RUNOFF AND SOIL LOSS UNDER DIFFERENT TILLAGE AND CROPPING SYSTEM PRACTICES AT GINCHI VERTSOL IN ETHIOPIA

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Abstract

To assess and predict runoff and soil loss on different tillage methods coupled with alternative cropping systems in the central highland vertisols of Ethiopia, a study was carried out at Ginchi, Agricultural Research Sub-Center during 1996. The experiment was conducted on runoff plots of 4 meter wide by 22 meter long, on surface slopes that range between 0.1% and 2.3%. The data collected was analyzed using regression models and an empirical formula developed by the Soil Conservation Service of America (SCS, 1964; 1972), known as curve number (CN). Both the regression model and the SCS simulated the mean daily runoff reasonably well with R2 93% and 83%, respectively. The overall results obtained explain that the improved tillage practice, BBF could drain the excess surface water safely.

Keywords: rainfall-runoff relationship, soil loss, tillage, BBF

1. INTRODUCTION

In Ethiopia out of the total land mass 10% (12.7 million hectares) are covered by vertisols and it is the fourth important soil order (Jutzi and Abebe, 1986). These soils also accounts 23% of the total arable land used for crop production (Debele, 1985). More than half of these vertisols (7.6 million hectares) are found in the central highlands of Ethiopia where the altitude is 1500 meters above m.a.s.l. In these central highlands, approximately 30% of the vertisols is supporting annual crops; the remaining 70% is under natural pasture (Serivastava et al., 1993).

Generally, vertisols have unique physicochemical characteristics. They have high montmorilliantic clay which undergo pronounced shrinkage during drying and swell when they are wet. Vertisols produce large cracks during shrinking that only closes after prolonged re-wetting. These soils became hard when dry and very sticky when wet (Kampes et al., 1981). They generally have a weak horizon differentiation. They also have low hydraulic conductivity, low infiltration rate and high soil water content at field capacity (Virgo and Munro, 1978; and Kamara and Haque, 1988c). In spite of all of the mentioned negative characteristics for crop production, vertisols in Ethiopia are believed to have a reliable agricultural potential if proper soil and water management systems are practiced (Abebe, 1998)

Ginchi research station, where this experiment was carried out, is located in the central highlands of Ethiopia. The vertisols in this region are dominance on surface slopes that ranges 0-8%. Cultivated fields include all slope ranges due to the shortage of land caused by population pressure. The unique physical and chemical properties of these soils coupled with the high amount of rainfall at the main cropping season (occurring June to September and consists of up to 70% of the annual rainfall), induces severe waterlogging and soil erosion problem that negatively impacts crop production. According to a survey study conducted in the Ethiopian highland vertisols areas farming system (Asamenew et al., 1989), the major constraints to crop production includes soil erosion.

Most farmers of the region are practicing mixed farming in a subsistence level with an average farm size of 3.1 hectares (Asamenew et al., 1989). They also practice late planting, scheduled towards the end of the rainy season, after the fields are considered optimally drained (Asamenew et al., 1989). In late planting practice, production of crops depends mostly on residual soil moisture. It is practiced in order to avoid drainage related problems. To control weeds and to prepare fine seedbeds, fields are cultivated before the onset of the main rainy season once or twice except for fields which would be covered with tef and noug. Tef and noug are mildly tolerant to waterlogging (Asamenew et al., 1989). All cultivated fields' remain bare during most of the main rain season. This practice exposes the loose and uncovered soil to the intense rainfall of the main rainy season (Serivastava et al., 1993; and Kampes et al., 1981).

Regarding the extent of the problems on surface drainage, runoff and soil erosion on different tillage practices and cropping systems, lacks enough research information. One important aspect is to understand the effect of surface drainage on runoff and soil erosion. A substantial yield (for wheat more than 50%) increase and growing period extension was achieved by the improved tillage practices that used to remove excess water from waterlogged fields (Abebe, 1982; Jutzi et al., 1987c; Mamo et al., 1992). It was also noted by different scholars, the traditional fallowing system during the rainy season causes serious soil, water and nutrient erosion (Haque et al., 1993; Serivastava et al., 1993; and; Kampes et al., 1981). The improved tillage practice (BBF) showed positive advantages by improving crop yields. It helped in extending growing period by allowing early planting. It also contributed for early coverage of bare left soil surface due to early planting. However, it was believed to have negative effects on runoff, soil and nutrient erosion if its orientation on different land surface slops is improper (Jutzi et al., 1992). According to a study conducted at Hidi and Debre Zeit in Eastern region of the central highland vertisols in 1987, it was revealed soil loss as high as 7.0 tons ha^{-1} on BBF laid at 2.7% gradient along the slop (Jutzi et al., 1992). The result is 3.3 tons ha^{-1} more soil loss than traditionally flat tilled treatment at Hidi; and 2.5 tons ha^{-1} more at Debre Zeit, on plots cropped wheat (Serivastava et al., 1993).

