Arid Land Research and Management, 25:294–307, 2011
Copyright © Taylor & Francis Group, LLC
ISSN: 1532-4982 print/1532-4990 online
DOI: 10.1080/15324982.2011.565859

Soil Erosion Control and Moisture Conservation of Arid Lands with Stone Cover

Majed M. Abu-Zreig[1], Abdullah Tamimi[2], and Abdulrahman A. Alazba[3]

[1]Civil Engineering Department, Jordan University of Science and Technology, Irbid, Jordan
[2]Research Assistant, Faculty of Agriculture, The University of Jordan, Amman, Jordan
[3]Alamoudi Water Chair, King Saud University, Riyadh, Saudi Arabia

Soil moisture conservation and combating soil erosion on agricultural fields are the highest priorities for crop production in arid lands. In this research, the effect of land application of rock fragments on runoff, soil loss, and vegetative cover on a silt loam soil has been tested under natural rainfall conditions. Field plots of 2 m wide by 10 m long were prepared in two locations with a deposit installed at the downstream end of the plots to collect runoff and sediments after each storm during the 2004/2005 winter season. Three treatments were used in the experiments in duplicates including plots covered with 5% and 15% stone and a control. Experimental results showed that rock fragments were highly effective in reducing runoff and soil loss. Runoff depth from plots covered with rock fragments at a rate of 5% and 15% was reduced by 17% and 30% compared to the control, respectively. The corresponding reductions in soil loss for both stone treatment levels were as high as 35% and 53%, respectively. The average soil moisture measured at the center of the plots during the entire season was always higher for stone treated plots and increased with stone coverage percentage compared to control. Consequently, vegetative cover was higher in the plots with 5% rock fragments cover. For higher stone coverage of 15%, rock fragments occupy more soil surface area and, therefore, reduce the space available for vegetation.

Keywords arid land, moisture conservation, runoff, soil erosion, stone cover

Jordan is considered to be one of the driest countries in the Middle East with an average annual rainfall of 160 mm (Fardous et al., 2004). Although concentrated irrigated agricultural area is found in the Jordan valley, all other agricultural practices are based on rainfall. Rainfed agriculture is being practiced by farmers especially in Ajloun and Irbid governorates where average rainfall is about 400 mm/year. Farmers in the highland of northern Jordan have adopted several conservation measures to conserve soil and water. One of these practices is the installation of stone bunds.

Received 13 July 2010; accepted 5 February 2011.
Address correspondence to Majed M. Abu-Zreig, Civil Engineering Department, Jordan University of Science and Technology, P.O. Box 3030, Irbid, Jordan. E-mail: majed@just.edu.jo

Stone bunds (also termed *masateb*) have been used extensively by farmers in the mountainous area for many years as a mean to reclaim hilly and rocky lands and to conserve soil and water in the farms. Contour stone bunds were constructed by placing long rows of stones and rock fragments spaced at various intervals, depending on land slope, along the contours. Runoff captured behind these barriers also allows the retention of soil, thereby serving as an erosion control measure on gentle slopes.

While the contour stone terraces system has well off-site soil conservation purposes, its role in water harvesting within the farm is minimal. Terraces and crop planting have not been integrated to maximize soil water management in the farms. Furthermore, the construction of contour stone terraces requires a large volume of stones that are obtained from deep plowing of the land with heavy tractors or bulldozers. After that, stones and rock fragments are collected by farmers and used for construction of bunds. The process of stone clearing out can continue for many years until the land is almost cleared from stones. Farmers believe that stone clearing reduces the tillage cost and increases the market value of the land. Unfortunately, this practice significantly retards water infiltration and increases surface runoff and erosion (Chow et al., 1992; Nyssen et al., 2001).

Previous works showed that surface rock fragments had a direct effect on soil water relations such as hydraulic conductivity because of their higher bulk density and lower water holding capacity. Magier and Ravina (1984) found that rock fragments decrease soil compaction, swelling, and hydraulic conductivity (K) because of the reduction in water-conducting pores areas. However, for compacted soil, rock fragments increased hydraulic conductivity. Mehuys et al. (1975) also found that rock fragments increased hydraulic conductivity because, at a given water content, the water is confined to a smaller volume of soil than if the stones were not there, thus increasing the water content of soil between stones. The overall effect is an increase in the soil hydraulic conductivity because K increased with water content at logarithmic scale. On the contrary, Edwards et al. (1984) and Dunn and Mehuys (1984) found that Ks decreased with stone content and stone size in the soil samples. Other studies suggested that the influence of soil stone content on hydraulic conductivity was affected by its weight percentage; Ks and infiltration of stony soil decreased at stone percentage up to 40%, then increased at stone percentage higher than 40% (Zhou et al., 2009).

