Turkish Journal of Agriculture and Forestry

Volume 23 | Number 6 Article 15

1-1-1999

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Tr. J. of Agriculture and Forestry
23 (1999) 659-665

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Received: 05.08.1998

Abstract: Hydraulic properties of soils and soil erodibility are expected to vary after rainfall because of the impact energy of raindrops. Resistance both to rainfall detachment and to runoff detachment might differ after rainfall, and temporal changes in soil erodibility take place. The main objective of this study was to evaluate the effects of subsequent rainfalls (namely the 2nd rainfall) on runoff and erosion, especially sheet and splash erosion. Forty rainfall events in laboratory condition were conducted on Kule clay loam and Musaağılı silt loam. Two consecutive rainfalls at an intensity of 60 mm h^{-1} were applied to soil trays at a slope of 30%, and soil surface was allowed to dry between events. Statistical analyses showed the main effects of rainfall sequence and soil type, as well as their interaction significantly changed the runoff, percolation, runoff sediment, and splash amounts from two soils. The runoff sediment was higher in the subsequent rainfall than those of the 1st rainfall. This was related to the decreased hydraulic conductivity and the following increased runoff. However, the splash was higher in the 1st rainfall. Decrease in splash amount was attributed to the increase in runoff depth in the 2nd rainfall and to the surface seal formation after the 1st rainfall.

Yapay Ardıl Yağışların Yüzey Akış ve Erozyon Üzerine Etkisi

Özet: Yağmur damlası vuruş enerjisi ile, toprakların su geçirgenliği ve erozyona duyarlılıklarının değişebileceği beklenmektedir. Hem yağış hem de yüzey akışların parçalama etkisine karşı olan toprak direnci farklılaşır ve toprak erozyon duyarlılıklarında geçici değişimler oluşur. Bu çalışmanın ana amacı ardıl yağışlar (ikinci yağışlar)'ın yüzey akış ve erozyon, özellikle yüzey ve sıçrama erozyonu üzerine etkilerini değerlendirmektir. Laboratuvar koşullarında, Kule ve Musaağılı toprak serilerinde kırk adet yapay yağmurlama gerçekleştirilmiştir. Ardıl yağışlar 60 mm $saat^{-1}$ intensiteli olarak %30 eğimle yerleştirilen toprak tavalarına uygulanmış ve iki yağmurlama arasında toprak yüzeyi kurumaya bırakılmıştır. İstatiksel analizler ardıl yağışlar, toprak tipi ve ikisi arasındaki etkileşimin, yüzey akış, sızma, yüzey akış sedimenti ve sıçrama miktarlarını önemli ölçüde etkilediğini göstermiştir. İkinci yağışlar yüzey akış sedimentleri, 1. yağışlara oranla daha fazla olmuştur. Sediment artışı, azalan su geçirgenliği ve artan yüzey akışlarla ilişkilendirilmiştir. Buna karşın, 2. Yağışlar sıçrayan tanecik miktarlarının, 1. yağışlara oranla daha az olduğu gözlenmiştir. Bu ise, 2. yağışlardaki yüzey akış kalınlığındaki artış ve 1. yağışlar sonrasındaki kabuk oluşumu ile açıklanmıştır.

Introduction

Hydraulic properties of soils change after rainfall with the formation of crust or seal on the soil surface, which significantly influences infiltration, runoff, and erosion (1, 2, 3, 4, 5). In the semiarid and arid regions, the problem of sealing appears to be the common and dynamic process that controls the infiltration of rain water into bare soils (6). The rate of increase in runoff and erosion may depend on the extent and predominant process of soil crusting (7, 8, 9, 10).