In Ethiopia the estimated average soil formation rate is approximated as 2.0 tons ha^{-1} $year^{-1}$ (Hurni, 1993). In contrary to the studies in Ethiopia, a study conducted in India deep vertisol at the Institute of Crop Research for Semi-Arid Tropics (ICRSAT) reported that soil loss and runoff are lower than on BBF than on flat cultivation which fallowed for cropping in the post-rainy season provided the BBF is laid on 0.4 to 0.6 % graded slope (Kampes et al., 1981).

Although vertisols have high crop production potentials, they are underutilized due to inadequate land, water and crop production management technologies and lack of basic information for developing interventions according to the immediate needs of farmers.

Taking in to account the positive and negative effects of the improved (BBF) and the traditional (flat fallowing) tillage practices, a study was initiated and conducted to evaluate and understand the effects of the tillage practices on runoff and soil loss. The aforementioned two tillage practices were evaluated under different cropping systems during the main rainy season. They also evaluated on different surface slope ranges. Runoff data collected also simulated by the empirical formula, curve number (CN) developed by Soil Conservation Service of America (SCS, 1964; 1972). It was used for estimating runoff from daily rainfall amounts. This study will help to collect basic information's that alleviate drainage and soil erosion related problems and there by contributes to the sustainable utilization of vertisols in Ethiopia.

2. OBJECTIVES

- To assess and quantify the amount of runoff and soil loss on traditional (flat) tilled and improved (BBF) tilled plots under different cropping systems of the area.
- To verify the empirical formula, curve number (CN) developed by Soil Conservation Service of America (SCS, 1964; 1972) that predicts runoff from daily rainfall under Ginchi vertisole condition.

3. MATERIALS AND METHODS

The experiment was conducted in the Ethiopian Institute of Agricultural Research (EIAR), at Ginchi Research Sub-Center in 1996. The station is located in the central highlands of Ethiopia about 85 km West of Addis Ababa on Longitude 380 13' 09'' East and Latitude 90 01' 05'' North. Its altitude is 2200m above mean sea level (amsl) and receives an annual rainfall of 1100 mm. The soil physical and chemical properties and climate of the area are presented in Table 1 and Figure 1. The study was conducted on runoff plots, 22 meters long and 4 meters wide, using a split plot design with two replications. The experiment consists of two main and six sub-plots. The treatments of the main plots are land preparation practices (flat and broad bed and furrows (BBF)).

The sub-plots are six treatments comprising the crops tef, wheat and chickpea planted with and without fertilizer. Flat land preparation planted with chickpea represents the local practice described by flat and late rain season planting. On the other hand, wheat planted at the end of June on BBF represents the improved package technology released by Vertisole Project.

The plots were laid on different land slopes, which range between 0.07% and 2.3%. Each plot was hydrologically isolated by fencing with asbestos sheets driven 20 cm. deep into the soil and protruding 40 cm. above the surface. At the lower end of each plot, runoff-collecting devices were installed according to the design and methods of Pathak et al. (1992). Each plot was plowed/cultivated twice during the short rainy season (April to May), using oxen driven local plough. The plots were once more cultivated immediately before planting, a normal practice used for smoothening and for leveling of the fields. Tef and chickpea was planted in mid-July and mid-September, respectively. Wheat was planted at the end of June, on the first week of the main rain season. UREA and DAP were applied at the recommended rates of 60/60, 40/60 and 30/46 N/P2O5 kg ha-1 for wheat, tef and chickpea, respectively. Runoff from 24 hours period rainfall was measured by recording the levels (heights) of the runoff in each of the three collecting boxes and a barrel installed for a plot. Soil loss was measured according to the procedure given by Pathak et al. (1992).

Table 1. Physical and chemical properties of the vertisols at Ginchi Research Station.

