Evaluation of soil drainage methods for the productivity of Waterlogged Vertisols in Jama district Eastern Amhara region, Ethiopia

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Abstract

*Vertisols are important agricultural soils in the Ethiopian highlands. The highland part of Jama district is one of which Vertisols have huge coverage and are underutilized due to waterlogging. Such a potential Vertisols areas needs to be put under wise cultivation. Thus, a study was conducted to investigate the effects of soil drainage methods on surface runoff, soil loss and yield of wheat crop as indicators of productivity improvement of typical Vertisols in Jama district of Amhara Region, Ethiopia during the rainy season of 2017/18. The treatments were three soil drainage methods (BBF-120cm*40cm, BBF-80cm*40cm and RF-40cm*40cm) arranged in a randomized complete block design with three replications on standard runoff plots. Statistical Analysis System, version 9.0 was used to perform analysis of variance and mean separation of the collected data on yield, soil loss and runoff. The result indicated that the effect of BBF-120cm*40cm brought significantly (P 0.05) higher difference on surface runoff, yield and biomass of wheat over RF-40cm*40cm. The rainfall of about 55.04%, 51.44 %, and 48.08% was lost as runoff from BBF-120cm*40cm, BBF-80cm*40cm and RF-40cm*40cm respectively. The drainage method, BBF-120cm*40cm gave 53% and 20.9% of grain yield advantage over the drainage methods of BBF-80cm*40cm and RF-40cm*40cm respectively. Whereas, Soil loss was not significantly (p >0.05) changed among all treatments and it is found in the range of soil loss tolerance in Ethiopia. As enhanced drainage is a requirement for successful crop production on Vertisols areas BBF-120cm*40cm is recommended for draining excess runoff and consequently maximizing the yield of wheat in the study area and others with similar farming system and agro-ecologies.*

Keywords: *drainage, grain yield, runoff, soil loss, Vertisols,*

Introduction

In Ethiopia, about 12.6 million ha of land is reported as Vertisol; it accounts the portion about 10% of the total area of the country and is almost constrained by waterlogging problem due to the excess rainfall during the main growing seasons (Jutzi, 1989; Asamenew *et al*., 1993; Debele and Deressa, 2016). The highland location where rainfall is plenty coupled with relatively noble inherent fertility status enables these soils to have great potential for crop. Vertisols are some of the most productive soils for rainfed agriculture. Their high water holding capacity allows them to compensate better than most other soils for the low and erratic rainfall. On the other hand, due to the integral physical characteristics of these soils together with high rainfall of which is concentrated on months from June to September, the yield is low mainly due to waterlogging. An old data showed that out of the 7.6 million hectares of Vertisols found in the highlands only 26% of this area was under cultivation mainly due to waterlogging, the difficulty of land preparation, and soil erosion (Tekalign and Haque, 1988; Haque, 1992; Asamenew *et al*., 1993). Vertisols take a significant share of productive agricultural soils in the Ethiopian highlands but challenging to achieve the expected level of production due to their poor internal drainage and subsequent waterlogging (Jutzi and Abebe, 1987).

The highland part of Jama district is one of which Vertisols have huge coverage and are underutilized due to waterlogging. It is long established that waterlogging results in poor aeration, lower soil microbial activities, loss and unavailability of plant nutrients, and poor workability; in turn, causes Vertisols in Ethiopia are underutilized. In swamplands, the soil pores inside the root zone of crops are saturated and air circulation is taken closed. Waterlogging, therefore, precludes the free circulation of air within the root zone. Thus, water work adversely affects the chemical processes and also the bacterial activities that are essential for the correct growth of a plant (Cook and Veseth, 1991 cited by Assen *et al*., 2000; Mekonen *et al*., 2013). McDonald and Gardner, 1987 reported that the water table reaches near the root zones of the crops as a result of waterlogging will cause the soil pores to become fully saturated and the normal circulation of air in the root zones of the crops has stopped and the growth of the crops decreased.

The root tips, where most water, air, and nutrient uptake takes place, are the first to suffer from waterlogging mainly due to lack of oxygen reducing the seminal root growth in particular. Consequently, the crop root zone is poorly aerated and nutrient uptake for growth and development will be impaired (van Ginkel *et al*., 1991). To overcome the waterlogging stress, farmers in the highlands of eastern Amhara adopt a drainage technology called broad bed and furrow (BBF). But using this technology they Plant late in the season around the end of August up to mid-September when the excess water naturally drained away so that the crops grow on residual moisture, however, planting late in the season has yield disadvantage as the crop would be exposed to terminal moisture stress and frost damage (Jutzi and Abebe, 1987; Teklu *et al*., 2005). In good years (if the rain extends to September and October), the harvest may be very good if no frost. However, as this often fails, the consequence can range from substantial yield reduction to total crop failure (Debele and Deressa, 2016). In high rainfall areas, it is common to

40 to 60 cm. In this traditional ridge and furrow system, the furrows take up 40-50% of the crop area (Astatke *et al*., 2001).

