SURFACE STRUCTURE OF A SANDY LOAM SOIL, AS AFFECTED BY LONG-TERM TILLAGE AND FERTILIZER IN THE POTOWAR PLATEAU OF PAKISTAN

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ABSTRACT

Changes of soil-structure of the rain-fed soils that result from continuous use of mechanized tillage and chemical fertilizer have not been documented in Pakistan. Long-term (5-year) moldboard and shallow (with tine-cultivator) tillage, and application of nitrogen and phosphorus (NP) and farmyard manure (FYM), separately or in combination, were studied for their effect on surface-structure of a sandy loam soil, classified as Typic Camborthid (Calcaric Fluvisols). In the surface horizon (Ap 0-11 cm), moldboard tillage compared to cultivator resulted in 0.04 Mg cm^{-3} lower bulk density (ρ_b). The combined application of NP-FYM under moldboard tillage resulted in the lowest ρ_b of the surface-soil. Moldboard tillage had lesser macro-porosity than shallow tillage and, therefore, the reduction in ρ_b with moldboard tillage was ascribed to an increase in < 60 μm porosity. Ponded and near-saturated infiltration was 15 to 30 mm h^{-1} greater with a combination of NP-FYM than with the NP treatment.

The cultivator tillage resulted in a larger mean pore radius and a greater number of macro-pores, with area of each pore class $\geq$ 60 μm radius than moldboard tillage. Similarly, farmyard manure, both alone and in combination with NP, resulted in a larger mean pore radius, greater number and area of all pores size classes than with no fertilizer and NP alone. The continuous use of NP reduced the mean pore radius and fraction of $\geq$ 60 μm radius pores, especially with moldboard tillage. Infiltration rate did not correlate with total porosity. Ponded and near-saturated infiltration corresponded better to the area of $\geq$ 380 μm radius pores. Infiltration at –40, –100, and –180 mm potentials correlated better with number of 380-150, 150-80, 80-60 μm radius pore classes, respectively. The long-term use of cultivator tillage and NP fertilizer with FYM resulted in a better soil structure than the moldboard tillage, especially without farmyard manure.

Keywords: *Surface soil structure; Macro-porosity; Saturated-, near-saturated, and un-saturated infiltration; Hydraulic conductivity.*

1. INTRODUCTION

Soil management practices influence soil-structure through changes in size and stability of aggregates and pore-size distribution, as well as its geometry (Norton, 1987) and, consequently, affect crop-production (Alakukku, 1996; Azooz et al., 1996). The two components of soil management: (a) tillage and (b) additions of organic matter play a vital role in maintaining soil-plant physical conditions in the root-zone. Tillage can pulverize compacted layers and improve soil permeability and percolation (Bennie and Botha, 1985), but the effect may not be sustainable in structurally unstable soils: Tillage with moldboard and chisel-plow initially creates greater volume of pores >150 μm, but the effect is only temporary (Hill et al., 1985; Benjamin, 1993). Multiple passes by tilling machinery can create compacted surface-layers with small size soil aggregates (Dexter, 1986) and reduced macropores (Ankeny et al., 1991). In contrast, no-tillage creates macro-pores in the surface layer over a longer period, which has been ascribed to enhanced faunal and microbiological activities (Doran, 1980; Drees et al., 1994). A long-term tillage effect on pore-size distribution has also been reported to depend on soil clay content (Heard et al., 1988).

Soil organic-matter encourages granulation, improving the tilth, increases porosity, which promotes water infiltration, and increases available water-capacity in mineral soils. High correlations between soil organic-matter and total porosity have been reported (Pikul and Zuzel, 1994). Increasing rates of manure-application improve physical conditions, encouraging rooting activity and saturated infiltration (Sommerfeldt and Chang, 1985; Darwish et al., 1995). Soil compaction reduces density of bio-pores (Alakukku, 1996) and a small increase in soil organic- matter reduces the compaction inflicted by heavy machinery (Soane, 1990). Approximately 3% organic matter is considered necessary for optimum soil physical conditions (Soane, 1990). In the arid sub-tropics, native concentration of stable organic-matter is low and, due to socio-economic factors, recycling of crop-residue is limited. Therefore, management of soil organic- matter is a critical issue in this region.

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Tine cultivation is used for both primary tillage and seedbed preparation in the rain-fed areas of the Potowar plateau of Pakistan. The traditional cultivator has 9 to 11 tines and is pulled with a 45 horsepower tractor. Continuous shallow tillage with tine cultivator has created a compact layer at 12-20 cm profile depth, with bulk density of 1.60 to 1.75 Mg m^{-3} in loam textures soils (Akhtar and Qureshi, 1999). Based on the agronomic-yield gain, ascribed to greater availability of water to plants from increased rainwater intake, primary tillage with moldboard is therefore recommended (Razzaq et al., 1989; Gill et al., 2000). On an average, 36% yield increase of wheat (*Triticum aestivum*) by moldboard tillage over the tine cultivator has been demonstrated (Razzaq et al., 1989; Gill et al., 2000). Changes in soil-structure created by these common soil- management techniques have never been determined in quantitative terms. Our objective was to determine the changes in soil-pore size-distribution and hydraulic characteristics, due to long-term tine cultivator or moldboard tillage and use of organic/inorganic fertilizer in the rain-fed area.