Physical and chemical properties	Average values of the top 1 meter
Percent sand	23.7
Percent silt	17.6
Percent clay	58.7
Saturated hydraulic conductivity (mm/day)	
0-150 mm depth	3.9
150-300 mm depth	2.2
Soil water content (%)	
at 1/3 bar	62.42
at 15 bar	44.12
pH (H_2O 1:1)	6.98
Organic matter (%)	0.94
Available P (Bray II ppm)	5.11
Total N (%)	0.046
Exchangeable cations (meq/gm of soil)	
Na	1.15
Ca	60.17
K	1.41
Mg	10.84

Source: Kamara, Haque & Beyene (1989) and Welderufael & Regassa (1993).

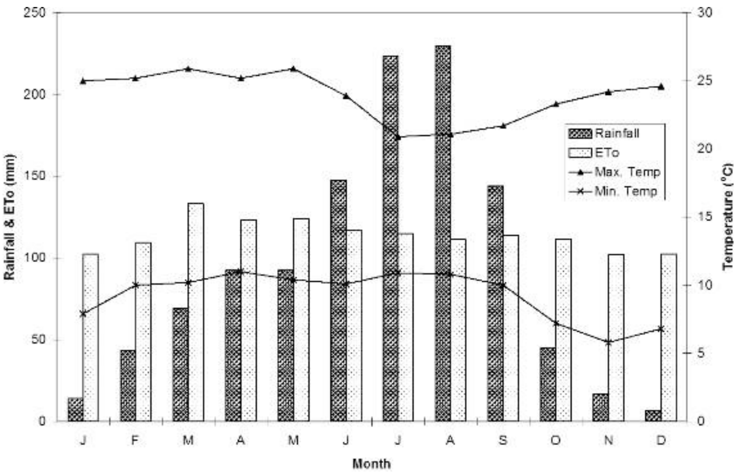

Figure 1. Long-term mean monthly rainfall and temperature distribution at Ginchi Research Sub-Center.

Data analysis

During the study period, for each plot 32 rainy days data were collected. The collected data were analyzed by regression models using SPSS computer program. Observed runoff data also used to verify the empirical formula, SCS which was developed by Soil Conservation Service of America and known as by the name curve number (CN) (SCS, 1964; 1972). The CSC gives an empirical relationship between depth of direct runoff and the depth of precipitation after runoff begins. The CSC was used to predict observed runoff. The empirical formula is based on selecting a CN, i.e. a number obtained from the relationships:

$Q = P - f$.

Where Q = runoff volume (mm)

P = Rainfall (mm)

f = cumulative infiltration (mm)

The standardized CN varies between 0 and 100 such as $0 \leqslant CN \leqslant 100$. A CN value of zero means no runoff. CN value of 100 means all rainfall will be changed to runoff, or no infiltration. The factors determining the CSC empirical model are reported in the publication, Soil Conservation Service (1972). The factors include, land use or cover, hydrological soil group and the antecedent moisture condition. In this study land use and land cover was taken for small grains as an average representative of the crops used in the study. The high clayey soil of Ginchi falls in soil group D which represents highly clayey soils.

The high moisture retention capacity of the soil, low evapotranspiration of the period and the almost continues daily rainfall during the rainy season, justifies the soil antecedent moisture condition (AMC) to be represented by AMC III. Soil group D and AMC III describes soils with low infiltration rates when they are thoroughly wetted and soils having a very low rate of water transmission. Examples are clay soils with a high swelling potential, soils with a permanently high water table, soils with a clay pan or clay layer at or near the surface, or shallow soils over nearly impervious material condition. Thus, the examples mentioned well agree to the condition of Ginchi vertisol during the rainy period. In anticipation to the antecedent soil moisture and soil group of the Ginchi vertisol, a CN 96 was found the best fitting value on the table of CN. Accordingly the runoff was estimated by the developed empirical formula expressed as:

$$Q = (P - 0.2\,S)\,2 / (P + 0.8\,S) \qquad (1)$$

And thus the potential maximum retention (soil storage) was determined from the following relationship:

$$CN = 25400 / 254 + S \qquad (2)$$

If $CN = 96$, then $S = 10$ mm.

Substituting $S = 10$ in equation 1 will give:

$$Q = (P - 2)2 / (P + 8) \qquad (3)$$

Where, Q = accumulated runoff depth (mm)
P = accumulated rainfall depth (mm)
S = potential maximum retention/potential water storage capacity of the soil (mm)
CN = curve number

Runoff and soil loss data collected in 1996, during the main rain season (June to September) were also analyzed by multiple regression models. The models used for prediction and evaluation of the effects of the different parameters of cropping systems (crop type, slope, land management and fertilizer application) on the amount of runoff and soil loss.

