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Residual effects of fallows on selected soil hydraulic properties in a kaolinitic soil subjected to conventional tillage (CT) and no tillage (NT)

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Abstract Improved fallows have been used to reduce time required for soil fertility regeneration after cropping in low input agricultural systems. In semi-arid areas of Southern Africa, *Acacia angustissima* and *Sesbania sesban* are among some of the more widely used improved fallow species. However the residual effects of improved fallows on soil hydraulic properties during the cropping phase is not known. The aim of this study was to quantify the residual effects of fallows and tillage imposed at fallow termination on soil hydraulic properties (infiltration rates, hydraulic conductivity and soil porosity) during the cropping phase. Treatments evaluated were planted fallows of *Acacia angustissima*, *Sesbania sesban* and natural fallow (NF) and continuous maize as a control. Steady state infiltration rates were measured using a double ring infiltrometer and porosity was calculated as the difference between saturated infiltration rates and tension infiltration measurements on an initially saturated soil. Unsaturated hydraulic conductivity (K_o) and mean pore sizes of water conducting pores were measured using tension infiltrometer at tensions of 5 and 10 cm of water on an initially dry soil. While there was no significant difference in steady state infiltration rates from double ring infiltrometer measurements among the fallow treatments, these were significantly higher than the control. The steady state infiltration rates were 36, 67, 59 and 68 mm h^{-1} for continuous maize, *A. angustissima, S. sesban* and NF respectively. Tillage had no significant effect on steady state infiltration rate. Pore density at 5 cm tension was significantly higher in the three fallows than in maize and varied from 285–443 m^{-2} in fallows, while in continuous maize the pore density was less than 256 m^{-2}. At 10 cm tension pore density remained significantly higher in fallows and ranged from 4,521–8,911 m^{-2} compared to 2,689–3,938 m^{-2} in continuous maize. Unsaturated hydraulic conductivities at 5 cm tension were significantly higher in fallows than in continuous maize and were 0.9, 0.7, 0.8 cm and 0.5 cm h^{-1} for *A. angustissima, S. sesban*, NF and continuous maize, respectively. However there were no significant treatment differences at 10 cm tension. Fallows improved infiltration rates,

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hydraulic conductivity and soil porosity relative to continuous maize cropping. Through fallowing farmers can improve the soils hydraulic properties and porosity, this is important as it affects soil water recharge, and availability for plant growth

Keywords Infiltration rate · Fallowing · Hydraulic conductivity · Porosity · Tillage

Introduction

Fallows improve hydraulic conductivity, infiltration rates and water retention, (Young 1997; Norwood 1994; Nyamadzawo 2003a). Infiltration into a soil was found to be directly related to macroporosity (Wang et al. 1986). However these properties are altered by tillage of the soil, (Elwell 1992; Beare et al. 1994). Andreini and Steenhuis (1990) observed preferential flow under no-till plots whereas there was no such flow under conventional tillage and they attributed this to existence of macropores under no-till.

Improved fallows add large quantities of biomass to the soil during fallow periods, which increase soil organic matter, and improve soils hydraulic properties (Alegre and Rao 1996; Norwood 1994). Soil organic matter affects infiltration rates (Young 1997), soil water-holding capacity (Colla et al. 2000), as well as reduce evaporation from the soil. However conventional tillage practices were reported to result in reduction in infiltration rates (Ankeny, et al. 1990; Stonehouse 1991).

Infiltration rates under a wide range of conditions can be analyzed using simulation models, such as the empirical Kostiakov model (Kostiakov 1932) and the more physically based models of Philips (Philips 1957). Double ring infiltrometer and tension infiltrometer can also be used to determine infiltration rates and hydraulic conductivities in different soils (Bouwer 1986; White and Sully 1987).

This study was conducted to quantify the residual effects of different fallows and two tillage practices, conventional tillage (CT) and no tillage (NT) on infiltration rates, hydraulic conductivity and soil porosity one year after fallow termination. It was hypothesized that introduction of cropping after fallowing resulted in deterioration in soil hydraulic properties and that CT resulted in faster deterioration than NT.