However, the effect of surface rock fragments on runoff-rainfall-erosion relationship seemed to be more consistent. Rock fragments reduce runoff and soil erosion (Saini and Grant, 1980; Edwards et al., 1984; de Figueiredo and Poesen, 1998; Poesen et al., 1999; Cerdà, 2001; Mandal et al., 2005; Fu, 2005). This is because stones can absorb rainfall energy, reduce runoff velocity, and obstruct suspended soil sediments. In a 12-year field study under natural rainfall Edwards et al. (1984) found that the runoff from stony watershed was 30% less compared to similar non-stony watershed. Soil loss from the stony watershed under no till condition was found to be zero compared to 1785 kg/ha in the non-stony watershed. Similar results were reported by Saini and Grant (1980) who found that stone removal from potato fields resulted in reduced infiltration, soil water and soil temperature, more runoff, erosion and soil compaction. A positive effect of rock fragments was also confirmed with laboratory studies. Cerdà (2001), using small field plot under simulated rainfall, showed that rock fragments up to 77% increased steady state infiltration rates by 100% and decreased runoff coefficient and erosion rates by 3 and 33 times compared to plots without rock fragments. Splash and wash erosion decreased significantly with stone coverage using small soil pins under simulated rainfall (de Figueiredo and Poesen, 1998) and under concentrated sheet flow condition (Poesen et al., 1999).

Rock fragments have also been found to maintain favorable biological activities (Lahav and Steinberger, 2001; Certini et al., 2004) improve soil moisture conditions (Pérez, 1998; Katra et al., 2008; Zhongjie et al., 2008), and increase crop yield such as the yield of apple orchard in a Mediterranean soil (Magier and Ravina, 1984), potato yield (Saini and Grant, 1980), corn yield (Edwards et al., 1984), and wheat yield in dry years (Kosmas et al., 1994).

Despite land clearing has been practiced for long time in Jordan, no work has been done to clarify the role of rock fragments on water conservation, soil erosion, and crop yield at the farm scale. In addition literature studies on stone effect seemed to be site specific and gave some conflicting results. For example, Chow et al. (1992) found that crushing of large stones to smaller stones of less than 50 mm in diameter enhanced runoff by 3 to 1.5 folds. Whereas van Wesemael et al. (1995) concluded that crushing of large stones into smaller ones improved soil macroporosity and caused deeper penetration of rainfall into the soil. In addition, field studies involving stone covers under natural rainfall conditions are extremely limited. Therefore, studying the influence of rock fragments under Jordanian soil and Mediterranean climate on water and soil conservation is necessary in order to achieve a higher agricultural production and a reduction in the soil and water losses in Jordan and other Mediterranean countries such as Tunisia and Spain. The objectives of this research are to investigate the influence of rock fragments on runoff, soil erosion, and native vegetative cover under natural rainfall conditions and to explore the relationships among rainfall, runoff, and soil loss in stony lands under Mediterranean climate.

Materials and Methods

Two experimental sites, named as S1 and S2, were located at the campus of Jordan University of Science and Technology in Northern Jordan with 32° 34′ N latitude, 36°01′E longitude, and 520 m altitude. This site represents an ecosystem with similar characteristics to many other sites in the Middle East and west-south of Saudi Arabia. The predominant soil type is clay loam to silt clay loam with low infiltration and high dispersion characteristics. It is characterized by an arid climate, mild rainy winters, and dry hot summers. The mean maximum air temperature in summer, occurred during July and August, as 32.1oC, while the mean minimum air temperature in winter as 5.8oC occurred during January. Rainfall occurs mainly in the winter season from October to March with heavy rainfall in January and February and the remaining months of the year are dry. Based on the 10 year data from 1995 to 2005, the mean annual rainfall in the experimental site was 211 mm and the mean annual potential evaporation was 930 mm.

The two sites are about 500 m apart with opposite orientation, S1 is facing south-west and S2 is facing north and differ slightly in soil type, slope, and soil depth. Land use in the two sites was fallow during the past four years but lands had been occasionally planted with barley for onsite animal grazing. Natural vegetation is dominated by wild oats, wild barley, and weeds emerge toward the end of winter season until May then dry slowly and completely in the summer months. No ground vegetations existed when the experimental plots were prepared. S1 is characterized by shallow soil depth of about 750 mm, a slope of 12% and average sand, silt, and clay ratios of 22, 44, and 34%, respectively (clay loam). S2 has a deep soil of about 2 m, a slope of 10% and sand, silt, and clay ratio of 14, 48, and 38%, respectively (silt clay loam). The field saturated hydraulic conductivity of soil was measured with double ring infiltrometer in three different locations for each sites and the average value for the two sites was found equal to 10 $mmhr^{-1} \pm 1.2$ Volumetric water contents at saturation and field capacity for the top 40 cm layer were equal to 40.5 and 24.2%, respectively. The average bulk density of soil in S1 and S2 were 1190 kg/m^3. A general view of the experimental site is shown in Figure 1.