4. RESULTS AND DISCUSSIONS

Multiple regression analysis was carried out by applying various parameter combinations which processed by stepwise regression analysis. Runoff and soil loss was well predicted by the following linear multiple regression models expressed as:

$$Q = (5.05V1 + 0.049D - 4.402) + (0.6035 + 0.038L - 0.008D)*R \quad (4)$$

$$SL = -23.14 + 216.74V2 + 10.96R - 0.88D \quad (5)$$

Where, Q = Runoff amount in mm
SL = Soil loss in kg/ha
D = the successive rainy days resulted runoff
L = Land management practice, 1 = Flat and 2 = BBF
R = Rainfall amount of 24 hours duration in mm
V1 = 0 for runoff amount less than or equal to 5mm, and
= 1 for runoff amount more than 5 mm
V2 = 0 if soil loss is less than or equals to 200 kg/ha, and
= 1 if the soil loss is greater than 200 kg/ha

Results of the analysis for runoff and soil loss are presented in Tables 2 and 3. The results obtained showed that runoff could be well predicted by the regression model developed with a coefficient of determination (r^2) equals to 83.3% and significant at P = 0.01 level. According to the results, runoff is significantly (at p = 0.01 level) affected by the amount of rainfall, type of land preparation and by the successive rainy days/accumulated soil moisture (Table 2). Increase in rainfall increases the runoff being the other parameters remain the same (Fig.1). The wetness of the soil (soil moisture) increases with the cumulative rainfall amount which implicitly represented by the successive rainy days. Increase in the cumulative rainfall in a daily basis decreases soil storage. Thus, the resultant low soil storage condition favored for increased runoff. On the other hand, if the interval between two rainy days is large enough to depilate the soil moisture retained significantly, the cumulative effect of the rainfall on the runoff could be trivial. Vertisols generally have high initial water storage capacity until they reach saturation. Once these soils reached saturation, they will retain it for longer time. At Ginchi, when saturated soil condition exists, most of the succeeding rainfall proportions end up as runoff. In waterlogged vertisols with very low sub-surface permeability, the runoff primarily generated by saturation excess condition. If the interval between two rainy days is large enough to cause significant soil water depletion, then rainfall following the dry days may end up with low runoff, contributing largely to sorptivity and the soil storage. Table 4 shows the percentage of rainfall changed into runoff on the different treatments.

The result of the study also disproved the hypothesis that assumed runoff and soil loss would be affected by the crop type (tef, wheat and chickpea), fertilizer management (with and without fertilizer) and land slope (0.1 to 2.3 %). Rather, only the land preparation methods showed significant differences in runoff amounts. Thus, the regression model for runoff reveals that BBF land management practice produced more runoff than the flat land preparation practice with the same amount of rainfall. The observed as well as the model predicted rainfall-runoff relationships (Figure 2) shows that rainfall amounts less than 10 mm are initiating insignificant amount of runoff.

They also poorly simulated by both models. From the graph of the rainfall-runoff relationships, one can also be able to deduce that only rainfall amounts greater than 10 mm have significant influence on the amount of runoff (Figure 2).

Table 2. Stepwise regression analysis results for runoff[a].

		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
Model		B	Std. Error	Beta		
1	(Constant)	-5.818	.262		-22.230	.000
	rainfall in mm	.867	.020	.851	43.377	.000
2	(Constant)	-3.782	.233		-16.223	.000
	rainfall in mm	.544	.023	.534	23.907	.000
	V1	5.065	.253	.447	19.987	.000
3	(Constant)	-3.676	.230		-15.990	.000
	rainfall in mm	.605	.025	.594	23.962	.000
	V1	4.991	.249	.440	20.022	.000
	RD	-4.111E-03	.001	-.098	-5.211	.000
4	(Constant)	-3.693	.229		-16.156	.000
	rainfall in mm	.549	.031	.539	17.589	.000
	V1	4.966	.248	.438	20.022	.000
	RD	-4.074E-03	.001	-.097	-5.194	.000
	RL	3.899E-02	.013	.074	3.051	.002
5	(Constant)	-4.402	.421		-10.459	.000
	rainfall in mm	.603	.041	.593	14.562	.000
	V1	5.048	.251	.445	20.122	.000
	RD	-8.029E-03	.002	-.191	-3.781	.000
	RL	3.802E-02	.013	.072	2.979	.003
	Day	4.916E-02	.025	.084	2.003	.046

