The effect of soil bunds on run-off, soil loss, soil moisture dynamics and crop yield in the Jawe-gumbura watershed, Ethiopia

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Summary

This study was undertaken in the Jawe-gumbura watershed of the Southern Ethiopia. The main objectives were to (i) to assess the effect of soil bunds on run-off, soil loss and yield of wheat, and (ii) understand soil moisture dynamics under conserved and non-conserved plots. Three treatments including (i) five-year-old soil bunds with Desho grass, (ii) 1-year-old soil bunds with Desho grass and (iii) control (without soil bunds) were compared at three farmers' fields. Runoff, soil loss, and crop yield and soil moisture were measured during 2015 rainy season. The result shows that in control and 5-year-old soil bund plots, 4.4 mm and 3.2 mm runoff were generated, respectively. The result of two days rainfall shows that 30% and 22% of the rainfall was converted into runoff in control and 5-year-old soil bund, respectively. The corresponding sediment concentration of runoff from control plots and 5-year old soil bunds plots were 11 g m^{-2} and 6.4 g m^{-2}. However, runoff and soil losses were generated only from two rainfall days out of 29 rainfall days. Soil moisture measurement over the growing period shows that there is spatial variability of soil moisture with reference to soil bunds. The moisture at different depths showed inconsistent results among the treatments. The average available soil water (%) were 29.3, 29.8 and 30.2 for the control, 1-year-old soil bunds and 5-year-old soil bunds, respectively. The average grain and biomass yields (g m^{-2}) of wheat were higher in plots with bunds compared with the control plot. However, when area occupied by soil bunds were considered, the total grain and biomass yield (t/ha) from control plots was higher than plots with bunds. This is mainly because significant proportion of the land was occupied by the soil bund. Farmers planted Desho grass to compensate the yield reduction. More long-term erosion plot studies are needed to support farmers' trade-offs and opportunities in soil conservation accounting for plot benefits in sustainable intensification.

Background and justification

Like the other parts of the country, land degradation in the form of soil erosion is one of the major challenges of crop production in Southern Ethiopia such as Jawe-gumbura watershed (Assefa and Hans-Rudolf, 2015; Moges and Holden, 2007). Promotion of soil and water conservation (SWC) practices, such as soil bunds have been done for more than 40 years as a key strategy to reduce land degradation and increase crop production (Adimassu et al., 2014; Shiferaw and Holden, 2000). Because of the lack of sufficient stones to construct stone bunds in Jawe-gumbura watershed, soil bunds were the only options that farmers can implement to tackle soil erosion. Hence, soil bunds are the major soil and water conservation practices in Jawe-gumbura watershed (Lemu District/Woreda) where Africa RISING (Africa Research in Sustainable Intensification for the Next Generation) project has been implemented. Understanding how soil bunds reduce run-off, losses of soil and soil moisture dynamic and its effect on crop yield is important to inform farmers and policy makers regarding the effectiveness of these practices and justify investment in soil and water conservation practices such as in soil bund.

Some successes of soil bunds have been recorded in Ethiopia. For instance, soil bunds significantly reduced run-off, soil loss and nutrient loss in different parts of the country (Adimassu et al., 2017; Adimassu et al., 2014, Amare et al., 2013; Gebreegziabher et al., 2008, Nyssen et al., 2000; Herweg and Ludi, 1999). The effects of soil bunds on crop yield are inconsistent and site specific. A comprehensive review and synthesis of more than 100 articles by Adimassu et al. (2017) showed that only 33% (n=15) level soil bund and 11% (n=44) of level fanya juu increased crop yield.

Nevertheless, information on the effect of soil bunds on runoff, soil loss, soil moisture dynamics and crop yield is limited in the study area. Although soil moisture conservation is one of the objective of level soil bunds, the effects of soil bunds on soil moisture dynamic have rarely been assessed in the country.

Objectives

The objectives of this study were to (i) to assess the effect of soil bunds on run-off, soil loss and yield of wheat, and (ii) understand soil moisture dynamics under conserved and non-conserved plots.

Description of study area:

The study was conducted in Jawe-gumbura watershed located in the Southern Nation, Nationalities and People's (SNNP) region in Southern Ethiopia (Figure 1). The watershed is part of Gibe basin with elevation ranging from 2105 to 2794 m above mean sea level. The watershed covers an area of 11.2 km^2. Mixed crop-livestock subsistence farming system characterizes the study area. Wheat (*Triticum astivum*) is the dominant crop grown in the study area. The experiment was conducted at the lower parts of Jawe-gumbura watershed with an average slope of 10%. Generally, the soil of the experimental site is Nitisols with clay texture (45% clay) and bulk density of 1.25 g cm^{-3}. The organic matter (OM) content of the soil in the experimental site was 3.6%. The long-term average annual rainfall of the Lemo district where the experiment has conducted was 1180 mm with more than 50% of the rainfall occurring in the main rainy season (June to October).

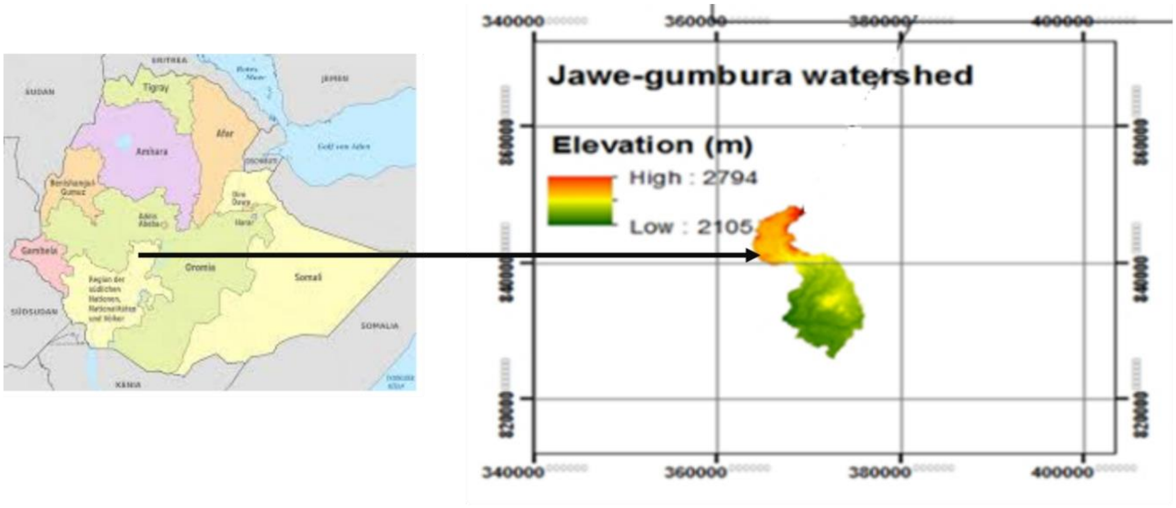

Figure 1. Map of study watershed in Ethiopia.

Materials and Methods

Setup of runoff plots and treatments

Runoff plots of 17 m length and 10 m width were prepared and bounded by a galvanized metal sheet of 60 cm, of which 15 cm was inserted into the ground to prevent lateral flow of water (Figure 2). As shown in Figure 2, runoff samples were taken using multi-slot divisors. Surface runoff was collected in the 1st tank, when full overflowed into a 2nd tank via a nine-slot divisor. When the 2nd tank with 5-slot divisor became full, it overflowed into the 3rd tank and then to the 4th tank (Figure 2). The volume of runoff in each tank was measured every 24h (at 9:00AM), and the total daily runoff volume per plot was calculated. From this, the annual runoff volume for all the rainy days in a year was calculated. Three treatments including (i) five-year-old soil bunds with Desho grass, (ii) 1-year-old soil bunds with Desho grass and (iii) control (without soil bunds) were compared in farmers' field. These treatments were replicated twice.

