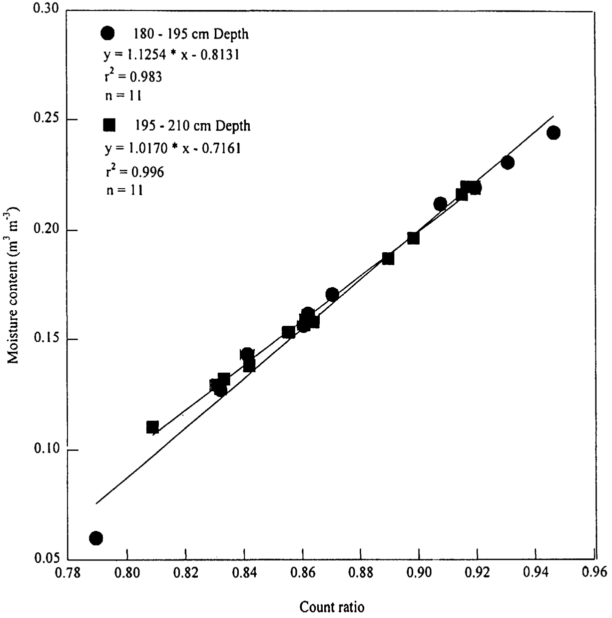

Figure 5. Neutron probe calibration curve for two depths from 180 to 210 cm.

APPENDIX III

The method for determining soil hydraulic properties from disc permeameter measurements in the field is given by White *et al.*, (1989) and is based on an analysis (Wooding, 1968) of the three-dimensional flow from a shallow circular pond or surface disc.

For a pond or disc of radius r_0, on the soil surface, Wooding showed that when water is supplied at a potential of Ψ_0 the steady-state volumetric rate q is

$$q = \pi r_0^2 (K_0 - K_n) + 4 r_0 \varphi \qquad (1)$$

The first term on the right essentially represents the contribution of gravity to the total flow from the surface disc and the second term contains the contribution due to capillarity. In the gravity term K_0 is the hydraulic conductivity at the supply potential Ψ_0, and K_n is the hydraulic conductivity at the initial soil water potential Ψ_n. For relatively dry materials K_n is much smaller than K_0 and we can safely ignore its effect. The capillarity term contains the matric flux potential φ, which is related to the conductivity by $\varphi = K_0 \lambda_c$.

The macroscopic capillary length λ_c is related to the sorptivity, S and the hydraulic conductivity (White and Sully, 1987)

$$\lambda_c = \frac{b S_0^2}{(\theta_0 - \theta_n) K_0}$$

θ_n is the initial moisture content at Ψ_n, θ_0 is the moisture content at the supply potential Ψ_0, S_0 is the sorptivity at Ψ_n with supply potential Ψ_0 and b is a dimensionless constant whose value lies between ½ and $\pi/4$. For field soils a mean value for b is 0.55. We can now rewrite equation (1) as

$$q = \pi r_0^2 K_0 + 4r_0 \frac{bS_0^2}{(\theta_0 - \theta_n)} \quad (2)$$

Dividing by the area of the disc, we find the steady-state flow rate per until area

$$\frac{q}{\pi r_0^2} = K_0 + \frac{4bS_0^2}{\pi r_0 (\theta_0 - \theta_n)} \quad (3)$$

Rearranging equation (3) to find the conductivity, we have

$$K_0 = \frac{q}{\pi r_0^2} - \frac{4bS_0^2}{\pi r_0 (\theta_0 - \theta_n)} \quad (4)$$

During the early stages of flow from the disc capillarity dominates flow irrespective of the size of the disc. At short infiltration times the system behaves as if it were one-dimensional. In this case the cumulative infiltration is given by (Philip, 1969)

$$\frac{Q}{\pi r_0^2} = S_0 t^{½}$$

Where Q is the total volume of water infiltrated and t is time from the commencement of infiltration. Sorptivity, then, is the slope of the cumulative infiltration versus $t^{½}$ plot.

To calculate hydraulic conductivity from equation (4), the measurements required are the sorptivity, the steady-state flow rate, the initial volumetric moisture content and the volumetric moisture content at the supply potential.

The sorptivity S_0 is calculated from the early time data. To find S_0 plot $Q/\pi r_0^2$ on the Y axis versus the square root of time $t^{1/2}$ on the X axis. The slope of the straight line portion is sorptivity and has units of length /time$^{1/2}$.

The steady state flow rate is found by plotting the cumulative infiltration during the last part of the infiltration as a function of time. The plot should be linear at large time. The slope of this line is the steady-state flow rate.

Hydraulic conductivity of the soil at the potential at which the measurement is being made is calculated from equation (4)

$$K_0 = \frac{q}{\pi r_0^2} - \frac{4bS_0^2}{\pi r_0 (\theta_0 - \theta_n)}$$

where r_0 is the radius of the ring, θ_0 is the volumetric moisture content at the measurement potential, θ_n is the volumetric moisture content at initial potential, and b is approximately 0.55. Moisture contents are expressed as decimal fractions.