Materials and methods

The study was conducted at the Domboshawa Training Centre in Zimbabwe (approximately 19°35′ S, 31°14′ E and 1,474 m altitude). The mean annual rainfall is 750 mm, usually received from November to April. The soils are classified as Alfisols (soil taxonomy) or lixisols (FAO). The soil texture is sandy clay loam, with 22% clay and 71% sand. Selected chemical properties of the soil at the beginning of the experiment in 0–30 cm layer were: pH (0.01 M $CaCl_2$) = 4.8, organic carbon = 6 g kg^{-1}, total nitrogen = 0.04 g kg^{-1}, extractable phosphorus = 3.8 mg kg^{-1} and exchangeable K = 0.03 $mmol_c$ kg^{-1} (Mafongoya and Dzowela 1999). The study was conducted in an experiment, initiated in the 1991–1992 season, with four treatments of *A. angustissima* (Mill) Kuntze, *S. sesban* (L), natural fallow and continuous maize (*Zea maize* L.). The fallows were first established in 1992–1993 season and were followed by four seasons of maize under conventional tillage (ox drawn mouldboard plough). Plots under *A. angustissima* were allowed to coppice during the cropping seasons while *S. sesban* had to be re-established at the beginning of 1998–1999 season. Measurements were done in October 2001, after one cropping season, and the average biomass yield of the previous crops were 1.1 t ha^{-1} conventional tillage and 0.78 t ha^{-1} under no tillage. Crop residues were removed from the plots at harvest as these are normally fed to livestock during the dry season in the smallholder sector.

Improved fallows were weeded once during the first season of fallow establishment. In the second year weeds were managed through slashing. At fallow termination all woody material was removed from the plots and only twigs and litter was left in the plots. Biomass produced at fallow termination was 10 and 5.7 t ha^{-1} for *A. angustissima* and *S. sesban* respectively. *A. angustissima* produced an additional 1.5 t ha^{-1} as coppice biomass during the cropping phase, these were left in the plots. Biomass from NF was burnt in the plots at fallow termination and maize stover in continuous maize plots was removed from plots at harvest.

After fallow termination, plots were randomly divided into sub-plots for imposing two tillage systems: conventional tillage (CT) and no-tillage (NT). Each subplot was 6 × 4.5 m in size. Conventional tillage involved ploughing using an ox-drawn mouldboard plough to a depth of 15 to 20 cm. In no tilled plots planting holes were opened using a hand hoe. All plots were weeded, disturbing the top 0–5 cm depth using hand hoes twice during the crop-growing season. Maize crop variety SC 517, was planted on 5 December 2000, and hand harvested on the 1st of May 2001.

(a) Infiltration rates using the double ring infiltrometer method

A double ring infiltrometer was used for measuring saturated hydraulic conductivity (Anderson and Ingram 1993). Measurements were done after harvesting the first crop, in October 2001 in both CT and NT plots of *A. angustissima*, continuous maize, *S. sesban* and natural fallow (NF) at Domboshawa Training Center. Stover or litter was cleared from 1.5 × 1.5 m^2 area, on soil surfaces that were not disturbed and metal rings (inner 30 cm diameter, outer 60 cm diameter, height 50 cm) were driven vertically into the soil for about 15 cm so that the smaller ring was centered in the larger ring, using a hammer. Both cylinders were filled with water to a height of 13 cm. Cylinders were refilled when the water level had dropped by 10 cm, to 3 cm, and the water level was noted before and after refilling the rings. Water levels in the inner and outer ring were always maintained at the same height. Cumulative infiltration was calculated from the differences in depth recordings after every centimeter decrease in depth, against time taken for the reading to decrease by a centimeter according to a method by Landon (1991). Infiltration rates were plotted and fitted to Kostiakov model (Hillel 1982), as shown in Eq. 1.

$$F = at^b \tag{1}$$

Where; F is the infiltration in cm/h, t is the time (h) after start of the experiment and a and b are constants. The constant a represents the cumulative infiltration after time t of infiltration. The constant b gives an indication of the relative importance of time to infiltration.

