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Rainfall infiltration and runoff from an Alfisol in semi-arid tropical India. II. Tilled systems[1]

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Abstract

Formation of low permeable crusts on Alfisols of semi-arid tropical India significantly affects runoff and erosion processes during rainstorms. The management options commonly used to reduce runoff are tillage and/or application of organic amendments. Daily runoff data from a field experiment conducted at International Crops Research Institute for the Semi-Arid Tropics, Hyderabad, India, were analyzed to quantify the benefits of two different types of tillages (shallow tillage to a depth of 10 cm and deep tillage to a depth of 20 cm) and application of amendments (farmyard manure at 15 Mg ha^{-1} yr^{-1} and rice straw (*Oryza sativa*) at 5 Mg ha^{-1} yr^{-1}) using a no-till, unamended system as a control. The no-till system is discussed in detail in Part I. Runoff from tilled plots declined sharply after tillage operation and reverted back to that from an untilled plot after a few storms totalling about 150 mm of rainfall. Consequently, the effective period of tillage varied from 5 days in 1989, when a single storm of 115 mm rain occurred 5 days after tillage, to about 60 days during 1993 and 1994. Quantitative rainfall–runoff relationships were developed by dividing 633 rainfall–runoff events over 6 years into three groups, depending on time of occurrence: fallow period, from time of tillage operation to receipt of 150 mm of rain, and the remaining events during the cropping period after 150 mm of rain to crop harvest. More than 73% of the variation in runoff from bare and farmyard manure plots could be explained by either rainfall amount or by the product of rainfall amount and 30 min intensity. In addition, soil cover was important during the fallow period. Using the 5 min rainfall intensities, we found that runoff of tilled systems may be reduced from 35% to 10% of rainfall by adding straw. The implication is that organic amendments (such as straw or farmyard manure, if available) offer a sustainable way for Alfisols to maintain a high infiltration rate and, thereby, both reduce runoff and increase the amount of water available for crop production. © 1998 Elsevier Science B.V. All rights reserved.

Keywords: Crust; Semi-arid tropics; Rainfall–runoff relationship; Alfisol; Infiltration; Runoff; Tillage

1. Introduction

On Alfisols in semi-arid regions, the formation of a crust reduces infiltration and increases runoff.

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Loss of rainwater as runoff not only limits the water available for crop production but also forms an erosion hazard. Runoff can be reduced by breaking up the crust by tillage and/or application of soil amendments. Traditionally, in India, two tillage implements are used: the animal-drawn wooden plough and the blade harrow. The wooden plough breaks up the crust and loosens the soil to a depth of 10 cm. The blade harrow disturbs the top 5 cm of soil to control weeds (Laryea et al., 1991). An improved tillage method, recently recommended, loosens the soil to 25 cm (Vijayalakshmi, 1987). Increased infiltration and reduced runoff resulting from tillage is temporary (Hoogmoed and Stroosnijder, 1984; Pathak et al., 1987; Mead and Chan, 1988). Tillage may also lead to decreased crop production by breaking down the soil's organic matter (Tisdall and Oades, 1982).

Farmyard manure is a traditional soil amendment used by farmers to reduce soil crusts and increase the amount of soil organic matter. Farmyard manure also improves the physical condition of the soil by promoting aggregation. Mulching with crop residues (such as rice straw) protects the soil against raindrop impact and results in less aggregate breakdown and smaller runoff amounts (Venkateswarlu, 1987).

Although the effectiveness of these practices in reducing crust formation, improving infiltration and reducing runoff is known qualitatively, there is very little quantitative information. In this paper we investigate the effect of tillage and addition of organic amendments on the infiltration and runoff and compare their effects with an unamended untilled system.