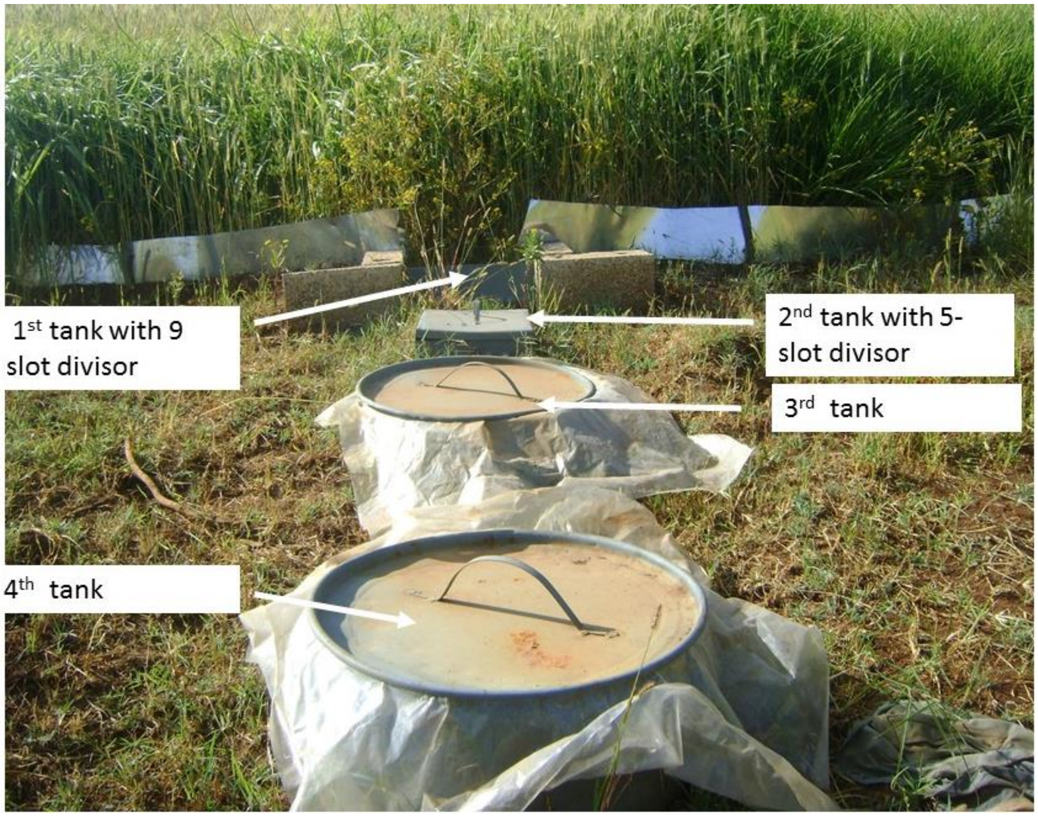

Figure 2. Experimental setup of runoff plots with runoff collection tanks.

Soil moisture measurement

Soil moisture was assessed using TDR moisture sensor (Type HH2) at five soil depths (10cm, 20cm, 30cm, 40cm and 60cm) and four different positions from the soil bunds. Four access tubes for soil moisture sensors were installed in each plot. The first tube (Tube 1) was installed at 4 m above the soil bunds; tube 2 was installed at 2 m above the soil bunds; tube 3 was installed at 2 m below the soil bunds and tube 4 was installed at 4 m below the soil bunds (Figure 3). Soil moisture was measured twice a week the various depths throughout the season.

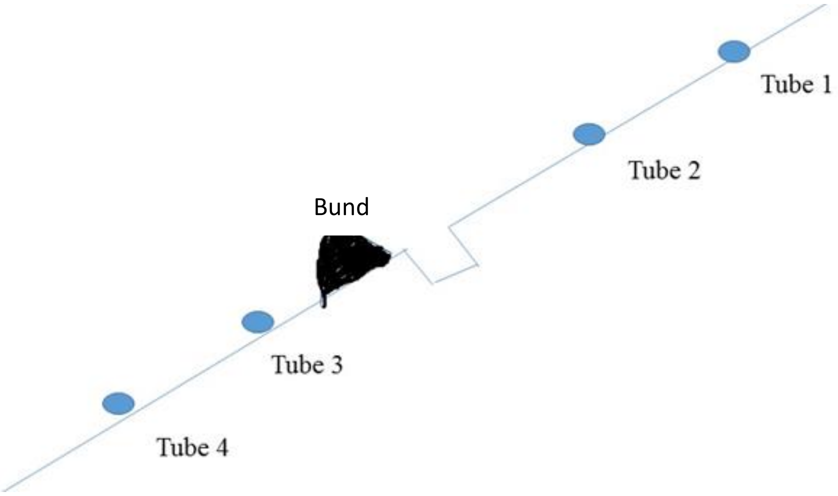

Figure 3. The position of soil moisture profile tubes from the soil bund

Moreover, available soil water was computed based on soil organic matter and soil textural classes (Kirkham (2014). Hence Available soil water was calculated using the following formulae (Allen et al., 1998; Brouwer et al., 1985):

$$\mathrm{ASM} = SM - PWP$$

Where, ASW is available soil water (%), SM is soil moisture at the time of reading (%, v/v)), and PWP is permanent welting point (%, v/v). Table 1 shows an over view of the physico-chemical properties of the soil in the Upper Gana (similar to the experimental site).

Table 1. Overview of soil physico-chemical properties in Upper Gana (n = 17).

	Min.	Max.	Mean ± SD[1]	CV (%)[1]
Bulk density (%)	0.99	1.83	1.3 ± 0.2	18
Field capacity (%)	22.5	36.3	32.3 ± 3.9	12

Permanent wilting point (%)	10.8	22.9	17.9 ± 3.2	18
Texture – Sand (%)	18.0	60.0	37.9 ± 9.5	25
Silt (%)	22.0	54.0	36.1 ± 7.7	21
Clay (%)	14.0	36.0	26.0 ± 6.1	23
Electrical conductivity (dS m^{-1})	0.04	0.59	0.19 ± 0.15	79
Organic Matter (%)	3.1	5.6	4.3 ± 0.8	19
Total Nitrogen (%)	0.12	0.36	0.22 ± 0.07	31
K (cmol kg^{-1})	0.31	1.22	0.63 ± 0.27	42

[1] SD = standard deviation; CV = coefficient of variation. (Source: Schmitter et al., 2016).

Rainfall, runoff and soil loss measurement

Rainfall was measured using ordinary rain gauge at the center of the plots and daily rainfall data were recorded during the experimental period (Figure 4). As shown in Figure 2, runoff samples were taken using multi-slot divisors. Surface runoff was collected in the 1st tank, when full and overflowed into a 2nd tank via a nine-slot divisor. When the 2nd tank with 5-slot divisor became full, it overflowed into the 3rd tank and then to the 4th tank (Figure 2). The volume of runoff in each tank was measured every 24h (at 9:00AM), and the total daily runoff volume per plot was calculated. From this, the annual runoff volume for all the rainy days in a year was calculated.