The Macroscopic capillary length λ_c is a scaling length which simplifies the treatment of multidimensional soil-water flows (Philip, 1985). It is defined as

$$\lambda_c = [K(\Psi_0) - K(\Psi_n)]^{-1} \int_{\Psi_n}^{\Psi_0} K(\Psi)d\Psi \qquad (5)$$

Since λ_c is a K-weighted mean potential, we can relate λ by simple capillarity theory to a characteristic pore dimension λ_m :

$$\lambda_m = \sigma / \rho g \lambda_c \qquad (6)$$

Where σ is the air/soil-water surface tension, ρ is the soil-water density, and g is the acceleration due to gravity. For estimating λ_c in the field as shown by White and Sully (1987)

$$\lambda_c = bS_0^2 / [(\theta_0 - \theta_n)K_0] \qquad (7)$$

For pure water at 20°C equation (6) becomes

$$\lambda_m = 7.4 / \lambda_c$$

where λ_m and λ_c are in mm.

APPENDIX IV

Table 1. Profile moisture storage (mm) in different treatments during the crop growth period in 1995 season.

Treatments		Days after sowing							
		1	4	18	25	27	32	37	44
Control	Crop	220	282	256	245	268	270	243	251
Control	Fallow	237	286	268	251	279	291	263	321
Control	Mean	228	284	262	248	274	280	253	286
Scoop	Crop	340	301	270	329	284	337	292	300
Scoop	Fallow	314	324	338	330	319	365	329	351
Scoop	Mean	327	312	304	330	302	351	311	326
Crop residue	Crop	377	377	391	370	370	389	326	350
Crop residue	Fallow	391	387	410	378	377	410	392	399
Crop residue	Mean	384	382	401	374	373	400	359	374
PVA	Crop	409	415	421	433	438	435	396	417
PVA	Fallow	457	433	440	446	456	465	423	424
PVA	Mean	433	424	430	439	447	450	410	420
Revegetation	Crop	472	449	515	479	488	474	479	477
Revegetation	Fallow	493	459	559	494	556	526	532	536
Revegetation	Mean	482	454	537	487	522	500	505	507
Mean	Crop	359	363	368	359	363	378	349	361
Mean	Fallow	380	376	391	378	385	398	371	383
SEm (±)	Main treatment	5	7	5	7	6	9	5	8
SE m (±)	Sub treatment	3	4	4	4	3	4	4	4
SEm (±)	Interaction effect	6	9	7	9	8	10	7	9
CD (0.05)	Main treatment	23	33	21	31	28	40	22	34
CD (0.05)	Sub treatment	11	16	15	15	14	15	14	14
CD (0.05)	Interaction effect	22	33	24	30	28	37	24	32

(Table 1 continued....)

Treatments		Days after sowing							
		46	49	55	61	67	73	79	88
Control	Crop	328	278	316	320	286	379	292	305
Control	Fallow	362	336	334	329	325	389	308	324
Control	Mean	345	307	325	325	305	384	300	315
Scoop	Crop	394	332	372	411	337	393	325	314
Scoop	Fallow	396	343	386	421	348	407	351	360
Scoop	Mean	395	337	379	416	343	400	338	337
Crop residue	Crop	413	377	403	452	350	403	391	348
Crop residue	Fallow	428	398	427	478	397	439	402	405
Crop residue	Mean	420	387	415	465	374	421	397	377
PVA	Crop	439	409	446	498	408	465	445	419
PVA	Fallow	454	434	462	515	444	488	496	424
PVA	Mean	447	421	454	506	426	476	470	422
Revegetation	Crop	472	470	516	556	483	504	503	491
Revegetation	Fallow	506	540	524	537	544	545	550	535
Revegetation	Mean	489	505	520	547	514	525	526	513
Mean	Crop	407	377	407	438	373	424	392	370
Mean	Fallow	421	397	423	454	393	437	412	388
SEm (±)	Main treatment	6	6	8	6	9	9	8	9
SEm (±)	Sub treatment	3	4	4	4	4	4	4	4
SEm (±)	Interaction effect	7	9	10	8	11	11	10	11
CD (0.05)	Main treatment	26	27	35	26	40	41	37	41
CD (0.05)	Sub treatment	13	17	15	16	16	16	16	16
CD (0.05)	Interaction effect	25	29	34	28	38	39	35	38

(Table 1 continued....)

Treatments		Days after sowing 96	111	116	123	130
Control	Crop	316	333	342	342	296
Control	Fallow	358	351	351	362	305
Control	Mean	337	342	347	352	300
Scoop	Crop	356	385	370	351	358
Scoop	Fallow	398	381	380	387	369
Scoop	Mean	377	383	375	369	364
Crop residue	Crop	426	415	399	388	375
Crop residue	Fallow	442	442	417	415	419
Crop residue	Mean	434	428	408	402	397
PVA	Crop	488	480	450	437	444
PVA	Fallow	494	528	472	472	460
PVA	Mean	491	504	461	455	452
Revegetation	Crop	541	523	501	479	466
Revegetation	Fallow	566	598	540	528	516
Revegetation	Mean	554	560	520	503	491
Mean	Crop	422	428	409	403	385
Mean	Fallow	441	449	424	417	402
SEm (±)	Main treatment	10	6	9	9	8
SEm (±)	Sub treatment	4	5	5	5	5
SEm (±)	Interaction effect	12	9	12	12	11
CD (0.05)	Main treatment	45	28	42	42	38
CD (0.05)	Sub treatment	17	19	20	20	18
CD (0.05)	Interaction effect	42	31	41	41	37

Table 2. Profile moisture storage (mm) in different treatments during the crop growth period in 1996 season.

