Effectiveness of native wood strand mulches for land rehabilitation in Iran under experimental conditions

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Abstract
Wood-based mulches are a preferred erosion control material for rehabilitation of degraded lands because they can be made from native wood materials; however, research is needed to verify the effectiveness of new products prior to application. The present study aims to assess the effectiveness of two types of native wood strand mulches from Iran (waste byproducts of Alnus glutinosa and Fagus orientalis working) in reducing runoff, soil loss, and sediment concentration under laboratory conditions. Toward this goal, rainfall simulations were conducted 27 times using a 50 mm hr⁻¹ rainfall during 20-min experiments on erosion plots with treatments of different cover percentages (bare, 30 and 70%) and strand dimensions (16 and 4 cm in length; 1.5 cm wide). The results showed that all strand applications reduced runoff (>12%), soil loss (>47%), and sediment concentration (>44%) compared to the bare plots. The most effective application treatment was a 70% coverage of the 4-cm strands of either material (p value < .002). The shorter strands were most effective for all hydrological and erosion variables reductions because they maintained more contact with the soil surface during simulated rainfall and then increased the soil retention potential, whereas the longer strands realigned in the direction of flow, thereby limiting their ability to retard flowing water. The small strands also facilitated the creation of microdams that blocked flow and promoted infiltration. Both materials were deemed effective native erosion control products in degraded sites in the Hyrcanian forests of Iran, particularly when small strands were applied at high cover rates.

KEYWORDS
erosion control, Iran, native wood strand mulch, rainfall simulation, soil conservation

1 | INTRODUCTION

Research to assess the effectiveness of erosion control measures is important because accelerated soil erosion is a major degradation process on disturbed lands throughout the world where forest conversion has taken place (Ekwue, Bharat, & Samaroo, 2009; Lucas-Borja et al., 2019; Pimentel et al., 1995). Forest removal increases the susceptibility of the soil to erosion by exposing unprotected surfaces to the direct rainfall drop impact that causes splash erosion (Darboux, Robin, & Fox, 2008; Inbar, Tamir, & Wittenberg, 1998). Furthermore, unprotected bare soil surfaces offer little resistance to erosion-producing overland flow that generates rills (Morgan, 2005; Rodrigo-Comino, Wirtz, Brevik, Ruiz-Sinoga, & Ries, 2017). Bare soil on disturbed lands such as logged and burned areas should be protected immediately with natural or artificial covers to reduce runoff generation, soil loss and sediment concentration (Alliaume, Rossing, Tittonell, Jorge, & Dogliotti, 2014; Letey,
2001; Malvar et al., 2017; Wagenbrenner, MacDonald, Coats, Robichaud, & Brown, 2015; Wagenbrenner, Robichaud, & Brown, 2016). Mulching is the one accepted erosion reduction strategy that protects the soil from rain drop detachment (Gholami, Sadeghi, & Homaeae, 2013; Jiménez et al., 2016; Kukal & Sarkar, 2010; Prats et al., 2012), facilitates ponding and infiltration (Adeklu, Olorunfemi, & Osunbitan, 2007; Kavian, Gholami, Mohammadi, Spalevic, & Falah Soraki, 2018), retards the movement of erosion-producing surface flow (Behzadfar, Sadeghi, Khanjani, & Hazbavi, 2017; Hazbavi, Sadeghi, & Younesi, 2013), and promotes vegetative regrowth (Fernández & Vega, 2014; Homyak, Yanai, Burns, Briggs, & Germain, 2008; Lai, 1999; Prats et al., 2012; Robichaud et al., 2012, 2013).

