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Assessment of runoff and sediment losses under different slope gradients and crop covers in semi-arid watersheds

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Abstract

Soil erosion is a serious threat to counter global population growth with increased and sustainable agricultural production. Torrential rains in sub-mountainous areas of Pakistan yields tremendous amount of runoff which is a major limiting factor to obtain maximum benefits of land use in sloppy areas. A study was planned to estimate the runoff and soil loss under different vegetation covers and slope. For this purpose, three slope gradients, i.e., 1, 5 and 10% were established having four plots of each slope gradient. Three crops, i.e., groundnut, mungbean and millet were sown with a fallow plot (bare soil), on each slope gradient. Runoff and sediment produced after every rainfall (≥ 20 mm) was collected and runoff and sediment losses under each crop cover and slope gradient, were calculated. The results showed that groundnut, mungbean and millet has decreased the accumulative soil sediment loss upto 40, 28 and 38% and runoff loss was decreased by 31, 30 and 24%, respectively, comparing with the bare soil. The highest soil and water losses were monitored at 10% slope gradient following 5 and 1% slope gradients, respectively under all vegetation covers. However, under the same topographic condition, different crops runoff and soil loss show obvious disparity. Topographic gradient has shown significant variation on soil and water loss. It was concluded that crop cover is the best option for appropriate soil and water conservation and profitable crop husbandry.

Keywords: Sloppy lands, sediment loss, water loss, slope gradients, cover crops, Pakistan

Introduction

Land degradation due to soil erosion from upstream areas of a watershed brings harmful onsite and offsite impacts. Onsite impacts include, decline in land productivity and farmers income. Offsite impacts include sedimentation, water pollution and floods etc. Erosion is closely related to water availability, especially for crop growth and production (Suyana and Senge, 2010). The factors involved in soil erosion are soil cover, soil texture, soil structure, porosity/permeability and topography (Moore and Burch, 1986). In addition, human activities and especially improper land management and use can influence the dynamics of these factors (Wischmeier and Smith, 1978). Slope runoff is greatest source of soil and water loss which is generated due to erratic and torrential rains in sloppy rainfed areas. According to Soil Survey Report (Ali, 1967), the climate of this region ranges from semi-arid to sub-tropical continental. Rainfall is erratic, about 60-70% of the total is generally received during monsoon, i.e., from mid June to mid September.

Concentrated rainfall and undulating topography are the main causes of erosion. The soils are medium to coarse textured, and are dominated by silt and sand particles because most of them were mainly derived from sandstone and loess parent material (Nizami *et al.*, 2004). Soil crusting after these rains decreases infiltration rate, decreases aeration and increases soil strength which reduces plant emergence and exposes soil surface to erosion. They have distinct plough pan and, at places fragipan which reduces water intake and hinder root penetration (Shafiq *et al.*, 2005).

The impact of high intensity rainfall followed by run off results in huge soil loss over greater slope length and this effect becomes more deleterious with the steepness (Rai and Mathur, 2007). The soil losses are continually leading to critical deterioration in soil properties, decreased soil productivity and crop yields, causing agro-ecological, environmental and watershed-function problems (Panomtaranichagul and Nareuban, 2005). Therefore, more effective soil and water conservation strategies are essential for sustainable increases in productivity on cultivated highland slopes. Erosion is expected to increase with increase in slope steepness and slope length could be a result of respective increase in velocity and volume of surface runoff (van Vliet and Hall, 1995).