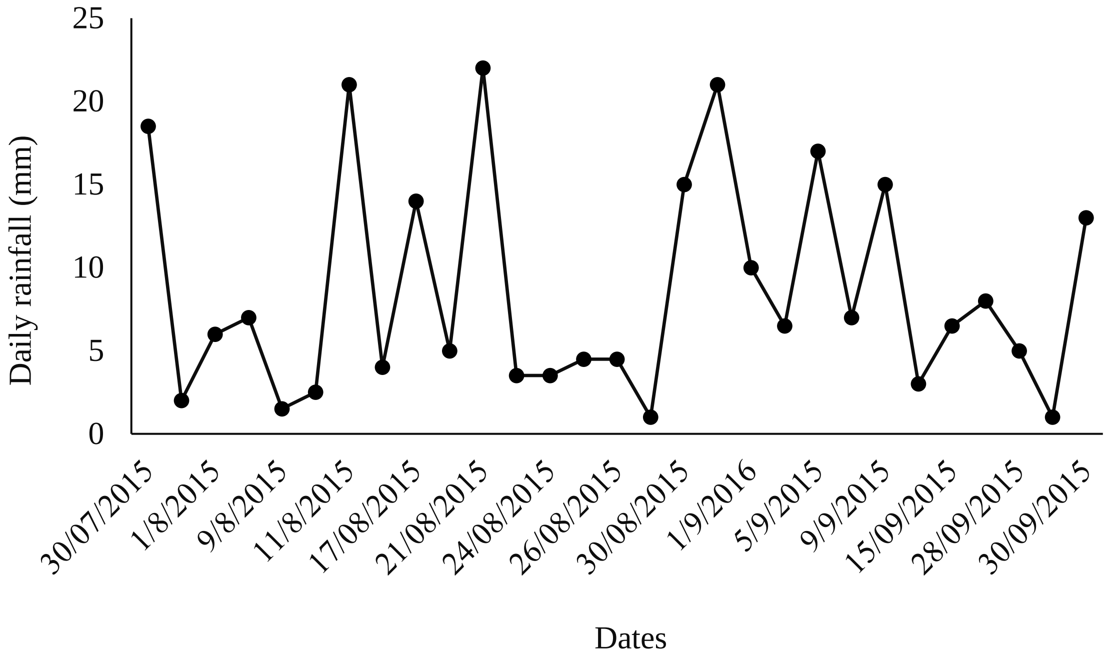

Figure 4. Rainfall distribution in the experimental site from July 30 to September 20, 2015.

The total amount of eroded soil was estimated through filtration of composite samples (Figure 3) collected from both tanks after thoroughly mixing the collected runoff and sediment (Adimassu et al., 2014; Hudson, 1993; Heron, 1990). The sediment retained after filtration (using filter paper) was dried at 105^0C for 24h and then weighed. Accordingly, the daily soil loss of each plot was calculated by multiplying the total runoff by the sediment concentration.

Yield measurement

Wheat (*Triticum aestivum* L) was used as a test crop in this particular experiment. Wheat was planted at the planting density of 175 kgha^{-1} using broadcasting. The recommended fertilizer rates applied for all treatments were 69 kg P_2O_5 and 60 kg N per hectare in the form of DAP and Urea. Weeding was done using hand weeding. To investigate the effects of soil bund implementation on wheat yield, 1m^2 quadrants were used to collect yield samples. Three samples were taken around each location of soil profile tubes for each experimental plots (Figure 5). Data for the control plots were collected following the same pattern along the slope. The grain and biomass yield were recorded with a weighing balance. The yield between treatments and locations from the bund were analyzed and compared.

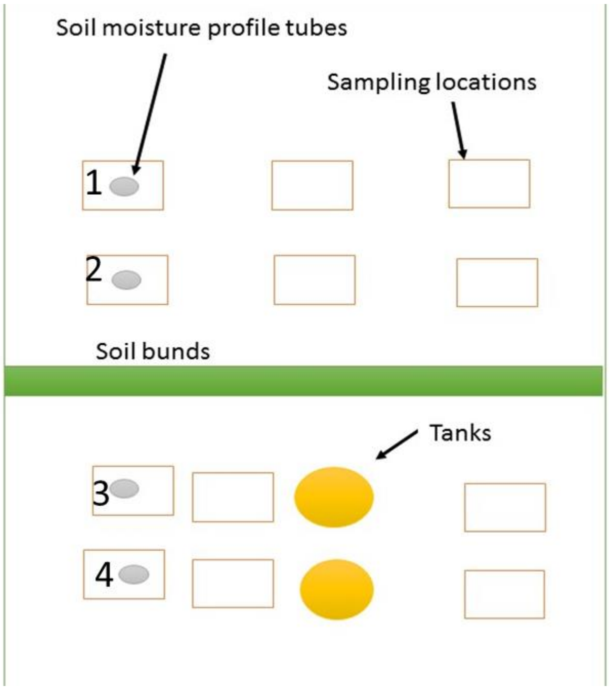

Figure 5. Crop yield-sampling locations in the runoff plots. 1, 2, 3, and 4 are locations where Tube 1, Tube 2, Tube 3 and Tube 3 were paced, respectively.

Results and discussion

Effect of soil bunds on run-off and soil loss

Due to the lowest rainfall season in 2015, runoff was generated only from two rainfall days. The average runoff and associated soil losses are presented in Table 2. As shown in the table, runoff was not generated from 1-year-old soil bunds. This is mainly due to the fact that the furrow was sufficient to accommodate the runoff and sediment. However, in control and 5-year-old soil bund plots, 4.4 mm and 3.2 mm runoff were generated, respectively. The result of two days rainfall shows that 30% and 22% of the rainfall was converted into runoff in control and 5-year-old soil bund, respectively (Table 1). Higher runoff from older (5-year-old) soil bunds compared with 1-year-old soil bund is mainly because furrow in the older soil bunds were filled-up with sediment during the previous years.

The effect of soil bunds on soil loss is indicated by sediment concentration in the runoff and soil loss (g m^{-2}). As shown in Table 2, the average sediment concentration of runoff from control plots and 5-year old soil bunds plots were almost similar. However, due to the different in the runoff depth, soil loss from control plots were higher (11 g m^{-2}) compared with soil loss from 5-year-old soil bunds (6.4 g m^{-2}). There was almost negligible soil loss from the 1-year bund because the stricture was not and able to deposit the soil erosion from within the plot.

Table 2: Effects of soil bund on runoff and soil loss in Jawe-gumbura watershed, Southern Ethiopia.

	Rainfall (mm)	Runoff (mm)	Runoff coefficient (%)	Sediment concentration (g/l)	Soil loss (g m^{-2})
Control	14.5	4.4	30.5	2.5	11.0
1-year old bund	14.5	0.0	0.0	0.0	0.0
5-year old bund	14.5	3.2	21.9	2.0	6.4

Effect of soil bunds on soil moisture dynamics

The effect of soil bunds on soil moisture dynamics are discussed in two sections. The first section describes the soil moisture dynamics at different locations from the soil bunds while the second sections discusses soil moisture dynamic along the soil profile.

Although soil moisture plays an important role in crop growth, it is highly heterogeneous in space and time even in small catchments (Petrone et al., 2004; Fu et al., 2003). This heterogeneity of soil moisture results from the heterogeneity of soil, topography, land uses and land management practices (Fu et al., 2003, 2000).

This study presents the effects of soil bunds on spatial and temporal variability of soil moisture from 17 m length and 10 m width experimental plots under three treatments (Figure 6). As shown in the figure, soil moisture content for the control treatment (no soil bund) at tube 1 and tube 2 was not different from the other treatments until mid-September. Generally, at tube 3 and 4, soil moisture content for the control treatment was lower than the other treatments throughout the season. The soil moisture content of all plots at all locations declined after mid-September. However, the moisture content of the soil under control treatment was lower than the other treatments after mid-September. This shows that depletion rate of soil moisture was faster in control plots at the end of the rain season.