Various natural (i.e., hydromulch and agricultural straw) and synthetic mulching materials are available (Kader, Senge, Mojid, & Ito, 2017; Parsakhoo, Jajouzadeh, & Rezaee Motlagh, 2018; Prats, Malvar, Vieira, MacDonald, & Keizer, 2016; Prosdocimi, Tarolli, & Cerdà, 2016; Sadeghi, Hazbavi, & Younesi, 2014). Most of them are installed on degraded forest lands where concern for intact aquatic ecosystems is crucial (Robichaud, Beyer, & Neary, 2000). Because environmental preservation/conservation is of concern in forest environments, appropriate erosion control materials should be derived from natural materials that are native to the catchment in which they are to be installed (Rivas, 2006). Recently, the necessity of nature-based solutions has been highlighted (Keesstra et al., 2018) emphasizing that adoption of soil-vegetation solutions including native wood mulching as a successful best management practice could enhance soil resilience and function. Doing so would promote not only watershed environmental conditions (Hazbavi, Keesstra, Nunes, Baartman, & Sadeghi, 2018) and a more sustainable world (Keesstra et al., 2018). Additionally, local wood-based materials (e.g., small wood chips and strands or forest residues derived from logging activities), for example, are more preferable than other products, including agricultural straw, which may be imported from outside areas (Kim et al., 2008). Wood-based mulches are also more resilient than straw to strong winds and other climate conditions that cause mulch materials to wear and decompose (Foltz, 2012). Furthermore, wood-based mulches derived from local on-site materials are potentially cheaper than imported products because of the lower transportation and manufacturing costs (Foltz & Dooley, 2003). In a nutshell, the greater lifetime and the initially low acquisition costs of local wood-based mulches make them attractive and cost-effective erosion control systems (Foltz, 2012).

Prior research has verified the erosion control effectiveness of wood-based mulches (e.g., Fernández, Vega, Jiménez, & Fonturbel, 2011; Foltz & Dooley, 2003; Jourgholami & Etehadi Abari, 2017; Negrón & Cain, 2018) and has provided insight into the appropriate physical design of the materials. For the first time in Idaho, Foltz and Dooley (2003) investigated the effectiveness of straw mulch and wood strands of Douglas fir veneer “fish tails” with combinations of 4 and 16 mm wide and 60, 120, and 240 mm lengths in reducing runoff volume and sediment production. They found that all covered treatments reduced the runoff and sediment production when compared with a bare treatment subjected to rainfall only and rainfall plus concentrated flow. Gronier, Foltz, and Showers (2005) evaluated the 30, 50, and 70% coverage of wood shred on sandy-loam soil erosion under simulated rainfall intensity of 50 mm hr\(^{-1}\). The results showed that the wood shred at 30, 50, and 70% coverage reduced sediment loss by 79, 92, and 98% as compared with bare plots. Thereafter, in Idaho, Yanosek, Foltz, and Dooley (2006) studied the efficacy of two wood strand blends (160–90 and 160–40 mm length) with three cover percentages of 30, 50, and 70 on two slopes (15 and 30%) and two soils (gravely sand and sandy loam). They concluded that wood strands significantly reduced runoff and erosion, in part, because the three-dimensional layering of the wood strands provided a highly stable matrix that prevented rill formation. Foltz and Copeland (2009) found that by simulating runoff and soil loss on plots of 30, 50, and 70% wood shred cover on coarse- and fine-grained soil, wood shreds reduced runoff and soil loss by 60% to nearly 100%. In another study, Foltz and Wagenbrenner (2010) applied the forest-native wood-based mulches with lengths of <25 mm (fines) and coverages of 50 and 70% to postfire erosion control in Washington, DC. The treatments were provided in three types: AS IS (standard blend produced by a Vermeer horizontal grinder), MIX (50% fewer fines by count than the AS IS blend), and REDUCED (fines removed). They found that the REDUCED blend with 50% ground cover was the optimum for both runoff and sediment concentration reduction under conditions of rainfall and rainfall plus concentrated flow.

Robichaud et al. (2013) also tested the wood shred and agricultural straw mulch impacts on postfire runoff and sediment yields under rainfall simulation, rill simulation, and natural rainfall experiments. Their results proved the effective role of study postfire hillslope treatments in southern British Columbia, Canada. It is revealed that 40–80% ground cover of agricultural straw and wood shred could effectively protect the soil against negative effects of fire. León, Badía, and Echeverría (2015) found that wood chip mulch reduced both runoff rate (from 9.39 to 4.36 mm hr\(^{-1}\)) and soil loss (3.82–1.92 g m\(^{-2}\)) by at least half when applied to burnt soils in north-eastern Spain. Additionally, Prats, Abrantes, Crema, Keizer, and de Lima (2017) tested eucalypt bark strands mulch in three strip lengths of 0.9, 1.8, and 2.7 m with two cover percentages of 50 and 70. According to their results, the 50% mulch was not able to reduce runoff, and the 70% mulch did not produce a statistical significant runoff reduction. Soil erosion mitigation was, however, high for both wood covers. More recently, Turk (2018) examined the effectiveness of reducing forest road induced sheet erosion by wood chips (4,000 g m\(^{-2}\) with a thickness of 1 cm) and slash (branch/leaf) logging residue (1,500 g m\(^{-2}\)) under field conditions in Turkey. The wood chips application was more effective that the slash for soil erosion.