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Soil erosion is a serious problem in watershed areas receiving frequent heavy rains. Soil loss on slopes covered with vegetation is very little. However, with removal of the vegetation, surface soil can easily erode. Therefore, when lands on slopes are cleared for cultivation, unless measures to stop soil erosion are taken, fertile surface soils may erode with heavy rain and the land may become barren within only a few years (Itani, 1998). Surface runoff or overland flow occurs when soil is not capable of absorbing rainwater, or removing it through transpiration, and in-situ infiltration. Overland flow depends on many factors which can be classified into two groups: 1) abiotic factors: relief and geomorphological characteristics, parent rock and soil composition and climate (primarily the intensity and amount of rainfall), and 2) biotic factors: vegetative cover of the slope, land use, anthropogenic factors, etc. Vegetation cover represents one of the most powerful factors influencing the runoff regime, (Hernandez *et al.*, 2000). Protection of soil by means of the vegetation cover is the basic principle to fight against water erosion (Saco *et al.*, 2007; Uhlirova and Podhrazska, 2007; Gordon *et. al.*, 2008) and it also enhances water infiltration rate (Hejduk and Kasprzak, 2004, 2005). Vegetation cover can cause a decrease in the frequency of the surface runoff and a small variation in vegetative cover can drastically affect the surface runoff (Wei *et al.*, 2011). Research findings on the relationship between soil loss and productivity indicate that erosion causes considerable deterioration in soil fertility and crop yields (National Soil Erosion-Soil Productivity Research Planning Committee, 1981). In Pakistan, rainfed regions have an uneven topography and is directly or indirectly dependent on rainfall. Almost 60-70% rainfall occurs in months of June to August. Knowledge of rainfall-runoff and runoff-soil loss relationship in these areas is very important to develop appropriate technology for soil and water conservation for increased crop production. In these relationships, not only the amount of rainfall but also its intensity is important. Erratic and torrential rainfalls are more damaging than gentle uniform rains. The other factor affecting these relationships is surface cover and gradient (Ahmad *et al.,* 1984). Keeping in view the long term sustainability and productivity of eroded lands, the present research was carried out to study the effect of slope steepness and different cover crops during summer season on soil and water losses to improve fertility of eroded lands through land and crop management practices.

Materials and Methods

Site description and experimental setup

In order to investigate the effectiveness of different crop covers at variable slope gradients on sloping lands of Fateh Jang (Pakistan), an outdoor experiment was planned in the campus of Soil and Water Conservation Research Station (SAWCRS), Fateh Jang (latitude 33.55° N, longitude 72.58° E and 402 m high from the sea level) by establishing artificial variable slope gradients viz., 1, 5 and 10%. The soil texture was sandy loam (Gee and Bauder, 1986). The mung, millet and groundnut crops were selected on the basis of local famer's priority during the summer season. Twelve runoff plots were installed on the experiment site, with slope length of 5 m and a width of 2 m. Brick walls were made to partition the plots and plastic tanks of 200 L capacity were connected to slope plots via a 5 inch diameter plastic pipe, at the down slope end of each plot to collect surface runoff and eroded soil. During the study, neither runoff event exceeded the storage capacity of these tanks, nor there was, any significant loss from tanks through evaporation. Brick boundaries of each plot were raised upto 15 cm to avoid the inter mixing of sediment. At the end of each rainy season, exposed soil was plowed to a depth of 30 cm to break up possible surface crust, so that the sealing effect from the previous rainy season would not carry over to the next. Air-dried soil stored in a warehouse was added to the re-plowed plots to compensate for lost soil. For those plots receiving fresh soil, manual grading was applied to achieve a uniform slope. Kharif crops (Mung, Millet and Groundnut) were grown on the slope plots in the respective growing season. Before sowing of crops recommended rates of fertilizer nutrients (Mung, NPK at 12, 23, 0 kg acre^{-1}, Millet 27, 14, 0 kg acre^{-1} and Groundnut 9 36 28 kg acre^{-1}) were added into the soil. One plot of each slope gradient was kept fallow as a check (bare soil).

Measurements

Measurements include daily precipitation, surface runoff and soil loss. The volume of surface runoff and soil loss was measured each time erosion occurred, usually after a storm or heavy rainfall. Runoff was measured all around the year. Recorded data about amounts of water were converted to cubic meters per hectare (m^3 ha^{-1}). The data about amount of washed-out soil related to the measuring unit of tons per hectare (t ha^{-1}) in a similar manner. The run off data was obtained for every rainfall event $\geq$ 20 mm. After each rainstorm of $\geq$ 20 mm, for the determination of the amount of soil and water loss per rainfall event, depth of runoff in each container was measured to calculate runoff volume and 1 L of runoff water was sampled from each container after stirring and mixing. After filtration, the remaining sediment was dried to measure sediment concentration. Depth of water in plastic tank was measured to calculate total amount of water loss per rain storm. Then, from this data, accumulative soil and water loss per cropping period was noted every year for each plot of all slope gradients as described by Tegenu (2009). Rainfall (mm) was measured at study site (Table 1).

