The Effect of Fallow Tillage Management on Aeolian Soil Losses in Semiarid Central Anatolia, Turkey

Amin Nouri,* Feras Youssef, Mustafa Basaran, Jaehoon Lee, Arnold M. Saxton, and Gunay Erpul

ABSTRACT

In semiarid Central Anatolia Turkey, winter wheat (*Triticum aestivum L.*) planted under a conservation tillage system undergoes a no-till fallow phase to reduce aeolian soil losses by maintaining the natural plant cover. This research was conducted to investigate the effectiveness of natural vegetation cover in relation to tillage-induced soil surface properties in reducing the wind erosion during the fallow periods. Climatic parameters at experimental plots subjected to no fallow tillage (NFT) and conventional fallow tillage (CFT) (disk) managements were measured and friction velocity ($u_*$) and aerodynamic roughness ($z_0$) over four high wind events (wind velocities $>5.7$ m s$^{-1}$ at 2 m high) were determined. Sediment fluxes at each management were measured using 20 sampling posts each holding five vertically placed sediment traps. Spatial dynamics of soil fluxes were related to the soil surface properties and the vegetation characteristics (coverage and configuration). Spatial variations in upwind vegetation characteristics were significantly ($p < 0.05$) related to the mass fluxes up to 40 cm above the soil surface. However, greater vegetation cover in NFT did not result in significant reductions in mass transport rate compared with CFT. This can be explained by substantially greater (>360%) loose material in NFT due to the dissipation of wheat residue during the early fallow period (23% in late March) and longer transport distance due to a lower surface roughness. These results corroborate that the elimination of fallow tillage alone may not generate sufficient natural vegetation cover to effectively reduce aeolian soil losses in fallow periods of winter wheat cropping systems.

*Corresponding author (anourigh@utk.edu).

Received 8 July 2018.  
Accepted 18 Sept. 2018.

Abbreviations: BEST, Basaran–Erpul Sediment Trap; CFT, conventional fallow tillage; CP, canopy cover; EPC, effective plant cover; IVR, indicator variable regression; NFT, no fallow tillage; OM, organic matter; $Q$, mass transport rate; SAC, Weibull scale factor; SRF, Saleh roughness factor; TDR, time domain reflectometer; $u_*$, friction velocity; $u_z$, threshold friction velocity; $u$, average wind velocity at height $z$; VFS, very fine sand; $WS_{avg}$, average wind speed; $WS_{max}$, maximum wind speed; $z_0$, aerodynamic roughness height; $z_{aer}$, aerodynamic roughness of random roughness.

In response to the rising demand for new food resources, large areas of Central Anatolia rangelands have been converted to croplands. Almost 36% of the 134,300-ha farmland area in Karapinar is under winter wheat (*Triticum aestivum L.*)–fallow cropping systems (Turkish Statistical Institute, 2008). According to Acar and Dursun (2010), most wind erosion cases in the region occur during the fallow phases of the cropping systems, which are deemed to be essential to boost the soil water storage for proceeding crops (Smika, 1983). However, there are several concerns associated with the fallow management in the regional winter wheat cropping system. Multiple tillage operations during the approximately 14 mo of fallow period degrade the soil aggregates and completely or partially remove the stubbles and residues remained at the soil surface from the previous wheat cultivation. Furthermore, spring tillage incorporates the natural plant cover, which develops rapidly during the spring rainfalls, leaving the soil surface unprotected against high spring winds. Moreover, spring tillage breaks up the crust layer, which may provide an effective coating over the soil surface and keep the loose soil particles in place (Valentin, 1995).
Growing single-species or legume−triticale (\textit{X} \textit{Triticeae} \textit{Wittm.}) cover crop combinations as a substitute for fallow in winter wheat−fallow cropping systems has been shown to reduce the wind erosion in southwestern Kansas, USA (Blanco-Canqui et al., 2013). However, cover crops use soil water storage through the fallow phase, which may lead to a decrease in main crop yield at the subsequent year (Unger and Vigil, 1998). Thus, it can be hardly expected from cover crops in semi-arid climates to yield a profitable forage feed, hydrologically support the main crop, and maintain an effective biomass at the soil surface against wind erosion (Nielsen et al., 2015).

As an alternate regional practice in conventional winter wheat−fallow rotation, local farmers apply disk plow down to 10 cm immediately after harvest in July to increase the surface roughness against fall winds, while retaining a fraction of residue cover at the soil surface. Farmers in the region eliminate the spring tillage to avoid the burial of residue remained from previous cultivation and to allow the natural standing plant cover to provide further protection at soil surface against erosive spring winds. Thereafter, in late April, they generally suppress the natural plant cover using herbicides to increase the water storage and to control the evaportranspiration and increase the residue cover and soil organic C. However, the effectiveness of the natural plant cover as a result of the elimination of spring tillage on agricultural soil losses and its consequent effect on the agricultural water availability has not been properly investigated (Mendez and Buschiazzo, 2015).

Mendez and Buschiazzo (2010) reported that the residue of goose grass [\textit{Eleusine indica} (L.) Gaertn] treated by herbicide on a no-till sunflower cropping provided 71% of surface cover and decreased the risk of wind erosion. Maintaining a proper residue cover at soil surface coupled with retention of naturally grown standing vegetation may provide a better protection for surface soil at fallow periods. Sharratt et al. (2012) reported 0.15, 2, and 15 times greater estimated sediment transport from conventional tillage than those for reduced, minimum and no-tillage, respectively. However, the effectiveness of no-tillage system in preserving the soil resources is closely tied with its potential to retain sufficient and long-lasting residue cover (Mendez and Buschiazzo, 2015) at the soil surface. Otherwise, it may even upsurge the wind erosion potential through enhancing the availability of loose material and providing a longer transport distance for detached particles. Standing plant cover, on the other hand, has a marked advantage over flat residue cover as it reduces the wind momentum through friction at some height above the soil surface and traps aeolian sediment (Wolfe and Nickling, 1993; Hagen and Casada, 2013). Leenders et al. (2007) observed that the trapping feature of scattered vegetation cover caused a substantial decrease in total sediment flux from agricultural fields in the Sahel in Africa.