2. Material and methods

In July 1988 an experiment was established on runoff plots measuring 28.5 m by 8.0 m with a landslope of 2% at the research farm of ICRISAT Center at Patancheru (18°N, 78°E), 26 km northwest of Hyderabad, Andhra Pradesh, India (Smith et al., 1992). The soil was a Rhodic Ustalf with a moisture content between 0.5% and 2%. Bulk density of the soil was between 1.4 and 1.6 g cm^3. Of the 15 different soil management systems tested, data from nine systems were used in this analysis. The nine systems were composed of three levels of amendments – no amendment (B), farmyard manure at 15 Mg ha^{-1} (F), and rice straw at 5 Mg ha^{-1} (S) – and three levels of tillage – zero tillage (ZT), shallow tillage to a depth of 10 cm (ST), and deep tillage to a depth of 20 cm (DT). All treatments were replicated three times. In this paper, each management system is designated by the letter for tillage followed by the letter for amendment. Thus, for example, ZTB designates the zero tillage system with no amendment and DTS designates deep tillage with an amendment of straw. The six management systems that involve tillage are discussed in depth. The zero tillage systems (ZTB, ZTF, and ZTS), which show a different runoff behavior than the tillage systems are only used for comparison (Rao et al., 1998).

Each year (generally in the second half of June), all fields (except for no-till treatments) were tilled to a depth of 10 cm using duck foot tines mounted on a tractor-operated tool bar. The two different tillage treatments (DT and ST) were then imposed. Organic amendments were applied at the time of sowing, generally within a week after tillage. Plots were cropped with either *Sorghum bicolor* (1989, 1990, 1993, and 1994) or *Zea mays* (1991 and 1992).

The methods used to record rainfall, runoff, and soil cover and to perform the regression analysis were described in Part I (Rao et al., 1998). Briefly, rainfall at the site was measured with a tipping bucket pluviometer (0.2 mm/tip) and runoff from the experimental plots was recorded with tipping buckets (approximately 0.05 mm/tip) at 1 min intervals using a Campbell CR10 logger (Smith and Thomas, 1988). From the field data, daily rainfall and runoff amounts and maximum 5, 15, and 30 min intensities of rainfall were calculated. During the 6-year study, a total of 265 rainfall events in excess of 45 mm were recorded of which 211 produced runoff. In the regression analysis, data from all replicates were used as opposed to their averages.

Soil cover was determined by taking slides of an area of 1.5×1.5 m^2 at two locations in each plot at time of tillage, application of amendments, approximately 30 and 60 days after sowing and after harvest of the crop. Soil cover for all rainfall events was derived by interpolation.

3. Results and discussion

3.1. Runoff

Although annual runoff from tilled plots was not statistically different from that of zero tilled plots with the same amendment (Smith et al., 1992; Yule et al., 1992; , individual storm data indicated that differences existed after tillage. For example, runoff for the STB system (shallow tillage without amendments) as a portion of the ZTB system (zero tillage without amendments) for individual events having 2 mm or more runoff is plotted against time in Fig. 1. Each year, runoff declined to a minimum following the tillage operation and reverted back to that of the untilled system after a few storms. In 1989, most of the benefit of tillage on increased infiltration rates was lost during a single storm of 115 mm of rain 5 days after tillage. In 1993 and 1994 tillage effect on infiltration rate lasted for 60 days. Most rainfall events during these 2 years were smaller than 20 mm and the crop protected the soil surface before the crust was fully developed. Thus, although the period that tillage reduced runoff varied from year to year, the runoff from tilled and zero tilled systems was similar after approximately 150 mm of rain after the soil was tilled.

To quantify rainfall–runoff observations, the rainfall–runoff events were divided into three groups: the Fallow Period (lasting from the crop harvest in October to the first tillage operation in the next season), Crop Period 1 (from the first tillage operation to an accumulation of 150 mm rainfall) and Crop Period 2 (from the end of Period 1 to harvest). Total runoff for each period over the 6 years is given in Table 1. The distribution of total rainfall was 30% during the Fallow Period, 25% during Crop Period 1 and 45% during Crop Period 2. Total runoff, compared with the ZTB system, was 93% and 80% for the STB and DTB systems, respectively. During the Fallow Period and Crop Period 2 runoff for the three tillage systems was similar. However, during Crop Period 1, runoff with

