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Post-harvest evaluation of water retention and transmission properties of soils subjected to residue burning

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Abstract: *Residue burning in semi-arid regions is considered a soil management practice given its time saving, pleasurable tillage, and easy seedbed preparation. Therefore, it is the focus of a great deal of research studies for surface runoff generation, flood susceptibility, and erosion hazard. The objectives of this study were to i) comparewater retention and transmission properties of completely-burned, moderately-burned, and unburned soil conditions and ii) simulatethe responses of soil conditions to water flow in the profile.The persistence of fire-induced impacts were studied in 3 hectare land for both burned and unburned conditions for two years. The air-entry value was significantly higher for unburned soils (P=0.045) than the one for completely burned soils and somewhat higher than moderately burned soils (P=0.054).Water transmission parameter Ksat was significantly higher in the moderately burned soils than the Ksat values of the rest of the treatments (P=0.001).The burned treatments had the highest water fluxes, hydraulic conductivities and the lowest retentive capacities comparing to the unburned treatments. Residue burning significantly changed soil structure and flow regime in the burned treatments. To conclude, residue burning is not as advantageous as retaining residue in the Amik plain soils.*
Keywords: *Burned soil, hydraulic conductivity, subsurface flow, water retention, water transmission*

I. Introduction

Residue burning in arid and semi-arid agroecosystems can change response of soils to water cycle by changing both soil physical and hydrological properties. After an intense fire, the most significant resultant effects were reported that all organic matter in the surface soil is combusted, ash stains and remnants occupy soil surface and void spaces, and an alteration of soil structure and charring of soil organic matter commonly occurred[1]. Ash and small soil particles can clog the soil pores[2],[3] to decrease infiltration rate and hydraulic conductivity[4]. Combustion of organic matter in coarse textured soils rather than finer textured soil trigger the formation of water repellent substances, thereby reducing infiltration and hydraulic conductivity of the soil [5],[6],[7],[8].Intense fire is reported to alter soil structure and texture [9], to increase soil bulk density[10], to decrease bulk density[11], and to reduce soil porosity and water holding capacity [12], and to increase soil aeration [13]. Kennard and Gholz[14] observed initially the lowest soil strength for the high-intensity burning treatment which, then,was sharplyraised during the first year. Similarly, infiltration rates were significantly low and bulk density values were significantly high after high-intensity fires coupling with organic matter losses and altered soil structure.This lowered soil water holding capacity and increased surface runoff.

Above and belowground processes were widely found fire intensity-dependent[15],[16]. Burned soils became highly water-repellent, lowered soil infiltration rates and increasedsusceptibility to erosion [17],[18].The time-extent of water-repellency was found highly dependent on the organic compounds, intensity, and duration of the fire[19]. Hydraulic properties of burned soils need quantifying for better soil management planning and sustainability of the soil functions and productivity potential. The burned soils gain different qualities from the unburned soils. This causes a concomitant input management issues specific to the burned soils. As a result, modeling water retention and transport processes in these soils can provide some range of threshold values of soil hydrological processes to conserve and monitor in terms of soil sustainability.

The objectives of this study were to i) compare water retention and transmission properties of completely-burned, moderately-burned, and unburned soil conditions and ii) evaluate the responses of soil conditions to water flow in the Amik Plain, Turkey.

II. Materials And Methods

1.2. Study Site Details

The study field is about 2.5 hectare (ha) area, cropped to wheat (Triticumaestivum). The research site (*36°.17ꞌ N, 36°.11ꞌ E*) is located near the university campus area, BüyükDalyan, Hatay, Turkey.The harvest was on May 26, 2013. A typical soil profile in the site is clay loam and clay and soil profile depth ranges from 90 to 162 cm in the field. The landform is flat with the slope <2%. The Plains soils predominantly consist of clayey texture because of the fluvially transported alluvial calcareous parent material accumulating in geologically young depressions in the Quaternary time [20]. Topsoil has brown and dark brown colors (according to Munsell color chart), while subsoil layers are generally pale brown, or greyish in the study area. The soils are very low (<1 %) in lime content around Antakya-Kırıkhan Highway to the north in the region, whereas the rest of the Plains have lime content above 5 % [21],[20],[22]).The soils of research field are classified by Kılıç et al. [20] as poorly and somewhat poorly drained TypicHaploxerert.