In Iran, although various attempts of land rehabilitation have been attempted using different soil amendments including organic (e.g., Behzadfar et al., 2017; Hazbavi & Sadeghi, 2016; Jourgholami, Labelle, & Fegghi, 2017; Kavian et al., 2018; Khalili Moghadam, Jamili, Nadian, & Shahbazi, 2015; Kia Kianian, Asgari, Bahadori, Resources, & Agricultural, 2019; Masumian, Naghdi, Zenner, Nikooy, & Lotfalian, 2017; Sadeghi, Hazbavi, & Kiani-Harchegani, 2016) and inorganic (e.g., Emami & Astaraei, 2012; Hazbavi et al., 2013; Kia Kianian et al., 2019; Padidar et al., 2016; Safari, Kavian, Parsakhoo, Saleh, & Jordân, 2016) soil amendments under different conditions, very limited research (Gholami, Khaledi Darvishan, & Kavian, 2016; Jourgholami &
Etehadi Abari, 2017) has been done on reducing runoff and soil erosion control using wood-based mulches. Importantly, no study has examined reducing runoff, soil loss and sediment concentration behavior using different wood lengths and coverages. Our research is motivated by the high risk of accelerated soil erosion in Iran (Kavian, Azmoodeh, & Solaimani, 2014; Masumian et al., 2017). The northern forests of Iran (Hyrcanian forests) are valuable economic resources that are currently being exploited by wood industries. Extraction of timber from these forests has required extensive road networks to be constructed, nearly always without consideration for soil conservation and erosion mitigation (Parsakhoo, Lotfalian, Kavian, & Hosseini, 2014). Mechanical logging and skid trail construction have led to high rates of erosion on disturbed logging surfaces (Jourgholami & Etehadi Abari, 2017; Lotfalian, Parsakhoo, Kavian, & Hosseini, 2013; Safari et al., 2016). In addition, unsustainable cultivation practices (Kavian et al., 2014) and various other land use activities have accelerated erosion rates in the last several decades (Kelarestaghi & Jafarian, 2011).

Throughout Iran, more than 70% of the total area is exposed to soil erosion that produces an estimated 2 billion tons of soil loss each year (Jafarzadeh, Garosi, Oustan, & Ahmadi, 2013). On average, soil erosion in Iran is three times more than other Asian countries; and Iran has one of the highest country-wide erosion rates in the world (Darvish, 2016). Based on a recent work that valued soil loss in Iran at US$28 per ton (Darvish, 2016), the potential cost of soil erosion in the country is on the order of US$50–60 billion. Thus, there is much interest in mitigating accelerated erosion and rehabilitating degraded lands through use appropriate erosion control systems, especially biodegradable, environmentally sensitive wood-based mulches that are inexpensive and can be sourced locally. Unfortunately, limited work has been conducted to date to identify such products in Iran. Therefore, the research reported in this article builds on these and other research conducted in North America (e.g., Foltz & Wagenbrenner, 2010; Negron & Cain, 2018) and Europe (e.g., Prats et al., 2017) to investigate the effectiveness of two native wood mulches from Iran. The goal of the experiment was to determine the effectiveness of two different types of native wood strands in reducing runoff, soil loss, and sediment concentration during laboratory rainfall simulations, and therefore, assess its appropriateness for use in degraded forested catchments in Iran.

2 | MATERIALS AND METHODS

We assessed the effectiveness of two types of wood strands (Alnus glutinosa and Fagus orientalis) of two lengths (4 and 16 cm) and two cover percentages (30 and 70%) in reducing runoff and soil erosion. We performed three replications for each treatment combination and the bare control (27 total experiments) on silty loam soil representative of forest soils in northern Iran. A summary of treatments characteristics of the experiment is given in Table 1. The soil had a bulk density of 0.83 g cm$^{-3}$, low organic matter content (~2%), and high pH (8.36). The soil was collected from the upper 10 cm of the forest ground surface and passed through 6-mm sieve to remove large particles (Gholami et al., 2016). Samples were air-dried, then homogenized, before packed lightly into the simulator plots (1 m wide × 2 m long × 0.2 m deep) to a bulk density similar to field conditions.