Knowledge on the effectiveness of natural plant cover in controlling the wind erosion in presence of dynamic soil and climatic variables is essential for more improved tillage and cropping strategies as well as for more realistic wind erosion predictions. Vegetation properties such as coverage ratio, distribution pattern, frontal density and specific alignment relative to the wind direction may considerably affect its effectiveness in reducing the amount of soil losses (Dupont et al., 2014). Considerable soil losses can be measured in relatively high canopy covers, if the cover provides protection only over a small fraction of area since the irregular distribution of plant units leads to the formation of erodible zones or paths between plant units. Okin (2008) introduced a model representing the non-erodible roughness elements for shear stress partitioning on vegetated surfaces. This model uses the size distribution of erodible zones between plants to characterize the shear stress partitioning on the surface. Their model resulted in a more accurate estimation of sediment flux than that of Raupach (1992) model, which utilizes the canopy cover ratio to quantify the sheltering effect. In a wind tunnel experiment, Youssef et al. (2012) showed that the vegetation cover and its arrangement across the area had a significant impact on the relocation of wind-blown sediment.

The impact of the biological and physical characteristics and distribution of natural vegetation cover on aeolian sediment transport has been investigated in multiple field (Lancaster and Baas, 1998; Gillette and Pitchford, 2004; King et al., 2006; Bergametti and Gillette, 2010) and laboratory studies using natural (Burri et al., 2011; Ozcan et al., 2012) or artificial roughness elements (Raupach et al., 1980; Musick et al., 1996; Cornelis and Gabriels, 2005; Youssef et al., 2012). However, tillage-induced, dynamic variations in natural plant cover and its effect on aeolian soil losses in the fallow phase of cropping system have not been fully discovered. In wind tunnel studies, the soil losses in presence of vegetation are often defined by a soil loss ratio (Armbrust and Lyles, 1985). Nevertheless, soil loss ratio is normally seen as just being proportional to the wind speed, disregarding many of the influential factors existing in real conditions. These can be controlled under laboratory conditions to some extent, though there are some questions as to how well those settings could reflect the natural conditions. In field conditions and especially during the rainy seasons, the abundance, mass, and size of the natural plant community may significantly change from one storm event to another one.

Therefore, the objectives of this field study were twofold. The first objective was to investigate the impact of two fallow tillage management systems and subsequent changes in natural plant cover and surface characteristics on aeolian soil losses in semi-arid Central Anatolia. The second objective was to study the relationship between the vertical distribution of wind-blown soil fluxes and vegetation characteristics in prevailing wind direction.

**MATERIAL AND METHODS**

**Study Site**

The experiment took place in the Great Konya Basin of Central Anatolia, Karapinar, Turkey (37°42′55.15″ N, 33°32′47.65″ E) (Fig. 1), situated 188 km southeast of the city of Konya. Karapinar covers approximately 293,900-ha land area, 51% of which is cultivated agricultural fields and 44.4% is rangeland (Turkish Statistical Institute, 2008). The annual mean temperature in the region is 11.8°C and summer daytime temperature is 30 to 36°C. The mean annual precipitation in the region is about 284 mm and 72% of precipitation falls between December and May. Prevailing winds blow from north-northeast and south-southwest (Fig. 2), with maximum velocities of 20 to 25 m s⁻¹. Spring rains in the region are generally accompanied by severe wind storms. Konya basin covers 69.2% of 465/913-ha wind erosion susceptible area in Turkey (Acar and Dursun, 2010).
Fig. 1. Location of the experimental plots within the study area in Karapinar, Turkey.

Fig. 2. Wind rose diagram shows the frequency distribution of wind speed vs. wind direction at the experimental site over the study period.
Fallow Tillage Managements

Two experimental plots of 60 × 45 m were established in the windy spring season on two winter wheat–fallow cropping systems. Soil analyses at conventional fallow tillage management (CFT) showed the upper 5 cm soil as a sandy loam containing 64% sand, 23% of which was composed of very fine sand particles (Table 1). The field was plowed with moldboard immediately after harvest in late July, which entailed the spring tillage in late March. The instruments were established in the field 1 d after the spring moldboard tillage. The second plot was a winter wheat cropping system with no fallow tillage management (NFT). This plot was situated about 920 m south of the CFT plot and had almost the same soil texture as CFT plot did. The field was disked in late July, immediately after harvest, and remained undisturbed through the fallow phase.

Data Collection

Weather data were collected by a weather station located at a downwind edge of the NFT plot. A Campbell Scientific CR1000 model data-logger recorded the climatic data over the study period at 5-min time intervals. To obtain the wind profile, five anemometers were mounted on the tower at the heights of 110, 150, 210, 290, and 390 cm above the soil surface. A wind vane was mounted 2 m above the soil surface to record the wind directions. An air temperature and humidity sensor, a tipping bucket rain gauge, TDR soil probe, and a saltiphone (Spaan and Van den Abeele, 1991) were also connected to the data-logger. In addition to the TDR measurements, gravimetric soil water content was determined by disturbed samples collected from the surface layer (0–3 cm) in three random replicates after each wind event.