1.3. Climatic Descriptions of the Study Field

The climate of the study is semi-arid with mean annual rainfall of 1124 mm and evaporation of 1877 mm based on the last50 years in the region. The mean annual temperature is 18.1 ^{o}C.Percentage distribution of the rains in the region was registered as 35 % in winter, 29 % in spring, 12 % in summer, and 24 % in autumn[23]. The most rain falls in winter while the summer is hot and dry. The spring and fall seasons are less wet than winter levels in the Plain soils. The wetter fall season starts by October[24]. The Amik Plain soils were drained through open drainage channel systems by DSI, the Turkish State Hydraulic Works[23]. However, soil salinity poses a threat to water ponding areas from poor to moderate levels.

1.4. Soil Samples

The sampling design was a grid system and approximately 20 m x 20 m grids were used to collect the disturbed and undisturbed soil samples from 0-10 cm thickness of surface soil.In the burned field, 36 undisturbed and 36 disturbed samples were collected with two replica. The same amount of sampling was repeated in the study site for unburned conditions in the year after. The disturbed samples were run for soil electrical conductivity, soil texture, pH, soil organic matter content, and lime content analyses while the undisturbed samples were used for soil hydrologic properties. Soil particle size analysis was performed by hydrometer method[25]. Undisturbed soil core samples were collected only for soil saturated hydraulic conductivity (Ksat) tests and the Ksat was measured through constant head Darcy permeameter in the University's soil physics and drainage research laboratory[26]. Soil bulk density, porosity and pore size classes were all determined from the intact core samples.

1.5. Crop Rotations andBurning Residue in the Field

The cropping pattern in the area includes winter-wheat (TriticumaestivumL.) and cotton(Gossypiumhirsutum L.) for the two cycle cropping period in rotation. Two cropping periods existbetween middle of spring and late autumn seasons in the Amik Plain soils. Since floodingis common in early spring and late fall seasons in the whole Plain, crop rotation is a very commonsoil and water conservation management practice in the region. The study site was cropped to winter wheat and harvest was performed on May 26, 2014 and 2015. The field was burned for high intensity fire (no remnants of postharvest residue in the field) and most of the field was under black ash and cracks and about 1 cm thickness of surface soil was colored black after burning. The field was divided approximately in equal three 1 ha plots. The soil sampling was conducted on one transect in the same direction in each parcel. The samples were taken from 0 to 10 cm depth over transects in the field. One parcel was completely burned, indicating no crop residue was describable after burning, another one was moderately burned, indicating that some parts of the residue after burning was still distinguished, and the other one was kept untouched for control treatment in the experiment.Three years after the experiment in the field, the field was expected to gain its resilience from the poor quality of its hydrological and physical properties owing to residue burning. As a result, a total of brand new 64 undisturbed core samples were collected in 2016 from almost the same spots of undisturbed samples back to date to compare water retention and transmission properties of the same soil's burned and unburned conditions.

1.6. HYDRUS-1DModel

2.6.1 Water Release Characteristic Curves

Undisturbed soil samples were collected by soil cores of 5 cm height x 5 cm diameter from the same depth in the surface soil with two replica. Soil saturated hydraulic conductivity (Ks) was measured for each core sample according to[26]. Bulk density, porosity, porosity, water retention curves (WRC), and soil hydraulic parameters were determined on the undisturbed soil core samples in the laboratory. These hydraulic retention parameters were optimized by RETC model [27]. Starting from saturation water content, water discharges during successive matric potential decreases was measured on both tension table and porous pressure plate successively in at 0, -10, -15, -33, and -1500 kPa. The van Genuchten[28] and Mualem[29] equation was fitted to the data points.