2. MATERIAL AND METHODS

2.1 Experimental site

The Crop Sciences Institute of the National Agricultural Research Center, Islamabad, Pakistan, initiated a study in July 1992 to determine crop-yield response of wheat-maize (*Triticum aestivum* and *Zea mays*, respectively) rotation to various long-term tillage and fertilizer treatments. The site was a Nabipur sandy loam soil series, classified as *Typic Camborthid* (*Calcaric Fluvisols*) at longitude 71.1°E and latitude 43.4°N. Mean annual rainfall in the area is 650 mm; a large proportion of it falls as a few monsoon storms during July and August, and the remaining proportion comes as gentle showers during the winter. The area has cool winters, with a low around 0 to 5°C and hot, dry summers, with a high around 40 to 45°C. The soil is developed from a mixed, calcareous alluvium, and is weakly differentiated, with native organic matter as low as <2.5g kg^{-1} (Khanzada, 1976).

2.2. Tillage and fertilizer treatments

Tillage operations and fertilizer application were done each year before planting wheat (2^{nd} week of November) and maize (2^{nd} week of July) under a permanent layout, with tillage as main plots and fertilizer as sub-plots. Shallow tillage consisted of two tine cultivations, followed by two plankings with a 100 kg wooden bar dragged behind a tractor-mounted tine-cultivator. The moldboard-tillage consisted of one operation with moldboard, followed by two plankings at planting times. Tillage depth was 10 to 12 cm in case of the tine cultivator operations and 20 to 25 cm in case of the moldboard tillage. Moldboard tillage is a conventional tillage in developed countries and the shallow tillage with a tine cultivator is close to reduced tillage.

The following four fertilizer-treatment combinations were applied in the sub-plots: (i) NP, 100-70-0 kg N-P-K ha^{-1} to wheat and 110-140-0 kg ha^{-1} to maize; (ii) FYM, 5000 kg ha^{-1} FYM to wheat; (iii) NP+FYM, NP plus FYM; and (iv) Control, without NP or FYM. Each treatment had 3 replicates, with a plot size of 17×6 m. A complete dose of each fertilizer-combination was evenly spread and mixed in the surface-soil at the time of seedbed preparation, before planting each crop.

2.3. Soil measurements

Infiltration characteristics and bulk-density of surface-soil (0-11 cm) were determined about 45 days after planting maize during September 1997. Soil-surface bulk-density was measured by placing a pre-calibrated Gamma (CPN 501) probe at 7.5 cm depth. Saturated infiltration was measured *in situ,* using a constant-head (+50 mm) well permeameter (Reynolds et al., 1985). The crusted surface (15 mm) was scraped off and a permeameter was installed in a 200 mm dia x 100 mm length PVC ring, inserted 25 mm into the ground. At steady state, four readings of drop in water-levels in the reservoirs were recorded at a 15 min time interval. From the steady-state rate of water-flow out of a cylindrical well, the infiltration flux, infiltration rate, field saturated hydraulic conductivity (K_{fs}), and matric flux potential (∅∅m) were calculated (Reynolds et al., 1985).

Infiltration characteristics of surface-soil in the potential (ψψ) range of –40 and –180 mm of water was measured, using a tension infiltrometer (Ankeny, 1992; Jarvis and Messing, 1995). Infiltration at close to 0 mm tension cannot be determined easily using a disk type infiltrometer; yet, it is required if information on changes in macropores is needed. Soil strength at near zero potential may not support the weight of the permeameter (White et al., 1992) and collapse under pressure, yielding negative hydraulic conductivity at zero potential ($K\psi\psi o$). Infiltration rates at 0 and –250 mm of water were predicted by regressing infiltration data from the same surface at +50, –40, –100, and -180 mm water pressure heads. Infiltration rate (infiltration flux per unit surface area, L h^{-1}), hydraulic conductivity ($K\psi\psi i$), and matrix flux potential ($\varnothing\varnothing\psi\psi i$) were calculated from the infiltration flux (Q, $L^3 T^{-1}$) for the potential ($\psi\psi i$) pairs: (i) 0/–40 (ii) –40/–100, (iii) –100/–180, and (iv) –180/–250 mm of water. Three measurements for bulk density and infiltration were made in each plot.

Calculations for $K(\psi\psi)$ and $\varnothing\varnothing(\psi\psi)$ were done using the Poiseuille's equation, $Q = \pi\pi\ r^2\ K + 4\ r\ \varnothing\varnothing$, (Wooding, 1968), where K is hydraulic conductivity ($L\ T^{-1}$) and $\varnothing\varnothing$ matric flux potential ($L^2\ T^{-1}$) (Ankeny, 1992; Akhtar et al., 1999).