Crop production and livestock feeding have been pushed by an increasing population pressure to steep slopes in the way of causing serious de-vegetation and soil erosion while Vertisols remain underutilized. There is a big opportunity to meet the demand for food doubling population if management strategies could be implemented towards the novel Vertisols of which with large moisture-holding capacity and relatively high fertility (Wubie, 2015). In Ethiopia where the people are suffering from food scarcity, removing production constraints in Vertisol areas is significantly an important alternative (Tekalign *et al*., 1993). Vertisol which covers an enormous landmass of the country needs to be put under cultivation with excess water draining innovations to achieve food security in Ethiopia. Furthermore, it has been reported that the removal of excess water from Vertisol significantly enhances nutrient uptake in crops (Asnakew *et al*., 1991). It is also proved that substantial increases in crop yield could be obtained on Vertisols if excess surface soil water is drained off and if appropriate cropping practices are used (Wubie, 2015). Therefore, this study was conducted to investigate the effects of soil drainage technologies on (i) enhancing surface drainage as an indicator of improved productivity through making effective ridge and furrow system, (ii) soil loss as indicators of the extent of soil degradation, and (iii) runoff generation for further discoveries related with water management to improve the productivity of typical Vertisol in the highland area.

Materials and Methods

Description of the study area

The experiment was conducted during the main rainy seasons from 2017 to 2018, in Jama district of south Wollo administrative zone of the Amhara national regional state in the northeastern highland vertisol area of Ethiopia at the research station of sirinka agricultural research center (Figure 1); which is 362 km northeast from Addis Ababa. Geographically the district is located between 10º 06´ 24" to 10º 35´ 45" N latitude and 39º 04´ 04" to 39º 23´ 03" E longitude with an altitude of 2850 masl at the specific area of a research station.