Surface sealing has a dramatic effect on the hydraulic properties of a soil. Jennings et al. (11) showed clearly that there was a dramatic reduction in the rate of hydraulic conductivity change just after the fine aggregates had received four minutes of 55 mm h^{-1} intensity rain. Several mechanisms, such as further compaction and consolidation due to drop impact and wetting-drying cycles, progressive breakdown of aggregates due to drop impact and slaking during wetting, and clogging of small pores due to translocation of fine particles within the soil profile, might cause the decline in the infiltration rate (12).

Soil erodibility might also exhibit a variation during or after rainfall. Soil detachability is inversely related to soil strength; strength is generally low at higher water contents and high at low water contents (13, 14). Mutchler

* This research is sponsored by Ankara University Research Fund (Project number: 92-25-00-09) and Turkish Scientific and Technical Research Council (Project number: TOAG-906).

Table 1. Some physical and chemical properties of two soils.

	Kule clay loam			Musaağılı silt loam		
Mechanical composition %	Clay	Silt	Sand	Clay	Silt	Sand
	32.84	35.23	31.93	13.46	63.29	23.25
Aggregate stability%		24.03			14.39	
Dry bulk density g cm^{-3}		1.32			1.25	
Organic matter%		2.07			0.46	
$CaCO_3$%		20.93			21.94	
pH		7.81			8.04	
ECM mmhos cm^{-1}		0.6			0.6	
CEC me $(100\ g)^{-1}$		53.4			63.6	
Exchangeable cations	Na^+	K^+	Ca^{2+}+Mg^{2+}	Na^+	K^+	Ca^{2+}+Mg^{2+}
Me $(100\ g)^{-1}$	0.35	1.02	51.94	0.37	0.90	62.33

and Carter (15) examined temporal changes in soil erodibility from natural rainfall erosion plots. Differences in soil erodibility factors would be explained by the variation in (a) infiltration characteristics and resistance to surface sealing, (b) resistance to rainfall detachment, (c) resistance to runoff detachment, and (d) detached particle size and density (16).

Owing to the variations either in the hydraulic properties of soils or in the soil erodibility, the alteration in soil loss is as well anticipated temporally. Erosion rates decrease with time due to densification or consolidation and loss of readily transportable sediments (17). Densification and increased soil shear strength or cohesion with surface sealing decrease soil detachment (18). Between erosion events, soil densifies due to time and drying stresses, causing increased stability (19). Nevertheless, there are recent experimental evidences that processes occurring with drying-wetting cycles may indeed increase soil erodibility (20; 21). As surface seal forms, splash erosion decreases with time (22), while surface erosion may increase with time. Formation of incipient rills increases sediment yield, depending upon the slope (20), soil type (23), and duration of the rain (24). Shrinking of clays upon drying weakens the cohesive forces within the crust, rendering it susceptible to pitting by raindrops (25) and new aggregates with possibly lower stability are formed (26). The depth of flow also affects the erosion rates. Splash was greatest where the thickness of overland flow was shallowest (27, 28).

The aim of this laboratory rainfall simulation study is to determine the effects of subsequent rainfall on runoff and soil erosion.

Materials and Methods

The drop-former type rainfall simulator described in details by Gabriels and De Boodt (29) was used. Rainfall simulations were conducted on two agricultural soils. Two soils were A horizons of Kule clay loam and Musaağılı silt loam, which were taken from the Kenan Evren Research and Application Farm of Ankara University Agricultural Faculty. Some physical and chemical properties of these soils are presented in Table 1.

The soil that was air-dried, and sieved through 8 mm was packed loosely in 30 by 30 cm perforated trays, at 5 cm deep. The trays were placed under the rainfall simulator at a slope of 30% and subjected to the rainfalls with a constant intensity of 60 mm h^{-1} for two hour duration.

After the 1st rainfall on the initially air-dried soil, every soil tray was exposed to the 2nd rainfall. The soil was left for drying at approximately 35 °C in a green-

Table 2. Runoff, percolation, runoff sediments, and splash measurements from two soils in the consecutive rainfalls.