Twelve plots, 6 in S1 and 6 in S2, of 2 m by 10 m were constructed in the field, and bordered by 200 mm high stone border. There were 2 treatments in S1 and S2 plus a control including, stone coverage at 5%, stone coverage at 15% in duplicates. Deposits or barrel with 130 L capacity were installed at the end of each plot for run-off collection. Experimental plots were smoothed with hand tools to remove soil irregularities and create a uniform slope that varied with the original land slope. A TDR probe was installed, 50 cm deep below soil surface at the middle of each plot to measure soil moisture along the season. Irregularly shaped stones, size range from about 100 to 300 mm in diameter, collected from nearby area were placed randomly by hand on 8 plots, 4 in each locations with an area coverage of 5% and 15%. The stone coverage percentage was measured by point count method and visual observation (Elzinga et al., 2001). A one-square meter wooden frame was randomly placed on three locations on the soil surface of stone-treated plots and the surface area of stones was plotted and later measured by digital planimetry. Two replicates were used for each treatment in both locations. The experimental design was complete block design in which the 6 plots in each location, S1 and S2, were randomly divided into 3 groups, of two plots in each group. One group in each location was left as a control and the other two groups were covered with stone at a rate of 5 and 15% in replicates. These rates were suggested based on personal communication with

Figure 1. General view for the experimental plots; the 15% stone cover plot is shown in the right and the 5% stone cover plot is on the left.

farmers and personal observation in the cultivated fields of the highlands of northern Jordan. Control plots were kept clean from stone cover.

The collected runoff volume in the deposits was measured after each storm for the 12 plots and infiltration depth, equal to the difference between rainfall and runoff depth collected from a plot, was calculated. Five water samples from the collecting deposits of each plot were taken to measure the average sediment concentration in the runoff water and to estimate the subsequent soil loss after each storm for each plot. Five water samples were taken to minimize errors in the measurements of sediment concentrations as runoff water in the collecting barrels needs continuous agitation during sediment sampling. Sediment concentrations were measured by drying. The influence of stone on runoff, infiltration, and soil loss were assessed by comparing these parameters between stone treated and control plots in each location separately. Differences among treatments were tested using Tukey HSD multiple range test at 0.05 significant levels.

Results and Discussion

Twenty storms were recorded for the entire rainy-winter season 2004/2005 (from November to May) with rainfall ranging from 2 mm to 35 mm per day and total rainfall of 206 mm measured by an onsite rainfall gage. Runoff was observed for thirteen storms having rainfall greater than 5 mm whereas no runoff occurred for the other seven storms. Runoff and infiltration depths from the experimental plots are summarized in Table 1 and soil loss data are summarized in Table 2.

Effects of Rock Fragment Cover on Runoff and Infiltration

The presence of stones significantly decreased runoff and increased infiltration depth compared to control (Table 1). Figure 2 shows runoff reduction in stone treated plots compared to control. The average amounts of runoff in the control plots in the two sites were 51 mm compared to 42 mm for 5% stone treated plots (17% reduction) and 36 mm for the 15% stone plots (30% reduction) and these differences were significant at 95% probability level. Although, the runoff from S2 is constantly lower, due to its higher depth, than for S1, but runoff differences between these two sites were small and insignificant and, therefore, only average values of replicates were reported in Table 1. These results are in agreement with literature studies involving stone treatment under laboratory and field conditions.

Further analysis was performed to test the long term effect of stone coverage during the winter season. The ratio of runoff coefficient, calculated as the ratio of runoff over rainfall depths, from stone treated plots (Cs) divided by that of control plots (Cc) for each storm event were plotted with time and the results are shown in Figure 3. A trend line between the data showed a constant decrease in the runoff coefficient ratios during the season indicating that the efficiency of stone in decreasing runoff from stone treated plots is improving over time. It is clear from the figure also that the runoff coefficient ratios for the 15% stone coverage plots were always lower than that for the 5%. The presence of stones seemed to create a zone of water depression that decreased water velocity thus decreasing runoff and soil erosion.