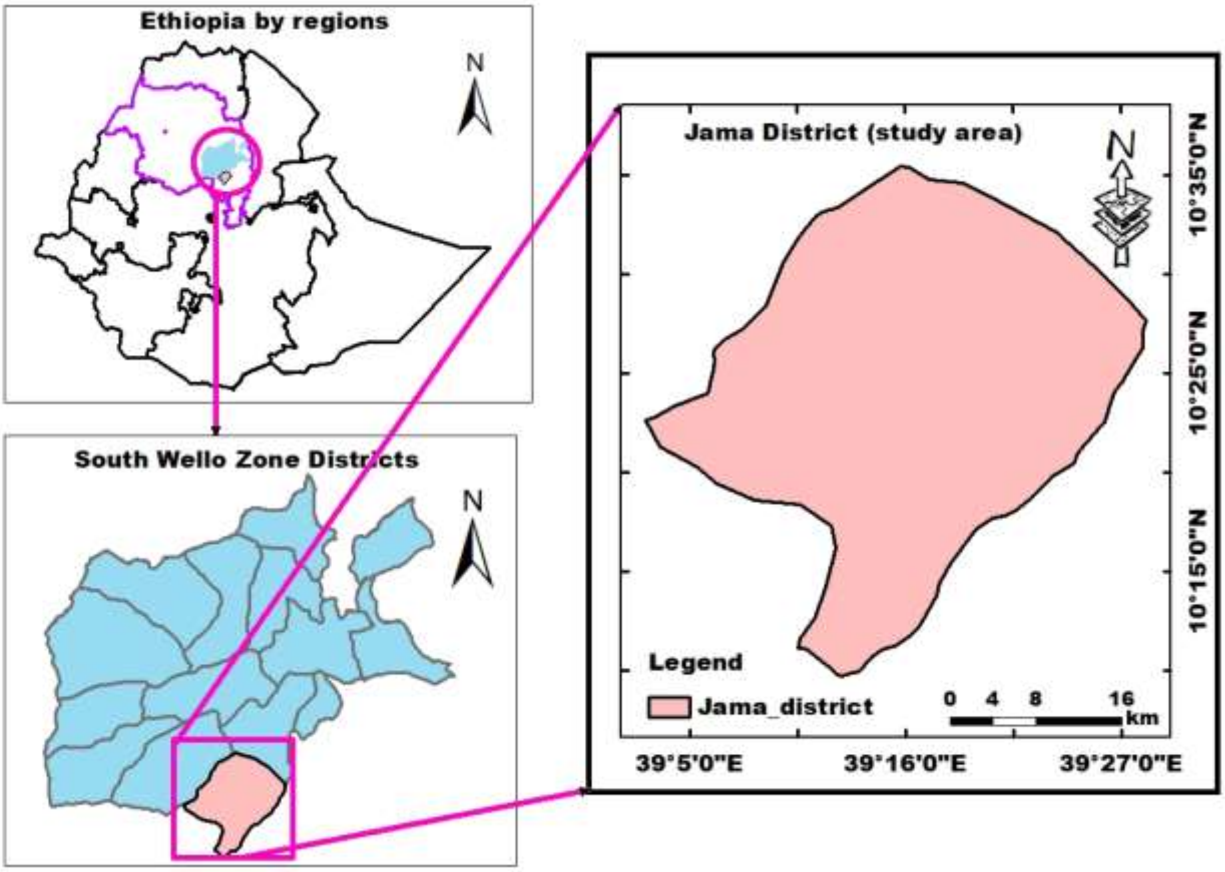

Figure 1. Location of the study area at Jama district in northeastern Ethiopian highlands

Based on 10 years (2008-2018) climatic data, the area receives an average annual rainfall of 1012.0 mm of which 74.6% is received during the main rain season (June to September) and the highland plateau of Jama has a very cold temperature which ranges from 0 to 20 ^{o}c. The dominant soil in Jama is vertisol which is a black to gray clay with high swelling and shrinking character. It is poorly drained when wet and cracking when dry. The land use is mostly cultivated field crops: wheat (*Triticum aestivum L.*), teff (*eragrostis tef*), and fabbabean (*Vicia faba L.*) In rotation, while the marginal lands along the roadsides and communal pasture lands purposely left for feed sources are the major grazing grounds (Getaw, 2000).

Treatments and experimental design

Treatments of three soil drainage techniques/planting beds (Table 1) were arranged in a randomized complete block design, with three replications on plots having a size of 4.8 m width and 10 m length dimension of measurable runoff producing area (Figure 2).

Table 1. Treatment description

Treatment name	Remark
BBF-120 cm*40 cm (T_1)	
BBF-80 cm*40 cm (T_2)	
RF-40 cm*40 cm (T_3)	

NB: T_1=treatment one; T_2=treatment two; T_3=treatment three: Use this table for further identification of treatments in all sections of the paper

*BBF-120 cm*40 cm (T1):* This system was constructed manually by scooping the soil from two sides of the furrows and distribute evenly on the upper part of the bed after the land is plowed by a traditional ox-drawn tine-plow implement having 40 cm width. The effective growing area is 120 cm wide and 20 cm high, separated by 40 cm wide furrows, to facilitate surface drainage between the beds. The crops are sown at the beginning of July, depending on the onset of rain and the type of crop to be grown.

*BBF-80 cm*40 cm (T1):* this was made with an effective bed width of 80 cm and 40 cm wide and 20 cm deep drainage furrows. This land preparation method is a recommended surface drainage system for Vertisol areas like Inewarie.

*RF-40 cm*40 cm (T3):* This is a traditional soil drainage method in the study area and neighbor districts of Northeastern highland Vertisol of Ethiopia for crops susceptible to waterlogging. It is constructed with the traditional tine plow after the seed is broadcast with an effective bed width of 40 cm and 40 cm wide and 20 cm deep drainage furrows, so that the crops grow on the ridges, allowing the excess water to drain out of the field through the furrows. In the case of our experiment, we adopted the method with its standard as of its conventional applicability while planting techniques and inputs were applied based on the recommended packages for the area.