<table>
<thead>
<tr>
<th>Treatments characteristics</th>
<th>Species</th>
<th>Alnus glutinosa</th>
<th>Fagus orientalis</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Species</strong></td>
<td></td>
<td>Alnus glutinosa</td>
<td>Fagus orientalis</td>
</tr>
<tr>
<td><strong>Mulch</strong></td>
<td></td>
<td>4</td>
<td>16</td>
</tr>
<tr>
<td>Length (cm)</td>
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<td>4</td>
<td>16</td>
</tr>
<tr>
<td>Wide (cm)</td>
<td></td>
<td>1.5</td>
<td>1.5</td>
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<tr>
<td>Thickness (mm)</td>
<td></td>
<td>1.5–2</td>
<td>1.5–2</td>
</tr>
<tr>
<td>Cover (%)</td>
<td></td>
<td>30</td>
<td>70</td>
</tr>
<tr>
<td>Lignin (%)</td>
<td></td>
<td>32.5</td>
<td>22.15</td>
</tr>
<tr>
<td>Cellulose (%)</td>
<td></td>
<td>47.3</td>
<td>45</td>
</tr>
<tr>
<td>Application rate (g m$^{-2}$)</td>
<td></td>
<td>350</td>
<td>930</td>
</tr>
<tr>
<td><strong>Rainfall and plot</strong></td>
<td></td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>Plot slope (%)</td>
<td></td>
<td>BEX (3/8 S24 W)</td>
<td></td>
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<tr>
<td>Nozzle type</td>
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<tr>
<td>Raindrop mean diameter (mm)</td>
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<td>1.05</td>
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<tr>
<td>Rainfall intensity (mm hr$^{-1}$)</td>
<td></td>
<td>50</td>
<td></td>
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<tr>
<td>Rainfall duration (min)</td>
<td></td>
<td>20</td>
<td></td>
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<tr>
<td><strong>Soil</strong></td>
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</tr>
<tr>
<td>Texture</td>
<td></td>
<td>Silty loam</td>
<td></td>
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<tr>
<td>Bulk density (g cm$^{-3}$)</td>
<td></td>
<td>0.83</td>
<td></td>
</tr>
<tr>
<td>Organic matter (%)</td>
<td></td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>EC ($\mu$s cm$^{-1}$)</td>
<td></td>
<td>0.36</td>
<td></td>
</tr>
<tr>
<td>pH (%)</td>
<td></td>
<td>8.36</td>
<td></td>
</tr>
<tr>
<td>CaCO$_3$ (%)</td>
<td></td>
<td>3.31</td>
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</tr>
</tbody>
</table>

EC = Electrical Conductivity.
The wood strands were sliced from pieces of *A. glutinosa* and *F. orientalis* factory waste material by hand (Figure 1). These two forest species are prevalent in the northern forests of Iran and are harvested frequently during road construction and other commercial exploitation. The wood strands were 1.5–2 mm thick, 1.5 cm wide, and of lengths 4 and 16 cm (Figure 1). Two coverages applied (30 and 70%) corresponded to application rates of 350 and 930 g m\(^{-2}\), respectively. The cover percentages were measured using image-processing method according to Kavian, Mohammadi, Cerda, Fallah, and Abdollahi (2018). The two wood strands of *A. glutinosa* and *F. orientalis* (Table 1) have approximately similar percentages of lignin (32.5 and 22.1%, respectively) and cellulose (47.3 and 45.0%, respectively), two properties that are useful for evaluating moisture absorption ability (based on Technical Association of the Pulp and Paper Industry [TAPPI] Standard, 2018).