Continuous monitoring of soil water content confirmed that rainfall infiltration was always higher in stone treated plots compared to the control as shown in Figures 4 and 5. The soil moisture content also increased with stone coverage

Table 1. Rainfall and runoff data for the experimental plots during the season

Storm number	Date	Rainfall (mm)	Runoff (mm)† Control (S1)	Stone (S1)5%	Stone (S1)15%	Control (S2)	Stone (S2) 5%	Stone (S2) 15%
1	2004/10/30	21.0	4.7	3.8	3.4	4.5	3.6	3.1
2	2004/11/05	10.5	2.7	2.2	1.9	2.5	2.1	1.8
3	2004/11/24	24.0	4.6	4.5	3.8	4.4	4.3	3.7
4	2004/11/29	9.0	3.9	3.9	3.4	3.4	3.5	3.0
5	2004/12/03	10.0	2.1	1.1	0.7	2.0	1.0	0.6
6	2005/12/10	4.0	0.0	0.0	0.0	0.0	0.0	0.0
7	2005/12/20	2.0	0.0	0.0	0.0	0.0	0.0	0.0
8	2005/12/26	4.0	0.0	0.0	0.0	0.0	0.0	0.0
9	2005/01/05	12.0	3.0	2.4	1.9	2.8	2.2	1.6
10	2005/01/19	2.0	0.0	0.0	0.0	0.0	0.0	0.0
11	2005/01/21	2.5	0.0	0.0	0.0	0.0	0.0	0.0
12	2005/01/24	11.0	2.1	1.3	1.0	2.4	1.0	0.6
13	2005/01/28	8.0	4.0	3.4	3.3	3.8	3.5	3.2
14	2005/02/03	4.5	0.0	0.0	0.0	0.0	0.0	0.0
15	2005/02/07	35.0	9.4	8.2	7.0	9.0	8.0	7.2
16	2005/02/08	13.0	5.7	4.6	3.8	5.5	5.0	4.1
17	2005/02/12	13.5	4.9	4.0	3.5	4.7	3.9	3.6
18	2005/02/13	8.0	3.2	2.3	1.3	2.7	2.0	1.6
19	2005/03/10	5.0	0.0	0.0	0.0	0.0	0.0	0.0
20	2005/05/05	7.0	2.3	1.6	1.4	2.2	1.5	1.3
Total		206.0	52.6a	43.2b	36.3c	49.7a	41.4b	35.2c
F (mm)			153.4					

†Average data for the replicates.
F: Cumulative seasonal infiltration depth.
Numbers with different letters in a raw are statistically different at 95% significance level.

Table 2. Rainfall and soil loss data for the experimental plots

		Soil loss (kg/ha)					
Storm number	Date	Control (S1)	Stone (S1) 5%	Stone (S1) 15%	Control (S2)	Stone (S2) 5%	Stone (S2) 15%
1	2004/10/30	543.5	370.0	257.8	559.3	317.7	226.5
2	2004/11/05	182.3	82.1	75.2	110.4	73.7	43.9
3	2004/11/24	467.1	387.6	241.6	393.4	263.3	196.2
4	2004/11/29	92.7	48.3	29.5	66.9	55.4	21.2
5	2004/12/03	25.6	9.7	2.0	19.8	11.4	5.2
9	2005/01/05	24.5	16.0	10.0	21.4	15.6	9.7
12	2005/01/24	13.8	6.7	3.0	12.0	3.0	1.0
13	2005/01/28	24.8	16.7	13.1	22.4	14.8	10.8
15	2005/02/07	1098.5	659.8	499.5	833.4	566.0	449.4
16	2005/02/08	139.3	72.3	52.3	95.4	72.0	48.1
17	2005/02/12	41.6	26.7	19.3	35.1	20.4	14.9
18	2005/02/13	15.4	10.0	4.6	13.1	7.8	5.3
20	2005/05/05	2.5	1.1	1.0	2.0	1.0	0.6
Total		2671.5a	1706.9b	1208.9c	2184.6d	1422.1e	1032.7f

Numbers with different letters in a row are statistically different at 95% significance level.

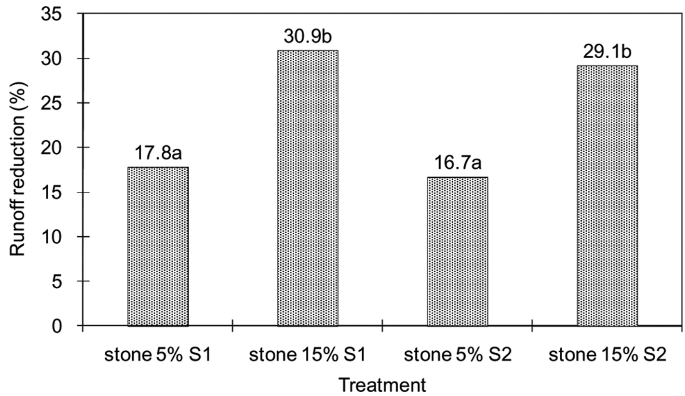

Figure 2. The runoff reduction caused by stone coverage. Variability between plots in each treatment were less than 2%. Values with different letters are statistically different at 95% significance level.

percentage. Soil water contents were always higher in plots covered with 15% stone compared to plots covered with 5% in both sites. As expected, moisture contents in control plots in S2 were always higher, due to its finer soil, than those in S1. Soil moisture differences among treatments were large at the beginning of the rainy season and continued in this trend until the beginning of March. This is because rainfall during that period exceeds evaporation and, therefore, moisture content is proportional to the ability of soil covered with rock fragments to store more water compared to control. After March, when evaporation starts to exceed rainfall, moisture content differences start to diminish especially among stone treated plots.