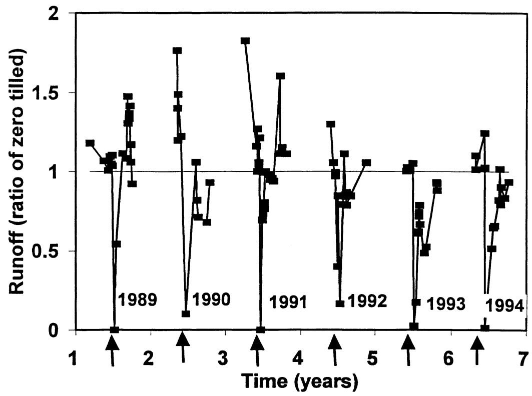

Fig. 1. Comparison of runoff from shallow tillage without amendments (STB) plots with zero tillage without amendments (ZTB) plots. Arrows indicate time of tillage for STB plots.

Table 1
Cumulative runoff from different systems between 1989 and 1994 in different periods

Treatment	Runoff (mm) during			
	Fallow Period (1165)	Crop Period 1 (949)	Crop Period 2 (1740)	Total (3854)
ZTB	417	336	415	1168
ZTF	333	153	173	659
ZTS	225	62	85	372
STB	468	225	391	1084
STF	323	111	196	630
STS	255	48	110	413
DTB	386	195	348	929
DTF	353	102	162	617
DTS	247	30	91	369

Legend: Figures in parenthesis indicate total rainfall (mm) during the period; Crop Period 1: From first tillage operation to 150 mm rain following tillage; Crop Period 2: From 150 mm rain since tillage to harvest of crop; The first two letters of the treatments indicate type of tillage – ZT: Zero; ST: Shallow; DT: Deep; The last letter is the type of amendment – B: Bare no amendments; F: Amended with 15 Mg ha^{-1} yr^{-1} farmyard manure; S: Amended with 5 Mg ha^{-1} yr^{-1} rice straw.

the STB and DTB systems was 67% and 58% of that with the ZTB system runoff, respectively. Amended systems resulted in lower runoff than unamended systems for all periods. The highest reduction in runoff was observed during the crop season (Crop Periods 1 and 2). Total runoff for systems with farmyard manure ranged from 53% to 56% of the zero tilled system without amendments (ZTB). For the systems with rice straw mulch the total runoff was approximately 1/3 of the ZTB system. Tillage had no effect on runoff when amendments were added. To develop quantitative relationships between runoff and other variables, such as rainfall amount and intensity, we carried out a regression analysis. Variables with significant correlation were selected using a procedure similar to that described in Part I (Rao et al., 1998).

3.2. Fallow period (from harvest to planting in the next season)

During the fallow period, runoff was high because the soil remained bare with very little residue or stubble cover and the surface had a well-developed crust. About 51% to 67% of the total runoff from the unamended system plots and more than 50% of the total runoff from the amended system plots occurred during this period (Table 1). Rainfall amount and soil cover were significantly related to runoff. Rainfall alone explained about 84% of the variation in runoff for the STB system while only 46% of the variation in runoff for the DTS system was due to rainfall. Correlation coefficients between runoff and soil cover ranged between 0.189 and 0.314. The best fit equations for different systems under this group are given in Table 2. The relations were relatively poor for rice straw systems (R^2 ranged between 55% and 60%) compared to bare and farmyard manure systems (R^2>73%).

The relationship between rainfall and runoff at mean surface cover (20%) for different systems are compared in Fig. 2. These relationships essentially represent the residual effect of tillage and amendment application at the beginning of the crop season. Runoff can be expected with 6 to 7 mm of rainfall. Shallow tillage did not lead to decreased runoff during the fall period. In fact, runoff with the STB system was slightly higher than with the ZTB system. This might indicate the long-term negative effect of tillage on soil structure and infiltration rate. The addition of farmyard manure had no effect under deep tillage and runoff with the DTF system was similar to that with the DTB system. Structural amelioration with farmyard manure was more evident under shallow tillage. This is attributed to the dilution of organic matter content through mixing of soil to a greater depth under deep tillage. The effect of rice straw was very similar under both shallow and deep tillage.