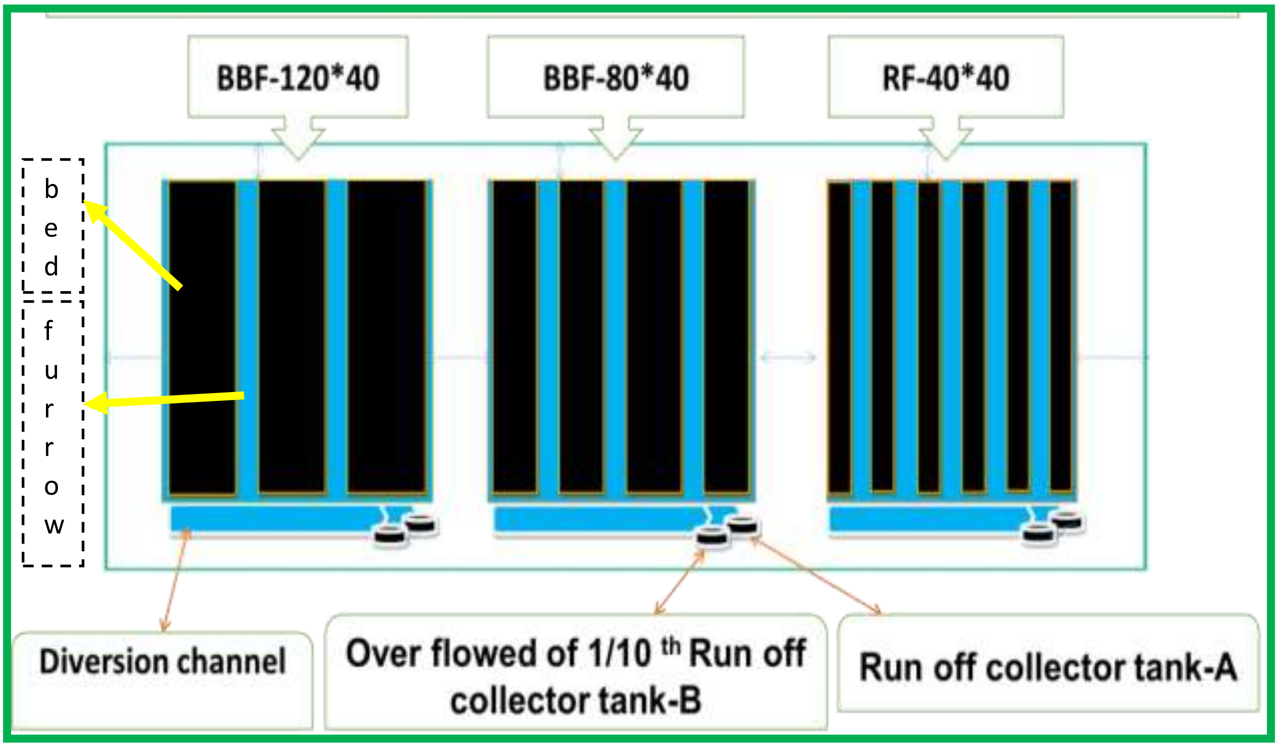

Figure 2. Experimental layout of the treatments

Runoff and soil loss measurements

Nine hydrologically isolated runoff plots of 10 m long and 4.8 m wide (48 m^2) were delineated on uniform land and the beds and furrows were graded along the slope to facilitate surface drainage through the furrows between the beds so that the crops grown on the drained beds. Plots were bounded by a galvanized metal sheet of 50 cm depth, of which 25 cm was inserted into the ground to prevent the lateral flow of runoff and the rest above the ground to block overland flow from entering the experimental plot. At the lower side of each plot, a water collector channel was constructed to collect the water drained from the furrows and beds (Figure 2). This water collector channel was also integrated with a small sediment trap (micro-pond) excavated at the outlet on which a barrel-like cylindrical tube was installed to measure the amount of runoff generated and soil removed from each drainage techniques/treatments. The rain gauge was installed near the experimental plots to record daily rainfall of the area.

Runoff was measured through using multi-slot divisors in the way that surface runoff was collected in the first tank, which when full overflowed into a second tank via a nine-slot divisor. The amount of runoff in each tank was measured daily (at 9:00 AM), and then the total daily and annual runoff amount for all the rainy days in a year per treatment for the main rainy season (Kiremit) was calculated as a ratio of runoff volume (m^3) to the area of runoff plot (48 m^2) and then converted to equivalent rate in a hectare of land. Similarly, the runoff coefficient was

calculated as the percentage of daily runoff (mm) to daily rainfall (mm). The total amount of eroded soil was determined through filtration (paper type *Whatman-597*, a pore size of 4-
of composite samples collected from both tanks after thoroughly mixing the collected runoff and sediment (Figure 3). After filtration the remained sediment was oven-dried at 105 ^{o}C for 24 hours and then weighed and compared with the weight of another filtration paper of the same size as a control to estimate the daily average soil loss from each replicated treatment as per the respective total runoff measured in the area (Adimassu *et al*., 2014).

Figure 3. Land preparation, water sample collection, and sediment filtration process

Agronomic practices and data collection

Tillage practices were applied 3 times a year on this area. The first plowing was done during the short rainy season, from March to May; and the secondary and tertiary tillage operations were undertaken at the mid of June to end June respectively. All beds and ridges were prepared in the first week of July at the first rain shower when the soil becomes moist for the ease of cultivation because the soil at this time is not bulky (not heavy) for bed preparation. Wheat (*Triticum aestivum L*.) was used as a test crop to evaluate the effect of soil drainage methods on runoff, soil loss and wheat yield. The seeding rate of wheat (variety *sora*) at a rate of 150 kg ha^{-1} was applied in row. Recommended fertilizer rate for the area (115 kg/ha N and 69 kg/ha P_2O_5) was

as Plant height, biomass and grain yield was taken from the respective experimental plots by excluding border effects.