2.6.2. Model Description

Vertical flow of water was simulated according to atmospheric boundary condition with a constant head zero and free drainage as the upper and lower boundary conditions in the flow domain, respectively. The Richards equation for saturated and unsaturated soil conditions was numerically solved in HYDRUS-1D.

The Richards equation as follows:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[K(\theta)\left(\frac{\partial h}{\partial z}+1\right)\right] \quad (eq. 1)$$

Where h is the water pressure head (cm), θ is the volumetric water content (cm^3/cm^3), t is the time (day), z is the measurement depth of soil (cm), $K(\theta)$ is unsaturated hydraulic conductivity function. No root water uptake was considered in the Richards equation. The model inputs the observed and calculated retention model parameters and then, simulates for the optimal hydraulic model parameters with the lowest mean squared error term and explained variance of R^2.
The van Genuchten[28] model is given as the following.

$$\theta(h) = \begin{cases} \theta_r + \dfrac{\theta_s - \theta_r}{[1 + (\alpha|h_m|)^n]^m} & h \leq 0 \\ \theta_s & h \geq 0 \end{cases} \quad (eq. 2)$$

$$K(h) = K_s S_e^l [1 - \left(1 - S_e^{\frac{1}{m}}\right)^m]^2 \quad (eq. 3)$$

$$m = 1 - \frac{1}{n} \qquad n > 1 \quad (eq. 4)$$

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} \quad (eq. 5)$$

Where, $\theta(h)$ is water retention curve function, θ_r the residual volumetric water content, θ_s saturated volumetric water content, h_m is the matric head (cm). The parameter α is air-entry parameter and m and n are retention curve fitting parameters. $K(h)$ is unsaturated hydraulic conductivity function computed from the water retention curve. K_s (referred to as Ksat) is saturated hydraulic conductivity. S_e is the reduced water content and l is the pore connectivity parameter with an estimated value of 0.5[29].The residual water content, θ_r, is the water content value blow which water no longer be removed from the soil by plants and it is equal to wilting pointwater content of sandy soils. The hydraulic parameters of soil, θ_r, θ_s, α, and n, were initially determined from the measured soil water retention data according to[28] computational steps (θ-h relationship).

1.7. Statistical Analyses

The data were analyzed using One-Way Analysis of Variance (ANOVA). ANOVA produced one-way analysis of variance for a quantitative dependent variable by a single factor (independent) variable. ANOVA tested the hypothesis that several means were equal. A post hoc test in ANONVA was used to compare means at 95% confidence interval and alpha of 0.05. Within- and between groups variances were determined in ANOVA. Tukey's honesty significant difference test (HSD) and the least significant difference (LSD, P<0.05) values were calculated from the residuals of the analysis of variance. The mean of a single variable was also compared to a hypothesis test value zero through one-sample *t*-test where the means were not equal to each other in ANOVA test. Burned and unburned soil properties were compared.IBM SPSS Statistics 22.0 statistical package was used to perform the ANOVA and other procedures.

III. Results And Discussion

3.1. Water Retention Curves and Soil Hydraulic Model

Table 1.Bulk density ρ_b, saturated hydraulic conductivity K_{sat}, and optimized retention parameters for three soil conditions

Soil Conditions	ρ_b, g.cm^{-3}	θ_r, cm^3.cm^{-3}	θ_s, cm^3.cm^{-3}	α, cm^{-1}	n	K_{sat}, cmd^{-1}	R^2
Burned	1,66	0,121	0,438	0,0035	2,176	14,3	0.919
	1,42	0,136	0,499	0,0046	2,302	27,5	0.972
	1,1	0,147	0,498	0,0046	2,401	105,3	0.964
Moderately Burned	1,01	0,148	0,493	0,0045	2,41	466,6	0.965
	1,012	0,089	0,506	0,0052	1,988	349,4	0.995
	1,11	0,005	0,517	0,0076	1,471	137,4	0.970
Unburned	1,41	0,101	0,499	0,0052	1,89	24,5	0.983
	1,16	0,156	0,523	0,0083	1,775	144,3	0.981
	1,28	0,112	0,515	0,0064	1,829	143,6	0.981

Hydraulic model parameters required by HYDRUS-1D are listed for three intact sol cores for each treatment in Table 1.In general, soil bulk density decreased in the order of unburned treatments > burned treatments > moderately burned treatments, which was not significant change of means (ANOVA, P=0.061).