As an estimate of soil structure, macroscopic capillary length, λc, was calculated, following White and Sully (1987) and Ankeny (1992). Since $\lambda\lambda_c$ is a K-weighted mean soil-water potential (L), we can relate $\lambda\lambda c$ by the capillarity theory to obtain a characteristic pore dimension, λm, that controls the flow when infiltration occurs through the surface: $\lambda\lambda m = \sigma/\rho g\lambda\lambda_c$, where σ is the water surface tension (72.75 kg s^{-2}); ρ is the water density (1000 kg m^{-3}); g is the acceleration due to gravity (9.80 m s^{-2}); and $\lambda\lambda_c$, characteristic capillary length (Bouma, 1991; Ankeny, 1992).

Assuming cylindrical pores, an equivalent radius, r, is $2\sigma\cos\alpha/\rho g\psi\psi i$ (Danielson and Sutherland, 1986) where α is the contact angle and $\psi\psi_i$ is the water-potential level. Since water from a pore can be removed when suction exceeds the force acting to retain it, infiltration at $\psi\psi_{-40}$, $\psi\psi_{-100}$, $\psi\psi_{-180}$, and $\psi\psi_{-250}$ mm water-potential will exclude pores of equivalent radius, r > 380, 150, 80, and 60 μm, respectively, from the flow process. With known r, the number of effective pores per area (m^{-2}) is $8\ \mu\ I / \pi\rho g(r)^4$, where μ is the viscosity of water (kg $m^{-1}\ s^{-1}$), I is the infiltration- rate (m s^{-1}) at a given potential, and r is the minimum radius (m) for the pore class (Watson and Luxmoore, 1986; Wilson and Luxmoore, 1988). The infiltration rate associated with >380, 380–150, 150–80, and 80–60 μm pore radii was calculated as the difference between the infiltration- rate at $\psi\psi_{-0}$ and $\psi\psi_{-40}$; $\psi\psi_{-40}$ and $\psi\psi_{-100}$; $\psi\psi_{-100}$ and $\psi\psi_{-180}$; and $\psi\psi_{-180}$ and $\psi\psi_{-250}$, respectively. The total effective porosity, Φm ($\Phi m = N\ \pi\ r^2$) where N is the number of pores per m^2 and r is the pore radius, is a unitless quantity (Wilson and Luxmoore, 1988; Watson and Luxmoore, 1986).

1.4. Statistical analysis

SAS's General Linear Model (PROC GLM) was used for analysis of variance, to determine whether the surface-structure parameters varied by tillage and fertilizer treatments, as well as their interaction. Comparison of treatment means was made by Duncan's Multiple Range test (SAS Institute, 1992).

3. RESULTS

3.1 Soil bulk density (ρb)

The average ρb of the soil-profile with shallow tillage was 1.57 Mg m^{-3} and was 1.53 Mg m^{-3} with moldboard tillage. Tillage with moldboard resulted in a reduced bulk-density, specifically of Ap (0-11 cm) (Fig. 1) and BA (11-23 cm) horizons, compared to that of shallow tillage even when no fertilizer was applied (data on BA not presented). Continuous use of chemical fertilizer (NP) or farmyard manure (FYM) alone reduced ρb in the case of shallow tillage over the Control, but there was no further decrease with moldboard tillage. Further, combined application of farmyard manure and NP resulted in a significantly lower average ρ_b in the moldboard tillage, but not in the shallow tillage.

3.2. Saturated infiltration and hydraulic conductivity (K_s)

The saturated infiltration for Ap horizon is depicted in Fig. 2 at 50 mm potential on *x-axis.* The infiltration-rate in the shallow-tillage plots (mean of all fertilizer treatments) was greater than that of the moldboard plots. Saturated infiltration increased from 28 to 47 mm h^{-1} with a combined application of NP and farmyard manure, but moldboard tillage significantly ($p < 0.05$) modified the fertilizer effect (Fig. 2). The Control had the same saturated infiltration, both in the shallow and moldboard tillage, but application of NP alone, compared to that of Control, resulted in greater infiltration in shallow tillage and lesser in the