Data analysis

The data from each of the two years separately and altogether were statistically analyzed to understand the effect of drainage methods on runoff, soil loss, and wheat yield. Microsoft Office Excel 2010 and SAS version 9.2 (SAS, 2008) were used to analyze the data. Analysis of Variance (ANOVA) was performed to test whether the changes in runoff, soil loss, and wheat yield induced by treatments were statistically significant. Mean values were compared with the LSD test at $P<0.05$.

Results and Discussion

The effect of soil drainage methods on surface runoff

The total and average rainfall amount in the growing periods (in the year 2017 and 2018) is illustrated in Figure 4. The total rainfall received during the rainy seasons of 2017 and 2018, 54.08 % and 55.90 % was lost as runoff from trt-1 (BBF-120 cm*40) respectively compared with 52.50 % and 50.49 % from trt-2 (BBF-80 cm*40) and the lowest runoff coefficient (47.53% and 48.58%) for the years 2017 and 2018 respectively were recorded from trt-3 (RF-40 cm*40). This might be attributed to the reduced speed of runoff from ridge and furrow system due to flat and uniform slope, which have resulted in higher opportunity time for infiltration or evaporation from depression storage on created furrows (Guzha, 2004). Total seasonal rainfall transformed to runoff from all treatments was not significantly vary in years in this study. As shown in Figure 7 below, there have been statistically significant differences ($P<0.05$) among the treatments in terms of surface runoff. In 2017, surface runoff was highest in BBF-120 cm*40 cm (272.27 mm) and BBF-80 cm* 40 cm (264.29 mm), however the lowest (239.29 mm) runoff was recorded from RF-40 cm*40 cm. In 2018, alike in 2017, the highest surface runoff (312.37 mm) was obtained from BBF-120 cm*40 cm, the lowest from BBF-80 cm* 40 cm (282.10 mm) and RF- 40 cm*40 cm (271.40 mm). The two-year average surface runoff was significantly highest (292.32 mm) in BBF-120 cm*40 cm and the lowest (255.34 mm) from RF-40 cm*40 cm. the research finding is in contrast with Mekonen *et al.*, (2013) that showed RF was draining the excess water out of the field due to a large number of furrows constructed on the land of which can drain better with simple facilitation of furrows. Although the drainage density is relatively higher in treatment three (RF-40 cm*40 cm), increased volume of runoff was shown from BBF- 120 cm*40 cm. This situation could be attributed to reduced surface storage capacity from the experimental plots of treatment one (BBF-120 cm*40 cm) because the surface was relatively smooth and flat that facilitates the water to be retained rather than being transformed into a runoff.

Traditionally, surface roughness is created through tillage /ridge and furrow system/, which forms micro depressions in which excess water is stored (Govers *et al.*, 2000*;* Lipiec *et al*., 2006; Lindstrom *et al*., 1984). Unlike the case of Mekonen *et al*., (2013) these large numbers of created micro depressions by RF method coupled with flat slope allows water to be stored along the channel instead of drained out. On the other hand, BBF with a large bed size and a small number of furrows could significantly enable the runoff to be drained from relatively large catchment to furrows of which widely spaced and it gets the energy to flow out of the plot through powerful concentration on the channels. The runoff coefficient for all the treatments, and particularly for BBF-120 cm*40 cm was substantial. Our finding is in line with other studies that BBF induced more surface runoff than RF at flatlands in the highlands of Ethiopia (Erkossa *et al*, 2005). To solve the problem of crop failure due to moisture stress and to avoid losses of soil and nutrients changing this water resource into production through supplementary irrigation and other purposive techniques needs to be explored.

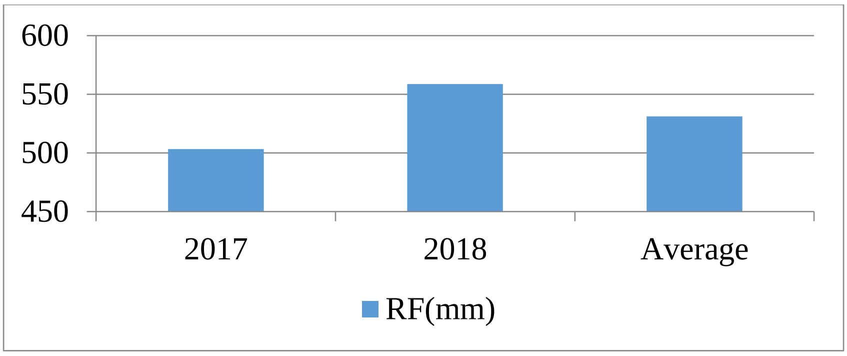

Figure 4. The total and average rainfall amount in the growing periods (in the year 2017 and 2018)