Table 2
Regression equations for runoff from different systems during the fallow period (N=192)

Treatment	Equation	R^2
STB	Q=0.601*P−0.079*SC−2.530	0.868
STF	Q=0.414*P−0.088*SC−0.980	0.725
STS	Q=0.330*P−0.068*SC−0.135	0.602
DTB	Q=0.458*P−0.058*SC−1.590	0.750
DTF	Q=0.461*P−0.081*SC−1.574	0.756
DTS	Q=0.301*P−0.069 *SC+0.093	0.55

Legend: Q=event runoff (mm); P=event rainfall (mm); SC=Soil cover (%); The first two letters of the treatments indicate type of tillage – ZT: Zero; ST: Shallow; DT: Deep; The last letter is the type of amendment – B: Bare no amendments; F: Amended with 15 Mg ha^{-1} yr^{-1} farmyard manure; S: Amended with 5 Mg ha^{-1} yr^{-1} rice straw.

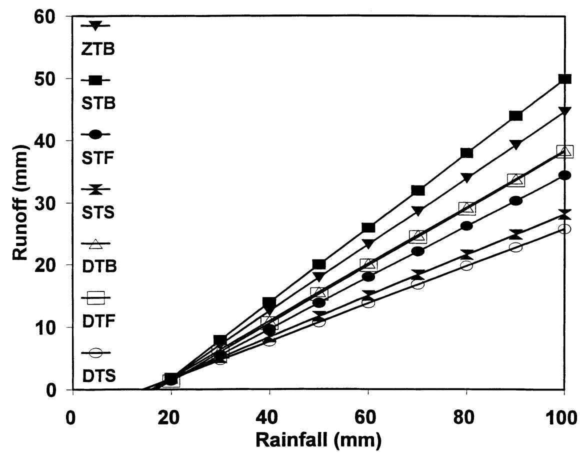

Fig. 2. Predicted rainfall and runoff relationship for different tillage systems during the Fallow Period with 20% cover. The first two letters of the treatments indicate type of tillage – ZT: Zero; ST: Shallow; DT: Deep; The last letter is the type of amendment – B: Bare no amendments; F: Amended with 15 Mg ha^{-1} yr^{-1} farmyard manure; S: Amended with 5 Mg ha^{-1} yr^{-1} rice straw.