Saltiphone is an acoustic sensor that provides a continuous recording for saltating particles, which are generally in the size range of 63 to 500 μm. Whenever wind speed exceeds the threshold friction velocity \( u_{*} \), sand particles are carried upward and blown downwind and strike a 23-mm diameter built-in microphone, which is continually faced to the wind direction. Strikes are recorded by data-logger as counts per unit time. We placed the saltiphone on a bare surface free of any residue and obstacles, about 10 cm above the soil surface. Saltiphone data were used in two ways. First, the minimum wind speed at which the saltation process was initiated was considered as the threshold friction velocity. Second, by summing up the 5-min time intervals the saltation process was initiated was considered as the threshold friction velocity.

Sediment Collection

Wind-blown soil losses at each management was measured using five Basaran–Erpul Sediment Traps (BEST) mounted on each of 20 posts at 20, 40, 60, 80, and 100 cm above the soil surface. Traps were established in a grid arrangement with side lengths of 15 m (Fig. 3). Wind vanes attached to the trap posts ensured that the trap inlets would be pointed into the wind direction through the course of the experiment. BEST sediment trap has an inlet area of 240 mm² and based on the wind tunnel calibration results, has an average overall trapping efficiency of 0.85 (Basaran et al., 2011). After each wind event, the sediments collected in traps were emptied and weighed.

Climatic Parameters

Friction velocity and aerodynamic roughness length at the weather station were determined by the linearized form of the Prandtl–von Karman equation (Eq. [1]) using the mean wind velocities recorded by anemometer at five heights above the soil surface.

\[
U_z = \frac{u_*}{k} \ln \left( \frac{z}{z_0} \right)
\]

where \( U_z \) (m s⁻¹) is the average wind velocity at height \( z \) (m) at the weather station, \( u_* \) (m s⁻¹) is the friction velocity at the weather station, \( k \) is von Karman’s constant, and \( z_0 \) (m) is the aerodynamic roughness height at the weather station.

To determine the aerodynamic roughness of random roughness in experimental plots, the Weibull scale factor for shelter angle was calculated (Porter et al., 1990). A shelter angle is the largest roughness angle above the soil surface to the top of any upwind point. Then, the aerodynamic roughness including the random roughness and flat biomass was determined using Eq. [2]:

\[
z_{on} = \exp \left( 2.1546 - \frac{14.44}{SAC_n} \right); SAC_n > 2
\]

where \( z_{on} \) is the aerodynamic roughness of random roughness including the flat biomass cover (mm) and SAC_n is the Weibull scale factor for degree of shelter angle distribution.

Thereafter, the friction velocities at two fallow tillage managements across four wind events were determined using Eq. [3] (Hagen, 1996):

\[
u_p = \frac{u_*}{0.067} \left( \frac{\sigma_{pp}}{\sigma_{pp}} \right)^0.067
\]

Table 1. General soil properties of conventional fallow tillage (CFT) and no fallow tillage (NFT) managements. Calcium carbonate (CaCO₃), organic matter (OM), bulk density (ρb), and particle-size distribution of soil samples were determined using acid neutralization, degtjareff method, the core method, and the hydrometer method, respectively. Near-surface soil sampling was performed randomly in six replicates for each management down in 5 cm.

<table>
<thead>
<tr>
<th>Treatments</th>
<th>pH</th>
<th>CaCO₃</th>
<th>OM</th>
<th>ρb</th>
<th>VFS†</th>
<th>Sand‡</th>
<th>Silt§</th>
<th>Clay¶</th>
</tr>
</thead>
<tbody>
<tr>
<td>CFT</td>
<td>7.57</td>
<td>392</td>
<td>15</td>
<td>1.39</td>
<td>232</td>
<td>643</td>
<td>189</td>
<td>168</td>
</tr>
<tr>
<td>NFT</td>
<td>7.54</td>
<td>353</td>
<td>13</td>
<td>1.36</td>
<td>218</td>
<td>665</td>
<td>168</td>
<td>167</td>
</tr>
</tbody>
</table>

† Very fine sand (50–100 μm).
‡ Sand (50–2000 μm).
§ Silt (2–50 μm).
¶ Clay (<2 μm).
where $u_p^*$ is the friction velocity at study plot (m s$^{-1}$), $u_s^*$ is the friction velocity at the weather station (m s$^{-1}$), $z_{0p}$ is the roughness length at study plot, and $z_{0s}$ is the roughness length at the weather station.

**Field Measurements**

Soil surface properties including the plant coverage ratio, plant height, crust thickness, crust stability, availability of loose material on the soil surface, surface roughness and the fraction of nonerodible roughness elements were measured immediately after wind events in six replicates at frontal areas. Crust stability was measured by a Humboldt H4195 hand penetrometer. Crust thickness was measured using a hand trowel and a ruler through excavating a shallow channel and measuring the height of the crusted section of the channel sidewall. Since ridge heights were not distinctive from the random roughness elements (especially after the first wind event), the surface roughness was measured only for random roughness using the Saleh chain method (Saleh, 1993) (Eq. [4]).

$$SRF = 100 \times \left(1 - \frac{L_2}{L_1}\right)$$

where $L_1$ is the stretched chain length and $L_2$ is the shortened chain length, following the surface topography.

Then, SRF was converted to the random roughness factor described by Allmaras et al. (1966) using a regression equation provided by Gilley and Kottwitz (1995). Using a regular soft brush, the availability of loose erodible material on the soil surface was determined.