Kule clay loam				Musaağılı silt loam			
Runoff (ml)	Percolation (ml)	Runoff sediment (g)	Splash (g)	Runoff (ml)	Percolation (ml)	Runoff sediment (g)	Splash (g)
1nd rainfall							
3980	1880	78.90	451.22	3620	3190	128.30	459.40
3620	1960	84.71	429.29	3845	3905	132.08	486.24
3290	1890	72.97	435.78	3890	3552	132.75	444.51
3820	1850	68.84	410.31	3750	3725	147.79	467.12
3690	1865	72.45	466.39	4070	3200	136.70	443.98
3775	1635	73.96	402.72	3900	3635	136.56	484.32
3500	1885	75.39	450.97	3615	3575	130.10	476.61
3305	1775	71.61	421.06	3615	3740	136.16	512.92
3785	1780	69.26	421.97	3610	3470	125.52	430.56
3275	1705	81.91	401.02	3835	3755	149.92	470.70
2nd rainfall							
5710	1230	142.84	372.73	5655	2605	155.08	305.87
5520	1345	141.37	387.86	4920	3105	157.12	288.85
5900	1345	147.23	355.24	6080	2780	145.75	292.05
5330	1385	128.27	359.09	4750	3135	152.26	275.21
5890	1290	147.16	340.06	5750	2300	155.48	263.11
5175	1400	125.04	380.45	5005	2885	165.36	251.15
5930	1335	161.86	361.27	5660	2655	162.86	338.11
5060	1365	136.47	382.61	5110	3240	157.42	297.63
5785	1395	150.89	338.22	5485	2890	159.12	329.23
5590	1435	141.09	382.67	4805	3340	158.17	264.32

house for one week between subsequent rainfall. The surface was dry and cracking (shrinking) was evident after the drying. Total number of rainfall simulations were forty (20 rainfall events for each soil, 10 for the 1st rainfall and 10 for the subsequent 2nd rainfall). All soil carried from surface runoff during each rainfall was trapped in the sample holder and the soil splashed was collected in splash board positioned on the side of the tray, later dried and weighted. During each rainfall event the volume of water percolating and running over were measured.

Results and Discussions

Table 2 shows runoff, percolation, runoff sediment, and splash measurements from two soils in the consecutive rainfalls.

Changes in runoff, percolation, runoff sediment, and splash amount as corresponding means are given in Table 3. Factorial test results showed that the main effect of subsequent rainfall was statistically significant at $P = 0.001$ level for runoff, percolation, runoff sediment, and splash. The main effect of different soils was also signifi-

Table 3. Means on replicates of runoff, percolation, runoff sediment, and splash in two consecutive rainfalls.

Soil	Rainfall	Runoff (ml)	Percolation (ml)	Runoff sediment (g)	Splash (g)
Kule	1st	3604.0	1822.5	75.0	429.1
	2nd	5589.0	1352.5	142.2	366.0
Musaağılı	1st	3775.0	3574.7	135.6	467.6
	2nd	5322.0	2893.5	156.9	290.6

Table 4. Results of two-way factorial tests of runoff, percolation, runoff sediment, and splash as dependent variables.

	Dependent variable			
Source	Runoff	Percolation	Runoff sediment	Splash
Soil	NS	***	***	*
Rainfall	***	***	***	***
Soil x rainfall	*	NS	***	***

* and *** Significant at P = 0.05 and 0.001, respectively; NS is not significant at 0.05 level.

cant for percolation, runoff, and splash at P = 0.001, 0.001, and 0.05, respectively. However, neither the main effect of the soil type for runoff nor the effect of the interaction between the subsequent rainfall and the soil type for percolation was found to be significant at the level of P = 0.05 (Table 4).