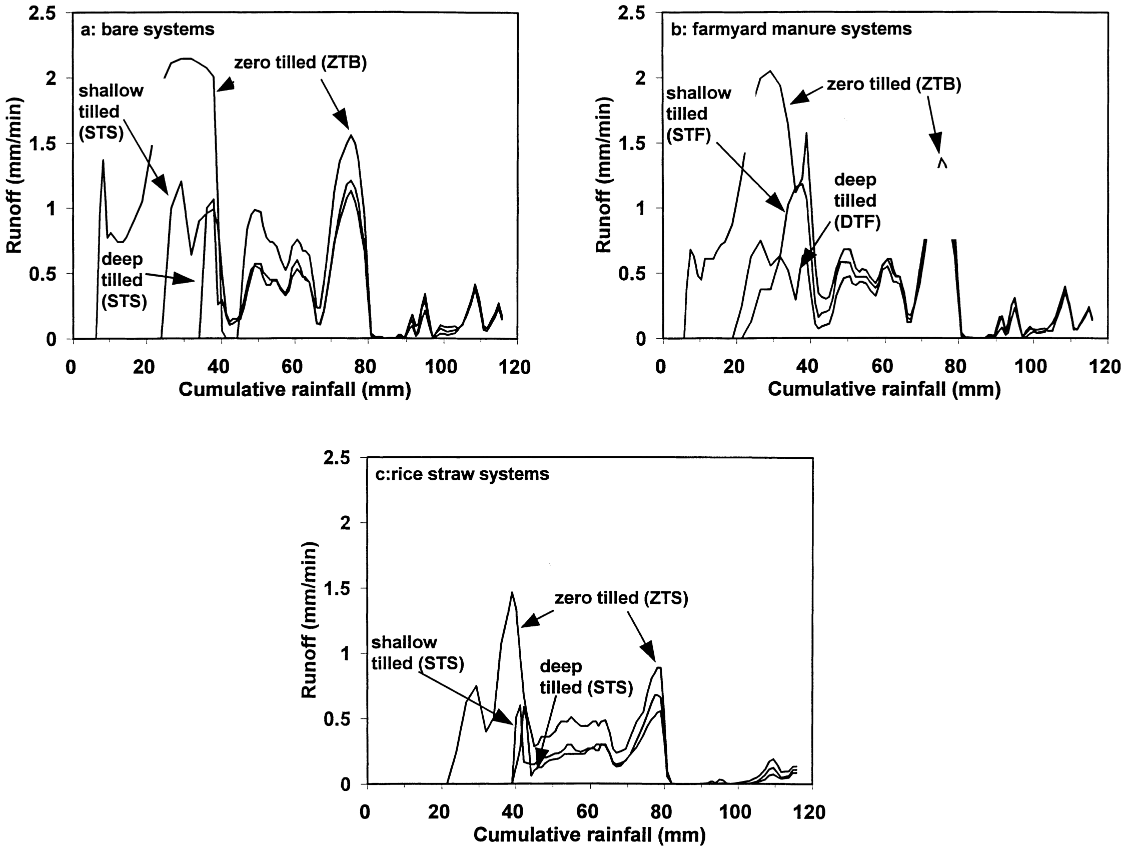

Fig. 3. Rate of runoff during a 115 mm rainstorm shortly after tillage for: (a) tillage systems without amendments, (b) farmyard manure systems, and (c) rice straw systems.

3.3. *Crop period 1 (from tillage to 150 mm rain after tillage)*

Runoff with the ZTB system in this period was similar to that during the fallow period (in both periods, 35% of rainfall was lost as runoff). Amendments and tillage were effective during this period as evidenced by low runoff volumes (Table 1). The gradual increase in the rate of runoff with tilled systems can best be illustrated by the rainfall-runoff data of the 115 mm rainstorm that occurred a few days after tillage in 1989 (Fig. 3). At the beginning of the storm, the zero tillage system with all amendments resulted in a higher runoff rate than the tilled system with the same amendments. However, as the storm progressed, runoff rates became nearly equal. Tilled systems also resulted in a greater amount of rainfall before runoff started compared to the zero tilled system: Runoff started from the ZTB, STB, and DTB system plots after 7.9, 22.0, and 32.0 mm of rainfall, respectively (Fig. 3a). Runoff rates with the three systems were almost equal after approximately 105 mm of rainfall. Runoff rate from the DTB system plot was less than that from the STB system plot during the first 40 mm of rainfall. For farmyard manure systems, runoff due to the three tillage methods was similar after about 80 mm of rainfall (Fig. 3b). For the first 65 mm of rain, rates of runoff were lower from DTF system plot. Thereafter, the runoff pattern was similar with the STF and DTF systems. Straw systems resulted in longer times before runoff started and lower runoff rates (Fig. 3c). The effect of different tillage methods persisted through the entire storm.

The infiltration rate for the STB system is plotted against cumulative rainfall since tillage in Fig. 4. The infiltration rates were obtained from the rainfall and

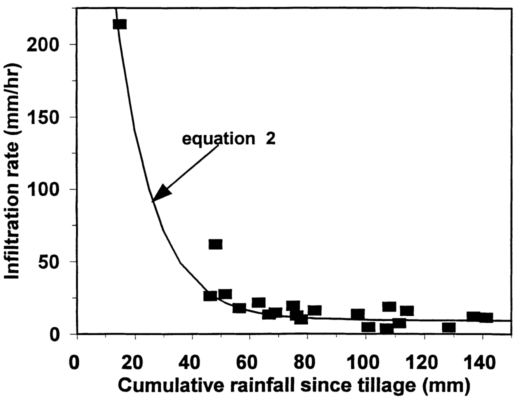

Fig. 4. Infiltration rate as a function of cumulative rainfall for the shallow tilled system without amendments (STB).

runoff hydrographs of the events that occurred from the date of tillage up to when the accumulated rainfall equaled 150 mm. The infiltration rate for freshly tilled soil is difficult to obtain by this method as the first rains normally do not result in runoff. Consequently, the infiltration rate without a crust at the time of planting was measured with the double ring infiltrometer (Bajracharya et al., 1996).