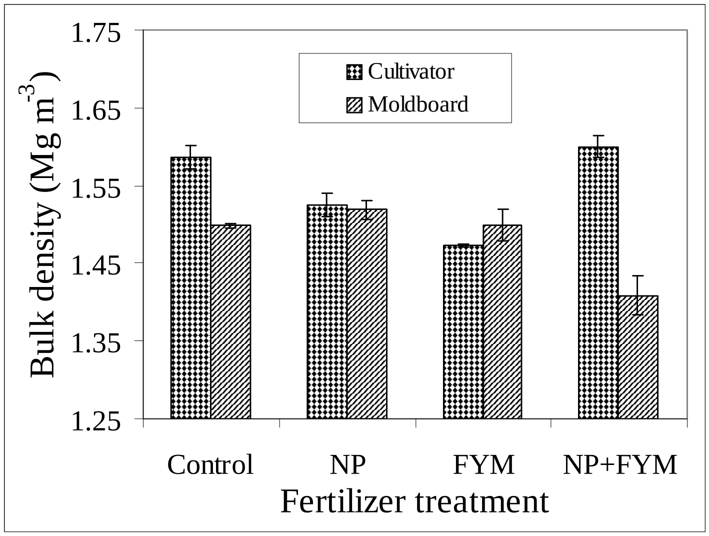

Figure - 1: Bulk density of the surface soil (0-11 cm) as affected by five-year tillage and fertilizer management: Control, no fertilizer; NP, nitrogen and phosphorus fertilizer; FYM, farmyard manure; and NP+FYM, combination of NP and farmyard manure. Bar equals stnadard deviation divided by the number of samples.

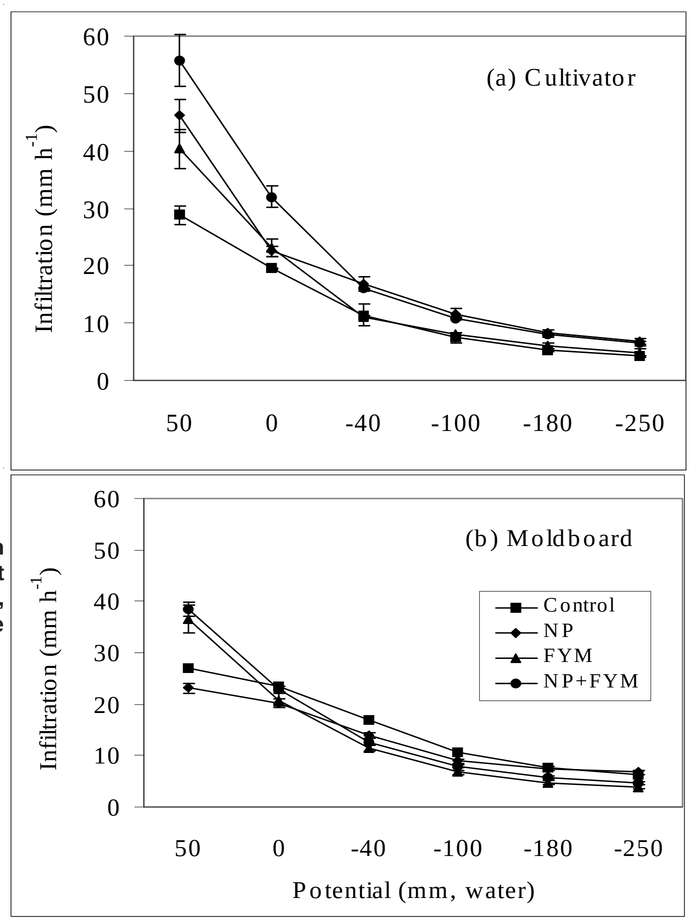

Figure - 2: Infiltration determined by Guelph permeability meter (+50 mm head) (Reynolds et al., 1985) and tension infiltrometer (White et al., 1992). Treatments and the bar, as defined in the caption of Fig. 1

moldboard tillage (Fig. 2a,b). Combined application of NP+FYM had the highest infiltration in shallow tillage. The saturated hydraulic conductivity had the same trend (data not presented).

3.3. Infiltration and hydraulic conductivity at near-saturation and under-saturation

In the shallow tillage plots, combined application of NP and farmyard manure resulted in the highest infiltration (33 mm h^{-1}) at near-saturated (0 mm water potential) (Fig. 2a). In the moldboard plots, all the fertilizer treatments had a similar infiltration-rate of 20 to 25 mm h^{-1} (Fig. 2b). Infiltration in the –40 to –250 mm potential range was greater with farmyard manure alone or in combination with NP in the shallow tillage plots, while in the moldboard plots the fertilizer-treatment difference was insignificant, except at –40 mm. At –40 mm potential, the control had greater infiltration rate than the other fertilizer treatments (Fig. 2b). The magnitude of difference in both cases decreased as the saturation decreased, with the potential setting growing more negative from 0 to –250 mm.

Hydraulic conductivity at 0 mm water-potential ($K_{\psi 0}$) varied from 10 to 18 mm h^{-1} in the shallow-tilled plots and 8.5 to 12.0 mm h^{-1} in moldboard tilled plots. The $K_{\psi -40}$ decreased to 4.0 mm h^{-1} in the shallow tilled plot and to 4.6 mm h^{-1} in the moldboard. The $K_{\psi -180}$ varied from 0.75 to 1.50 mm h^{-1} and the treatment-effect was non-significant. The fertilizer-treatments had significant effect on K_{ψ} , especially in the potential range of 0 to –40 mm water. The combined application of NP and farmyard manure resulted in a generally greater K, at all potential levels, than the other fertilizer treatments (Fig. 3a). The combined application of NP and FYM and application of NP alone resulted in significantly greater $K_{\psi -40}$ than the control and FYM alone in the shallow-tillage plots. In the moldboard plots, the control had greater $K_{\psi -40}$ than the other fertilizer treatments.