Treatments		Days after sowing							
		2	5	8	13	16	20	27	29
Control	Crop	306	268	300	337	312	317	265	312
Control	Fallow	331	317	357	385	358	371	349	369
Control	Mean	318	292	329	361	335	344	307	341
Scoop	Crop	318	301	329	342	328	334	307	339
Scoop	Fallow	372	334	375	401	380	399	372	392
Scoop	Mean	345	318	352	372	354	367	340	365
Crop residue	Crop	358	339	363	380	346	366	323	363
Crop residue	Fallow	404	388	452	468	445	429	400	444
Crop residue	Mean	381	364	407	424	396	398	361	404
PVA	Crop	395	363	389	405	393	391	347	384
PVA	Fallow	444	416	485	497	481	478	441	461
PVA	Mean	419	390	437	451	437	435	394	423
Revegetation	Crop	408	394	407	425	403	414	395	412
Revegetation	Fallow	479	462	503	529	502	505	482	485
Revegetation	Mean	444	428	455	477	453	459	439	448
Mean	Crop	357	333	358	378	356	365	327	362
Mean	Fallow	406	384	434	464	433	436	409	430
SEm (±)	Main treatment	1.86	4.14	3.16	2.62	3.47	3.72	5.71	3.92
SEm (±)	Sub treatment	1.56	4.00	1.92	3.94	2.35	3.57	3.31	2.68
SEm (±)	Interaction effect	2.89	7.01	4.16	6.15	4.81	6.27	7.38	5.45
CD (0.05)	Main treatment	8.38	18.64	14.22	11.7	15.63	16.72	25.68	17.64
CD (0.05)	Sub treatment	6.13	15.69	7.52	15.46	9.23	14.01	12.99	10.53
CD (0.05)	Interaction effect	9.67	23.55	14.18	21.67	16.20	21.05	25.27	18.35

(Table 2 continued....)

		Days after sowing							
		33	36	40	44	47	51	56	58
Control	Crop	300	337	329	327	320	334	343	333
Control	Fallow	367	353	388	405	400	404	415	405
Control	Mean	333	345	358	366	360	369	379	369
Scoop	Crop	340	373	356	366	358	374	362	357
Scoop	Fallow	384.	390	414	437	424	446	450	432
Scoop	Mean	362	382	385	401	391	410	406	394
Crop residue	Crop	369	400	383	397	387	396	377	382
Crop residue	Fallow	440	453	458	468	464	490	480	470
Crop residue	Mean	405	426	420	432	426	443	428	426
PVA	Crop	391	433	440	424	413	418	423	414
PVA	Fallow	487	487	474	486	488	506	520	495
PVA	Mean	439	460	457	455	450	462	471	455
Revegetation	Crop	458	489	483	464	442	457	473	465
Revegetation	Fallow	531	539	510	511	514	531	540	526
Revegetation	Mean	495	514	496	488	478	494	507	495
Mean	Crop	372	406	398	396	384	396	395	390
Mean	Fallow	444	448	449	461	458	475	481	465
SEm (±)	Main treatment	2.20	3.20	3.48	3.35	3.31	3.74	4.32	4.30
SEm (±)	Sub treatment	4.09	2.16	0.96	1.49	2.41	2.05	3.48	4.39
SEm (±)	Interaction effect	6.20	4.42	3.74	3.96	4.76	4.73	6.54	7.55
CD (0.05)	Main treatment	9.92	14.38	15.67	15.08	14.92	16.81	19.44	19.34
CD (0.05)	Sub treatment	16.08	8.47	3.78	5.85	9.47	8.05	13.65	17.24
CD (0.05)	Interaction effect	22.39	14.89	14.80	14.20	15.95	16.33	21.88	25.48

(Table 2 continued....)