Runoff and percolation

Figure 1 displays the mean values of the runoff measurements for the consecutive rainfalls (the values are given in Table 3). The runoff amount explicitly increased in the 2nd rainfalls in comparison to those of the 1st rainfalls. The same trend of increase in runoff and similar amounts from the 1st and the 2nd rainfalls for two soils were observed. Differences in runoff were very slight for the type of soil in terms of both the 1st and the 2nd rainfalls. This is further demonstrated by the factorial test results shown in Table 4. This implies that the differences of runoff in two rainfalls were not influenced by the soil type.

The increase of runoff in the 2nd rainfalls is related to the decline in the infiltration rate due to physical disintegration of soil aggregates and their compaction caused by the impact action of raindrops at the soil surface during the 1st rainfalls, resulting in surface sealing and crusting (30, 31, and 32) upon drying. This was obvious at the end of the one-week drying period. It could be concluded

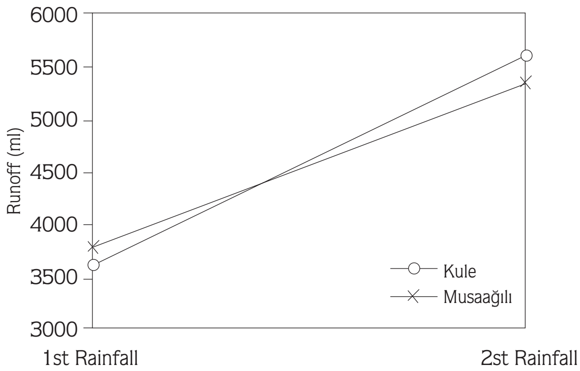

Figure 1. Mean runoff for two consecutive rainfalls with soil surface dried between events.

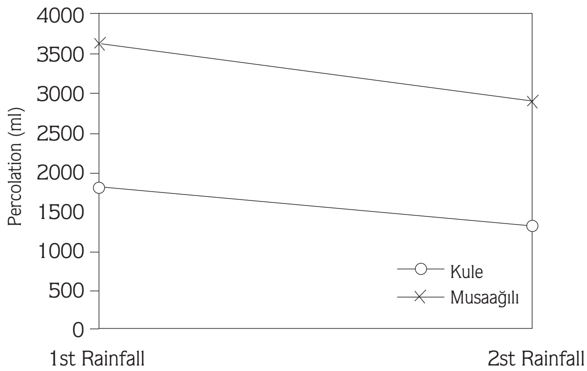

Figure 2. Mean percolation for two consecutive rainfalls with soil surface dried between events.

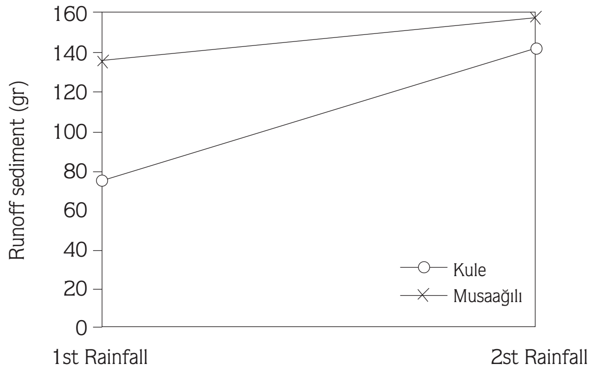

Figure 3. Mean runoff sediment for two consecutive rainfalls with soil surface dried between events.

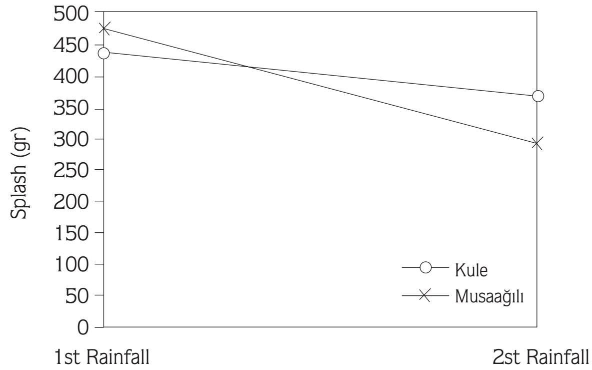

Figure 4. Mean splash for two consecutive rainfalls with soil surface dried between events.

that crust formation and the compaction on the surface caused the reduction in hydraulic conductivity, leading to the increased runoff in the subsequent rainfalls (11, 33).