4. DISCUSSION & CONCLUSIONS

Change in distribution of pore-size, in response to the long-term treatments in the semi-arid environment is a significant finding of the study. Total porosity reflects soil-bulk, which is directly affected by tillage-methods (Heard et al., 1988). Our result on bulk-density conforms with Azooz et al. (1996), who reported greater bulk-density under no tillage (or reduced tillage) at the surface, compared to tilled soil. Further, the combined application of farmyard manure and NP resulted in a significantly lower average ρ_b than the control, in case of moldboard tillage but not in case of shallow tillage. Previously, a decrease in bulk-density as a result of long-term manuring (Sur et al., 1993; Ohu et al., 1994) and organic-matter application (Sommerfeldt and Chang, 1985) have also been reported. In this study, separate application of NP and farmyard manure also reduced the bulk-density over no fertilizer, which could be ascribed to better rooting-activity in the presence of optimum nutrients.

Total porosity realized from the bulk-density was the greatest in the moldboard plots receiving a combined application of NP and FYM, and the lowest in shallow tillage receiving the same treatment; but our results on macro-porosity, discussed later, did not support this conclusion. Bulk-density was determined by placing the radiation-source at 5.5 cm depth and, consequently, the values are average of 0-11 cm layer, while actually there may be a gradient of bulk-density within the 0 to 11 cm surface layer.

Average saturated infiltration and hydraulic conductivity (K_s) of the soil-profile was greater with the moldboard tillage than with the shallow tillage (Akhtar et al., 2001), but the reverse was true in the surface-soil. However, the K_s values were comparable to the reported values on another sandy loam under conventional tillage and no tillage, respectively (Azooz et al., 1996). Contradictory observations of tillage-effect on infiltration (and bulk density) do exist in literature. Greater saturated infiltration with moldboard tillage, compared to zero tillage and chisel (Heard et al., 1988), greater K_s under zero-tillage than the conventional moldboard tillage (Chang and Lindwall, 1992); and no difference between zero-tillage and moldboard (Sing et al., 1991); have all been reported. The general consensus is that, initially, zero-tillage (or the reduced tillage) has greater bulk-density and lower infiltration than moldboard tillage, but the condition reverses with time, due to increased biological activity in the intact surface (McCoy et al., 1994).

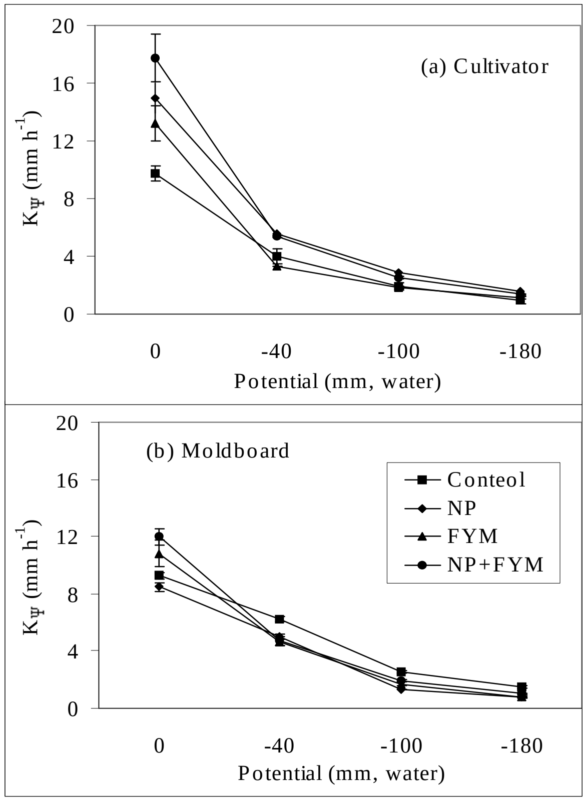

Figure - 3: Hydraulic conductivity at various potentials (Ankey, 1992). Treatments and the bar, as defined in the caption of Figure 1.