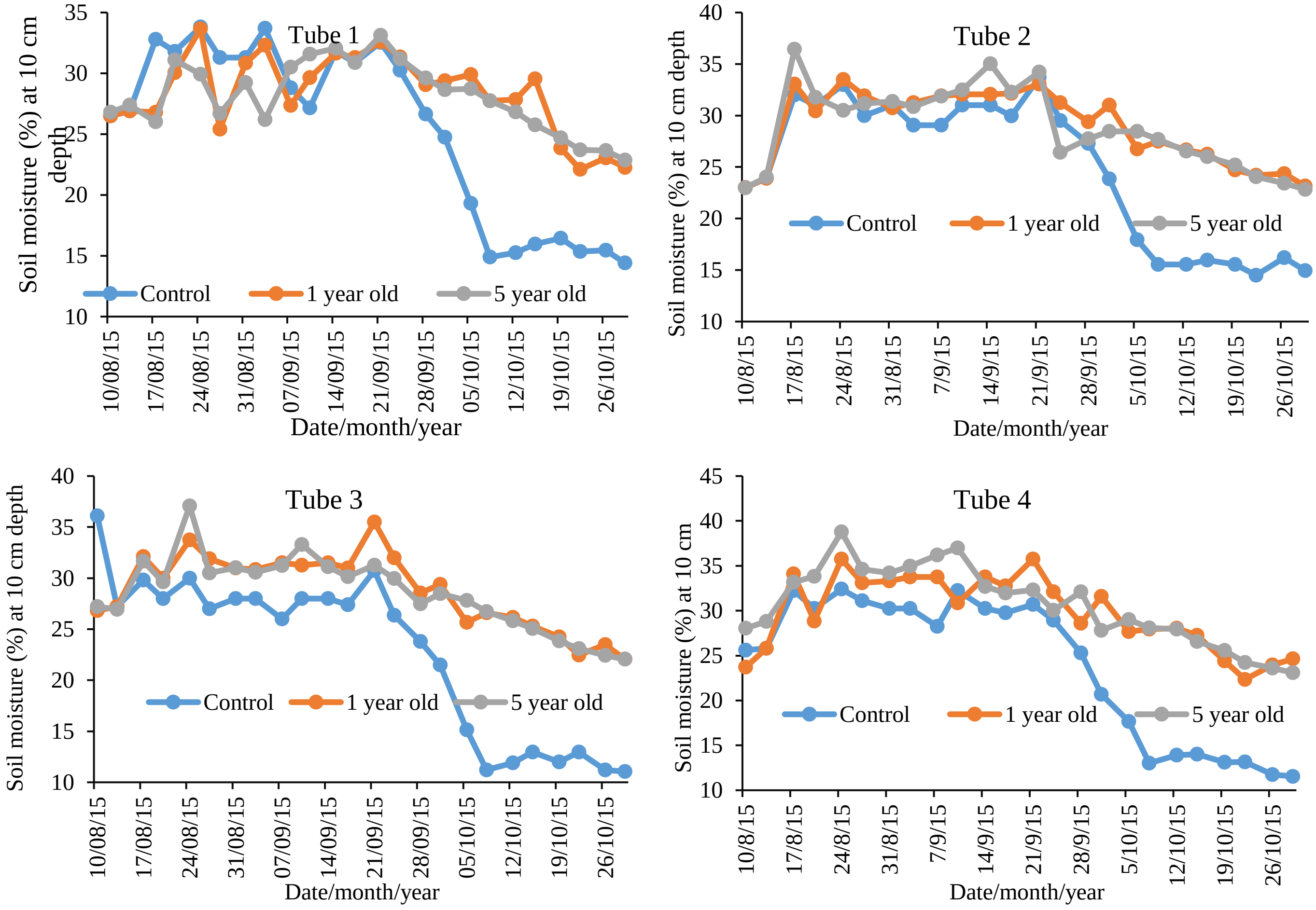

Figure 6. Soil moisture dynamics at 10 cm depth in soil bund treatments. Tube 1: 4 m above the bund, Tube 2: 2 m above the soil the bunds, Tube 3, 2 m below the soil bunds and Tube 4: 4 m below the soil bunds.

Unlike at 10 cm depth, the effect of soil bunds on soil moisture content at 20 cm depth was inconsistent (Figure 7). At 20 cm depth, the soil moisture content of control plots was slightly greater compared with other treatments until mid-September at tube 1, tube 2 and tube 3. The soil moisture content of all experimental plots at all locations declined after mid-September. Unlike the observation at 10 cm depth, the soil moisture content of control plots were higher than other plots except at tube 4 (Figure 7).