Treatments		Days after sowing 62	65	69	71	76	78	82	86
Control	Crop	337	338	323	345	335	319	327	335
Control	Fallow	388	404	376	429	404	412	383	386
Control	Mean	362	371	349	387	369	366	355	360
Scoop	Crop	365	371	359	387	372	343	344	355
Scoop	Fallow	443	446	398	455	426	446	407	400
Scoop	Mean	404	408	379	421	399	394	375	378
Crop residue	Crop	386	388	389	402	391	382	379	376
Crop residue	Fallow	476	478	438	482	452	463	438	449
Crop residue	Mean	431	433	414	442	421	422	409	412
PVA	Crop	418	426	432	435	419	436	413	405
PVA	Fallow	502	495	481	532	499	497	483	488
PVA	Mean	460	461	456	483	459	466	448	446
Revegetation	Crop	456	472	488	495	452	472	461	431
Revegetation	Fallow	544	565	500	560	529	531	502	505
Revegetation	Mean	500	519	494	528	491	502	482	468
Mean	Crop	393	399	398	413	394	390	385	380
Mean	Fallow	470	478	439	492	462	470	443	446
SEm (±)	Main treatment	6.20	4.71	2.93	8.51	3.75	3.55	3.93	5.57
SEm (±)	Sub treatment	2.32	1.20	2.18	2.49	2.11	3.64	3.27	2.91
SEm (±)	Interaction effect	7.02	5.01	4.26	9.21	4.79	6.26	6.07	6.93
CD (0.05)	Main treatment	27.91	21.19	13.19	38.29	16.90	15.97	17.69	25.08
CD (0.05)	Sub treatment	9.11	4.70	8.58	9.79	8.28	14.31	12.84	11.44
CD (0.05)	Interaction effect	26.11	20.11	14.27	36.06	16.50	21.13	20.30	24.12

(Table 2 continued....)

		Days after sowing 90	97	104	111	119
Control	Crop	330	326	318	315	326
Control	Fallow	413	417	382	385	380
Control	Mean	371	372	350	350	353
Scoop	Crop	360	365	322	322	350
Scoop	Fallow	442	432	408	405	401
Scoop	Mean	401	399	365	363	376
Crop residue	Crop	388	395	350	354	384
Crop residue	Fallow	482	466	434	446	439
Crop residue	Mean	435	431	392	400	412
PVA	Crop	404	434	368	379	414
PVA	Fallow	512	511	462	466	462
PVA	Mean	458	472	415	422	438
Revegetation	Crop	464	491	436	434	471
Revegetation	Fallow	550	538	472	492	497
Revegetation	Mean	507	515	454	463	484
Mean	Crop	389	402	359	360	389
Mean	Fallow	480	473	431	439	436
SEm (±)	Main treatment	4.05	3.83	4.09	6.19	6.29
SEm (±)	Sub treatment	3.45	3.84	4.29	3.94	3.31
SEm (±)	Interaction effect	6.34	6.65	7.32	8.32	7.85
CD (0.05)	Main treatment	18.21	17.23	18.42	27.84	28.33
CD (0.05)	Sub treatment	13.55	15.08	16.85	15.46	13.01
CD (0.05)	Interaction effect	21.21	22.39	24.75	28.19	27.28

Table 3. Soil-water flux (cm day^{-1}) at 1.95 m depth in different treatments on days when heavy rains were received during 1995 crop growth period indicating deep percolation.

		Days after sowing							
		13 (10.8)	14 (16.0)	15 (13.8)	17 (54.4)	20 (34.8)	22 (9.6)	28 (7.0)	36 (9.6)
Control	Crop	10.79	16.20	12.40	49.11	26.73	11.08	7.04	9.63
Control	Fallow	9.06	12.10	9.81	41.86	22.52	10.02	6.83	8.95
Control	Mean	9.93	14.15	11.10	45.48	24.63	10.55	6.93	9.29
Scoop	Crop	6.00	11.68	9.00	39.52	21.40	8.24	5.24	7.77
Scoop	Fallow	4.17	10.85	8.24	31.16	19.87	7.94	4.79	6.85
Scoop	Mean	5.09	11.27	8.62	35.34	20.63	8.09	5.01	7.31
Crop residue	Crop	3.30	8.95	6.95	29.92	16.46	6.36	3.15	5.36
Crop residue	Fallow	2.00	6.27	5.66	21.12	16.02	5.06	2.24	4.68
Crop residue	Mean	2.65	7.61	6.31	25.52	16.24	5.71	2.69	5.02
PVA	Crop	2.06	5.34	4.66	26.48	14.16	4.60	2.08	3.45
PVA	Fallow	1.85	4.57	3.68	20.44	12.19	3.53	1.71	2.15
PVA	Mean	1.95	4.95	4.17	23.46	13.18	4.06	1.89	2.80
Revegetation	Crop	1.08	3.45	2.98	18.44	10.93	2.30	0.71	1.06
Revegetation	Fallow	0.94	1.71	1.53	15.16	9.34	1.62	0.26	0.72
Revegetation	Mean	1.01	2.58	2.26	16.80	10.13	1.96	0.48	0.89
Mean	Crop	4.65	9.12	7.20	32.69	17.94	6.51	3.64	5.45
Mean	Fallow	3.60	7.10	5.78	25.95	15.99	5.63	3.16	4.67
SEm (±)	Main treatment	0.46	0.25	0.60	0.52	0.54	1.19	0.52	0.33
SEm (±)	Sub treatment	0.34	0.34	0.57	0.46	0.40	0.15	0.12	0.70
SEm (±)	Interaction effect	0.54	0.41	0.30	0.52	0.12	1.21	0.58	1.04
CD (0.05)	Main treatment	1.57	1.23	1.23	1.24	1.30	5.37	2.30	1.47
CD (0.05)	Sub treatment	0.23	0.95	1.01	1.85	1.54	0.59	0.46	1.23
CD (0.05)	Interaction effect	1.30	1.20	1.35	2.64	2.63	4.21	2.23	1.06

(Figures in parentheses indicate the amount of rainfall (mm) received on that day)

(Table 3 continued....)