The soils are loamy sands or sandy loams in texture and bulk densities were fairly low. Residual water content ($\theta_{r,}$) did not show any significant differences between the means of three levels of burning in field (Akis, 2016[30]). The tendency of decreasing values for treatments was in the order completely burned > unburned > moderately burned. The other hydraulic model parameters ($\theta_{s,,}$ α, and n) were not significant at 5% level, but p-value between 0.054 and 0.082. Soil saturated hydraulic conductivity significantly changed after residue burning (ANOVA, P=0.001).The simulated highest Ksat was recorded in the moderately burned treatments while the simulated lowest Ksat was recorded in the completely burned treatments (Table 1). This situation is also presented in Figure 1 in the sense that water transmission function is the highest for the moderately burned soil treatment simulations than the other treatments. This could be a result of incomplete burning of wheat stubbles and unburned roots in the surface soil layer and ashy material that accumulated in well-graded and aggregated soil structure in the field in comparison to completely burned soil treatments. The high values of coefficient of determination (r^2) indicates the optimized hydraulic model parameters and the fitted model highly accurate to describe water retention processes for the treatments (Table 1).

Leij et al.[31]used geometric means of triplicate intact soil cores to evaluate the effects of three different aqueous solutions on water retention parameters of three different soil textures. The average of triplicate core values in Table 1 was used to develop soil hydraulic model for particular soil water pressure heads (Fig. 1). The fact that optimized soil hydraulic parameters are strictly related to soil texture [32] and there is a need to produce similar set of water content values at particular pressure heads applied requires preferring a geometric average of these triplicate cores for each parameter that was used in simulations Geometric means of these triplicate core values optimized in HYDRUS-1D program [33] and retention curves were developed based on these values. Although ANOVA test compared equal means of hydraulic model parameters, except Ksat, no significant difference between the means were evident[30]. Therefore, one-sample t-test was used to uncover if any means of each hydraulic parameterdiffered from zero (the test value). This test revealed that, except θ_r (P=0.191), all model parameters were significant in their mean difference from zero (the null hypothesis value). This means each sample value differs from zero significantly and these values of hydraulic model parameters can serve a threshold value for the treatments in the evaluation of water flow processes in these soils. Air-entry values, referred to h_e[31] and is the pressure head value to start the largest pore's drainage of water, decreased in ascending order -236, -173, and -150 cm for completely burned, moderately burned, and unburned treatments, respectively. As a result the lowest air-entry value was recorded in the completely burned treatments and the lowest one was observed in the unburned treatments, meaning the burned soil treatments gained some water repellent properties and lost some of their retention properties. Therefore, less amount of moisture was retained in the completely burned treatments in comparison to unburned treatments (Fig. 1). Similarly hydraulic conductivity function for completely burned treatments transmitted more water than the unburned soil's function (Fig. 1).Residue burning resulted in structural change in soil. Because the unburned soils have lower conductivity values (i.e., water contents for a particular pressure heads) above θ=0.27, the other treatments yielded significantly high conductivity values ≤ 1cm.h^{-1} (Figure 1). The moderately burned soils had characteristically the highest conductivity values at particular water contents because of its significantly and characteristically low bulk density values.