Analysis of the runoff-rainfall relationships (Eq. 1) in stone treated plots showed linear functions with coefficients of determination ranging from 0.74 to 0.81 as shown in Table 3.

$$R = a(P - b) \tag{1}$$

where R is the runoff depth, mm; a is the calculated slope of the line; P is the rainfall, mm; and b is the calculated threshold rainfall to initiate runoff, mm.

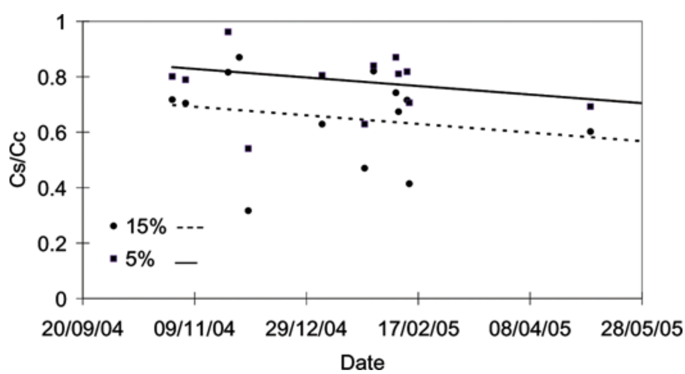

Figure 3. Changes in the ratio of runoff coefficient of stone treated plots (Cs) to that of control plots (Cc) along the winter season 2004/2005.

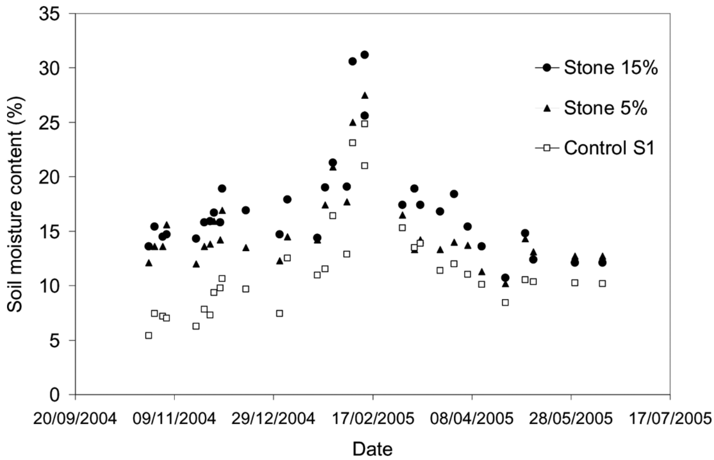

Figure 4. Volumetric soil water content for stone treated and control plots measured during the season for site 1.

The slope of the line decreased from 0.27 for control plots to 0.23 for 5% stone and 0.21 for 15% stone plots. The average threshold rainfall value for both sites, S1 and S2, was about 0.67 mm for control plots and increased to 1.36 mm for 5% and 1.65 mm for the 15% plots. The threshold rainfall for S2 was higher than that for S1 due to its finer soil.

Effect of Rock Fragments on Soil Loss

The influence of stone on soil loss is summarized in Table 2 for each runoff producing storm, whereas soil loss reduction with respect to control is shown in Figure 6. Soil loss from stone treated plots in S1 and S2 was significantly smaller than in the corresponding control plots for each storm for both stone coverage rates

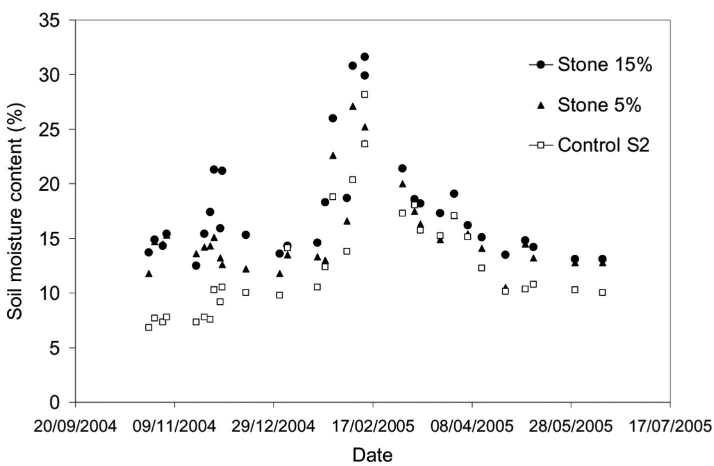

Figure 5. Volumetric soil water content for stone treated and control plots measured during the season for site 2.