Erosion plots were inclined at a 20% angle similar to the slope of the soil origin (Figure 1). Several holes, 2 mm in diameter and 10 mm apart, were drilled in the bottom of the plot container to allow free subsoil drainage (Adekalu, Okunade, & Osunbitan, 2006). Wood strand covers were applied by hand casting in attempt to create a uniform distribution. Before and after each rainfall simulation, soil moisture content was measured by oven-drying grab samples at 105°C. The rain was applied using a rainfall simulator consisting of a 500-L water tank and one precalibrated BEX (3/8 S24 W) nozzle, which has the ability to simulate 1.05-mm mean diameter raindrops at an energy approximating natural rainfall (Abdollahi, Sadeghi, & Khaledi Darvishan, 2013; Gholami et al., 2016). Initially, the plot was (pre)wetted using a rain intensity of 50 mm hr\(^{-1}\) for 10 min to saturate the soil surface, but not induce ponding. This rainfall did not produced any runoff. The soil contained a moisture content of 15%. A rainfall intensity of 50 mm hr\(^{-1}\) was then applied during 20-min simulations corresponding to climatological conditions of soil origin (Kavian, Mohammadi, et al., 2018; Safari et al., 2016). The rainfall intensity and duration were sufficient to make the entire prewetted plot area contribute to runoff generation (Foltz & Wagenbrenner, 2010).

Runoff and sediment samples were collected in several plastic containers at 5-min intervals to calculate runoff, soil loss, and sediment concentration rates. Total sediment in each sample was determined by oven drying at 105°C (Mohamadi & Kavian, 2015). Given that the sample number was low (n = 3 for all combinations), we examined the median ± median absolute deviations (MADs) (Rousseeuw & Croux, 1993; Sadeghi, Najafi, Bakhtiar, & Abdi, 2014) and performed statistical tests on various combinations with the nonparametric Kruskal–Wallis test (KW) (Kruskal & Wallis, 1952; Sadeghi, Raeisi, & Hazbavi, 2018; Singh Sidhu, 2015). To test the significance in the differences between the two wood strand types (*A. glutinosa* and *F. orientalis*), two application rates (or ground cover of 30 and 70%) and two strand sizes (4 and 16 cm) as compared to bare soil, we used the nonparametric Mann–Whitney U test (Mann & Whitney, 1947; Singh Sidhu, 2015).
3 | RESULTS

Median ± MADs of total runoff, soil loss, and sediment concentration on the bare soil control plots were 4.7 ± 0.1 mm, 106.5 ± 4.0 g m$^{-2}$, and 87.8 ± 0.3 g L$^{-1}$, respectively (Table 2, Figures 2–4). The hydrological data indicated that all treatments reduced total runoff by 12–78% (Table 2). The 4-cm Alnus treatment applied at 70% coverage was the most effective (KW, $\alpha \leq 0.003$) at reducing runoff: 1.0 ± 0.5 mm versus 4.7 ± 0.1 mm on the bare control (78% reduction; Table 2). The second most effective treatment (KW, $\alpha \leq 0.003$) also involved 4-cm strands applied at 70% coverage of Fagus material. This treatment reduced total runoff from 4.7 ± 0.1 to 2.1 ± 0.0 mm (54% reduction; Table 2). Runoff reductions for the other treatments were less (12–29%), of which the reduction by the 16-cm strands applied at 30% coverage was the

### TABLE 2  Median total runoff, soil loss, or sediment concentration values for the rainfall simulation experiments conducted using different treatments of Alnus glutinosa and Fagus orientalis mulching strands