(b) Porosity

Total effective porosity and pore density were calculated using a method by Watson and Luxmore, (1986). Measurements were taken soon after the double ring infiltrometer measurements using a tension infiltrometer. The soil was assumed to be saturated, hence steady state conditions were assumed. Pore sizes (mm) were estimated using the capillarity equation (Watson and Luxmore (1986).

$$r = \frac{-2\sigma \cos \alpha}{pgh} \approx \frac{-0.15}{h} \tag{2}$$

Where: σ is the surface tension of water, α is the contact angle between water and the pore wall (assumed to be 0), p is the density of water (kg m^{-3}), g *is* acceleration due to gravity (ms^{-2}), r is the pore radius (mm) and h is negative pressure (cm H_20).

At tensions of 5 and 10 cm, pores > 0.06 and >0.03 cm in diameter were excluded from the transport process, respectively. The two tensions were chosen because these affect pores which transport most of the water in the soil at very high water potentials. A thin layer of fine grain silica sand was placed on the surface of the mineral soil to enhance hydraulic contact between the porous ceramic base of the tension infiltrometer and the soil matrix. Since both ponded and tension infiltration measurements were determined under approximately steady state or saturated conditions, a unit hydraulic gradient was assumed.

Macropore conductivity (K_m) was determined as the difference between the ponded infiltration (K_p) and the infiltration rate (K_f) at 5 cm of water tension. Using the minimum pore radius of 0.03 cm and applying the capillarity equation in conjunction with Poiseuille's equation (Watson and Luxmore (1986), the maximum number of effective macropores per unit (N) area for the 5 cm tension was given by;

$$N = 8\,\mu\,\mathrm{K_m} \Big/ \pi\,\rho\,\mathrm{g}(0.03)^4 \tag{3}$$

Where: μ is the viscosity of water ($\mathrm{ML^{-1}T^{-1}}$), $\mathrm{K_m}$ is the macropore conductivity.

The total effective macroporosity, $\theta_{\mathrm{m},}$ ($\mathrm{m^3\ m^{-3}}$) was found by multiplying maximum number of effective macropores per unit area (N), calculated from Eq. 3, by the cross sectional area of the pores using the minimum pore radius for the 5 cm tension and was given by;

$$\theta_{\mathrm{m}} = N\pi r^2 = N\pi(0.03)^2 \tag{4}$$

Macropores were defined in this study as pores that emptied at tensions >10 cm of water. This range was chosen because it includes the pore sizes that impact root growth (Ankeny et al. 1990).

(c) Unsaturated hydraulic conductivity using a tension infiltrometer

Measurements were carried out on an initially dry soil in October 2001, after one cropping season. Tensions of 5 and 10 cm which excluded pores >0.06 and >0.03 cm in diameter from the transport process were used.

(i) Cumulative infiltration

Cumulative infiltration was calculated using a method by CSIRO (1988);

$$I = Q \big/ \pi r^2 \tag{5}$$

Where: I is the cumulative infiltration, Q is the volume of water infiltrated in time t, r is the radius of the base of the tension infiltrometer.

(ii) Sorptivity

$$\mathrm{I} = \mathrm{S_o} t^{1/2}$$

Sorptivity ($\mathrm{S_o}$) was obtained by fitting data from the first 10 readings from the tension infiltrometer measurements to equation 5, (CSIRO, 1988), and to find $\mathrm{S_o}$, $Q/\pi r^2$ was plotted on the y-axis versus the square root of time ($\sqrt{t}$) on the x-axis. The slope of the straight-line portion is the sorptivity and has units of length/($\sqrt{t}$).

(iii) Steady state flow rate

Steady state flow was found by plotting the cumulative infiltration of the last 10 readings during the tension infiltrometer measurements as a function of time. The slope of this line gives the steady state flow rate $Q/\pi r^2$, (CSIRO, 1988).