		Days after sowing							
		38 (9.0)	45 (53.0)	46 (32.6)	52 (9.8)	53 (27.0)	54 (35.6)	67 (18.4)	69 (24.4)
Control	Crop	10.78	47.55	30.27	10.93	24.41	33.09	13.84	25.74
Control	Fallow	9.25	42.60	29.20	9.34	22.31	31.29	10.87	22.16
Control	Mean	10.02	45.08	29.73	10.13	23.36	32.19	12.36	23.95
Scoop	Crop	8.38	40.76	30.40	8.00	21.42	29.70	9.21	23.19
Scoop	Fallow	7.09	38.93	27.19	7.94	20.27	27.63	8.06	20.52
Scoop	Mean	7.74	39.84	28.79	7.97	20.85	28.66	8.64	21.85
Crop residue	Crop	6.21	34.69	25.76	6.98	20.78	24.44	7.42	17.70
Crop residue	Fallow	5.92	30.35	23.40	5.30	18.87	22.70	6.51	14.69
Crop residue	Mean	6.06	32.52	24.58	6.14	19.82	23.57	6.97	16.20
PVA	Crop	4.45	27.62	20.84	4.06	16.25	20.61	5.27	16.18
PVA	Fallow	3.30	23.67	18.63	3.53	14.49	19.25	4.21	13.71
PVA	Mean	3.87	25.65	19.74	3.80	15.37	19.93	4.74	14.95
Revegetation	Crop	2.83	20.88	15.20	2.36	12.05	16.48	3.83	12.40
Revegetation	Fallow	1.53	15.02	13.08	1.85	9.42	13.46	2.27	9.47
Revegetation	Mean	2.18	17.95	14.14	2.11	10.74	14.97	3.05	10.93
Mean	Crop	6.53	34.30	24.49	6.47	18.98	24.86	7.92	19.04
Mean	Fallow	5.42	30.11	22.30	5.59	17.07	22.87	6.39	16.11
SEm (±)	Main treatment	0.48	0.17	0.98	0.78	0.80	0.88	0.52	0.70
SEm (±)	Sub treatment	0.64	0.78	0.44	0.46	0.96	0.05	0.30	0.23
SEm (±)	Interaction effect	1.02	0.44	0.11	0.06	1.57	0.17	0.57	0.73
CD (0.05)	Main treatment	1.25	0.56	0.41	1.26	1.24	1.26	1.02	4.32
CD (0.05)	Sub treatment	1.02	0.42	1.72	1.80	1.03	0.25	2.04	0.98
CD (0.05)	Interaction effect	1.63	1.64	2.01	1.45	0.60	1.05	1.53	3.65

(Figures in parentheses indicate the amount of rainfall (mm) received on that day)

(Table 3 continued....)

		Days after sowing							
		73 (24.0)	78 (9.6)	96 (9.2)	97 (10.0)	101 (33.4)	104 (34.8)	106 (64.8)	120 (7.4)
Control	Crop	23.45	9.70	8.68	10.70	30.27	31.74	57.44	5.66
Control	Fallow	20.40	8.02	7.65	9.78	27.82	28.35	55.27	5.18
Control	Mean	21.93	8.86	8.16	10.24	29.05	30.04	56.35	5.42
Scoop	Crop	19.30	9.08	7.07	8.53	28.90	27.46	51.03	4.54
Scoop	Fallow	18.45	7.35	6.06	7.19	25.57	25.77	48.73	3.26
Scoop	Mean	18.88	8.21	6.56	7.86	27.23	26.61	49.88	3.90
Crop residue	Crop	17.76	6.36	5.08	6.95	22.06	20.37	45.33	2.82
Crop residue	Fallow	15.03	5.83	4.46	5.30	20.72	17.84	43.16	2.69
Crop residue	Mean	16.39	6.10	4.77	6.13	21.39	19.10	44.24	2.76
PVA	Crop	13.25	4.72	3.22	4.64	19.66	14.01	42.63	1.97
PVA	Fallow	11.99	3.37	2.71	3.06	18.43	11.04	36.64	1.05
PVA	Mean	12.62	4.05	2.96	3.85	19.05	12.53	39.64	1.51
Revegetation	Crop	9.38	2.60	1.59	2.95	13.60	8.89	30.98	0.74
Revegetation	Fallow	7.30	1.08	0.52	1.73	9.03	3.35	20.17	0.50
Revegetation	Mean	8.34	1.84	1.06	2.34	11.32	6.12	25.57	0.62
Mean	Crop	16.63	6.49	5.13	6.75	22.90	20.49	45.48	3.15
Mean	Fallow	14.63	5.13	4.28	5.41	20.31	17.27	40.79	2.54
SEm (±)	Main treatment	0.96	0.79	0.41	0.74	0.92	0.09	0.56	0.59
SEm (±)	Sub treatment	0.56	0.30	0.39	0.74	0.81	0.85	0.62	0.13
SEm (±)	Interaction effect	0.25	0.84	0.69	1.28	0.47	0.62	0.54	0.46
CD (0.05)	Main treatment	2.31	4.20	1.85	3.31	2.13	1.04	1.23	1.68
CD (0.05)	Sub treatment	1.21	1.18	1.53	0.50	1.96	0.88	1.22	1.66
CD (0.05)	Interaction effect	1.05	3.21	2.31	2.30	2.20	2.01	1.55	1.12

(Figures in parentheses indicate the amount of rainfall (mm) received on that day)

Table 4. Soil-water flux (cm day^{-1}) at 1.95 m depth in different treatments on days when heavy rains were received during 1996 crop growth period indicating deep percolation.