**Mass Flux Calculations**

During the field campaign, four erosive wind events were recorded and after each event, the sediments were collected and weighed. Using sediment weight and mean event duration, the horizontal mass flux, $q(z)$ (g m$^{-2}$ s$^{-1}$) at each vertical distance from soil surface $z$ (m) was calculated. Using the method of Sterk and Raats (1996), horizontal mass flux was related to the measurement height as shown in Eq. [5]:

$$q(z) = a(\varepsilon + 1)^b + c \exp\left(-\frac{z}{\beta}\right)$$

where $\varepsilon$ is dimensionless height, and $a$, $b$, $c$, and $\beta$ are regression coefficients.

This combined mass flux model describes the vertical distribution of horizontal mass flux from the soil surface to any desired height which was one meter in this study. Mass transport rate $Q$ (g m$^{-1}$ s$^{-1}$) at each measurement point was obtained by integrating Eq. [5] from the soil surface to the top of the measurement heights using the Eq. [6].

$$Q = \int_0^1 q(z) dz$$

The values were then corrected for the overall efficiency of the BEST sediment traps and multiplied by the wind duration to obtain the total mass transport at each sampling point.

**Characterization of Vegetation Cover**

After each wind event, plant cover percentage, vegetation height, the distance of the nearest plant unit(s) at upwind location of the sediment traps and the number of plant units at the frontal area...
of sediment traps within the interquartile range of wind direction were measured and effective plant cover index was generated. In the proposed index it was assumed that with a given number of vegetation elements on a known area, an even distribution of vegetation elements would provide the most uniform and effective coverage over the soil surface. In the systematic arrangement of plant units, there is a certain distance between two nearby plants. Any deviation from this even spacing arrangement, groups the vegetation elements into one or more clusters. Plant units with a spacing distance less than the obtained value were therefore placed in a separate cluster. Single plant units far enough from the other plants or clusters were counted as separate plant groups. The number of clusters, $n$, within any frontal area, therefore, would range between 1 and $N$, where $N$ is the total number of vegetation elements. Ideally, the plants are evenly spaced, so $n$ approaches $N$, or $n/N$ approaches 1. A value of $n/N$ close to 1 indicates more even distribution and minimal unsHELtered areas within the frontal zone, while a value of $n/N$ near zero indicates uneven plant distribution and the possible presence of the unsHELtered areas prone to wind erosion. Since this ratio does not account for the actual number of plants or coverage, it was multiplied by the average canopy cover percentage to provide a measure of the effective plant cover which is therefore defined as:

$$EPC = \frac{CP \times (n/N)}{d}$$

where EPC is the effective plant cover, CP as explained by (Armbrust and Bilbro, 1997) is the percentage of soil surface (0–100%) covered by live canopy, $n$ is the number of clusters, $N$ is the number of vegetation elements, and $d$ is the distance between the nearest plant unit and associated sediment trap post aligned into the wind direction.

Presence of vegetation element(s) immediately before sediment traps in upwind location could obstruct the sediment traps and cause a significant bias in the assessment of vegetation effectiveness in reducing wind-blown soil fluxes. This impact was therefore minimized by regular removal of plants within a 0.5-m radius around each sediment trap. A regression curve provided by Bradley and Mulhearn (1983) shows that the friction velocity can approach to its upwind value behind a shelter-fence of 50% porosity at nearly 10 times the shelter height. Likewise, Leenders et al. (2007) in a field study showed that the required distance for wind speed downwind of a single shrub to recover its upwind value was about 7.5 times the height of plant. Our assumption was that closer distances would decrease the soil losses although the formation of eddies at the lee of single vegetation could increase the local erosion.

**Statistical Analyses**

The experiment was a completely randomized design with repeated measures. Analysis of variance was conducted using MIXED procedure (SAS V9.3; SAS Institute, 2010). The mean comparisons were conducted with management, event, and their interaction as fixed effect and measurement location nested in each management as random effect. Wind events were modeled as repeated measures with autoregressive correlation. Using indicator variable regression, the relationship between the vegetation characteristics in the frontal area of the sediment traps and sediment collection at five heights above the soil surface was determined. In indicator variable regression (IVR) (also known as dummy regression), a regression line for each treatment level is modeled, allowing slopes and intercepts to be compared. Here, the sediment entrapped at each height above the soil surface was considered as a separate treatment level. A full model with linear, quadratic, and all interactions with treatments was executed and using a stepwise procedure, nonsignificant terms ($p < 0.05$) were dropped, giving:

$$\text{Mass flux}_j = \mu + \text{Height}_i + \beta_1 \times \text{EPC}_{ij} + \beta_2 \times \text{EPC} \times \text{Height}_i + \gamma \times \text{EPC}_{ij} \times \text{EPC}_b + \varepsilon_j$$

where mass flux was measured on the $j$-th trap at the $i$-th height, $\mu$ is the common intercept, $\beta$ and $\gamma$ are slope parameters, and $\varepsilon$ is the error term. The polynomial term was discarded in two out of eight analyses because it was not significant statistically ($p > 0.05$).