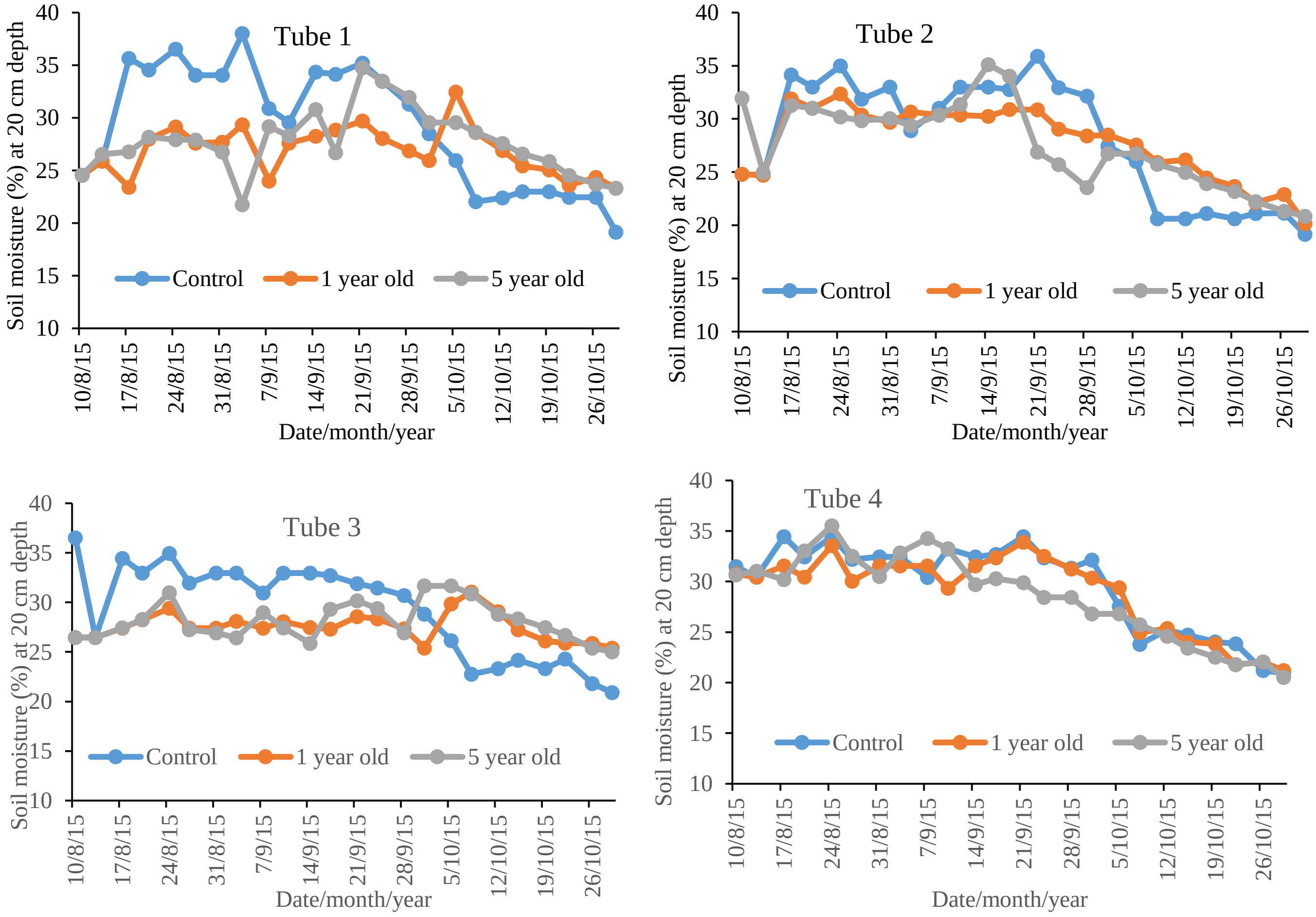

Figure 7. Soil moisture dynamics at 20 cm depth in soil bund treatments. Tube 1: 4 m above the soil bund, Tube 2: 2 m above the bund, Tube 3, 2 m below the soil bund and Tube 4: 4 m below the bund.

Spatial and temporal variability of soil moisture under soil bund treatments at 30 cm depth is shown in Figure 8. The result shows that the moisture content of the plots at tube 1 and tube 2 declined after mid-September for almost all of the treatments. In tube 3 and tube 4, soil moisture content recession started after the third and last week of September for control plots. The recession at tube 4 for other treatments started at the first week of October (Figure 8). This shows soil bunds extends the soil moisture depletion at the end of the growing season below the bunds.

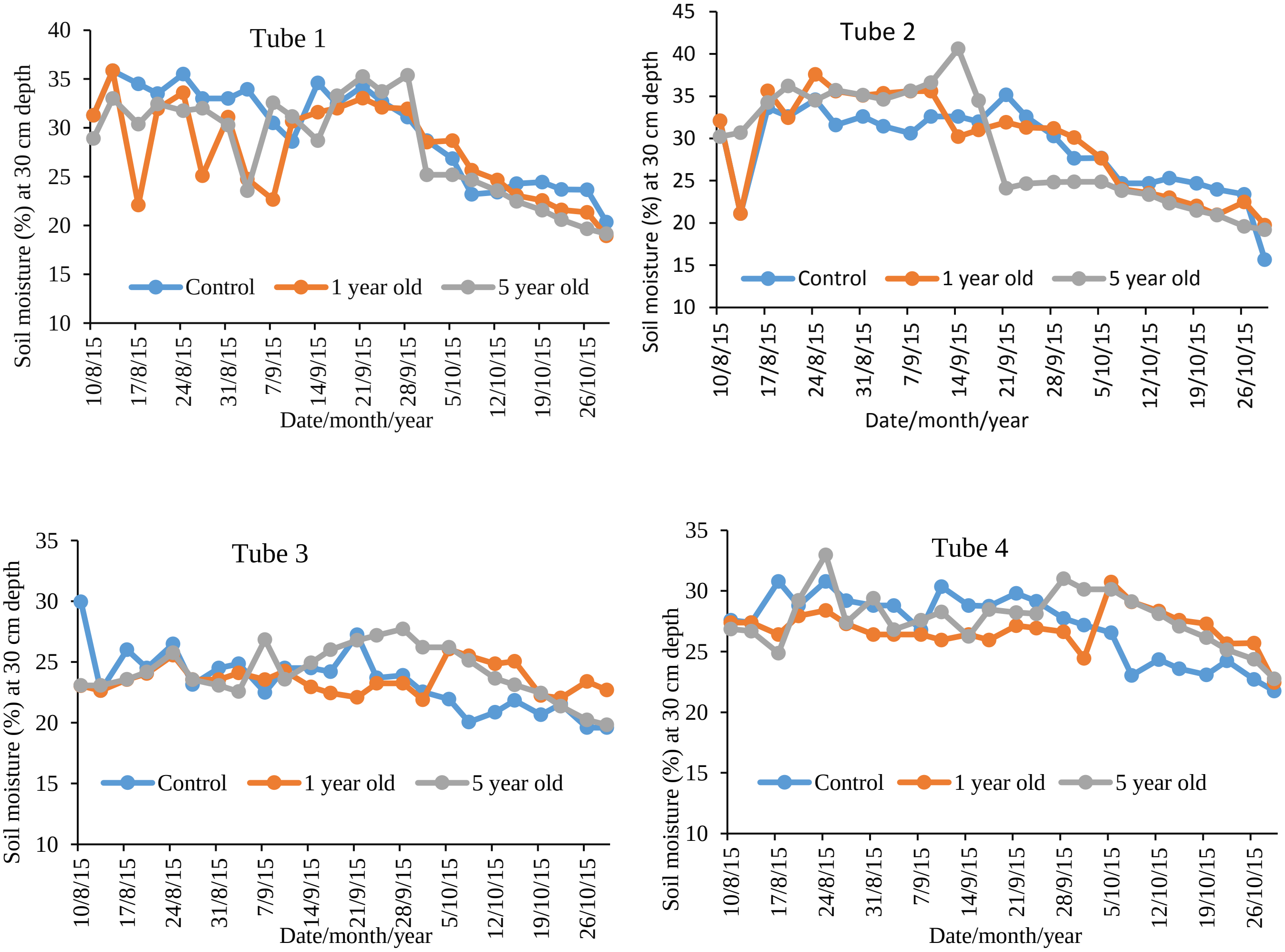

Figure 8. Soil moisture dynamics at 30 cm depth in soil bund treatments. Tube 1: 4 m above the bund, Tube 2: 2 m above the bund, Tube 3, 2 m below the bund and Tube 4: 4 m below the bund.

Soil moisture content at 40 cm depth was highly inconsistent (Figure 9). At tube 1, soil moisture content slightly declined after the third week of September. Generally, at tube 2, soil moisture content in control plots was lower than other treatments throughout the season. At tubes 3 and 4, soil moisture content for all treatments were almost similar until the third week of September. As shown in figure 8, at tubes 3 and 4, soil moisture was the highest in 5-year-old soil bunds after the 4th week of September. However, soil moisture content was the highest in 1-year-soil bund after the 2nd week of October. For all locations except tube 1, soil moisture contents were higher in plots with soil bunds as compared to control plots (Figure 9).