		Days after sowing								
		5 (34.3)	10 (72.2)	26 (13.8)	30 (5.0)	33 (13.8)	37 (40.0)	41 (7.8)	44 (30.4)	48 (43.0)
Control	Crop	40.24	66.91	21.01	5.05	20.18	44.36	16.11	30.52	40.89
Control	Fallow	36.14	64.23	19.95	4.08	19.00	39.81	13.32	29.62	38.65
Control	Mean	38.19	65.57	20.48	4.56	19.59	42.09	14.72	30.07	39.77
Scoop	Crop	31.42	60.04	17.51	3.63	17.19	35.69	11.08	26.65	35.83
Scoop	Fallow	30.60	56.66	16.13	3.13	15.44	31.72	8.87	24.90	32.92
Scoop	Mean	31.01	58.35	16.82	3.38	16.31	33.70	9.97	25.78	34.38
Crop residue	Crop	27.96	53.11	15.44	2.65	13.38	28.81	7.95	22.13	30.86
Crop residue	Fallow	25.53	49.59	14.93	2.05	11.52	26.09	6.84	21.27	27.34
Crop residue	Mean	26.74	51.35	15.18	2.35	12.45	27.45	7.40	21.70	29.10
PVA	Crop	23.02	46.57	12.93	1.59	10.67	24.69	5.62	20.56	26.19
PVA	Fallow	22.90	45.87	11.01	1.31	9.28	23.95	3.93	18.26	23.97
PVA	Mean	22.96	46.22	11.97	1.45	9.97	24.32	4.78	19.41	25.08
Revegetation	Crop	20.75	42.26	10.40	1.03	8.83	21.91	2.43	16.76	21.83
Revegetation	Fallow	17.51	38.29	7.98	0.87	6.98	19.38	1.93	14.78	19.88
Revegetation	Mean	19.13	40.28	9.19	0.95	7.91	20.64	2.18	15.77	20.85
Mean	Crop	28.68	53.78	15.46	2.79	14.05	31.09	8.64	23.32	31.12
Mean	Fallow	26.54	50.93	14.00	2.29	12.44	28.19	6.98	21.77	28.55
SEm (±)	Main treatment	0.48	0.83	0.27	0.04	0.72	0.59	0.54	0.07	0.46
SEm (±)	Sub treatment	0.39	0.45	0.29	0.05	0.21	0.33	0.18	0.50	0.46
SEm (±)	Interaction effect	0.73	1.05	0.49	0.09	0.78	0.75	0.60	0.71	0.80
CD (0.05)	Main treatment	2.17	3.72	1.23	0.15	1.24	1.65	1.45	0.33	1.06
CD (0.05)	Sub treatment	1.54	1.77	1.13	0.21	0.81	1.21	0.70	0.60	0.58
CD (0.05)	Interaction effect	1.45	1.61	1.25	0.30	1.05	1.59	1.30	1.52	1.34

(Figures in parentheses indicate the amount of rainfall (mm) received on that day) (Table 4 continued....)

		Days after sowing							
		54 (95.6)	59 (35.4)	62 (11.6)	68 (67.0)	73 (14.8)	75 (23.2)	87 (19.6)	108 (9.8)
Control	Crop	71.45	37.12	17.85	64.55	19.56	26.01	24.77	19.77
Control	Fallow	67.99	35.48	15.96	61.99	18.71	24.02	22.82	18.25
Control	Mean	69.72	36.30	16.90	63.27	19.13	25.01	23.79	19.01
Scoop	Crop	64.19	32.97	13.90	57.99	16.03	21.59	21.90	14.63
Scoop	Fallow	61.51	30.96	12.20	55.36	15.47	20.91	20.16	12.93
Scoop	Mean	62.85	31.97	13.05	56.68	15.75	21.25	21.03	13.78
Crop residue	Crop	57.56	29.84	11.99	52.58	13.80	18.23	19.25	11.28
Crop residue	Fallow	55.03	27.86	10.13	49.51	12.10	17.85	17.64	10.72
Crop residue	Mean	56.29	28.85	11.06	51.05	12.95	18.04	18.45	11.00
PVA	Crop	53.87	26.64	9.47	46.07	11.11	16.89	16.07	9.12
PVA	Fallow	51.51	24.29	8.09	43.52	10.72	15.77	15.22	8.30
PVA	Mean	52.69	25.47	8.78	44.79	10.92	16.33	15.64	8.71
Revegetation	Crop	49.85	25.00	7.00	40.33	9.83	14.84	14.16	7.32
Revegetation	Fallow	47.82	22.02	6.31	37.99	8.15	13.99	13.87	4.47
Revegetation	Mean	48.83	23.51	6.66	39.16	8.99	14.41	14.02	5.89
Mean	Crop	59.38	30.32	12.04	52.30	14.07	19.51	19.23	12.42
Mean	Fallow	56.77	28.12	10.54	49.67	13.03	18.51	17.94	10.93
SEm (±)	Main treatment	0.61	0.53	0.22	0.59	0.62	0.15	0.11	0.44
SEm (±)	Sub treatment	0.46	0.41	0.39	0.46	0.10	0.13	0.39	0.25
SEm (±)	Interaction effect	0.89	0.79	0.59	0.88	0.64	0.23	0.57	0.57
CD (0.05)	Main treatment	1.25	1.23	0.99	1.24	1.81	0.65	0.48	1.93
CD (0.05)	Sub treatment	0.90	0.92	0.53	0.94	0.38	0.50	0.72	0.98
CD (0.05)	Interaction effect	1.42	1.31	1.02	1.33	1.72	0.77	1.02	0.82