**RESULTS AND DISCUSSION**

**Soil Surface Properties and Sediment Flux**

Soil surface properties under two fallow tillage managements were measured on 28 March, immediately after the spring tillage on CFT when the random roughness was about 20 mm in CFT and 6 mm in NFT. Crust cover was not apparent in CFT while a structural crust with 25 mm of thickness was covering approximately 80% of the surface in NFT. However, a total of 32 mm of rainfall (28 March–4 July) decreased the random roughness of CFT by 26% and resulted in a 16.8 mm crust layer covering 48% of the area (Table 2). The fine sandy texture at the surface layer of both managements was found to be highly prone to crust formation (Robinson and Woodun, 2008; Rajot et al., 2003). However, despite the relatively high calcium carbonate content, crust stability at both managements remained below the minimum measurable limits throughout the study period, which indicated the vulnerability of crust material to detachment and transport. The results are in agreement with the findings of Feng et al. (2013), who applied 0.15 to 0.60 mm of simulated rainfall on five dominant soil types from Columbia Plateau and observed a lower penetration resistance in sandy loam with greater calcium carbonate than in silt loam soil. After the first event on 4 July, except for a scattered flat residue, no measurable live vegetation cover was observed in CFT while NFT had a low-density preexisting natural plant cover at the surface. This resulted in nonsignificant EPC differences between two managements ($p < 0.05$) after the first event. In accordance with Mendez and Buschiazzo (2010), during the first 8 mo of fallow phase, wheat residue showed a significant reduction of 40 and 28% in NFT and CFT, respectively. The spring tillage further decreased the residue in CFT to an average value of 10% over the study period (Table 2). However, the temporal changes in residue cover were not significant in any of the managements. Insufficient residue cover in NFT and raindrop impact resulted in a considerable accumulation of erodible loose material (54.6%) lying on the smooth crust layer. In contrast, spring moldboard on CFT broke down the crust layer and significantly ($p < 0.05$) decreased the loose material at the soil surface. The erodible material in CFT remained lower than those in NFT throughout the study period.
Table 2. Mean values of soil surface properties as affected by conventional fallow tillage (CFT) and no fallow tillage (NFT) managements.

<table>
<thead>
<tr>
<th>Surface properties</th>
<th>Tillage management</th>
<th>4 Apr.</th>
<th>13 Apr.</th>
<th>19 Apr.</th>
<th>26 Apr.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residue cover, % CFT</td>
<td>12b†</td>
<td>10b</td>
<td>10a</td>
<td>8a</td>
<td></td>
</tr>
<tr>
<td></td>
<td>NFT</td>
<td>23a</td>
<td>21a</td>
<td>18a</td>
<td>18a</td>
</tr>
<tr>
<td>Random roughness, mm CFT</td>
<td>14.8a</td>
<td>13.4a</td>
<td>12.3a</td>
<td>12.1a</td>
<td></td>
</tr>
<tr>
<td></td>
<td>NFT</td>
<td>5.4b</td>
<td>5.7b</td>
<td>4.8b</td>
<td>4.9b</td>
</tr>
<tr>
<td>Crust thickness, mm CFT</td>
<td>16.81b</td>
<td>18.34a</td>
<td>17.61b</td>
<td>19.22a</td>
<td></td>
</tr>
<tr>
<td></td>
<td>NFT</td>
<td>25.64a</td>
<td>23.51a</td>
<td>28.37a</td>
<td>24.67a</td>
</tr>
<tr>
<td>Crust cover, % CFT</td>
<td>48b</td>
<td>56b</td>
<td>64b</td>
<td>73a</td>
<td></td>
</tr>
<tr>
<td></td>
<td>NFT</td>
<td>78a</td>
<td>82a</td>
<td>85a</td>
<td>84a</td>
</tr>
<tr>
<td>Erodible loose material, %</td>
<td>8.6b</td>
<td>14.8b</td>
<td>13.7b</td>
<td>13.12b</td>
<td></td>
</tr>
<tr>
<td></td>
<td>NFT</td>
<td>54.6a</td>
<td>63.2a</td>
<td>66.23a</td>
<td>47.39a</td>
</tr>
<tr>
<td>Average EPC CFT</td>
<td>0.4a</td>
<td>1.9b</td>
<td>4.2b</td>
<td>9.3b</td>
<td></td>
</tr>
<tr>
<td></td>
<td>NFT</td>
<td>1.3a</td>
<td>7.04a</td>
<td>14.4a</td>
<td>31.8a</td>
</tr>
</tbody>
</table>

† Means within a factor followed by different letters are significantly different according to protected LSD at P < 0.05.

Table 3. Total rainfall, maximum wind speed (WS_{max}), average wind speed (WS_{avg}), mean integrated mass flux (Q), and the range of mass transport rate for conventional fallow tillage (CFT) and no fallow tillage (NFT) managements across the wind events.

<table>
<thead>
<tr>
<th>Date</th>
<th>Rainfall</th>
<th>WS_{max}</th>
<th>WS_{avg}</th>
<th>Q</th>
<th>Range</th>
<th>Q</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 Apr.</td>
<td>32</td>
<td>12.78</td>
<td>2.11</td>
<td>374 ± 49†</td>
<td>118–800</td>
<td>471 ± 52</td>
<td>132–922</td>
</tr>
<tr>
<td>13 Apr.</td>
<td>1.1</td>
<td>10.71</td>
<td>2.7</td>
<td>206 ± 37</td>
<td>81–281</td>
<td>145 ± 22</td>
<td>76–190</td>
</tr>
<tr>
<td>19 Apr.</td>
<td>0.9</td>
<td>12.49</td>
<td>3.28</td>
<td>604 ± 66</td>
<td>148–1012</td>
<td>591 ± 38</td>
<td>200–882</td>
</tr>
<tr>
<td>26 Apr.</td>
<td>31.1</td>
<td>7.21</td>
<td>1.39</td>
<td>169 ± 18</td>
<td>84–329</td>
<td>141 ± 16</td>
<td>69–346</td>
</tr>
</tbody>
</table>

† ± is standard error.