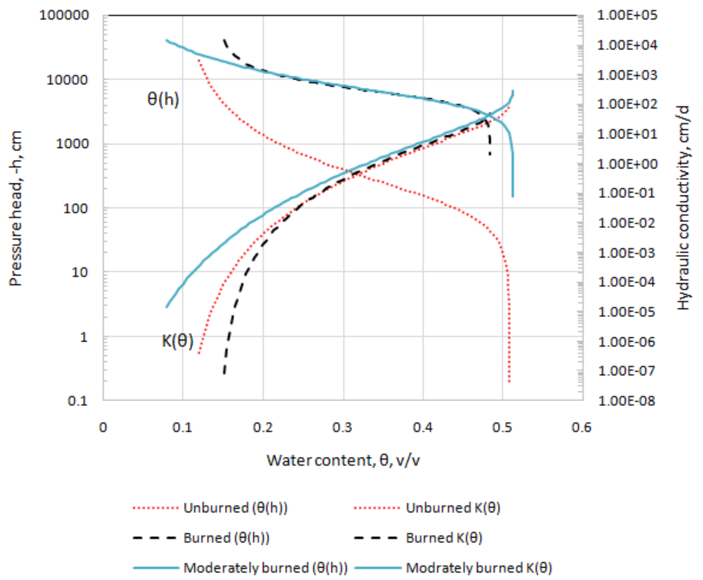

Fig. 1: Water retention *h(θ)* and (transmission) hydraulic conductivity *K(θ)* curves for the treatments

1.7.1. Simulations of water retention and flow properties

Vertical water retention and transport was simulated using HYDRUS-1D code [33]. Geometric averages of triplicate soil cores were the inputs to the HYDRUS-1D model. Atmospheric boundary conditions on the surface soil with a prescribed pressure head of zero cm, a measured 16-day continuous rainfall with variable intensities and daily evapotranspiriations (ET), and critical pressure head value of -10000 cm was applied to model water retention and transport in three 100-cm depths of soil profiles with different treatments. The lower boundary condition was defined as free drainage in the model code. Initial conditions for the treatments were chosen to be pressure head conditions for the entire soil profile. A matric head of -280 cm was chosen between 10 kPa and 33 kPa negative pressures, which was the closest value to the real field conditions so that the model simulations converged. Soil surface was saturated by applying zero tension through atmospheric boundary conditions on the top of soil with 1.5 cm water head. The measured rainfall guaranteed this amount of water ponding for 16 days in the research period. Figure 2 displays that water flux is higher in burned treatments than unburned treatments. This is because water contents are much smaller in the burned treatments than the unburned treatments (Fig. 3). On the other hand, water retention was the highest for unburned treatments and the lowest for the completely burned treatments (Fig. 3). High water retention property of unburned soil yielded lower fluxes than the burned soil treatments. The unburned treatments produced higher fluxes than completely burned treatments when the wetting front reached at around 50 cm depth of the soil profile. High fluxes, high conductivity values, and low water retention for the moderately burned treatments resulted in high cumulative infiltration of water compared to unburned treatment soils. As a result, low water retention capacity for burned treatments in comparison to unburned treatments reduced the sorption of ponding water on the surface soil and thus high Ksat caused higher water fluxes in the soil profile (Fig. 4). Leij et al.[31] reported similar results for soil Ksat and flux behaviors in their constant head boundary analysis.