(Figures in parentheses indicate the amount of rainfall (mm) received on that day).

Table 5. Bromide flux (mol m^{-2} day^{1}) at different depths during 1995 season for different treatments.

		Depth (cm)						
		15	30	45	60	75	90	105
Control	Crop	7.94	7.06	6.55	5.81	3.97	2.75	2.44
Control	Fallow	8.42	7.72	7.38	6.58	4.40	3.74	3.07
Control	Mean	8.18	7.39	6.97	6.20	4.18	3.25	2.75
Scoop	Crop	8.93	7.86	7.51	6.90	5.28	4.39	3.52
Scoop	Fallow	9.57	8.43	7.92	7.58	6.80	4.74	4.14
Scoop	Mean	9.25	8.14	7.71	7.24	6.04	4.56	3.83
Crop residue	Crop	10.24	9.16	8.87	7.94	7.05	5.65	5.01
Crop residue	Fallow	10.36	9.60	9.90	8.46	7.98	6.52	5.92
Crop residue	Mean	10.30	9.38	9.39	8.20	7.52	6.09	5.46
PVA	Crop	10.61	10.04	9.19	8.91	8.86	6.90	6.10
PVA	Fallow	11.05	10.33	9.98	9.09	8.79	7.17	6.99
PVA	Mean	10.83	10.19	9.58	9.00	8.83	7.04	6.55
Revegetation	Crop	11.81	11.74	10 22	9.99	9.17	7.86	7.24
Revegetation	Fallow	12.95	12.33	11.47	10.81	9.58	8.55	7.53
Revegetation	Mean	12.38	12.04	10.84	10.40	9.38	8.20	7.38
Mean	Crop	9.91	9.17	8.47	7.91	6.87	5.51	4.86
Mean	Fallow	10.47	9.68	9.33	8.50	7.51	6.15	5.53
SEm (±)	Main treatment	0.22	0.11	0.12	0.16	0.10	0.11	0.16
SEm (±)	Sub treatment	0.13	0.07	0.08	0.11	0.08	0.07	0.08
SEm (±)	Interaction effect	0.29	0.15	0.17	0.22	0.15	0.15	0.19
CD (0.05)	Main treatment	0.99	0.51	0.55	0.70	0.46	0.49	0.71
CD (0.05)	Sub treatment	0.53	0.29	0.32	0.44	0.29	0.29	0.31
CD (0.05)	Interaction effect	0.99	0.52	0.57	0.75	0.49	0.51	0.68

(Table 5 continued....)

		Depth (cm)					
		120	135	150	165	180	195
Control	Crop	1.36	1.07	0.93	0.71	0.61	0.43
Control	Fallow	2.24	1.51	0.60	0.59	0.52	0.42
Control	Mean	1.80	1.29	0.76	0.65	0.57	0.43
Scoop	Crop	2.91	1.92	0.79	0.56	0.52	0.54
Scoop	Fallow	3.34	2.07	0.94	0.64	0.68	0.41
Scoop	Mean	3.12	1.99	0.87	0.60	0.60	0.47
Crop residue	Crop	4.08	2.53	1.18	0.74	0.65	0.50
Crop residue	Fallow	4.84	2.90	1.91	0.95	0.97	0.60
Crop residue	Mean	4.46	2.72	1.54	0.85	0.81	0.55
PVA	Crop	5.17	3.09	2.20	1.09	0.95	0.85
PVA	Fallow	5.38	3.31	2.67	1.58	0.91	0.90
PVA	Mean	5.28	3.20	2.43	1.33	0.93	0.87
Revegetation	Crop	5.80	3.93	3.31	1.95	1.07	0.93
Revegetation	Fallow	6.96	4.67	3.78	2.17	1.31	0.95
Revegetation	Mean	6.38	4.30	3.55	2.06	1.19	0.94
Mean	Crop	3.86	2.51	1.68	1.01	0.76	0.65
Mean	Fallow	4.55	2.89	1.98	1.19	0.88	0.65
SEm (±)	Main treatment	0.16	0.04	0.09	0.06	0.03	0.01
SEm (±)	Sub treatment	0.08	0.10	0.06	0.05	0.02	0.01
SEm (±)	Interaction effect	0.19	0.15	0.12	0.09	0.05	0.01
CD (0.05)	Main treatment	0.71	0.20	0.39	0.28	0.14	0.03
CD (0.05)	Sub treatment	0.30	0.41	0.24	0.18	0.10	0.01
CD (0.05)	Interaction effect	0.68	0.57	0.41	0.31	0.16	0.03

Table 6. Bromide flux (mol m^{-2} day^{-1}) at different depths during 1996 season for different treatments.