Table 3. Stepwise regression analysis results for soil loss

Model		Un standardized coefficients		Standardized Coefficients	t	Sig
		B	Std. Error	Beta		
1.	(Constant)	68.470	4.764		14.427	0.000
	V2	302.439	8.827	0.789	34.264	0.000
2.	(Constant)	-37.138	9.667		-3.842	0.000
	V2	221.105	10.435	0.576	21.188	0.000
	Rainfall	10.799	0.884	0.332	12.211	0.000
3.	(Constant)	-23.144	11.549		-2.004	0.045
	V2	216.737	10.595	0.565	20.457	0.000
	Rainfall	10.963	0.885	0.337	12.385	0.000
	Day	-0.877	0.398	-0.047	-2.201	0.028

Table 4. Observed mean and total runoff in mm for the different treatments

No.	Treatment	Total	Mean	% of rain
1	L1F1C1**	239.22	4.06bc*	33.9
2	L1F1C3	282.19	4.70abc	38.7
3	L1F1C2	227.62	3.56c	29.2
4	L1F2C2	309.00	4.98abc	40.9
5	L1F2C1	263.81	4.79bc	42.6
6	L1F2C3	236.02	3.75bc	30.8
7	L2F2C3	340.59	5.49ab	45.3
8	L2F1C1	243.52	4.13bc	35.5
9	L2F1C2	294.44	4.60abc	37.7
10	L2F2C2	373.45	6.44a	53.8
11	L2F1C3	293.63	4.74abc	39.2
12	L2F2C1	150.62	3.14c	27.7
	Mean			**37.9**

* Treatment means followed by the same letters are not significantly different (LSD = 0.05)

** L1= land management 1 or flat tillage practice
L2= land management 2 or broad bed and furrow
F1= without fertilizer; F2= with fertilizer
C1= crop 1 or tef; C2= crop 2 or wheat; C3= crop 3 or chickpea

While calculating the potential maximum retention of the soil (S) in the SCS equation, its value was found to be 10 mm. The SCS was also well simulated the mean daily runoff obtained from all the plots (Figures 2 & 3). The performance of the SCS was tested by R^2 (Nash & Sutcliffe, 1970 efficiency index).

$$R^2 = (F0^2 - F^2)/F0^2 \quad (6)$$

Where, R^2 = the proportion of the initial variance accounted for by that model
The initial variance, $F0^2 = \Sigma (q - \mu)^2$
Where, q = observed runoff
μ = mean of the observed runoff data
And $F^2 = \Sigma (q' - q)^2$ (7)

Where, F^2 = analogous to the residual variance of a regression analysis
q' = model predicted runoff (mm)
q = observed runoff (mm)

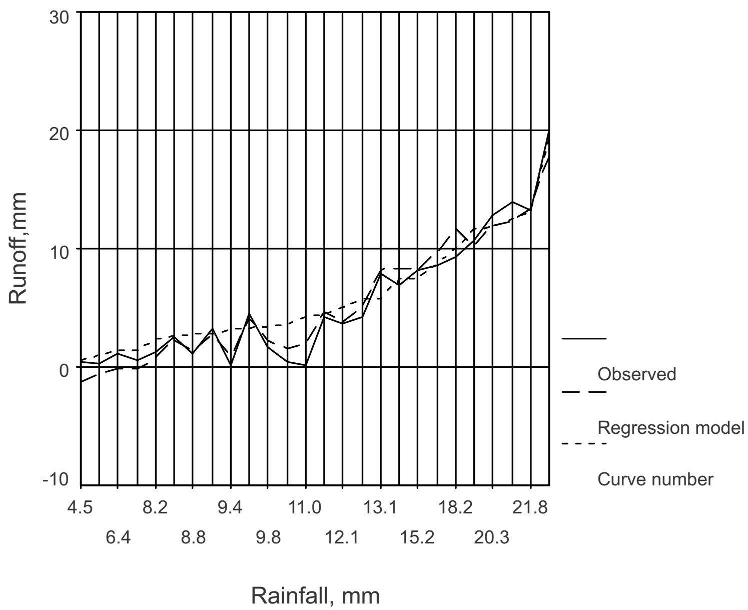

Figure 2. Relationship between rainfall and daily mean runoff at Ginchi vertisol, 1996