<table>
<thead>
<tr>
<th></th>
<th>Control</th>
<th>16 cm–30%</th>
<th>4 cm–30%</th>
<th>16 cm–70%</th>
<th>4 cm–70%</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Total runoff (mm)</strong></td>
<td></td>
<td></td>
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<tr>
<td>Alnus glutinosa</td>
<td>4.7 ± 0.1 e</td>
<td>3.8 ± 0.2 cd</td>
<td>3.6 ± 0.1 c</td>
<td>3.4 ± 0.0 c</td>
<td>1.0 ± 0.5 a</td>
</tr>
<tr>
<td>Fagus orientalis</td>
<td>4.1 ± 0.1 de</td>
<td>3.3 ± 0.1c</td>
<td>3.3 ± 0.1c</td>
<td>3.3 ± 0.1c</td>
<td>2.1 ± 0.0 b</td>
</tr>
<tr>
<td><strong>Runoff reduction (%)</strong></td>
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</tr>
<tr>
<td>A. glutinosa</td>
<td>–</td>
<td>18</td>
<td>22</td>
<td>27</td>
<td>78</td>
</tr>
<tr>
<td>F. orientalis</td>
<td>–</td>
<td>12</td>
<td>29</td>
<td>29</td>
<td>54</td>
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<tr>
<td><strong>Total soil loss (g m$^{-2}$)</strong></td>
<td></td>
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<tr>
<td>A. glutinosa</td>
<td>106.5 ± 4.0 d</td>
<td>49.5 ± 7.5 bc</td>
<td>23.5 ± 1.0 bc</td>
<td>8.0 ± 4.5 ab</td>
<td>1.5 ± 0.1 a</td>
</tr>
<tr>
<td>F. orientalis</td>
<td>56.0 ± 2.5 c</td>
<td>31.0 ± 4.5 bc</td>
<td>17.5 ± 4.5 ab</td>
<td>6.0 ± 1.5 ab</td>
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<tr>
<td><strong>Soil loss reduction (%)</strong></td>
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<td></td>
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<td></td>
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<tr>
<td>A. glutinosa</td>
<td>–</td>
<td>54</td>
<td>78</td>
<td>92</td>
<td>99</td>
</tr>
<tr>
<td>F. orientalis</td>
<td>–</td>
<td>47</td>
<td>71</td>
<td>84</td>
<td>94</td>
</tr>
<tr>
<td><strong>Total sediment concentration (g L$^{-1}$)</strong></td>
<td></td>
<td></td>
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<tr>
<td>A. glutinosa</td>
<td>87.8 ± 0.3 d</td>
<td>45.2 ± 5.7 bc</td>
<td>34.9 ± 6.3bc</td>
<td>7.6 ± 4.0 a</td>
<td>4.9 ± 1.4 a</td>
</tr>
<tr>
<td>F. orientalis</td>
<td>49.3 ± 2.1 c</td>
<td>31.9 ± 4.7 BC</td>
<td>19.6 ± 5.5 ab</td>
<td>8.7 ± 1.5 a</td>
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<tr>
<td><strong>Sediment concentration reduction (%)</strong></td>
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<tr>
<td>A. glutinosa</td>
<td>–</td>
<td>48</td>
<td>60</td>
<td>91</td>
<td>94</td>
</tr>
<tr>
<td>F. orientalis</td>
<td>–</td>
<td>44</td>
<td>64</td>
<td>78</td>
<td>90</td>
</tr>
</tbody>
</table>

Note: $N = 3$ for all groups of simulations on two types of material (Alnus glutinosa and Fagus orientalis), two strand sizes (4 and 16 cm), and two coverages (30 and 70%). The control simulation was performed on bare soil. The runoff, soil loss, and sediment concentration reductions are expressed as percentages of the treatments as compared to bare soil. Different lowercase letters indicate significant differences among treatments for each total runoff, soil loss or sediment concentration variables, $p < .05$.

**FIGURE 2** Cumulative runoff from the bare plots and plots with various treatments of Alnus glutinosa (a) and Fagus orientalis (b) wood strand mulching. Error bars indicate median absolute deviations.
poorest (12–18% for the two materials; Table 2). Odd was the rather poor performance of the 70% coverage of 16-cm strands, which allowed 3.3–3.4 mm of runoff (reductions of only 27–29%). With respect to runoff reduction, the 4-cm (70%) treatments of Fagus and Alnus strands reduced runoff significantly, compared with all other treatments and the control (Table 2 and Figure 2).

Similar to the runoff results, the most effective treatment (KW, $\alpha \leq .003$) for reducing soil loss on the erosion plots was the 4-cm strands of either material applied at a 70% coverage (Table 2, Figure 3). Median total soil loss values for the Alnus ($1.5 \pm 0.1$ g m$^{-2}$) and Fagus ($6.0 \pm 1.5$ g m$^{-2}$) materials were only about 1 and 6% of 106.5 ± 4.0 g m$^{-2}$ of total loss that occurred on the bare soil plots (Table 2). The second most effective treatment was the 16-cm strands of either material applied at a 70% coverage (Table 2, Figure 3). The median soil losses of 8.0 ± 4.5 g m$^{-2}$ (Alnus) and 17.5 ± 4.5 g m$^{-2}$ (Fagus) represented 92 and 84% reductions (KW, $\alpha \leq .003$) from the median of the bare soil control plots (Table 2). In comparison, the 30% cover treatments were less effective at reducing soil loss, regardless of material or strand size. Nevertheless, these treatments were effective at reducing soil loss. For example, the treatment with the worst performance (16 cm Fagus strands applied at 30% coverage) reduced total soil loss by nearly 50% (56.0 vs. 106.5 g m$^{-2}$ on the control).