		Depth (cm)						
		15	30	45	60	75	90	105
Control	Crop	8.90	7.72	6.54	5.66	5.91	4.04	3.09
Control	Fallow	9.03	8.27	7.13	6.95	6.50	4.65	4.28
Control	Mean	8.96	8.00	6.83	6.31	6.21	4.35	3.69
Scoop	Crop	9.46	8.97	7.01	7.05	7.05	5.04	4.27
Scoop	Fallow	10.21	9.05	8.54	7.81	7.31	5.59	4.73
Scoop	Mean	9.83	9.01	7.77	7.43	7.18	5.32	4.50
Crop residue	Crop	10.69	9.99	8.40	7.93	7.39	5.96	5.70
Crop residue	Fallow	10.90	10.23	9.67	8.59	7.35	6.04	5.02
Crop residue	Mean	10.80	10.11	9.03	8.26	7.37	6.00	5.36
PVA	Crop	11.22	10.87	9.93	8.73	8.51	6.86	5.62
PVA	Fallow	12.35	11.67	10.43	9.89	8.45	6.04	6.38
PVA	Mean	11.78	11.27	10.18	9.31	8.48	6.45	6.00
Revegetation	Crop	13.03	12.35	11.25	9.99	9.12	7.80	6.05
Revegetation	Fallow	13.73	12.81	11.59	10.55	9.77	7.96	7.00
Revegetation	Mean	13.38	12.58	11.42	10.27	9.44	7.88	6.52
Mean	Crop	10.66	9.98	8.62	7.87	7.60	5.94	4.94
Mean	Fallow	11.24	10.41	9.47	8.76	7.88	6.06	5.48
SEm (±)	Main treatment	0.13	0.24	0.23	0.19	0.11	0.06	0.11
SEm (±)	Sub treatment	0.19	0.14	0.25	0.13	0.10	0.11	0.12
SEm (±)	Interaction effect	0.30	0.31	0.42	0.26	0.18	0.17	0.21
CD (0.05)	Main treatment	0.57	1.07	1.01	0.84	0.51	0.27	0.50
CD (0.05)	Sub treatment	0.75	0.56	1.00	0.50	0.39	0.44	0.48
CD (0.05)	Interaction effect	1.06	1.06	1.44	0.87	0.60	0.61	0.70

(Table 6 continued....)

		Depth (cm)					
		120	135	150	165	180	195
Control	Crop	1.06	1.44	0.92	0.31	0.18	0.19
Control	Fallow	1.58	1.95	0.65	0.51	0.19	0.50
Control	Mean	1.32	1.69	0.79	0.41	0.19	0.35
Scoop	Crop	2.17	1.05	0.83	0.80	0.28	0.33
Scoop	Fallow	2.68	1.68	0.97	0.87	0.33	0.50
Scoop	Mean	2.42	1.37	0.90	0.83	0.31	0.41
Crop residue	Crop	3.74	2.41	1.41	0.92	0.45	0.35
Crop residue	Fallow	3.33	2.58	1.73	1.67	0.52	0.67
Crop residue	Mean	3.54	2.49	1.57	1.30	0.49	0.51
PVA	Crop	3.96	2.21	2.25	1.28	0.69	0.55
PVA	Fallow	4.49	3.04	2.49	1.04	0.75	0.70
PVA	Mean	4.22	2.62	2.37	1.16	0.72	0.62
Revegetation	Crop	4.74	3.83	2.68	1.92	0.85	0.71
Revegetation	Fallow	4.01	3.85	2.92	1.98	0.94	0.83
Revegetation	Mean	4.37	3.84	2.80	1.95	0.89	0.77
Mean	Crop	3.14	2.19	1.62	1.05	0.49	0.43
Mean	Fallow	3.22	2.62	1.75	1.21	0.55	0.64
SEm (±)	Main treatment	0.15	0.19	0.20	0.25	0.26	0.03
SEm (±)	Sub treatment	0.12	0.16	0.17	0.17	0.05	0.07
SEm (±)	Interaction effect	0.22	0.21	0.31	0.35	0.03	0.11
CD (0.05)	Main treatment	0.66	0.83	0.88	0.10	0.18	0.13
CD (0.05)	Sub treatment	0.45	0.65	0.67	0.67	0.21	0.29
CD (0.05)	Interaction effect	0.74	0.90	0.13	0.16	0.14	0.30