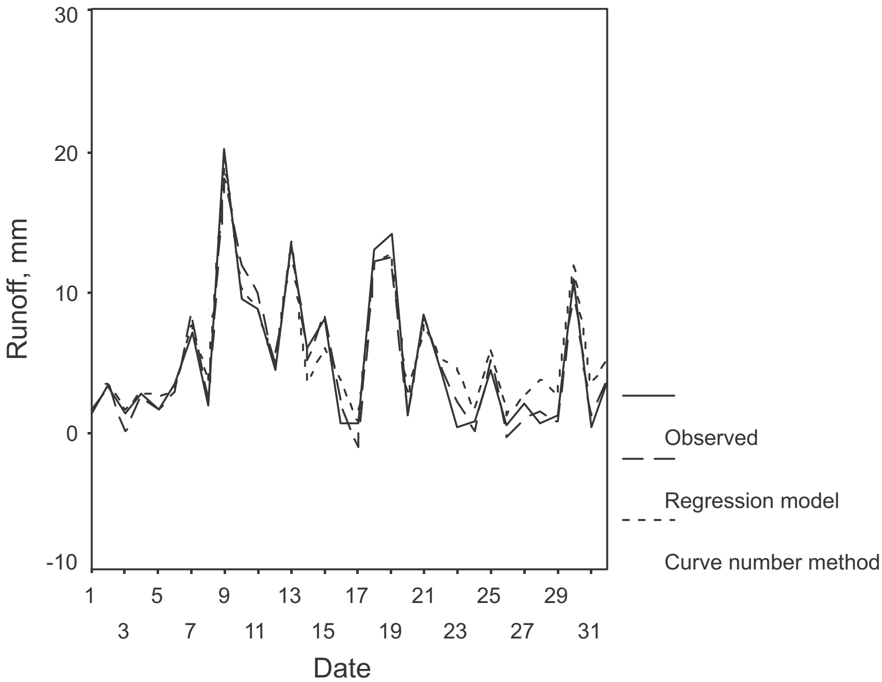

Figure 3. Observed and predicted mean runoff at Ginchi vertisol in the main rain season of 1996.

Thus, R^2 for the SCS empirical formula was found to be 84% while for the regression model R^2 is 93%. The index R^2 is useful for general interpretation of the efficiency of a model or a part. The highest value of R^2 reflects the increased efficiency of the model to simulate/generate the real situation. Therefore, the high R^2 values prove that the regression model and the SCS can reasonably well predict the runoff under the considered situations. Especially, the SCS can be useful to estimate the peak runoff amount for designing different water management projects and soil and water conservation structures with minimum cost. It can also help to design water-harvesting structures provided the preconditions are fulfilled. The SCS verified for Ginchi climate and soil type was used to predict the amount of runoff resulted from rainfall after the soil gets wet (saturated).

The soil loss data for 1996 was also analyzed using regression model. The results of the stepwise multiple regression analysis is given in Table 3. The results disproved the hypothesis that states soil loss could be affected by the different land preparations, or cropping systems and fertilizer applications, or else by the undertaken slopes.

Instead, the results reveals that soil loss can only be affected by the amount of rainfall and the antecedent soil moisture, which in the regression model described implicitly by the successive rainy days where runoff data was taken. It also showed that late planted chickpea which represents the farmers practice resulted relatively more soil loss than the other crops. This is may be because of the chickpea field that left uncropped (i.e. cultivated and left bare) until mid-September planting. In contrary to the hypothesis conceived before, the land preparation method, BBF doesn't cause significant soil loss under the considered slope ranges. Most importantly, BBF produced more runoff compared to flat land preparation, which is desirable for its intended purpose, removing excess surface water otherwise, which would have been caused waterlogging problem, and hence reduction of crop yields.

5. CONCLUSIONS

From the study conducted, it is possible to draw important conclusions, which helps in giving basic information for future follow-up works. The following are important conclusions:

- BBF land preparation method could not cause significant soil erosion than the traditional land preparation method in the undertaken slope ranges (between 0.1% and 2.3%). It rather gave more runoff which is desirable for its intended purpose, removing excess surface water to tackle the major problem of the area which is surface waterlogging.
- For Ginchi Pelic Vertisol and similar agroclimatic zones the empirical formula SCS could contributes to estimate the amount of runoff for various researches and development works.

6. ACKNOWLEDGMENTS

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