The effect of soil drainage methods on soil loss

The effect of drainage methods on soil loss for two consecutive years (2017 and 2018) is presented in Figure 5 and Figure 6. Soil loss was not significantly varying ($P > .05$) between treatments in both years. The finding indicated that soil loss showed an increment tendency corresponding to the runoff in both 2017 and 2018 growing seasons for all treatments. Though, unlike the runoff, the effects of the treatments on soil loss were not statistically significant in all years ($p \geq 0.05$) between each treatment but numerically highest soil loss (9.12 t ha ^{1}) was recorded in BBF-120 cm*40 cm and the lowest (7.45 t ha ^{1}) from RF-40 cm*40 cm (Figure 7) on average basis. The soil amount eroded from all treatments in 2018 is relatively higher compared with the year 2017 due to the highest proportional extent of runoff generated in 2018 as well. Two years combined analysis result of soil loss from all drainage methods (trt-1: 9.12 t ha ^{1} yr ^{1}, trt-2: 8.64 t ha ^{1} yr ^{1} and trt-3: 7.45 t ha ^{1} yr ^{1}) is in the range of soil loss tolerance in

Ethiopia (2 10 t ha ^{1} yr ^{1}) (Hurni, 1993). This eludes the fear of soil erosion and suggests the possibility to use drainage methods that can drain excess water with better crop yield.

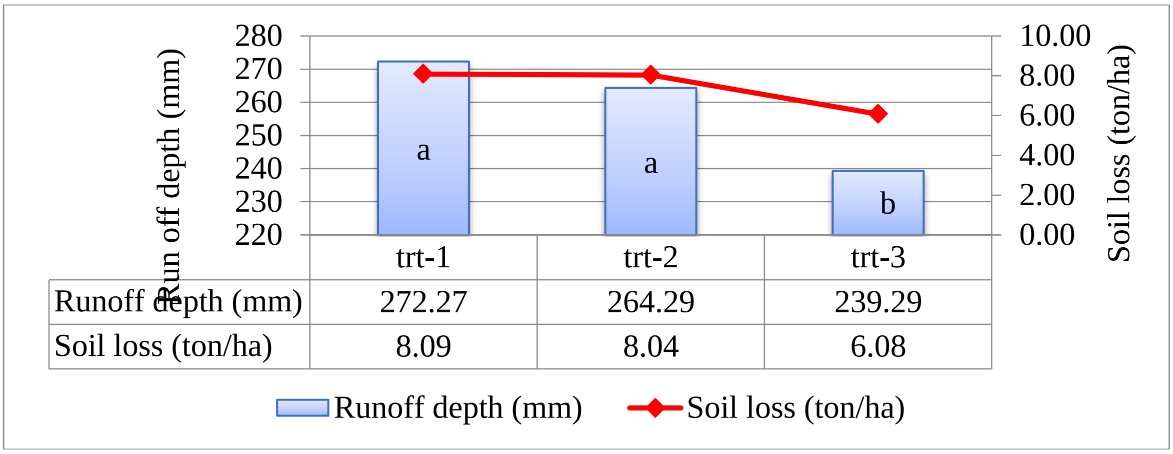

Figure 5. Runoff depth and soil loss amount in the year 2017 growing seasons (*Note: trt, treatment; different superscript letters in the same column represents significant differences (P<0.05)*).

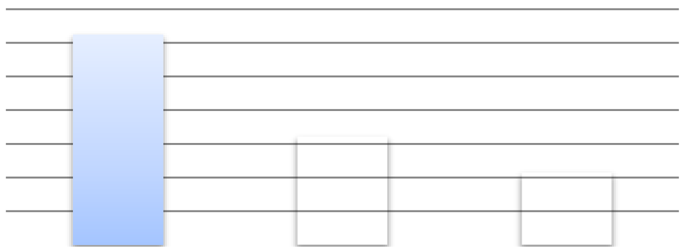

Figure 6. Runoff depth and soil loss amount in the year 2018 growing seasons (*Note: trt, treatment; different superscript letters in the same column represents significant differences (P<0.05*), *Means followed by the same letter in the same column are not significantly different at P = 0.05.*)