In spite of a greater surface coverage (crust and standing bio-cover), during the first event, NFT showed 53% higher soil losses than CFT (Table 3), which can be attributed to the higher availability of loose material at NFT due to the long-term exposure of soil surface to erosive forces as well as the greater roughness length and friction velocity (Table 4) in CFT. On a Syrian silt clay loam, Masri et al. (2015) also observed in average 28% lower sediment transport on a tilled barley (Hordeum vulgare L) cropping management than adjacent untilled fields. It is known that the amount of loose material formed on the crusted soil is directly related to the wind erosion potential which can further intensify the aeolian process by the act of abrasion (Zobeck et al., 2003). During the first event, the range of sediment fluxes was higher for NFT (790 g m⁻²) than for CFT (682 g m⁻²), which can be related to more homogenous soil surface condition generated by tillage in CFT.

On 13 April, after the second wind event, as a result of continued rainfall, random roughness in CFT decreased by 10%, although it was still significantly (p < 0.05) greater than in NFT. The crusted surface area also increased in CFT, while it remained almost unchanged in NFT. Loose material was more than five times more in NFT than CFT. Considering the mentioned surface properties, greater sediment fluxes could be expected in NFT than CFT. However, due to the rainfalls during the first event, the natural standing plant cover exhibited a rapid growth particularly in NFT during the second event, which resulted in almost three times higher mean EPC in NFT than CFT. In spite of 16% increase in loose material and substantially higher erodible particles, NFT showed in average 26% lower sediment flux than CFT during the second event. Bilbro and Fryrear (1994) have shown that standing biomass was nine times more effective than flat residue cover reducing the soil loss ratio.

Effective plant cover, after the third wind event on 19 April, averaged 4.2 in CFT with components of CP = 7%, n/N = 0.71, and d = 1.2 m, which was significantly (p < 0.05) lower than in NFT with EPC = 14.6 and associated parameters of CP = 22%, n/N = 0.65, and d = 0.98 m. The crusted area was also 28% and significantly (p < 0.05) lower under CFT. However, the sediment losses during the third event were almost identical in two managements (Table 3). The significance of differences in soil surface properties between two managements remained the same as the first and second events, while the difference in sediment flux between two management was more evident during those events. Despite the significant differences (p < 0.05) in surface roughness, EPC and the availability of loose material during the last event, differences in sediment fluxes measured on 26 April, were nonsignificant between the two fallow tillage managements.

Analysis of variance revealed no significant difference in soil losses between no fallow tillage and conventional fallow tillage managements (p = 0.36). This result can be explained by the complex interactions among surface characteristics created by tillage managements as well as the unexpected heavy precipitation during the week ending to the first event. For example, during the first
event lower amount of flat residue and standing biomass in CFT was effectively compensated by the greater surface roughness caused by spring tillage as well as the significantly lower erodible material due to the soil inversion. Furthermore, considerable precipitation during the initial stage of the experiment caused a rapid emergence and progressive development of natural plant cover in both managements. Although the effective plant cover in CFT remained constantly below the NFT levels, the presence of plant cover in CFT, especially after the second event was considerable.

However, a significant difference was evident in the event by event alterations in soil losses (p < 0.0001) under both managements with second and third wind events being significantly more erosive than the first and fourth events. The temporal variations in soil losses were significantly related to the climatic factors (Fig. 4), among which the relationship between the average wind speed with \( r = 0.93 \) and 0.97, cumulative precipitation with \( r = -0.75 \) and \(-0.98\) and maximum wind speed with \( r = 0.48 \) and 0.84, and aeolian soil losses were distinguished for CFT and NFT, respectively. Nan et al. (2018) also found that the soil surface wetness was eloquently related to the soil particle entrainments and wind velocities above 12 m s\(^{-1}\). Above-mentioned results apparently reveal the hardship in controlling the wind erosion in semiarid soils genetically abundant in fine sand particles and poor in binding organic agents (Han et al., 2015). Despite the appreciable plant coverage on NFT particularly after the second event, the magnitude of the soil fluxes in a temporal manner was dominantly controlled by the wind velocity (Fig. 4).

**Friction Velocity and Aerodynamic Roughness**

Friction velocity ranged from 0.22 to 0.27 m s\(^{-1}\) for CFT and from 0.19 to 0.24 m s\(^{-1}\) in NFT across four wind erosion events (Table 4). Below canopy \( u* \) was constantly higher under CFT than NFT primarily due to a greater roughness length created by spring tillage. Friction velocity is known to be governed by soil aerodynamic properties as well as the atmospheric condition (Stull, 2000). In this case, the coefficient of correlation showed that \( u* \) variations in CFT and NFT was 95 and 89% related to the average wind speed and 90 and 95% related to the maximum wind speed, respectively. The considerable decline in \( u* \) during the fourth wind event (19–28 April) was associated with the lowest mean (1.39 m s\(^{-1}\)) and maximum (7.21 m s\(^{-1}\)) recorded wind velocities at 2 m among all wind events. The greatest \( u* \) in both managements was observed within the period between 13 and 19 April when the maximum wind speed was 12.46 m s\(^{-1}\) and the average wind speed was the greatest (3.28 m s\(^{-1}\)) through the course of study. Temporal variations in \( u* \) were found to be meaningfully related to the mean soil fluxes (g m\(^{-2}\) s\(^{-1}\)) in CFT (\( r = 0.64 \)) and NFT (\( r = 0.94 \)), since a large near surface shear stress means a greater lift force against the gravitational force.