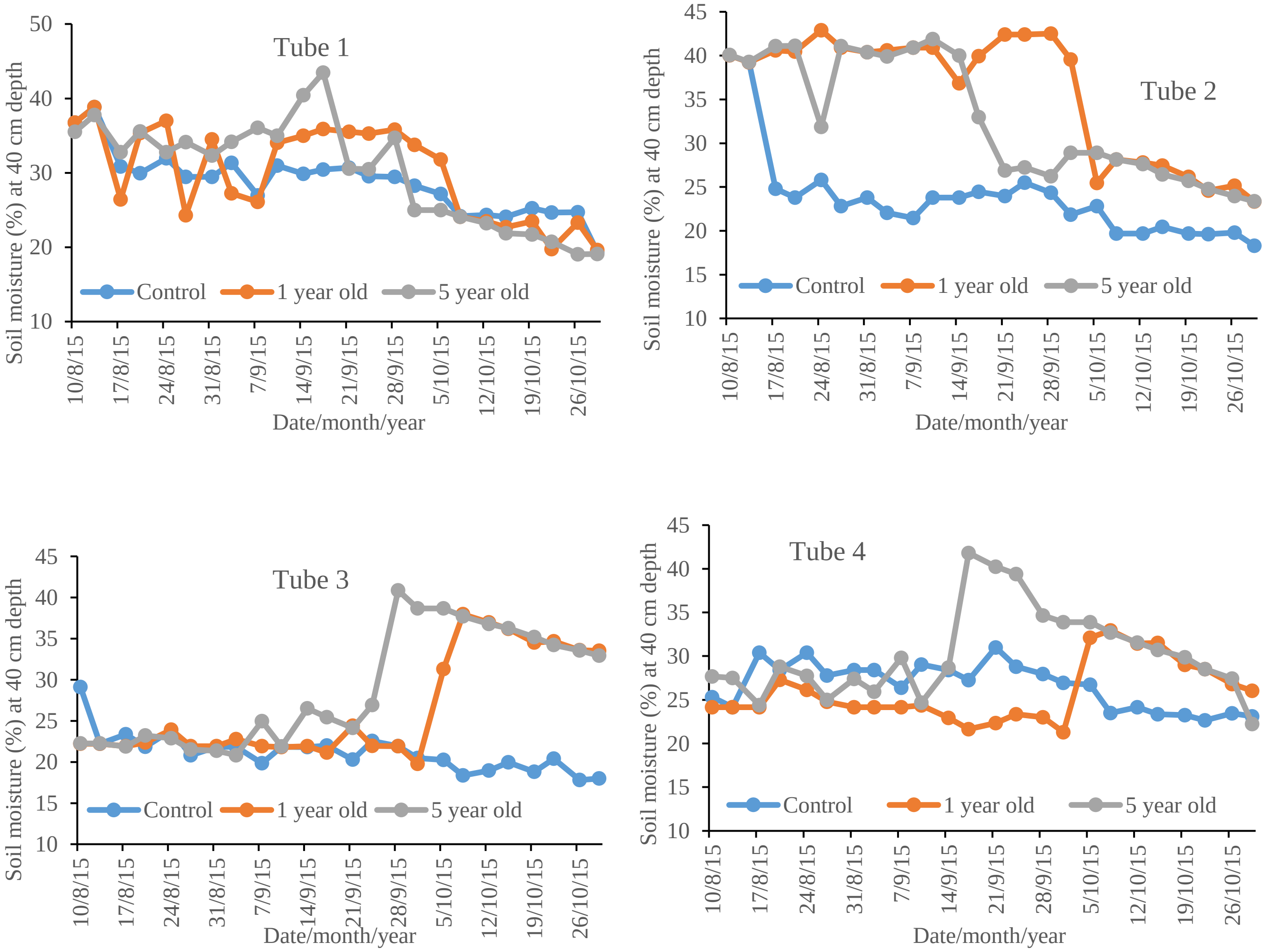

Figure 9. Soil moisture dynamics at 40 cm depth in soil bund treatments. Tube 1: 4 m above the soil bund, Tube 2: 2 m above the soil bund, Tube 3, 2 m below the soil bund and Tube 4: 4 m below the soil bund.

Figure 10 presents the temporal distribution of soil moisture at 60 cm depth across different locations from the soil bunds. At tube 1 (4 m above the soil bunds), soil moisture contents were similar for all treatments until the 1st week of September. After 1st week of September, soil moisture content decreased in 1- and 5-year old soil bunds. At tube 2 (2 m above the soil bund), soil moisture content in control plots were lower than other treatments until the 2nd week of September. However, after 1st week of October, the soil moisture contents became lower in 1-and 5-year-old soil bunds. At tube 3 (2 m below the soil bund), soil moisture contents in control plots were higher as compared to other treatments throughout the season (Figure 10). The soil moisture content at tube 4 followed similar trend with tube 3.

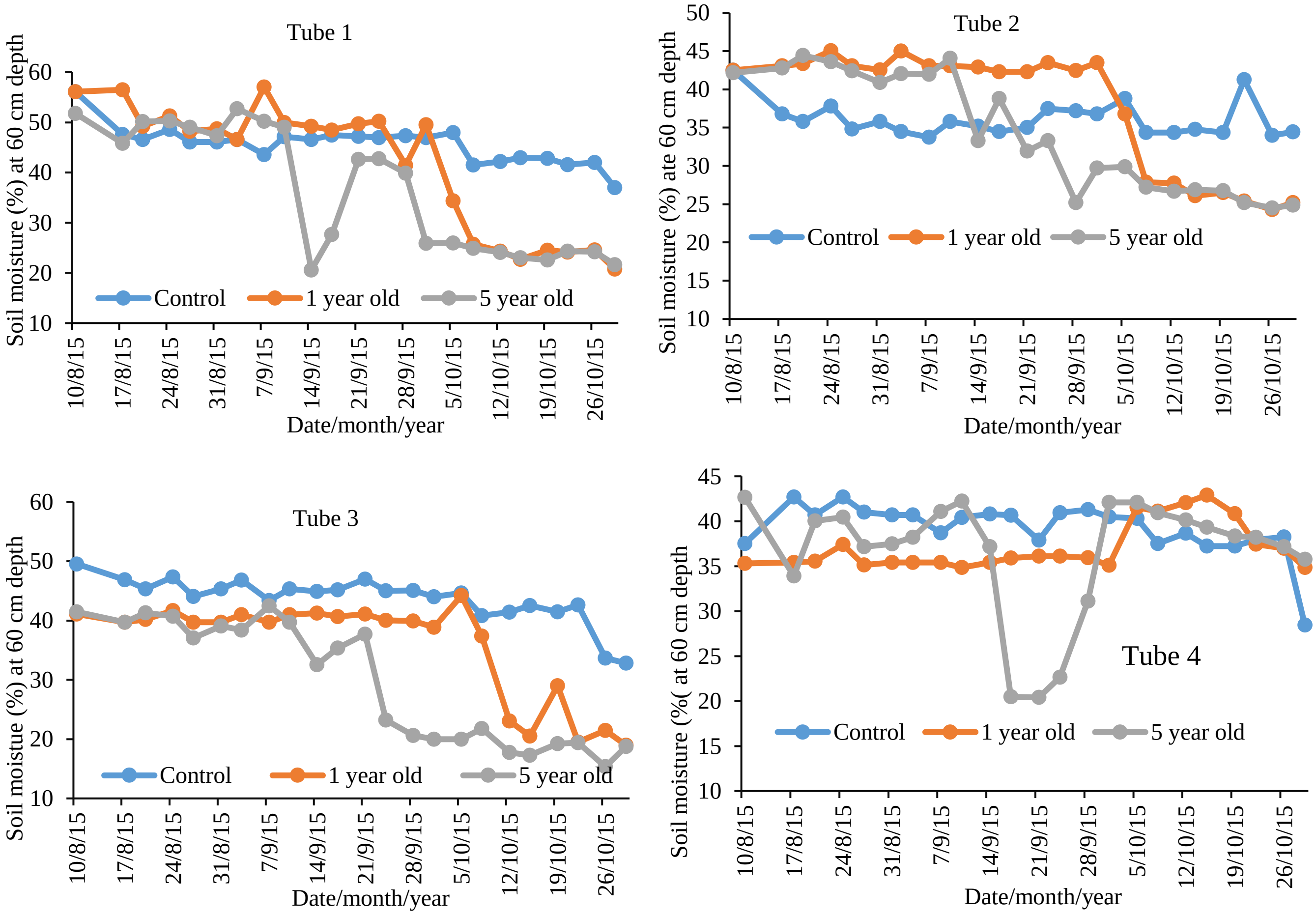

Figure 10. Soil moisture dynamics at 60 cm depth in soil bund treatments. Tube 1: 4 m above the soil bund, Tube 2: 2 m above the soil bund, Tube 3, 2 m below the soil bund and Tube 4: 4 m below the soil bund.