The decline in infiltration rate as shown in Fig. 4 is often described by an exponential equation as a function of time (Horton, 1940). Morin and Benyamini (1977) used cumulative rainfall instead of time, viz

$$i_t = i_f + (i_i - i_f)\exp(-b\Sigma R) \quad (1)$$

where i_t is infiltration rate at time t (mm h^{-1}); i_i is initial infiltration rate at tillage (mm h^{-1}); i_f=final infiltration rate (mm h^{-1}); b=empirical constant; ΣR=cumulative rainfall since tillage (mm).

From Eq. (1), taking the final infiltration rate, i_f, of 9.6 mm h^{-1} from Part I (Rao et al., 1998) and by linearly regressing the natural log of the infiltration rate and cumulative rainfall since tillage we find an initial infiltration rate of 610 mm h^{-1} and b=0.0757. The infiltration rate for the ZTB system can then be expressed as:

$$i_t = 9.6 + 600.4\exp(-0.0757\Sigma R) \quad (2)$$

The DTB systems had a slightly higher infiltration rates during the first rains, but the reduction in infiltration rate over time was very similar to the STB system.

Table 3
Regression equations for runoff from different systems during Crop Period 1 (tillage to 150 mm rain after tillage) (N=150)

Treatment	Equation	R^2
STB	Q=0.482*P−4.640	0.843
STF	Q=0.498*PI30−0.652	0.916
STS	Q=0.309*PI30−0.823	0.744
DTB	Q=0.401*P−3.706	0.816
DTF	Q=0.370*PI30−0.100	0.792
DTS	Q=0.162*PI30−0.330	0.711

Legend: Q=event runoff (mm); P=event rainfall (mm); PI30= product of rainfall in mm; and 30 min intensity divided by one hundred; The first two letters of the treatments indicate type of tillage – ZT: Zero; ST: Shallow; DT: Deep; The last letter is the type of amendment – B: Bare no amendments; F: Amended with 15 Mg ha^{-1} yr^{-1} farmyard manure; S: Amended with 5 Mg ha^{-1} yr^{-1} rice straw.

The amount of rainfall and product of rainfall amount and 30 min rainfall intensity were positively correlated with runoff during this period. While rainfall amount correlated well with runoff from bare system (STB and DTB) plots, the product of rainfall amount and 30 min intensity were correlated with runoff from amended system (STF, STS, DTF, and DTS) plots. Simple regression equations involving these variables explained 71 to 92% of the variation in runoff from the different system plots (Table 3). The relationships between rainfall and runoff for an average intensity of 20 mm h^{-1} indicate significant differences in runoff from bare system plots compared to that from amended system plots (Fig. 5). Both shallow and deep tillage reduced runoff compared to ZTB. The effect of tillage depth was relatively small with shallow tillage resulting in higher runoff.

3.4. Crop period 2 (from 150 mm rainfall since tillage to harvest)

Runoff from the ZTB system plots was about 24% of the rainfall compared to 35% during the other periods. Tilled systems without amendment (DTB and STB) resulted in runoff similar to the no-tilled systems (ZTB) while runoff from amended system plots was lower. Runoff from system plots amended with farmyard manure (DTF and STF) was 40% to 47% of that from the ZTB system plots and that from the straw plot was 21% to 26% of that from the ZTB system plot.