Aerodynamic roughness ranged from 0.49 to 0.62 in NFT and from 1.42 to 1.69 mm in CFT, which did not differ substantially from \( z_{0} \) of 2 mm reported for conventional tillage by Sharratt and Feng (2009). Dynamics of surface roughness as a result of spring tillage and the emergence of short and scattered vegetation elements were reflected in the trend of predicted aerodynamic roughness (Table 4). The constant decrease in \( z_{0} \) under CFT can be explained by the gradual decrease in random roughness, primarily due to the flattening impact of precipitation events. Heavy precipitation during the week prior to the first event decreased the random roughness of CFT by 26% (from 29 to 14.8 mm), which entailed a continued decline in \( z_{0} \) across the wind events. The trend of variation in \( z_{0} \) under NFT management, however, appeared to be mainly influenced by the development of the scattered and short plant units. Predicted below canopy aerodynamic roughness was constantly greater under CFT than under NFT across the wind erosion events, which indicates that the magnitude of \( z_{0} \) was more related to the random roughness created by tillage in CFT than the low residue cover existed in NFT.

**Relationship between the Vertical Distribution of the Soil Fluxes and the Natural Plant Cover**

To assess the effectiveness of EPC predicting the spatial changes in soil fluxes at five heights above the soil surface, mass flux was regressed against EPC using IVR (Fig. 5). Except for the wind event affected CFT from 28 March to 4 April, the mass flux by EPC interactions were significant (p < 0.05) for the rest
Fig. 5. Indicator variable regression (IVR) shows the spatial variations in sediment flux at five heights (g m⁻²) above the soil surface vs. the effective plant cover (EPC) in fallow tillage managements, conventional fallow tillage (CFT), and no fallow tillage (NFT) across four wind events. WD is wind duration in seconds.
of the event/management cases. Hence, the IVR model for mass flux prediction based on EPC seems valid. The reason for the nonsignificant EPC-mass flux interaction during this event/management case can be explained by insufficient vegetation cover in CFT measured shortly after tillage.

ANOVA showed that the average slope across five measured heights was less than zero in six out of eight event/management cases (Table 5). However, the significance of the model was primarily dictated by the significance of mass flux reductions with EPC in 20- and 40-cm heights. This means that the sediment entrapment in heights over 40 cm was not merely affected by the vegetation characteristics in the frontal area, thus being commonly underestimated by IVR. The coefficient of correlation between measured vs. predicted soil losses also showed a better mass flux prediction by IVR at lower heights (Fig. 6). The significant interaction in lower heights is likely due to the direct interaction and effective trapping of particles by vegetation cover (Burri et al., 2011), which rose up to the maximum height of 25 cm by the end of the experiment. The nonsignificant effect of increasing EPC on the mass flux in heights over 40 cm can be explained by the fact that the threshold friction velocity for the entrainment of finer particles is lower than that for coarser ones (Roney and White, 2004). Hence, they show a higher activity during the wind events and may be transported over longer distances and entrapped elsewhere at heights over the vegetation canopy.

The quadratic term of the IVR was significant ($p < 0.05$) in four out of eight management/event cases and close to the significant level in the last event associated with NFT ($p = 0.06$). Thus, the mass flux generally decayed exponentially with EPC (Table 5). The exponential reduction in mass flux due to the presence of vegetation agrees with several other field and laboratory studies (Lancaster and Baas, 1998; Li et al., 2007; Allgaier, 2008; Burri et al., 2011). In former studies, the effectiveness of vegetation cover has generally been represented by canopy cover. However, this index does not account for the arrangement of individual plants.

Temporal reductions in mass flux per unit increase in EPC was affected by the magnitude of the sediment fluxes (Table 3), which were controlled by wind characteristics and event duration. For example, the greatest mass flux reduction (~192 g m$^{-2}$) at the 20-cm height occurred during the third event in CFT and first and third events in NFT (~305 and ~68 g m$^{-2}$) (Table 5). Those events had the highest maximum wind velocities. However, disregarding the variations in wind velocity, by a temporal increase in EPC, its effectiveness in decreasing soil losses tended to vanish. Similarly, Armbrust and Bilbro (1997) observed that the reduction in sediment transport capacity beyond CP values around 10% either approaches zero or a steady state depending on the free stream wind velocity. On the other hand, event by event pairwise comparisons between managements showed that the mass flux reductions per unit increase in EPC at the 20-cm height were constantly lower under NFT than CFT. Although the mass fluxes at the heights above 20 cm in NFT declined considerably during the fourth event, the lower reductions in mass flux with EPC did not mean a considerably lower mean mass flux in NFT during the third and fourth events. This indicated the interference of factors other than vegetation cover and flow characteristics governing a fraction of mean mass flux. Among the surface properties, roughness length was significantly lower, and loose material was significantly higher under NFT than CFT within this period. This result reveals that even under eliminated spring tillage, the residue cover remained after wheat harvest, which was partially buried by summer disk plow did not provide a protective mulch at the soil surface against the erosive climatic forces during the fallow period. The outcome was the increased disintegrated loose particles at soil surface, which

Table 5. Reduction of mass flux (g m$^{-2}$) per unit increase in effective plant cover (EPC) at five heights above the soil surface predicted by indicator variable regression (IVR) for conventional fallow tillage (CFT) and no fallow tillage (NFT) managements across four wind events.