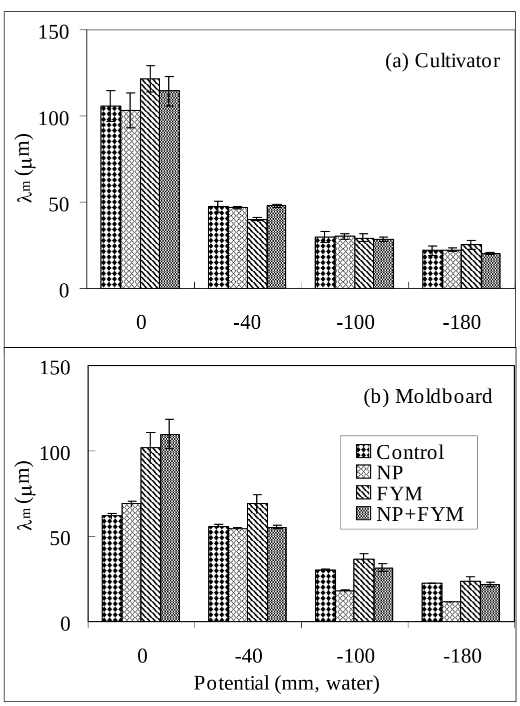

Figure - 4: Characteristics mean pore radii (Ankeny, 1992) as affected by the long-term treatments. Treatments and the bar as defined in the caption of Figure 1.

Saturated infiltration showed contradiction with total-porosity values determined from the bulk-density, e.g., the highest infiltration rate should be in the moldboard plots receiving combined application of NP and FYM, as these plots had the lowest bulk density (Fig. 1 and 2). This discrepancy may be due to either of two reasons: gradient in bulk-density of 0 to 11 cm layer (resulting in different values for the 0-5 cm layer and an average value of 0-11 cm, or macroporosity/pore continuity playing a stronger role in infiltration than total porosity (Singh et al., 1991). Infiltration rate and, consequently, hydraulic conductivity decreased as the potential decreased from 0 to –250 mm (Fig. 2 and 3), which was due to sequentially emptying the smaller and smaller pore-sizes as the size of the largest water-filled pores is inversely proportional to potential (Ankeny, 1992; Jarvis and Messing, 1995). In the given potential-level, effect of the long-term fertilizer and tillage treatments on infiltration was significant (Fig. 2), although the magnitude of difference decreased as the saturation decreased, with the potential setting growing more negative. The combined application of NP and FYM under shallow tillage had the highest near-saturation infiltration, while the control had the lowest (Fig. 2a), which may reflect greater porosity created by greater biological activities in the presence of organic matter. In the moldboard plots, treatment effect of FYM compared with the control was somewhat masked, due to overturning of the surface soil (Fig. 2b).

Hydraulic conductivity at near-saturated condition (0 water potential) varied more with both tillage and fertilizer-treatments than that of K at –100 and –180 mm water potential. The shallow tillage (cultivator) has greater pore-continuity than the moldboard tillage (Logsdon et al., 1990; Carter, 1992). Another study on a silt loam soil, where only cultivator tillage was done, reported approximately two times greater infiltration at –40 to –180 mm potential, due to long-term use of FYM and wheat-straw, compared to no organic matter application (Akhtar et al., 1999). An increased unsaturated hydraulic conductivity, due to long-term manuring (Ohu et al., 1994; Mbagwu, 1992) and other organic-matter sources (Obi and Ebo, 1995) has been reported and attributed to increased total porosity.

From the infiltration-data obtained at various potentials, we draw information on porosity and, particularly, the pore-size distribution. The capillarity equation gives the largest pore radius that can conduct water at a given potential. Therefore, at a given potential, pores varying in size from that defined by the equation to infinitesimally small would all be conducting water. Representative mean pore-radius (λ_m) is a characteristic mean pore-dimension that controls infiltration in the given range and has the utility for quantifying soil-structure and temporal changes in soil structure (Ankeny, 1992). At saturation, when all pores were conducting water, FYM had 120 μm λ_m compared to that of 103 μm of NP in the cultivator plots (Fig. 4a,b). It is obvious that characteristic pore-radius decreased with continuous use of chemical fertilizer under the moldboard tillage.

At –40 mm water-potential, when flow was through all the pores <380 μm, the shallow-tillage plots had λ_m varying between 28 and 31μm and the fertilizer-treatment effect was non-significant, while it was 54 to 69 μm in case of moldboard tillage. Also, the FYM treatment with and without NP had significantly greater λ_m than the other fertilizer treatments under the moldboard tillage (Fig. 4b). Therefore, continuous use of moldboard with chemical fertilizer (NP) without organic matter appears to have reduced mean pore-radius, especially in the range of macroporosity.

The λ_m at various potentials conforms to a previous study on a silt loam soil in the area, where 70 μμm at –40 mm potential and 30 μμm at –180 mm potential were reported (Akhatr et al., 1999). The λ_m also conforms to that of White et al. (1992). The largest difference in λ_m between FYM and NP treatments was in the bigger pore class. The study supports the conclusion of White et al. (1992) that tillage and biological activities have their most pronounced effect on size of connected pores of nominal pore-radius about 750 μm. Drees et al. (1994) reported average pore size in their no-till soil greater than their moldboard tillage soil, as determined through image analysis of thin-sectioned soil.