The effect of soil drainage methods on soil moisture content

Moisture data was taken from mid-august onward at the depth of 0-20 cm to observe if there is a difference in water content of the soil for different drainage methods corresponding to the amount of runoff drained out. The highest soil moisture content that (50.7%) was recorded in the RF-40 cm*40 cm drainage method and the lowest (45.5%) was also from the BBF-120 cm*40 cm land preparation technique for soil drainage. The reduced moisture from BBF-120 cm*40 cm in the above case could be attributed to reduced surface storage capacity because the surface was relatively smooth and then excess runoff was drained. A real difference in soil moisture content was observed among the treatments during the periods when there was optimum rainfall that enables runoff to occur. On an average basis, treatment three (RF-40 cm*40 cm) have retained higher moisture content up to 20 cm soil depth (29%) than treatment one (BBF-120 cm*40 cm) which retains 27.4%. This situation might be due to higher infiltration and lower loss of rainwater through runoff in treatment three (RF-40 cm*40 cm) than treatment one (BBF-120 cm*40 cm). The lower the capacity of drainage methods to drain excess water, the more opportunity for water to be stored on created micro depressions of the treatment with higher drainage density (Zhao *et al.*, 2014). After the period that rainfall declined, no more excess water is occurring then accordingly the difference in moisture content of the soil for each treatment gone insignificant. The lowest moisture content and highest runoff in the high rainy period from BBF-120 cm*40 cm indicated that this method enhanced surface drainage by removing more excess rainfall than BBF-80 cm*40 cm and RF-40 cm*40cm. Soil moisture content (MC) of each drainage methods at different dates of the growing season is shown in Figure 8.

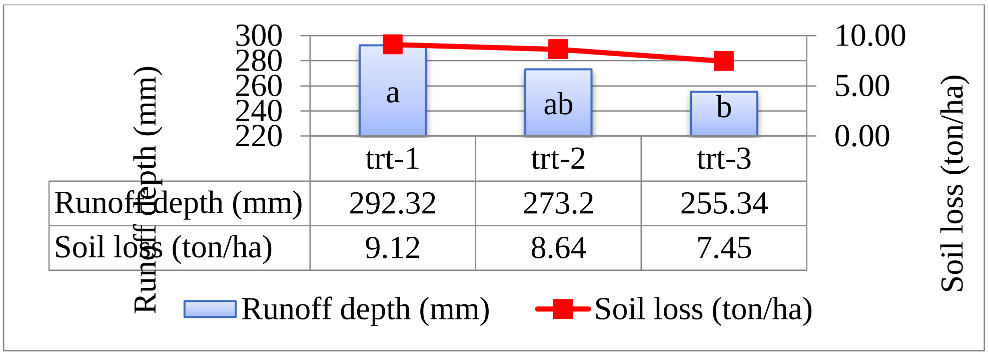

Figure 7. the two years average of runoff depth and soil loss amount (*Note: trt, treatment; different superscript letters in the same column represents significant differences (P<0.05)*).

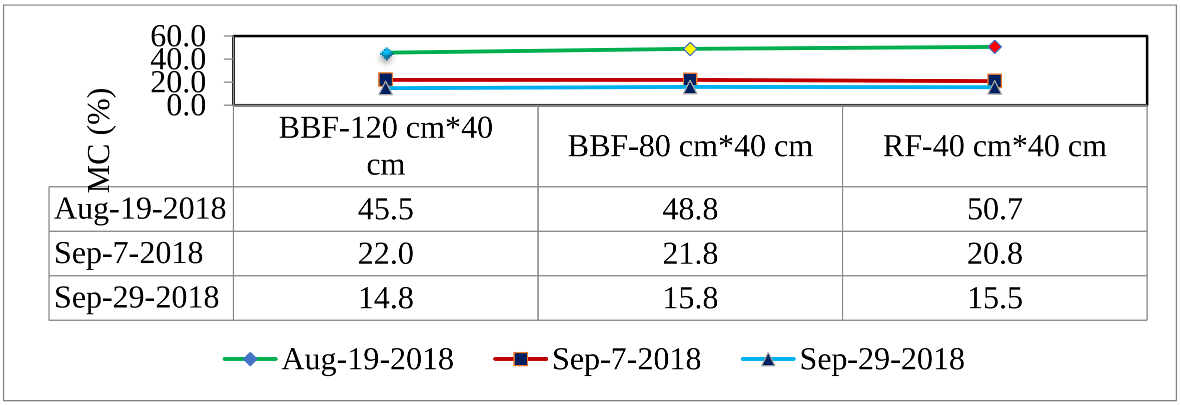

Figure 8. Soil moisture content (MC) of each drainage methods at different dates of the growing season

The effect of soil drainage methods on crop yield

As shown in Table 2, The two years (2017 and 2018) and combined analysis of grain and biomass yields of wheat were significantly affected (P<0.05) by the land preparation methods.