Crop yield determination

One m^2 of crop plants were sampled from all the plots of each slope gradients for grain yield assessment under different slope gradients.

Table 1: Rainfall (mm) at study site

Year	April	May	June	July	Aug	Sep	Average
2010	21	47	84	321	462	81	169.333
2011	62	11	96	335	258	82	140.667
2012	137	9	50	101	347	122	127.667

Table 2: Effect of slope gradients and cover crops on soil loss (t ha^{-1})

Cover crop	Slope gradient (%)	2010	2011	2012	Mean
Fallow	1	3.960 d	4.220 d	4.180 e	4.120
	5	5.360 bc	6.660 b	5.960 b	5.993
	10	6.870 a	7.450 a	7.700 a	7.340
Groundnut	1	1.670 g	2.100 f	2.800 fg	2.190
	5	2.220 fg	3.860 d	3.810 e	3.297
	10	4.680 cd	4.240 d	5.980 b	4.967
Mung	1	2.340 efg	3.220 e	3.980 e	3.180
	5	3.160 e	4.000 d	4.800 d	3.987
	10	5.130 bc	5.580 c	5.320 cd	5.343
Millet	1	1.980 fg	2.300 f	2.265 g	2.182
	5	2.780 ef	3.050 e	2.990 f	2.940
	10	5.560 b	5.880 c	5.610 bc	5.683

Statistical analysis

The data collected was statistically analyzed using RCBD described by Steel *et al.* (1997). The MS Word & Excel-2010 and M-Stat C computer softwares were used to compare the differences using LSD test.

Results and Discussion

Simulated sediment yield

Soil sediment yield was recorded after every rainstorm ≥ 20 mm and a significant relationship among different crops and slope gradients was found **(**Table 2**)**. Erosion was highly variable among and within slopes. In 2010, maximum sediment yield (5.560 t ha^{-1}) was recorded at 10% slope gradient in millet following the fallow while minimum sediment yield (1.670 t ha^{-1}) was recorded at 1% slope gradient in groundnut. The data recorded in 2011 showed that maximum soil was eroded (5.88 t ha^{-1}) in millet at 10% slope gradient following the bare soil where loss was maximum and minimum soil (2.1 t ha^{-1}) was lost in groundnut at 1% slope gradient. Almost a similar trend was observed in 2012. But it was also noticed that for medium slope gradients (5%), millet showed better performance compared to mungbean which was better stop wash barrier for 1 and 10% slope gradients.

In general, a decrease in surface cover causes a nonlinear increase in sediment yields (Larsen, 2009). The significant variability in sediment loss during the study years could be due to rainfall variation, slope gradient and cover crop. The main process involved in sediment delivery along these vegetated slopes was sheet erosion, as there were no rills or only poorly developed and discontinuous rills, allowing sediments to be retained within the slope, were noticed. Groundnut offered maximum resistance against soil loss, might be due its more vegetative cover and spreading roots since vegetation increases, protection of soil resources also increases and soil erosion consequently decreases (Moreno *et al.*, 2010) as greater soil loss occurred without vegetation cover. Slope angle was another factor that determined the sediment yield. Maximum sediment yield was obtained at 10% slope gradient and the least yield was recorded for 1% slope gradient since the slope gradient is the main factor for controlling soil erosion (Yong and Bao, 2012).

Furthermore, it was noticed that amount and distribution of rainfall was another factor which determined the soil sediment loss, slope is specially pronounced under high intensity precipitation conditions. Soil detachment in the form of sediment load was increased with amount and distribution of rainfall. Vegetation distribution strongly influences the pattern and extent of water and sediment loss

(Panomtaranichagul and Nareuban 2005) and rainfall intensity magnified runoff and soil loss (González-Pelayo *et al.*, 2010). As far as, crop covers are concerned, groundnut provided the maximum resistance against the soil erosion followed by mungbean. Whereas, millet, provided the least protection against soil sediment loss. Thornes (1988) suggested that 40% vegetation cover in soil is considered critical, below which accelerated erosion dominates on sloping lands. If the vegetation covers an area of more than 40%, it will be protective for land.