Maximum number of effective pores per m^2 surface soil at a given potential was calculated, using Poiseuille's equation (Wilson and Luxmoore, 1988; Watson and Luxmoore, 1986). The number of pores of > 380 μm radius were, on a $\log_{(10)}$ scale, 1.4 to 1.6, as compared to 2.6 to 2.8 of 150-80 μm size pores. The pores increased in number logarithmically as the

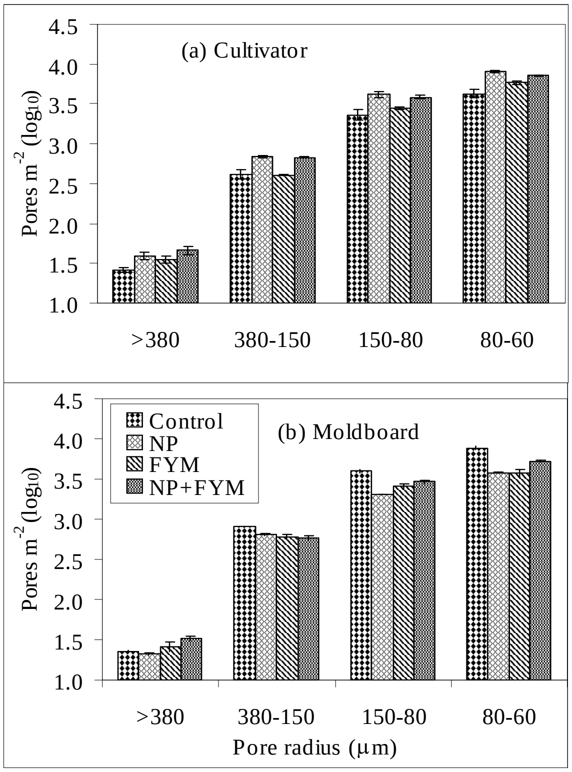

Figure - 5: Number of various size-class pores in a unit surface area (Wilson and Luxmoore, 1988) as affected by the long-term treatments. Treatments and the bar, as defined in the caption of Fig. 1

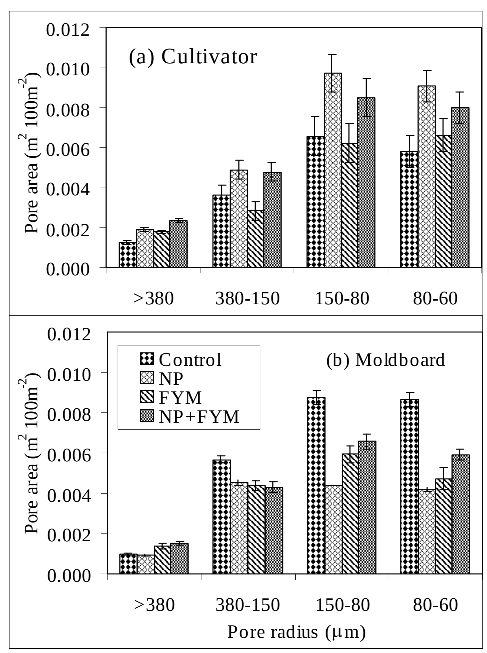

Figure - 6: Area of various size-class pores in unit surface area (Wilson and Luxmoore, 1988), as affected by the long-term treatments. Treatments and the bar, as defined in the caption of Fig. 1

pores radius decreased (Fig. 5). The number of pores participating in infiltration at –100 and -180 mm water potential were greater (in number) than that of at 0 to –40 mm, although infiltration was greater in the later case. The result conforms to the conclusion of Beven and Germann (1982), Wilson and Luxmoore (1988), and Logsdon et al. (1990) that fewer macropores have a great influence on the flow, although they are a small fraction of the total porosity. Therefore, in practice, total porosity may have less utility than pore-size distribution.

Thirty to 70 pores of ≥ 380 µm radius m^{-2} found in this soil (Fig. 5) fall within the general range previously determined by various techniques (McCoy et al., 1994). Smettem and Collis-George (1985) reported 37.5 hydrologically active macropores (≥ 220 µm radius) m^{-2}. Wilson and Luxmoore (1988) reported 94 and 183 pores ≥ 750 µm size pores in two Australian watersheds. Eighty pores of 25-125 µm radius in m^2 covering 20 m^2 area in 100m^2 in a long-term no-till plot and 91 pores covering 24 m^2 area in 100 m^2 in a moldboard plot was reported by Drees et al. (1994).
Tillage and fertilizer treatment effect on the number of pore in all the pores size classes was significant (Fig. 5a,b). The shallow tillage had greater number of ≥ 380 µm pores than the moldboard tillage but the later had larger number of 380-150 µm size pores (Fig. 5a,b). In the shallow tillage plots, application of NP with and without FYM generally had a greater number of pores in all pore size classes than the control and only FYM plots (Fig. 5a). In the moldboard plots, the control had a greater number of pores in all size classes except > 380 µm (Fig. 5b). It appears that thoroughly mixing FYM in the root-zone, which was not possible in case of shallow tillage, is important for increasing number of pores with manure application.