The grain yield of wheat ranged from 1744 to 2669 kg ha ^{1} while the biomass yield ranged from 4544 to 6704 kg ha ^{1}. BBF-120 cm*40 cm treatment gave the highest mean grain yield and biomass of wheat (2669.0 kg ha^{-1}, 6704 kg ha^{-1}) followed by BBF-80 cm*40 cm (2207.5 kg ha^{-1}, 5847 kg ha^{-1}) while RF-40 cm*40 cm gave the lowest grain yield (1744.30 kg ha^{-1}, 4544 kg ha^{-1}) respectively. The relatively low wheat biomass and grain yield performance from treatment three (RF-40 cm*40 cm) could attributed to size of productive area that is lost for drainage purpose (Table 3) and the capacity of the method to drain excess water. The more facilitation of BBF-120 cm*40 cm to drain excess water and advantage of limiting number of furrows gave an opportunity of saving more land on which crops were grown. Consequently,

m grain yield of wheat recorded from trt-1 (BBF-120 cm*40 cm) than trt-3 three (RF-40 cm*40 cm) over the two experimental years.

Table 2. Grain yield (kg/ha), Biomass (kg/ha), and Plant height (cm) of 2017/18 and combined results

-	**2734**	**2604**	***2669***
-	**2032**	**2383**	
-			

Although significantly different biomass and grain yield was observed among treatments, the

(result not shown). The reason for the situation is due to that variety trials on wheat in this area are not tracked in a similar technique of data collection. In this experiment the beds were different in size, so taking a sample only on selected beds was impossible, then whole plot (48m^2) was harvested for agronomic data analysis. Unlike we did to take harvested data, breeders in that area took a sample on the small size (0.6m^2~0.8m^2) or one bed for each treatment during their study with same test crop. In this case, the exaggerated yield performance might be reported when converted from small size to a hectare of land; on the other hand, taking whole plot for data analysis tells the

field but yield looks lower when compared with a data taken from small plot size (Jearakongman *et al*., 2003). As shown in Table 2, Treatment one (BBF-120 cm*40 cm) showed 17.3% and 34.6% grain yield advantage of wheat over Treatment two (BBF-80 cm*40 cm) and Treatment three (RF-40 cm*40 cm) respectively. As enhanced drainage is a requirement for successful crop production on Vertisol, these methods might improve crop productivity as well.

As shown in Table 3,
crops were not growing on rather used to drain excess water was varied in a range from 18.2% to 45.5% of the total cropland. When using BBF-120 cm*40 cm much more land (81.8%) is occupied by beds of which crops were grow than the area (18.2%) used to construct furrows for drainage purposes. The land lost due to furrows coupled with the capacity of land preparation methods to drain excess water on flatlands has resulted in lowest grain yield from BBF-40 cm*40 cm followed by BBF-80 cm*40 cm but the highest mean grain yield and biomass was observed from BBF-120 cm*40 cm. It is contributed to the unintended saving of more land to raise crops on the land treated with BBF-120 cm*40 cm which allows better advantage of draining excess rainfall. It further indicates BBF 120cm*40cm enables to grow crops on additional 27.3% (Table 3) land when compared with BBF 40cm*40cm that causes significant land loss due to much area engagement by furrows.

Table 3. Land proportion occupied by crops and furrows for different soil drainage methods

	Harvestable area	Area lost by furrows (%)
BBF-120cm*40cm	44	
BBF-80cm*40cm	44	
RF-40cm*40cm	44	

Conclusions and Recommendation

The rainfall of about 55.04%, 51.44 %, and 48.08% was converted to runoff from BBF-120 cm*40 cm, BBF-80 cm*40 and RF-40 cm*40 cm respectively. So, the runoff coefficient was accounted for more than 50% of the seasonal rainfall for the first two drainage methods. This indicates the capacity to drain excess water and feasibility of water harvesting systems for irrigation purpose during early harvesting periods. The treatments resulted in significantly different runoff volumes, trt-1 (BBF-120 cm*40 cm), and trt-2 (BBF-80 cm*40 cm) can save more land on which crops can grow well and induced more excess water to enhance surface drainage than trt-3 (RF-40 cm*40 cm). This contributed to the significant increase in grain and biomass yield of wheat grown using these methods. On the other hand, it was observed that all drainage methods showed a tolerable tendency to cause soil loss in the study area.

The finding in general revealed that trt-1 (BBF-120 cm*40 cm) gave the highest mean grain yield and biomass of wheat; and it could potentially drain excess rainfall without causing significant soil loss. The capacity of draining more runoff is desirable to tackle the major problem of the study area which is surface waterlogging. So, trt-1 (BBF-120 cm*40 cm) is the best option for draining excess runoff and accordingly maximizing crop yields of wheat. Besides, further study is required on water harvesting systems to enhance vertisol productivity through using the drained water for irrigation in the study area and other eastern Amhara highland areas with similar farming system and agro-ecologies.

Acknowledgments

The authors are grateful to Mr. Mohamed Yesuf for his valuable effort to carry out the field experiment and care full data collection. We are also pleased to acknowledge Sirinka Agricultural Research Center for its continuous follow-up for the field works.

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