Table 3. Relationship between runoff and soil loss with rainfall for control and treated plots†

	Runoff (mm)			Soil loss (kg/ha)		
Treatment	a	b (mm)	R^2	c (kg/ha-mm)	d (mm)	R^2
Control (S1)	0.27	0.56	0.81	30.0	5.6	0.85
Stone S1 (5%)	0.24	1.31	0.80	20.0	6.0	0.86
Stone S1 (15%)	0.21	1.48	0.78	14.6	6.1	0.85
Control S2	0.27	0.78	0.81	24.8	5.9	0.85
Stone S2 (5%)	0.22	1.41	0.74	16.7	6.0	0.86
Stone S2 (15%)	0.21	1.81	0.77	12.6	6.2	0.84

†Linear models were fitted to the data; R = a (P – b); SL = c (P – d), where R is the runoff in mm; P is the precipitation in mm; SL is the soil loss in kg/ha; and a, b, c, and d are constants.

($P < 0.05$). The total soil loss from the control plots in S1 and S2 were 2672 and 2185 kg/ha, respectively. Soil loss from S2 was significantly lower than in S1 because location 2 has deeper soil profile and more importantly has lower slope resulting in higher infiltration and lower runoff. Consequently, soil loss from stone treated plots in S2 was always lower than in S1, although the soil reduction percentages compared to control in each location separately were shown to be similar in Figure 6, 36% in S1 and 34% in S2.

The presence of stone on soil surface at 5% and 15% coverage reduces soil loss by an average of 35% and 54%, respectively (Figure 6). These results were in agreement with previous studies found in the literature (de Figueiredo and Poesen, 1998; Poesen et al., 1999; Cerdà, 2001; Nyssen et al., 2001; Mandal et al., 2005). The presence of stone and rock fragments seemed to improve soil structure, reduce runoff velocity, and absorb rainfall energy, thus, deceasing runoff and soil loss.

Analysis of soil loss versus rainfall for the whole season revealed a linear relationship with a threshold value of about 6 mm to initiate soil loss and a

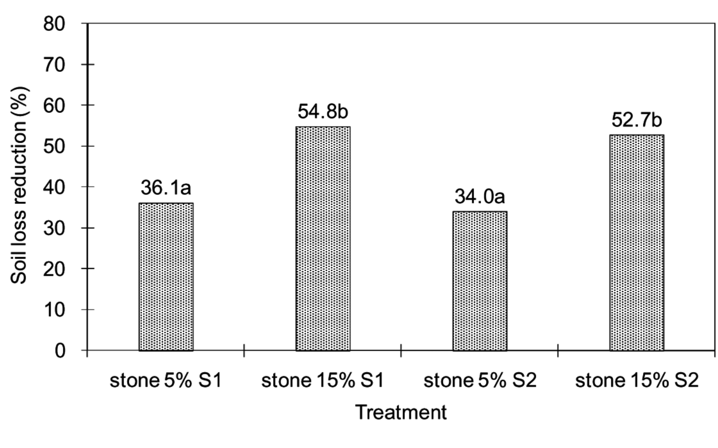

Figure 6. Soil loss reduction caused by stone treatment at 5% and 15% surface coverage. Variability between plots in each treatment was less than 3%. Values with different letters are statistically different at 95% significance level.

coefficient of determination of 0.85 for all treatments (Table 3) using the following linear model;

$$SL = c(P - d) \tag{2}$$

where SL is the soil loss in ($kg \cdot ha^{-1}$); c is the calculated slope of the line in ($kg \cdot ha^{-1} \cdot mm^{-1}$); P is the rainfall depth, mm; and d is the calculated threshold rainfall to initiate soil loss, mm.

While the threshold value increased slightly from 5.7 mm for control to about 6.1 mm for stone treated plots, the average line slope for the two sites decreased significantly from 27.4 $kg \cdot ha^{-1} \cdot mm^{-1}$ for control to an average value of 18.4 and 13.6 $kg \cdot ha^{-1} \cdot mm^{-1}$ for the 5% and 15% stone treated plots, respectively. This analysis confirmed the positive effect of rock fragments on combating soil erosion in arid lands.

Vegetative Cover and Dry Matter Yield

Vegetative cover (VC) and dry matter yield (DMY) measured at the end of the 2004/2005 growing season for all plots are shown in Table 4. A power relationship was found to be the best fitting relationship between DMY and VC with a constant of 100 kg/ha and R^2 of 0.87, as shown in Figure 7. This confirmed the validity of measurements and experimental procedure. Land application of rock fragments at lower stone coverage of 5% increased VC and DMY slightly by about 16% but this increase was not significant at 95% probability level. However, increasing stone percentage to 15% had no effect or even caused a light reduction to vegetative cover and dry matter yield, to some extent (Table 4). It seemed while stone cover at 15% had greater decrease in runoff and soil loss, it also decreased the soil surface area available for plant growth and vegetative cover. These results indicated that rock fragment can be beneficial for tree crops but its effect on yield of cash crops is limited.