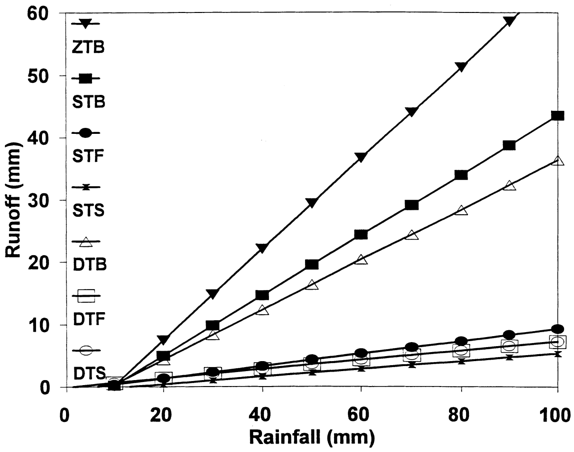

Fig. 5. Predicted rainfall and runoff relationship for different tillage systems during Crop Period 1 (first tillage up to 150 mm cumulative rainfall) for storms with an average 30 min intensity of 20 mm h^{-1}. The first two letters of the treatments indicate type of tillage – ZT: Zero; ST: Shallow; DT: Deep; The last letter is the type of amendment – B: Bare no amendments; F: Amended with 15 Mg ha^{-1} yr^{-1} farmyard manure; S: Amended with 5 Mg ha^{-1} yr^{-1} rice straw.

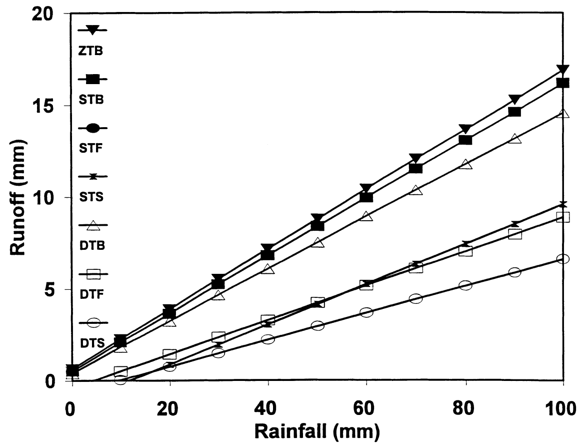

Fig. 6. Predicted rainfall and runoff relationship for different tillage systems during Crop Period 2 (150 mm cumulative rainfall up to harvest) for storms with an average 30 min intensity of 20 mm h^{-1}. The first two letters of the treatments indicate type of tillage – ZT: Zero; ST: Shallow; DT: Deep; The last letter is the type of amendment – B: Bare no amendments; F: Amended with 15 Mg ha^{-1} yr^{-1} farmyard manure; S: Amended with 5 Mg ha^{-1} yr^{-1} rice straw.

Among the variables tested, the product of rainfall amount and 30 min intensity resulted in the highest correlation with runoff for all systems. Best fit regression equations for different systems are summarized in Table 4 and their slopes (using an average 30 min rainfall intensity of 20 mm h^{-1}) are compared in Fig. 6. The equations explained from 73% to 83% of the variation in runoff. Better relation between runoff and the product of rainfall amount and 30 min intensity indicate that the infiltration rates were higher (Rao et al., 1998). This is attributed to the high percentage of crop cover.

Table 4
Regression equations for runoff from different systems during Crop Period 2 (from 150 mm rainfall since tillage to harvest of crop) (N=291)

Treatment	Equation	R^2
STB	Q=0.783*PI30+0.531	0.789
STF	Q=0.704*PI30−1.129	0.834
STS	Q=0.544*PI30−1.292	0.767
DTB	Q=0.709*PI30+0.411	0.728
DTF	Q=0.464*PI30−0.409	0.745
DTS	Q=0.364*PI30−0.685	0.729

Legend: Q=event runoff (mm); PI30=product of rainfall in mm; and 30 min intensity divided by one hundred; The first two letters of the treatments indicate type of tillage – ZT: Zero; ST: Shallow; DT: Deep; The last letter is the type of amendment – B: Bare no amendments; F: Amended with 15 Mg ha^{-1} yr^{-1} farmyard manure; S: Amended with 5 Mg ha^{-1} yr^{-1} rice straw.