Table 3: Effect of slope gradients and cover crops on water loss (m^3 ha^{-1})

Cover crop	Slope gradient (%)	2010	2011	2012	Mean
Fallow	1.0	696.1 c	756.2 d	741.2 e	548.6
	5.0	712.1 c	800.2 d	802.2 d	579.9
	10.0	908.1 a	1100.1 a	1080.0 a	774.6
Groundnut	1.0	345.1 e	456.3 g	394.7 j	299.3
	5.0	456.2 d	544.4 ef	518.1 h	380.9
	10.0	789.2 b	877.8 c	871.0 c	637.0
Mung	1.0	256.2 f	312.5 h	350.0 k	229.9
	5.0	478.9 d	587.2 e	570.6 g	410.4
	10.0	827.2 b	977.4 b	960.4 b	693.7
Millet	1.0	460.7 d	515.1 fg	498.9 i	368.9
	5.0	496.7 d	598.6 e	610.4 f	427.7
	10.0	800.7 b	900.4 c	870.5 c	645.4

Table 4: Effect of slope gradients and cover crops on grain yield (t ha^{-1})

Cover crop	Slope gradient (%)	2010	2011	2012	Mean
Fallow	1	*	*	*	*
	5	*	*	*	*
	10	*	*	*	*
Groundnut	1	12.20 a	7.56 a	8.10 a	9.29
	5	9.66 ab	5.22 b	6.22 b	7.03
	10	8.69 b	3.10 c	4.10 c	5.30
Mung	1	1.35 c	1.74 cd	2.12 d	1.74
	5	1.25 c	1.26 d	2.02 d	1.51
	10	1.05 c	1.11 d	1.87 de	1.34
Millet	1	0.23 c	0.21 d	0.78 def	0.41
	5	0.20 c	0.18 d	0.61 ef	0.33
	10	0.13 c	0.10 d	0.43 f	0.22

*No Crop

Simulated runoff

Runoff displayed great variability among and within the three experimental slopes (Table 3). Nevertheless, the magnitude of decline in runoff varied greatly depending on slope steepness and crop cover. For example, increased vegetation cover and declining slope gradient were correlated with decreased runoff. Results (Table 4) of this study showed that groundnut proved best for runoff control since least runoff (299.3 m^3 ha^{-1}) was measured in groundnut at 1% slope gradient which was 45% less compared with the plot with same gradient under fallow (bare soil). Similarly it was decreased by 34 and 18% at 5 and 10% slopes gradients, respectively, in groundnut. Cultivation of mungbean yielded 229.9 m^3 ha^{-1} run off, 58% less compared with bare soil in 1% slope gradient but its runoff decrease was 29 and 10% in 5 and 10% slope gradients compared with fallow. Since it was higher as compared with groundnut on steeper slopes, that is why it was ranked after groundnut. The runoff was 32, 26 and 17% less on 1, 5 and 10% slope gradients, respectively, by millet cultivation. The tendencies of water loss changes with an increase of gradient remained similar among the three crops.

A close relationship was found between sediment load and runoff volume. Similar to sediment loss, highest amount of water loss occurred at 10% slope gradient and least at 1% slope gradient. The runoff may be attributed to factors such as topography (Beven and Kirkby, 1979), rainfall characteristics, vegetation (Stieglitz *et al.*, 2003). Almas and Jamal (1999) and Khan and Bhatti (2000) demonstrated that maintenance of adequate surface cover may help to conserve soil and water. It was observed that rainfall pattern and intensity in each year contributed to runoff quantity since the highest runoff was produced in 2011 because it was the high rainfall year and least runoff occurred in 2010 being low rainfall year. High rainfal1 intensity could increase runoff amount (Songwel *et al.*, 2007). It was also seen that the quantity of water loss was not only influenced by the crop type and cover but also by slope steepness. Similar were the findings of Hartano *et al.* (2003). Generally, plots with steeper up slope (5 and 10%) had greater runoff loss than those with lower arrangements of slope steepness (1%) (Table 2). Plant cover enhanced the infiltration rates and decreased runoff volume (Akbarimehr and Naghdi, 2012). Negative exponential relationship between plant cover and runoff was reported by Garcia *et al.* (2007). The vegetation plays a very significant role in controlling runoff generation and its volume (Gomi *et al.*, 2008; Jordan Lopez *et al.*, 2009).