<table>
<thead>
<tr>
<th>Height/Soil loss interaction</th>
<th>Event 1</th>
<th>Event 2</th>
<th>Event 3</th>
<th>Event 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>EPC x 20 cm</td>
<td>–</td>
<td>–68.3</td>
<td>–192.1</td>
<td>–30.2</td>
</tr>
<tr>
<td>EPC x 40 cm</td>
<td>–</td>
<td>–38.4</td>
<td>–117.4</td>
<td>–9.8</td>
</tr>
<tr>
<td>EPC x 60 cm</td>
<td>–</td>
<td>–24.8</td>
<td>–86.0</td>
<td>–6.5</td>
</tr>
<tr>
<td>EPC x 80 cm</td>
<td>–</td>
<td>–30.9</td>
<td>–67.8</td>
<td>–4.9</td>
</tr>
<tr>
<td>EPC x 100 cm</td>
<td>–</td>
<td>–40.9</td>
<td>–73.1</td>
<td>–3.3</td>
</tr>
<tr>
<td><strong>ANOVA table† LSD protected, $p &lt; 0.05$</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Height</td>
<td>–</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>EPC</td>
<td>–</td>
<td>0.07</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>EPC x Height</td>
<td>–</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>EPC x EPC</td>
<td>–</td>
<td>0.05</td>
<td>0.03</td>
<td>0.18</td>
</tr>
<tr>
<td><strong>ANOVA table† LSD protected, $p &lt; 0.05$</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EPC x 20 cm</td>
<td>–305.1</td>
<td>–19.4</td>
<td>–68.4</td>
<td>–12.0</td>
</tr>
<tr>
<td>EPC x 40 cm</td>
<td>–141.8</td>
<td>–12.7</td>
<td>–33.1</td>
<td>–4.5</td>
</tr>
<tr>
<td>EPC x 60 cm</td>
<td>–108.3</td>
<td>–6.9</td>
<td>–25.4</td>
<td>–4.6</td>
</tr>
<tr>
<td>EPC x 80 cm</td>
<td>–102.3</td>
<td>–9.9</td>
<td>–10.6</td>
<td>–3.6</td>
</tr>
<tr>
<td>EPC x 100 cm</td>
<td>–98.9</td>
<td>–8.9</td>
<td>–11.1</td>
<td>–3.6</td>
</tr>
<tr>
<td><strong>ANOVA table† LSD protected, $p &lt; 0.001$</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Height</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>EPC</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>EPC x Height</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>EPC x EPC</td>
<td>0.04</td>
<td>0.03</td>
<td>0.2</td>
<td>0.06</td>
</tr>
</tbody>
</table>

† ANOVA table shows the significance of model terms ($p < 0.05$).
Fig. 6. Measured vs. predicted soil losses in fallow tillage managements based on the measurement height.
continued to transport even under appreciable natural vegetation cover. These results are in accordance with the findings of another field study conducted by Uzun et al. (2017) in the same region who observed that despite the rapid evolution of natural plant cover due to the spring rainfalls, the variations in soil losses were primarily controlled by wind velocity and event duration.

Substituting CP for EPC improved the prediction coefficient of IVR by increasing the minimum $R^2$ from 0.67 and 0.74 for CFT, to 0.73 and 0.82 for NFT. This result may be attributed to the fact that EPC penalizes the canopy cover percentage for the heterogeneity of distribution, which is known to affect the efficiency of vegetation cover by encouraging the formation of erodible gaps oriented to wind direction and stimulating the local, intensified erosion at the lee of the isolated plant units (Logie, 1982; Leenders et al., 2007; Dupont et al., 2013).

CONCLUSIONS

No fallow tillage has been promoted as a conservation management in the winter wheat-fallow cropping system to reduce the aeolian soil losses in semiarid Central Anatolia, Turkey. Our results show that the residue produced by winter wheat is not sufficient to provide an effective soil protection against the wind erosion over the long fallow period. During the first 8 mo of the fallow period, prior to the spring tillage, wheat residue decreased, and erodible loose material increased at the soil surface. Hence, despite the lack of spring tillage and significantly greater natural plant cover, the NFT management did not reduce the soil fluxes significantly compared with CFT across four wind events. Spring moldboarding at the conventional fallow tillage management was found to be helpful in mixing the soil particles and reducing the loose material at the soil surface. As expected, the lack of spring tillage significantly increased the natural plant cover in NFT along with preserving the preexisting plant cover and residue at the soil surface. Coverage density and distribution pattern of the natural plant cover significantly controlled the spatial variations in vertical distribution of sediment fluxes. However, the temporal variations in mass flux under both managements were primarily governed by the average and maximum wind velocities. We observed that fine sandy surface soil in absence of the effective physical protection and binding organic agents was easily disintegrated by the raindrop impact during the long fallow phase of the low residue winter wheat cropping system. Presence of loose material laid on a fragile crust further intensified the erosion process by the act of abrasion and hence the sediment continued to transport in NFT, even under appreciable vegetation cover. These results suggest that the priority in regional winter wheat farming systems should be maintaining a continuous biological cover at soil surface regardless of the type of adopted conservation tillage. Integrating or rotating the winter wheat with sod crops or ones with greater residue production are among the potential management strategies.

ACKNOWLEDGMENTS

This research was supported by the Scientific and Technological Research Council of Turkey (TUBITAK). We thank Dr. Daniel C. Yoder for his review and constructive comments on this manuscript. We also thank Necati Simukdi, Harun Kiyak, Zekeruya Toy, and the other staff of the Desertification and Erosion Research Center in Karapinar, Turkey, for accommodation and their competent assistance in data collection during the field campaign.

REFERENCES


King, J., W. Nickling, and J. Gillies. 2006. Aeolian shear stress ratio measurements within mesquite-dominated landscapes of the Chihuahuan Desert, New Mexico, USA. Geomorphology 82:229–244. doi:10.1016/j.geomorph.2006.05.004