4. Implications for soil management

Crop production on Alfisols in semi-arid tropics can be improved by increasing the amount of soil water available to the plants. Rainfall is the only source of water and loss of rainwater as runoff needs to be minimized. Runoff occurs on Alfisols whenever rainfall intensities exceed the infiltration rate of the soil (Morin, 1993). Hence, soil management options should include practices that maintain high infiltration rates. Because for crusted soils the infiltration rate becomes constant shortly after the rainfall starts, it is possible to estimate the fraction of rain that runs off by calculating a portion of rainfall in excess of infiltration rates of the soil. This is demonstrated below.

First, the rainfall amount in excess of a given intensity for all storms between 1989 and 1994 was calculated from 5 min totals. The results are plotted in Fig. 7, which is a plot of the percent of total rainfall

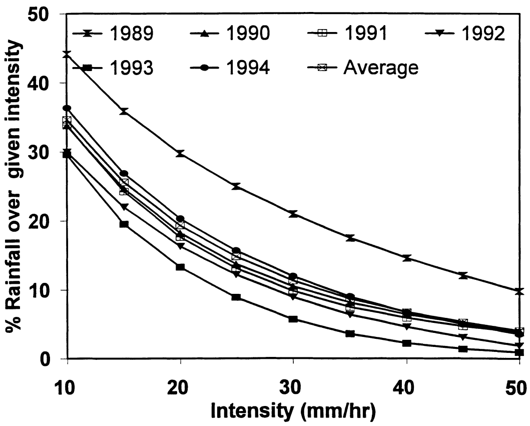

Fig. 7. Relationship of the percentage of total rainfall in excess of a given intensity.

that occurred in excess of a given intensity. Thus, for example in 1989, 45% of the total amount of rain exceeded an intensity of 10 mm h^{-1} and 10% was above an intensity of 50 mm h^{-1}. Next, the infiltration rate of the soil is estimated by assuming that rainfall intensity at which the fraction of rainfall (in excess of that rainfall intensity) is equal to the fraction of rainwater that runs off in Fig. 7. To test this assumption, we used the zero tillage system without amendments (ZTB) for which the infiltration rate of the soil was 9.6 mm h^{-1} (Rao et al., 1998). From Table 1 we find that the amount of runoff for the ZTB system is approximately 30% of the total rainfall amount, which corresponds reasonably well with a rainfall intensity in excess of 10 mm h^{-1} (Fig. 7). Thus, indeed the infiltration rate of crusted soils may be estimated by the rainfall intensity where the portion of total rainfall in excess of that intensity is equal to the (measured) portion of rain running off.

We can now estimate the infiltration rate for the systems with amendments using Table 1 and Fig. 7. The runoff from farmyard manure systems was approximately 16% of the total rainfall (Table 1) and represents rainfall in excess of 23 mm h^{-1} intensity (Fig. 7). We expect, therefore, the infiltration rate for the soil with manure amendments to be 23 mm h^{-1}. Similarly, the 10% runoff from straw systems (Table 1) equals the infiltration rate of 32 mm h^{-1} intensity. Thus, straw is, by far, the most effective management practice to increase the infiltration rate (a three-fold increase above the systems without amendments).

It may not be possible to eliminate runoff completely, considering the occasional intensities of exceeding 100 mm h^{-1} (far in excess of the infiltration rate under straw). An analysis of rainfall excess distribution at small time intervals is very useful in identifying the potential runoff. Soil management options can then be tailored to reduce runoff to desired levels by manipulating the infiltration rate or by creating surface storage.

5. Conclusions

The analysis of data reported here and in Part I (Rao et al., 1998) clearly indicates that a surface crust is the major factor that limits infiltration rates for Alfisols of semi-arid tropical India. Effectiveness of management practices in reducing runoff, therefore, depends on the ability to reduce the formation of crusts. The conventional practice of tillage to mechanically break the crust has little long-term impact in increasing infiltration rate as the effect of tillage is soon lost with the formation of a surface crust after a few rainfalls. Amendments offer a sustainable way to improve infiltration rates but is constrained by the availability of the material that may have other uses like fuel and fodder. There is a need to develop alternative methods to improve the organic matter content of the soil and the structural stability of the soil that are required to maintain high infiltration rates. Systems like perennial–annual rotations and agro-forestry hold promise.

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