(iv) Hydraulic conductivity

The hydraulic conductivity of the soil at the potential at which the measurement was being made was calculated using the steady state flow rate, sorptivity, and the volumetric water content of the soil using Eq. 6.

$$\mathrm{K_o} = Q \big/ \pi r_o^2 \ - \ 4bS_o^2 \big/ \pi r_o(\theta_o - \ \theta_n), \tag{6}$$

Where: $\mathrm{K_o}$ = hydraulic conductivity, $Q/\pi r^2$ is the steady state flow rate, $\mathrm{S_o}$ is the sorptivity, r_o is the radius of the ring, θ_o is the volumetric moisture content at the measurement potential, θ_n is the volumetric moisture content at initial matric potential and b is a dimensionless constant whose values lies between, 0.5 and $\pi/4$, an approximate value for field soils of 0.55 was used (CSIRO 1988).

(v) Macroscopic capillary length and mean pore size

The macroscopic capillary length was derived from the sorptivity, hydraulic conductivity and the moisture content at the measurement potential and initial potential, using Eq. 7, (CSIRO, 1988), (White et al. 1992).

$$\lambda_\mathrm{c} = b\mathrm{S_o^2} \Big/ (\theta_{\mathrm{o}} - \theta_{\mathrm{n}})\mathrm{K_o} \tag{7}$$

The mean pore size was calculated from the macroscopic capillary length data. A predetermined soil constant, 7.4, was divided by the macroscopic capillary length to give the mean pore size, (CSIRO, 1988) as shown in equation 8

$$\lambda_m = 7.4/\lambda c \tag{8}$$

Data analysis

Hydraulic conductivity, steady state infiltration rates, macroscopic capillary length, mean pore sizes, total effective porosity and pore density were subjected to an ANOVA using the split plot design to test for the effect of fallows and tillage. Fallows were the main treatment and tillage as the sub treatments.

Results

Steady state infiltration rates from the double ring infiltrometer

Steady state infiltration rates were significantly higher in fallow treatments relative to continuous maize (Fig. 1). There were no significant differences ($P < 0.05$) in (steady state) infiltration rates among fallow treatments, showing that the different fallows equally improved soil hydraulic properties (Table 1). However there were no significant tillage effects ($P < 0.05$) on steady state infiltration rates.

Soil porosity

Fallow treatments had a higher effective porosity than continuous maize at both 5 and 10 cm tension (Table 2). Conventional tillage (CT) lowered the effective porosity relative to no till except under continuous maize where the reverse was true at 5 cm tension. There were significant treatment and tillage interactions for total effective porosity and pore density at both 5 and 10 cm tension.

The pore density was significantly higher in fallow treatments relative to continuous maize (Table 1). Pore density ranged from 285–443 pores m^{-2}, under fallows while in continuous maize they were less than 256 pores m^{-2}. At 10 cm tension the pore density was significantly higher and ranged between 4,521 and 8,911 pores m^{-2} in fallows while it was less than 2,689–3,938 pores m^{-2} in continuous maize. Tillage effects on pore density was not consistent with higher number of pores in NT than in CT for continuous maize and NF and the opposite for *S. sesban* while there was no difference for *A. angustissima*.

Unsaturated hydraulic conductivity

Fallow treatments had significantly higher ($P < 0.05$) unsaturated hydraulic conductivities

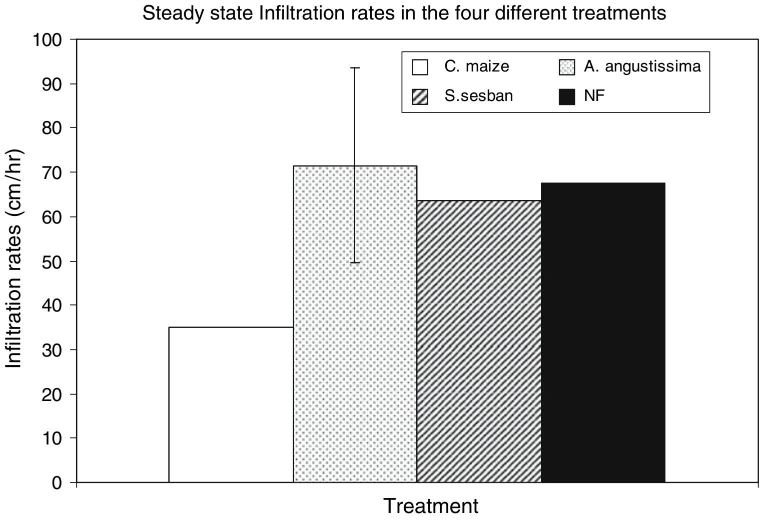

Fig. 1 Infiltration rates cm hr^{-1}, using double ring infiltrometer in the four treatments studied