Table 5: Effect of slope gradients and cover crops on biomass yield (t ha^{-1})

Cover crop	Slope gradient (%)	2010	2011	2012	Mean
Fallow	1	*	*	*	*
	5	*	*	*	*
	10	*	*	*	*
Groundnut	1	11.780 b	18.220 c	16.450 b	15.483
	5	9.450 c	14.140 d	13.640 c	12.410
	10	6.450 de	9.450 e	10.000 d	8.633
Mung	1	8.200 cd	12.810 d	13.140 c	11.383
	5	5.650 e	12.000 d	12.390 c	10.013
	10	3.440 f	3.440 f	3.900 e	3.593
Millet	1	16.780 a	26.740 a	23.080 a	22.200
	5	13.550 b	22.990 b	15.970 b	17.503
	10	11.880 b	14.230 d	12.600 c	12.903

Crops growth and yields

Almost similar trends of crop growth and yields were recorded during all the study years except changes were noticed with the pattern of rainfall. The data of grain yields of various crops varied significantly. A significant change was also recorded under different slope gradients. It was noticed that with an increase of topographic gradient, the grain yields of the three crops showed a decreasing trend. The average grain yield of groundnut, mungbean and millet was 9.29, 1.74 and 0.41 t ha^{-1}, respectively, on 1% slope gradient. The grain yields of groundnut, mungbean and millet decreased to 7.03, 1.51 and 0.33 t ha^{-1}, respectively on 5% slope gradient. Similarly grain yields of these crops were decreased to 5.30, 1.34 and 0.22 t ha^{-1}, respectively at 10% slope gradient. With an increase of topographic gradient, grain yields showed a decreasing trend indicating an adverse and strong influence of slope gradient. Biomass yield pattern (Table 5) of crops was similar to grain yield under different slope gradients during the study years. Grain and biomass yield showed an inverse relationship with soil and water loss which was increased with an increase in slope gradient.

Although grain yields of all crops declined as the gradient increased but different crops showed a different sensitivity to the variation of gradients and grain yields and above ground biomass increased from upper to lower slope positions in each slope. Similar findings were reported earlier by Su *et al.* (2010). The adverse effects of topographic gradient on crop yields were reported earlier (Yong *et al.*, 2009). Under the same topographic conditions, different crops runoff and soil loss showed variation that may be attributed to difference in soil cover, root development, plant population and density, available soil moisture and soil fertility. A distinct decrease in plant population and density was observed visually during this experiment towards the rising slope while the growth of crops and plant population was higher towards the down slope length indicating accumulation of soil moisture and nutrients at the bottom. The canopies of different crops can decrease the erosive power of the raindrops (Sinun *et al.*, 1992). Furthermore, their rooting systems will also hold soil particles effectively and make soils more resistant to erosion. Other studies confirmed that an increase of vegetation cover resulted in a significant decrease in discharge and sediment load (Niehoff *et al.*, 2002; Wegehenkel, 2002).

Conclusions

Topographic gradient has a significant influence on crop yields; increase in slope gradient decreased the crops yield. The vegetation cover played a very significant role in controlling runoff generation and soil erosion. Different vegetation covers revealed a significant change in magnitude and volume of runoff and soil losses. Groundnut showed best results in minimizing soil loss upto 40 and runoff loss up to 31% compared with fallow. Hence, groundnut could be the most suitable summer crop in these areas. Under the same topographic conditions, different crops runoff and soil loss indicated clear differences. The benefit of soil and water conservation from high to low rank was groundnut, millet and mungbean. However, these are preliminary results, further studies are required under different climatic, soil and topographic conditions to establish certain conclusion.

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