The soil loss reductions by all treatments were statistically significant (Table 2; KW, $\alpha < .05$). The most effective treatment was the 4-cm, 70% treatment (94–99% reduction) followed by 16-cm, 70% (84–92% reduction), 4-cm, 30% (71–78%) and 16-cm, 30% (47–54%). This ordering was true for both Fagus and Alnus materials, with no significant differences occurring between the two materials (Table 2; KW, $\alpha < .05$).

The lowest sediment concentration where associated with the 4-cm–70% and 16-cm–70% applications of Alnus material: 4.9 ± 1.4 and 7.6 ± 4.0 g L$^{-1}$, respectively (Table 2, Figure 4). All treatments, however, significantly reduced (KW, $\alpha < .05$) sediment concentration.
compared with the bare plot. Reductions ranged from 48 to 94% for Alnus and from 44 to 90% for Fagus materials. The results showed that the strands applied at 70% coverage of Alnus were general more effective in sediment concentration rather than Fagus with same coverage. The least effective of study treatments in sediment concentration reduction were the 16-cm average. The least effective of study treatments in sediment concentration were the 16-cm average. The least effective of study treatments in sediment concentration reduction were the 16-cm–30% coverage of Alnus (45.2 ± 5.7) and Fagus (49.3 ± 2.1), respectively (Table 2, Figure 4).

Collectively, the following synthesis can be made: (a) the 4-cm strands applied at 70% coverage reduced runoff, soil loss, and sediment concentration better than other treatments (KW, \( \alpha < .003 \)); (b) the 70% coverages of any length strand were more effective than the 30% coverages; and (c) the two products were almost equally effective in reducing soil loss and sediment concentration, particularly when small strands (4 cm) were applied at a high coverage (70%).

4 | DISCUSSION

Our various applications of the native wood strand mulch reduced runoff, soil loss, and sediment concentration of the erosion plots, respectively, by 12–78, 47–99, and 44–94%. The experimental observations verified the successful efficacy of the wood strands in reducing runoff, soil loss, and sediment concentration (almost significant at \( p \) value <.05) through increasing the soil water retention and soil protective cover. Similar results were reported for different soil amendments applications specifically wood-based mulches (e.g., León et al., 2015; Prosdocimi et al., 2016; Turk, 2018). The three-dimensional layering of the wood strands provided a highly stable matrix (Yanosek et al., 2006) leading to soil stabilization against rainfall and runoff. Foltz and Dooley (2003) verified the effect of wood strands (compared with straw and narrow strands [4 mm wide]) on runoff and sediment reduction of a silt loam soil in their three-phase experiment. Foltz and Copeland (2009) simulating runoff and soil erosion on plots of 30, 50, and 70% wood shred cover on coarse- and fine-grained soil, found that wood shreds reduced runoff and soil loss by 60% to nearly 100%, depending on the soil type, rate of concentrated flow, and wood shreds cover. Prats et al. (2012) also reported an 87% reduction in soil erosion associated with the application of chopped eucalyptus bark mulch following wildfire in Portugal and the same material was also found very effective against rill erosion under laboratory conditions (Prats et al., 2017).

Observations during the simulations provide two major insights regarding the effectiveness of some treatments. Firstly, strands applied at the 70% coverage provided more protection from raindrop detachment and splash transport than the 30% coverages. This finding is in agreement with those of other studies. For example, Robichaud et al. (2012) using a blend of sizes of wood chips at three cover percentages (0, 50, and 70%) found that the largest erosion reduction was for a 70% cover. Gronier et al. (2005) reported that a 70% coverage of wood chips reduced soil loss by 98%. Yanosek et al. (2006) determined that two wood strand blends both reduced sediment loss by >70% for a range of coverages (30, 50, and 70%) for different soil types, slopes, and overland flow rates. However, they found much higher reductions of runoff (80–99%) during simulated low-intensity storms than we observed (≤78%). They also found that a 70% cover delayed runoff generation by 7–12 min, compared with a bare treatment for a variety of soil types (also see Robichaud et al., 2013).