Table 1 Steady state infiltration rate from double ring infiltrometer

	Steady state infiltration rates (cm hr^{-1})
Continuous maize	35.1^{a}
A. angustissima	71.5^{b}
S. sesban	63.5^{b}
NF	67.5^{b}
LSD($P < 0.05$)	22

Different symbols (^{a,b}) shows significant differences, same symbols shows no significant differences

than continuous maize except for *S. sesban* under CT at 5 cm tension. There were no significant differences on unsaturated hydraulic conductivity among the fallow treatments at 5 cm tension. At 10 cm tension there was no significant treatment effect. Tillage did not have a significant effect on unsaturated hydraulic conductivity at both tensions (Table 3). The unsaturated hydraulic conductivity at 5 cm tension was generally at least two fold higher than that at 10 cm tension among all treatments.

Macroscopic capillary length

There were significant differences in macroscopic capillary length (λc) between fallow treatments and continuous maize. The λc levels were low in fallow treatments and higher in continuous maize showing that fallows had more continuous pores (Table 3). There were no significant tillage effects ($P < 0.05$) on macroscopic capillary length. Macroscopic capillary length was higher in continuous maize than in the fallow treatments at both tensions (Table 3).

Mean pore size and total effective porosity

There were significant differences ($P < 0.05$) in mean pore sizes between treatments. Fallow treatments had higher mean pore sizes (0.07–0.09 mm) relative to continuous maize, which had 0.03 mm, (Table 3). There were no significant tillage effects on mean pore sizes (Table 3).

Discussion

Double ring infiltration measurements

High infiltration rates measured in fallow treatments were due to the improvement in the soil's hydraulic conductivity during the fallowing phase as compared to continuous maize, which had a lower steady state infiltration rate. The non-significant effect of tillage was probably because the plots had been subjected to tillage treatment for only one cropping season.

Unsaturated hydraulic conductivity using a tension infiltrometer

Measurements using the tension infiltrometer showed that hydraulic conductivity was higher in fallow treatments relative to continuous maize (Table 3). Fallows also had more pores which were involved in the transport process, (Table 3),

Table 2 Macroporosity parameters estimated from ponded and tension infiltration and Poiseuille's equation

Treatment	Total effective porosity (m^3/m^3)		Pore density (m^{-2})	
	5 cm	10 cm	0–5 cm	5–10 cm
Continuous maize CT	6.2^{b}	107.0^{a}	256.0^{b}	$3938·0^{b}$
Continuous maize NT	4.8^{a}	96.0^{a}	175.0^{a}	2689.0^{a}
A. Angustissima CT	10.2^{c}	157.0^{b}	379.0^{d}	6074.0^{d}
A. angustissima NT	12.0^{d}	179.0^{b}	443.0^{e}	6494.0^{d}
S. sesban CT	7.2^{b}	115.0^{a}	285.0^{c}	4521.0^{c}
S. sesban NT	12.0^{d}	180.0^{b}	439.0^{e}	8911.0^{f}
NF CT	9.9^{c}	181.0^{b}	443.0^{e}	7065.0^{e}
NF NT	12.0^{d}	160.0^{b}	387.0^{d}	6177.0^{d}
LSD ($P < 0.05$)	1.1	34.0	16.5	535.0

Note: means in the same column followed by the same letter are not significantly different at $P = 0.05$

Table 3 Unsaturated hydraulic conductivity (Ko), macroscopic capillary length and pore sizes