The results obtained in this research are in agreement with most of other international studies found in the literature (Saini and Grant, 1980; Edwards et al., 1984; de Figueiredo and Poesen, 1998; Cerdà, 2001; Fu, 2005). However, reductions in runoff and soil loss found here seemed to be lower than those reported by Edwards et al., (1984) and Cerdà (2001). This is the result of the differences in the experimental conditions such as scale, soil type, and rainfall characteristics. The degree

Table 4. Vegetative cover and dry matter yield at the end of the season

Treatment	Vegetative cover (%)	Dry matter yield (kg/ha)
Control S1	33	872a
Stone S1 (5%)	29.6	984a
Stone S1 (15%)	40.9	1042a
Control S2	59.4	1215b
Stone S2 (5%)	38.6	980a
Stone S2 (15%)	54.0	1221b

Numbers with different letters in a column are statistically different at 95% significance level.

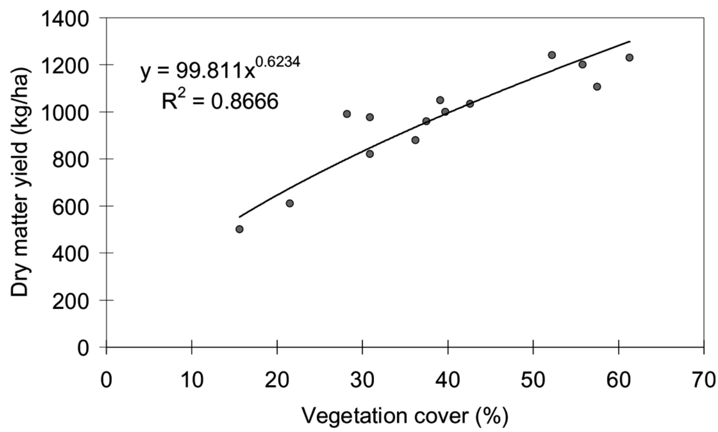

Figure 7. Relationship between the dry matter yield and vegetative cover for the experimental plots.

of reduction in runoff and soil loss due to rock fragments can vary widely and seemed to be site specific. Nevertheless, the findings of this research can have an important effect on the sustainable crop production in stony lands such as those found in northern Jordan. As mentioned in the introduction, farmers of northern Jordan usually clear their land from stones and rock fragments to improve land tillage and increase their market value. However, this research confirms that rock fragments improve land productivity, conserve soil moisture, and reduce soil erosion. Therefore, this research is directed to improve farmers' agricultural practices of the high land in Jordan.

However, the advantages of stone cover are somewhat limited in high rainfall where soil moisture is not the limiting growth factor. In addition leaving rock fragments on the soil surface seemed to be suitable for tree crops that need minimum or zero tillage in some cases. Further research works are needed in some farms having various topography, soil characteristics, and types of trees to clarify the effectiveness of rock fragments on soil moisture conservation, soil loss, and fruit yield.

Conclusions

Field experiments under natural rainfall conditions showed that stone and rock fragments in the field decreased runoff and soil loss from the field and increased infiltration, natural and wild vegetative cover, and possibly crop yield such as wheat and barley. Application of stone at 5% and 15% surface coverage caused a reduction in runoff by an average of 17% and 30%, respectively. The corresponding reductions in soil loss for both stone treatments were as large as 35% and 53%, respectively.

Runoff and soil loss from control and treated plots seemed to follow a linear pattern with rainfall. The most affected parameter was the slope of the soil loss versus rainfall curve interpreted as the amount of soil loss per hectare per one mm of rainfall. Stone coverage at 5% and 15% reduced this parameter by 42%.

The effect of stone coverage on vegetative cover and dry matter yield of wild vegetation was complex. Stone coverage increased water infiltration and decreased soil loss thus it was expected to increase vegetation growth. However, stone also covered part of the soil surface thus preventing growth of vegetation in these covered areas. The net results obtained from this experiment were a slight increase in vegetation growth in plots with low stone coverage of 5% only. However, growth of trees is expected to get better with stone and rock fragment due to the increase in infiltration and decrease in soil loss. Therefore, leaving some stones and rock fragments reasonably in the field can improve agricultural production in arid land.

References

Cerdà, A. 2001. Effects of rock fragment cover on soil infiltration, interrill runoff and erosion. *European Journal of Soil Science* 52(1): 59–68.

Certini, G., D. Colin, A. Campbell, and C. Edwards. 2004. Rock fragments in soil support a different microbial community from the fine earth. *Soil Biology & Biochemistry* 36: 1119–1128.