Available soil water from August 10/2015 to 29/October 2015 is shown in Figure 11. As shown in the figure, the trend of the available soil water follows the trend of soil moisture (compare figures 9 and 10). Accordingly, the available soil water was lower for the control plots at the end of the rain season (after October 1, 2015). The average available soil water (%) were 29.3, 29.8 and 30.2 for the control, 1-year-old soil bunds and 5-year-old soil bunds, respectively. If we consider the rooting depth of wheat as 1.2 m (FAO, 2005), average the available soil water for wheat are 352 mm, 358mm and 362mm in the control, 1 year old soil bunds and 5 year soil bunds, respectively.

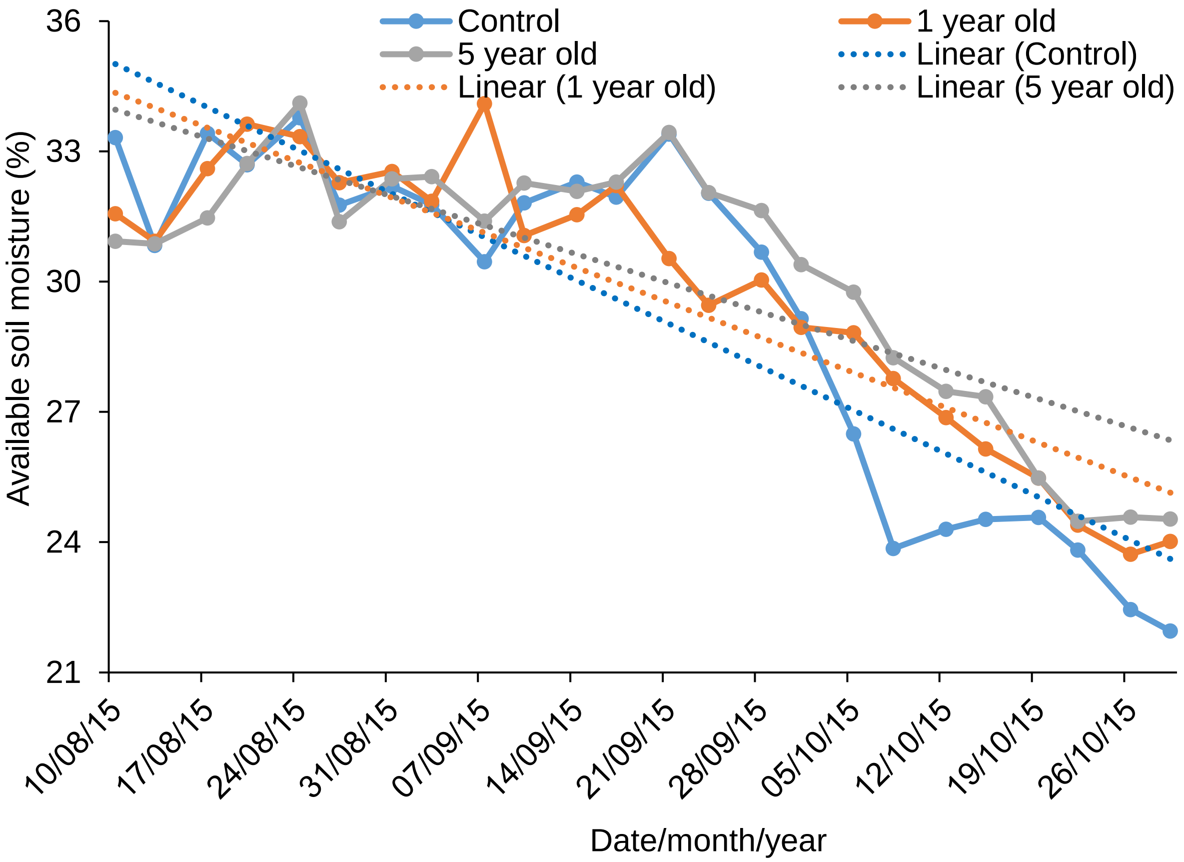

Figure 11. Available soil water (%) in Jawe-gumbura watershed, Ethiopia

Average available soil water from at different positions from bunds is also presented in Figure 12. As shown in the figure, the trend of the available soil water was the lowest at Tube 1 (4 m above the soil bund) compared with the other three positions. On average, the highest available water content (%) was recorded at Tube 3 (2 m below the bund). This shows that the effect of soil bunds on available soil moisture was prominent at the lowest soil of the bunds.

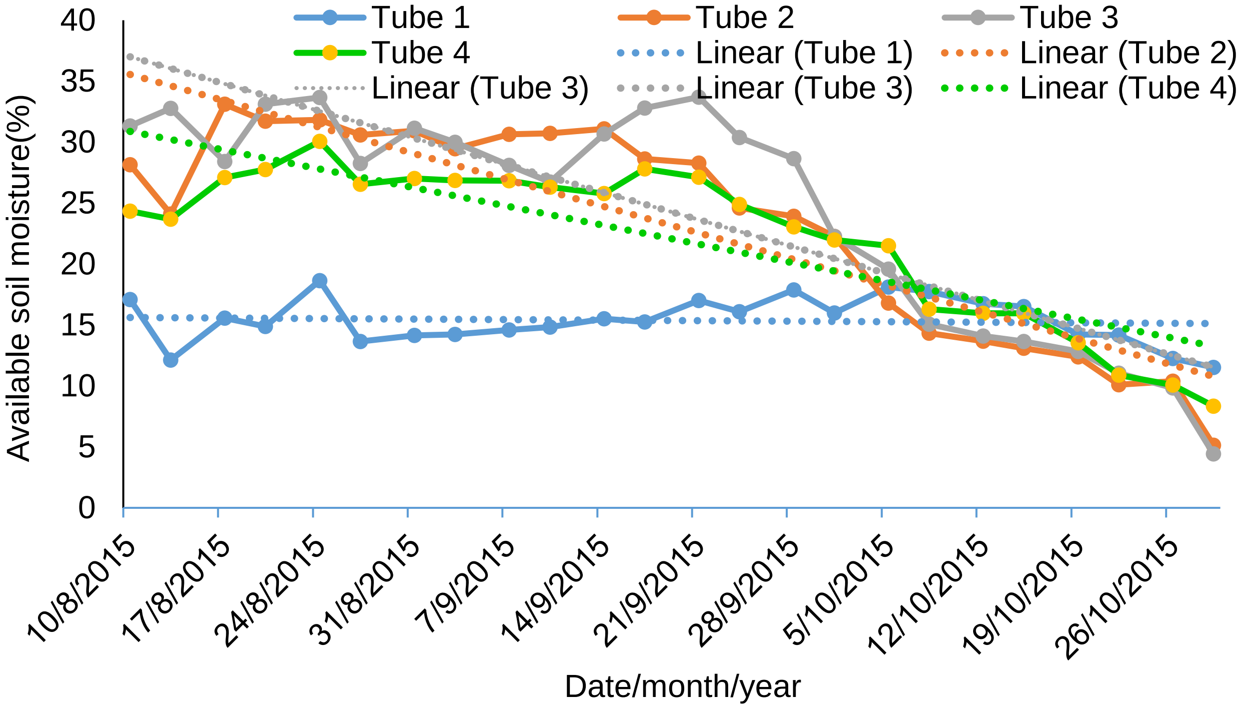

Figure 12. Available soil water (%) in Jawe-gumbura watershed, Ethiopia

Effects of soil bunds on crop yield

Crop yield (g m^{-2})

The grain and biomass yields *(g m^2)* of wheat for each treatment at different positions of the bund are presented in Tables 3 and 4. For the control plots, crop yield at all positions are not significantly different. In 1-year and 5-year old soil bunds, significantly higher grain yields were recorded at Tube 3 (two meter below the bunds) and Tube 4 (4 meter below the soil bunds) compared with Tube 1 and Tube 2. Similarly, in 5-year old soil bund, the biomass yield was significantly higher at Tube 3 and Tube 4 compared with Tubes 1 and 2. This indicates that the effect of soil bunds on grain and biomass yield was recorded below the soil bunds.