	Ko cm h^{-1}		Macroscopic capillary length (mm)		Mean pore size diameter (mm)	
	5 cm tension	10 cm tension	5 cm tension	10 cm tension	5 cm tension	10 cm tension
Maize CT	0.50^{a}	0.25^{a}	280^{a}	558^{c}	0.03^{a}	0.02^{a}
Maize NT	0.45^{a}	0.30^{a}	261^{a}	236^{a}	0.03^{a}	0.03^{a}
A. angustissima CT	0.80^{b}	0.23^{a}	20^{b}	93^{b}	0.07^{b}	0.08^{b}
A. angustissima NT	0.90^{b,c}	0.26^{a}	80^{b}	104^{b}	0.09^{b}	0.07^{b}
S. sesban CT	0.65^{a,b}	0.26^{a}	54^{b}	82^{b}	0.08^{b}	0.09^{b}
S. sesban NT	0.74^{b}	0.20^{a}	47^{b}	99^{b}	0.09^{b}	0.07^{b}
NF CT	0.8^{b}	0.45^{a}	83^{b}	52^{b}	0.08^{b}	0.07^{b}
NF CT	0.8^{b}	0.45^{a}	83^{b}	52^{b}	0.08^{b}	0.07^{b}
LSD ($P < 0.05$)	1.9		129		0.03	

Note: means in the same column followed by the same letter are no significantly different at $P = 0.05$

CT = conventional tillage, NT = no tillage

resulting in higher hydraulic conductivities. Although there have been reports to the effect that CT can destroy soil structure relative to NT (Ankeny et al. 1990; Stonehouse 1991; Nyagumbo 2002 and Chow et al. 2000), there were no significant differences in hydraulic conductivities between CT and NT. This may be because the duration in which the plots were under the two tillage systems was short for any tillage effects to be shown. Weeding may have also resulted in the disturbance of the topsoil 0–5 cm layer in NT plots and this may have resulted in no significant differences between the two tillage systems. Weeding was carried out using hand hoes, twice during the growing season and it mixed the to 0–5 cm layer of soil. Fallows added residues to the soil surface and increased soil organic matter, which improved soil structure, porosity and hence increased hydraulic conductivity. Higher water infiltration rates in fallows relative to continuous maize was a result of improve structural conditions during fallowing.

Macroscopic capillary length

The λc was lower in fallow treatments, this showed that the soils had an improved structure relative to continuous maize. In continuous maize, which was poorly aggregated, the soil matrix had broken down (Nyamadzawo et al. 2003b), there were few macro-pores, hence a large λc. For broken down soil structure soil, λc is expected to be large and for coarse and aggregated soil, λc should be small, as λc is inversely proportional to the soils characteristic microscopic length or flow weighted mean pore size (Philips 1987; White and Sully 1987).

Mean pore sizes and pore density

The mean pore sizes were lower in continuous maize and higher in fallow treatments. This reflects the effects of fallows in improving porosity and the number of pores per unit area when compared to continuous cropping systems. Fallowing increased mean pore sizes and number of pores as a result of improved aggregation. The mean pore sizes in fallows at 5 cm tension were (0.07–0.12 mm) relative to continuous maize, which had 0.03 mm, this meant that most of the pores were left out of the transport process. However, from the work by Watson and Luxmoore (1986), macropores should make up a small proportion of the total pores to contribute significantly to total hydraulic conductivity. The authors found that macropores were closely correlated to the ponded flow rate. At 10 cm tension, fallows had more pores per m^{-2} than continuous maize and these pores contributed much to hydraulic conductivity.

Conclusion

Fallowing improved the soil infiltration rates, unsaturated hydraulic conductivity, and soil porosity during the fallowing phase and this could benefit the crop during the first year of cropping.

Tillage had largely no significant effect on infiltration rates, hydraulic conductivity and soil porosity of soils after one cropping season. Weeding which disturbed the top 0–5 cm layer may have masked the NT effects from becoming apparent. Significant tillage effects were however shown in some treatments, for example, total effective porosity in *S. sesban*, and in NF, in this case the weeding did not mask the tillage from being apparent. From these results, the hypothesis that fallowing will result in improve soil hydraulic properties and soil structure and this is important for profile water recharge was accepted.

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