Chow, T. L., H. W. Rees, and R. L Moodie. 1992. Effects of stone removal and stone crushing on soil properties, erosion, and potato quality. *Soil Science* 153: 242–249.

de Figueiredo, T., and J. Poesen. 1998. Effects of surface rock fragment characteristics on interrill runoff and erosion of a silty loam soil. *Soil and Tillage Research* 46: 81–95.

Dunn, A. J., and G. R. Mehuys. 1984. Relationship between gravel contents of soils and saturated and saturated hydraulic conductivity in laboratory tests, pp. 55–63, in J. D. Nichols, ed., *Erosion and productivity of soils containing rock fragments*. SSSA Special Publication No. 13, Madison, Wisconsin.

Elzinga, C. L., D. W. Salzer, J. W. Willoughby, and D. P. Gibbs. 2001. *Monitoring plant and animal populations, chapter 12: Sampling to estimate cover*, pp. 219–222. Blackwell Scientific Publications, Abingdon, United Kingdom.

Edwards, W. M., P. F. Germann, L. B. Owens, and C. R. Amerman. 1984. Watershed studies of factors influencing infiltration, runoff, and erosion on stony and non-stony soils, pp. 45–54, in J. D. Nichols, P. L. Brown, and W. J. Grant, eds., *Erosion and productivity of soils containing rock fragments*. SSSA Special Publication No.13, Madison, Wisconsin.

Fardous, Abdel-Nabi, M. Mudabber, M. Jitan, and R. Badwan. 2004. *Harnessing salty water to enhance sustainable livelihoods of the rural poor in four countries in West Asia and North Africa: Egypt, Jordan, Syria and Tunisia*. Ministry of Agriculture, National Center for Agriculture Research and Technology Transfer, Jordan, p. 43.

Fu, S H. 2005. Effect of soil containing rock fragment on infiltration. *Journal of Soil and Water Conservation* 19(1): 171–175.

Katra, I., L. E. Hanoch, and S. Pariente. 2008. The effect of rock fragment size and position on topsoil moisture on arid and semi-arid hillslopes. *Catena* 72: 49–55.

Kosmas, C., N. Moustakas, N. G. Danalatos, and N. Yassoglou. 1994. The effect of rock fragments on wheat biomass production under highly variable moisture conditions in Mediterranean environments. *Catena* 23: 191–198.

Lahav, I., and Y. Steinberger. 2001. The contribution of stone cover to biological activity in the Negev desert, Israel. *Land Degradation & Development* 12: 35–43.

Magier, J., and I. Ravina. 1984. Rock fragments and soil depth as factors in land evaluation of Terra rossa, in J. D. Nichols, P. L. Brown, and W. J. Grant, eds., *Erosion and productivity of soil containing rock fragments*. Soil Science Society of America (SSSA) Special Publication Number 13, 13–30, Madison, Wisconsin, USA.

Mandal, U. K., K. V. Rao, P. K. Mishra, K. P. R. Vittal, K. L. Sharma, B. Narsimlu, and K. Venkanna. 2005. Soil infiltration, runoff and sediment yield from a shallow soil with varied stone cover and intensity of rain. *European Journal of Soil Science* 56(4): 435–443.

Mehuys, G. R., L. H. Stolzy, J. Letey, and L. V. Weeks. 1975. Effects of stones on the hydraulic conductivity of relatively dry desert soils. *Soil Science Society of America Proceedings* 39: 37–42.

Nyssen, J., M. Haile, J. Poesen, J. Deckers, and J. Moeyersons. 2001. Removal of rock fragments and its effect on soil loss and crop yield, Tigray, Ethiopia. *Soil Use and Management* 17: 179–187.

Pérez, F. L. 1998. Conservation of soil moisture by different stone covers on alpine talus slopes Lassen, California. *Catena* 33: 155–177.

Poesen, J., E. De Luna, A. Franca, J. Nachtergaele, and G. Govers. 1999. Concentrated flow erosion rates as affected by rock fragment cover and initial soil moisture content. *Catena* 36: 315–329.

Saini, G. R., and W. J. Grant. 1980. Long-term effects of intensive cultivation on soil quality in the potato-growing areas of New Brunswick (Canada) and Maine (USA). *Canadian Journal of Soil Science* 60: 431–428.

van Wesemael, B., J. Poesen, and T. de Figueiredo. 1995. Effects of rock fragments on physical degradation of cultivated soils by rainfall. *Soil & Tillage Research* 33: 229–250.

Zhongjie, S., Y. Wang, P. Yu, L. Xu, W. Xiong, and H. Guo. 2008. Effect of rock fragments on the percolation and evaporation of forest soil in Liupan Mountains, China. *Acta Ecologica Sinica* 28(12): 6090–6098.

Zhou, B., S. Ming'an, and S. Hongbo. 2009. Effects of rock fragments on water movement and solute transport in a Loess Plateau soil. C. R. *Geoscience* 341: 462–472.