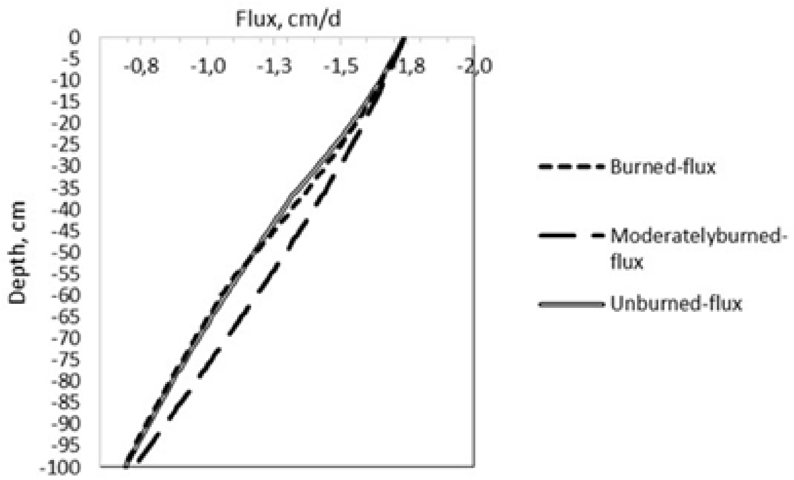

Fig. 2: Simulated water fluxes for the three levels of the treatments

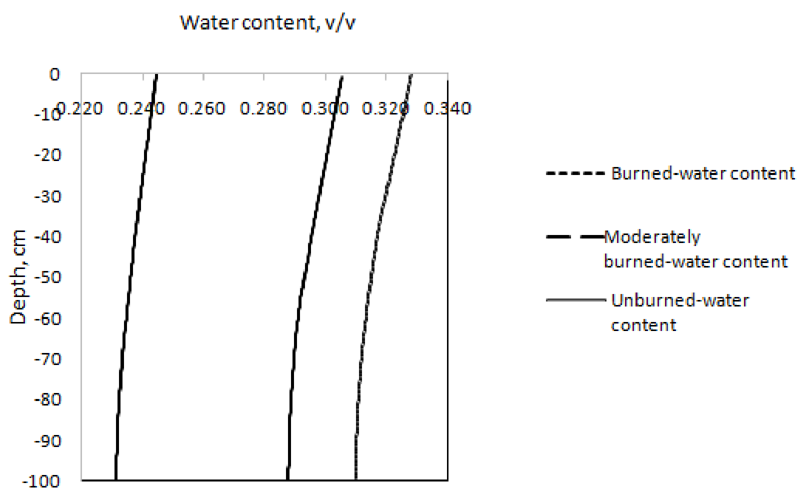

Fig.3: Simulated water contents for the treatmetns

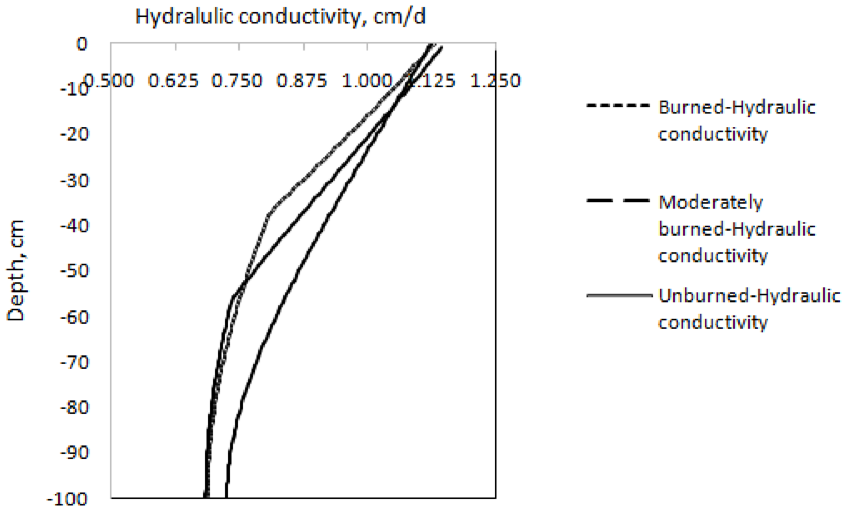

Fig. 4: Simulated hydraulic conductivities for the treatments

IV. Conclusions

Water retention and transmission properties under the effect of residue burning with different intensities were compared, simulated, and evaluated. Burning residues resulted in significant changes in soil structure and thus water retention and transport processes. Water flux and hydraulic conductivity in the burned treatments were higher than unburned soils. This resulted in high infiltration rates and cumulative infiltration depths in burned treatments. Although the burned treatments did not have high water contents all over the soil profile, their water retention capacity was low resulting in less liquid moisture to retain in the soil profile. On the other hand, the unburned treatments released lowest amount of fluxes in the soil profile and retained significantly high amount of available water due to their high sorption capacities. After 50-cm depth of the profile, the completely burned soil gained more retentive properties over the unburned soils. This was a result of the residue burning that increased smaller pores and dead pores rather than storage pores. This also shows that residue burning strongly chanced flow regime and soil hydraulic conductivity by changing soil structure. Therefore, soil water regime should be prevented from adverse effects of residue burning by developing new soil and water conservation measures to use soil for long years to com.

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