Decline in the hydraulic conductivity was evaluated by the percolation measurements (Figure 2). Decrease in percolation in the 2nd rainfalls is marked. However, the amount measured was significantly different for two soils. As twice as more percolation occurred in the rainfalls on Musaağılı silt loam than those on Kule clay loam. The soil type and the subsequent rainfall as main factors played significant role in the changes of the percolation. The parallelism of the lines in Figure 2 shows the lack of the significant interaction between rainfall sequence and soil type (Table 4).

Sheet erosion

The runoff sediment was higher in the 2nd rainfalls than in the 1st rainfalls (Figure 3). A significant increase in the runoff sediments in the 2nd rainfalls might be explained by the decline in the hydraulic conductivity and the resulting increased runoff (7, 8, 9, 10), and more importantly depending on the soil type (23), by the differences existed in the soil erodibility (15, 16).

Difference in the sediment lost by runoff between the 1st and the 2nd rainfalls for Kule clay loam was more pronounced than that of Musaağılı silt loam. The lost in the 2nd rainfalls was as twice as higher than that of the 1st rainfalls in Kule clay loam. This clearly showed us that the soil erodibility of Kule clay loam significantly changed after the 1st rainfalls. In the 2nd rainfalls, the soil considerably displayed the reduced resistance to the rainfall and runoff detachment, resulting in higher susceptibility to the sheet erosion (20, 21, 22, 24, 25, 26).

Although the sediment loss by runoff from Musaağılı silt loam occurred in larger amount compared to that of Kule clay loam, the differences in the runoff sediments between the 1st and the 2nd rainfalls were not as notable as Kule clay loam. This result was related to the fact that Musaağılı silt loam is more erodible than Kule clay loam. During the 1st rainfalls, Musaağılı silt loam eroded more easily than Kule clay loam, leading to larger amount of runoff sediment. In the 2nd rainfalls, in spite of increased runoff, since readily transportable sediments were already lost in the 1st rainfalls (17), the amount lost by runoff was controlled by the available particles to transport and did not increase as much as those from Kule clay loam.

Splash erosion

Figure 4 represents that the splash was higher in the 1st rainfalls than in the 2nd rainfalls for either soil types. Decrease in the splash amount in the 2nd rainfalls was attributed to the increase in the runoff depth (27, 28) and to the formation of surface seal (22). These prevented soils from splash erosion in the 2nd rainfalls. Either thicker runoff layer diminished the beating action of raindrops, or increased soil shear strength or cohesion with surface sealing decreased the soil detachment.

The comparison of slopes of the lines shown in Figure 4 explains that difference in the splash between the 1st and the 2nd rainfalls was more notable in the Musaağılı silt loam than in the Kule clay loam. The effect of soil type on splash is additionally shown by the factorial test result (Table 4).

Conclusions

This study investigated the effect of subsequent rainfalls on the runoff and the erosion. Poorer hydraulic properties were observed in 2nd rainfalls, resulting in larger amount of runoff sediment. However, the splash amount was less due to the increased runoff depth and to the surface seal formation after the previous rainfall upon drying.

The effect of subsequent rainfalls was significantly interacted with the soil type. The amount lost by the runoff and splash varied depending on the soil type and their different soil erodibility.

The results showed that the erodibility of soils significantly changes after the rainfall, leaving the soils more prone to the sheet erosion. The rate of transport was, however, limited to the amount of sediments available. In conclusion, temporal changes in the soil hydraulic properties and erodibility controlled the soil erosion rates in the subsequent rainfalls.

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