Treatment effect on pores of ≥ 380 µm radius was of special interest due to their influence on near-saturation infiltration. The lowest number of this size class was found in the NP treatment under the moldboard tillage and the highest in the case of the combined application of NP and FYM with the shallow tillage (Fig. 5a,b). Within the moldboard plots the highest number of ≥ 380 µm size pores class was found in the case of the combined application of NP and FYM and the lowest in the NP treatment (Fig. 5b).

Effective porosity (Φ) is a unit-less quantity and can be thought of as an aerial coverage by a given pore size class to surface area (Wilson and Luxmoore, 1988). This method for estimating soil macroporosity has assumptions including (i) laminar flow of pure water, (ii) smooth cylinderical pores, and (iii) the pore radius determined by capillary theory. With the hidden discrepancy that the method ignores the effect of pore length on infiltration, the approach does provide estimates of equivalent soil porosity classes (Wilson and Luxmoore, 1988).

In the shallow tillage plots, aerial coverage by ≥ 380 µm pores were in the range of 1.22 x 10^{-3} in the control to 2.34 x 10^{-3} in the NP+FYM and 1.0x10^{-3} in the control to 1.52 x 10^{-3} in the NP+FYM in the moldboard plots (Fig. 6). Two forest soils had 1.7 x 10^{-4} and 3.2 x 10^{-4} Φ associated with > 750 µm pores and 1.5 x 10^{-3} and 1.2 x 10^{-3} associated with 110 µm pores (Wilson and Luxmoore, 1988). Edwards et al. (1988) reported 0.005 to 0.003 m^2 m^{-2} of surface area consisted of > 150 µm radius pores. Our Φ associated with various pore size classes provides reasonable comparison to the values. In the shallow tillage plots NP with and without manure had a greater Φ of all size classes than that of control and the only manure treatment (Fig. 6a). In the moldboard plots, combined application of NP and FYM had a greater Φ than that of NP only but lower than the control except for ≥380 µm pores class (Fig. 6b).

SOME CONCLUSIONS

Finally, we compare tillage and the fertilizer treatments for their effect on total effective macro-porosity (Φ_T), which is defined as the sum of Φ associated with ≥ 60 µm size pore. The moldboard plots under the control had a greater Φ_T than the corresponding shallow-tillage plots (Fig. 7). This difference is very well reflected in bulk-density values of the two treatments (Fig. 1). Further, when only chemical fertilizer (NP) was applied, the Φ_T decreased drastically in the moldboard plots, compared to that of the shallow tillage plots (Fig. 7). There was no statistical difference between the moldboard and shallow tillage when only FYM was applied, and both had approximately equal bulk density (Fig. 1 & 7). When NP and FYM were applied in combination, the shallow-tillage had a greater Φ_T than the moldboard tillage, although bulk- density was less in the later

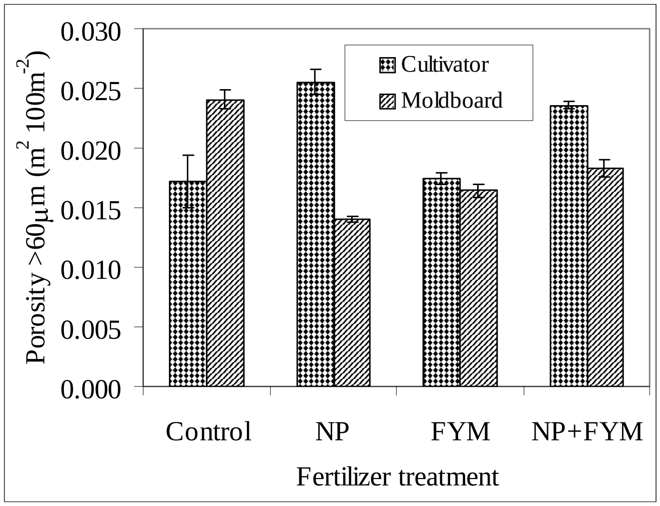

Figure - 7: Macroporosity (area of pores > 60 µm), as affected the long-term treatments. Treatments and the bar, as defined in the caption of Fig. 1

treatment combination. This suggests that lower bulk-density (greater total porosity) in the moldboard was due to a greater micro-porosity, (pores <60 µm radius). It would be of interest to compare number and area of macropores per unit surface to infiltration data. Infiltration at +50 mm head corresponds better to the area of ≥ 380 µm radius pores than the area of any pore size class or total macro-porosity in both the shallow tilled and moldboard tilled plots (Figs. 2, 6, and 7). Infiltration at –40, –100, and –180 mm potential settings conform with Φ associated with 380-150, 150-80, and 80-60 µm radius pore classes, respectively.

Our data point to

(i) conservation of macroporosity and surface-soil structure, with long-term use of the shallow-tillage with a tine cultivator and

(ii) deterioration of the same with continuous use of chemical fertilizers under moldboard tillage, especially, when no organic matter is incorporated into the farming system.

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