Table 3. Grain yield (g m^{-2}) of wheat at different positions from the soil bund. Values in the parenthesis are standard deviations.

	Tube 1	Tube 2	Tube 3	Tube 4
Control	184 (4)	194 (23)	183 (13)	178 (6)
1-year old soil bund	188 (16)^{b}	191 (13)^{b}	202 (18)^{a}	218 (22)^{a}
5-year old soil bund	186 (18)^{b}	184 (9)^{b}	217 (19)^{a}	234 (16)^{a}

Means followed by the different letter within a row are significantly different at P = 0.05 level of significance

Table 4. Biomass yield (g m^{-2}) of wheat at different positions from the soil bund. Values in the parenthesis are standard deviations.

	Tube 1	Tube 2	Tube 3	Tube 4
Control	1120 (97)	1183 (197)	1075 (209)	1050 (114)
1-year old soil bund	1208 (139)	1184 (151)	1242 (206)	1358 (146)
5-year old soil bund	1008 (102)^{b}	1108 (120)^{b}	1383 (123)^{a}	1467 (75)^{a}

Means followed by the different letter within a row are significantly different at P = 0.05 level of significance

At Tube 1 and 2, the grain and biomass yield for the control, 1-year-old soil bund and 5-year-soil bund are similar (Tables 5 and 6). At Tube 3, grain yield (g m^{-2}) for 1-year old soil bund and 5-year old soil bund were 10 and 18% higher than the control plots, respectively. Similarly, at Tube 4, grain yield (g m^{-2}) for 1-year old soil bund and 5-year old soil bund were 22 and 31.5% higher than the control plots, respectively. Similar trend was observed regarding the effect of soil bunds on biomass yield of wheat (Table 6).

Table 5. Effect of position from the soil bunds on grain yield (g m^{-2}) of wheat

Treatments	Position from the soil bund				Average
	Tube 1	Tube 2	Tube 3	Tube 4	
Grain yield (g/m^{2})					
Control	184 (4	194 (23)	183 (13)	178 (6)^{b}	185 (14)^{b}
1-year old soil bund	188 (16)	191 (13)	202 (18)	218 (22)^{a}	199 (20)^{a}
5-year old soil bund	186 (18)	184 (9)	217 (19)	234 (16)^{a}	205 (26)^{a}

Means followed by the same letter within a column are not significantly different at P = 0.05 level of significance

Table 6. Effect of position from the soil bunds on biomass yield (g m^{-2}of wheat

Treatments	Position from the soil bund				Average
	Tube 1	Tube 2	Tube 3	Tube 4	
Control	1120 (97)	1183 (197)	1075 (209)	1050 (114)^{b}	1107 (160)
1-year old soil bund	1208 (139)	1184 (151)	1242 (206)	1358 (146)^{a}	1248 (166)
5-year old soil bund	1008 (102)	1108 (108)	1383 (123)	1467 (75)^{a}	1242 (216)

Means followed by the same letter within a column are not significantly different at P = 0.05 level of significance

Crop yield (t ha^{-1})

Although grain yield and biomass yield in the conserved plots is higher than the control plot, the total grain and biomass yield (t/ha^{-1}) was different when the area occupied by the soil bunds are taken in to account during crop yield calculation. (Table 7). Accordingly, as shown in Table 7, the average grain yield of wheat from conserved plots is lower than the yield from control plots.

Table 7. Grain and biomass yield (t ha^{-1}) of wheat. Values in the parenthesis are standard deviations

Treatments	Mean grain yield (t ha^{-1})	Mean biomass yield (t ha^{-1})	Harvest Index (HI)
Control	1.85 (0.14)	9.41 (1.36)	0.20
1-year old soil bund	1.69 (0.17)	10.61 (1.42)	0.16
5-year old soil bund	1.75 (0.22)	10.55 (1.82)	0.17
Average	1.67 (0.19)	10.79 (1.72)	0.15

The yield in control plots is 5% higher than the yield recorded from plots with 5-year-old soil bunds. Similarly, the yield from control plots is 9% higher than yield recorded from plots with 1-year old soil bunds. This might be because significant proportion of cultivated land was occupied by the bunds. The area occupied with soil bunds accounted up to 20% of the total area (Figure 13). However, this area was covered by Desho grass to compensate the wheat yield reduction.

Figure 13. Soil bund occupied significant area at Jawe-gumbura watershed

The effect of soil bunds on the total yield of crops (t ha^{-1}) is not different from previous results in Ethiopia. For example, a study in the Galessa watershed of Ethiopia showed that 3-year-old soil bunds reduced total grain yield of barley by 7% as compared to control plots (Adimassu et al., 2014). Nevertheless, it is difficult to make this generalization, as there are cases where soil or stone bunds increase crop yield in drier parts of Ethiopia. For example, soil and stone bunds increased crop yield per hectare (Vancampenhout et al., 2006; Kato et al., 2011). This shows that the effect of soil bunds on crop yield is site specific.

Conclusions and recommendation

This study assessed the effect of soil bunds on runoff, soil loss, soil moisture and wheat yield. Due to the lowest rainfall during the experimental season, the study did not determine the total runoff and soil loss from experimental plots. Nevertheless, the result indicates that soil bunds reduced runoff and soil loss if and only if bunds are frequently maintained to accommodate runoff and sediment.

Generally, soil bunds with grass improved soil moisture content of the soil mainly during the end of rain season. This shows that soil bunds can extend the growing period of crops. So far, researchers tried to assess the effect of SWC practices such as soil/stone bunds above the bund (Amare et al., 2013; Nyssen et al., 2000). However, our study shows that higher soil moisture contents were recorded at 2 and 4 meters below the bunds. This indicates to standardize methodologies to assess the impact of SWC practices.

The average grain and biomass yields (g/m^2) of wheat were higher in conserved plots compared with the control plot. Similar to soil moisture, higher grain and biomass yields per quadrant (g/m^2) were recorded at 2 and 4 meters below the bund. Although, grain and biomass yields (g/m2) were higher in conserved plots, the total grain and biomass yield (t/ha) from control plots was higher than conserved plots. This is mainly because significant proportion of the land was occupied by the soil bund. Farmers planted Desho grass to compensate the yield reduction. Hence, the benefit of Deso grass and the off-site impact of sediments trapped by soil bunds should be considered while assessing the comprehensive impacts of SWC practices.

Limitation of the study

There are two major limitations of the study. The first limitation is related to the setup of the experiment that the effects of Desho grass and soil bunds could not be disaggregated. Moreover, the treatments were replicated only two times, which makes the degree of freedom of replications 1. The second limitation is that runoff and soil losses may not represent the actual situation of the study areas as the experiment was conducted only for one-season. This suggests the need for further research to consider these limitations.

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