Secondly, we found that small strands were the most effective in mitigating runoff and erosion processes as they were widely dispersed across the simulation surface and created numerous microdams on the soil that retarded surface runoff. In comparison, the 16-cm strands did not always adhere tightly to the soil surface, and therefore, were less effective in blocking surface flow, creating dams, and retarding soil entrainment. In some cases, the long 16-cm strands (re)aligned in the direction of flow, aiding the formation of small rills. Our results were consistent with findings of by Foltz and Dooley (2003) who noted that longer (24 cm) wood strands bridge over the soil rather than lie in contact with the soil in contrast with the 6- and 12-cm wood strand. They encountered difficulty in the spreading of long wood strands and suggested using wood strands with lengths up to 12–15 cm. Pannuk and Robichaud (2003) studying the application of two lengths of pine needles (2.6 and 16.5 cm), also found that the shorter needles were more effective in controlling interrill erosion due to higher contact with the soil surface; however, longer needles were effective in reducing rill erosion. Yanosek et al. (2006) concluded that the wood strands provided a highly stable matrix that helped to reduce soil loss, in part, by preventing rill formation. However, there are contrary results obtained by Fernández et al. (2011) who achieved very low effectiveness from 400 g m⁻² wood chips applied in the field. They attributed this to the shortness of the chips, which allowed them to float and be transported away with the runoff.

It is expected that different factors including wood type, length, wide, thickness, application rate, rainfall characteristics, soil properties, and slope gradient contribute to the effectiveness of wood strand in runoff and soil erosion reduction. For example, the wood strand type is an intrinsic characteristic that could result in differences depending on its biodegradability rate, moisture-holding ability, fiber, and permeability potential. Some of the differences between our results and those of prior studies could relate to material composition.

Although Foltz and Copeland (2009) believed that mulch cover percentage was more important than mulch material in determining effectiveness, Foltz and Wagenbrenner (2010) found no significant difference between 50 and 70% wood shred cover. Prosdocimi et al. (2016) by reviewing the effect of different mulches on behavior of different hydrological and erosive variables, noted significant differences among wood-based mulches effectiveness due to different measurement methods and types of mulch with respect to the soil loss and/or soil erosion rate.

While our simulations provide insight on effective application rates of the native Iranian wood strand mulches, we recognized the limitation that rainfall simulation on small plots of disturbed soil does not necessarily reflect natural conditions. Hence, it is suggested to test the efficiency of the two study natural products in different application rates and coverages on soil loss mitigation under disturbed soil conditions that are subjected to accelerated erosion processes, particularly splash detachment and interrill erosion.

Other researches with mulch in laboratory (Foltz & Wagenbrenner, 2010; Prats et al., 2017) and field conditions (Lucas-Borja et al., 2019;
Prats et al. (2012) showed a low effect on runoff, which is likely a consequence of the mulching acting as a filter for the runoff water and retaining the sediments in place. Furthermore, Foltz and Wagenbrenner (2010) verified the limited effectiveness of wood shreds on the reduction of runoff and sediment concentration due to steep slope of the study plots (ca. 40%). The low runoff reduction in Prats et al. (2017) study was attributed to the low application rate (i.e., 100–260 g m$^{-2}$) and the removal of the forest residue mulch less than 4 cm in length. In addition, the strip length and strip ground cover factors significantly explained portions of the variation in the hydrologic and erosive responses. They reported that the runoff depended most on mulch cover, while soil losses depended most on strip width.

As our runoff and erosion responses were similar to those found in other studies, we have confidence in the effectiveness of the two products in mitigating runoff and mainly soil loss and sediment concentration. It is believed that the treatment–soil contact is an important factor contributing to soil erosion mitigation. Adapting similar field trials would be the logical next step in this line of inquiry. It is also highly suggested to test the similar methodology on longer slopes at disturbed sites in the field where rill erosion is likely to occur. We also believe it worthwhile to test combinations of long and short material to see how they work in tandem to reduce interrill and rill process.

5 | CONCLUSIONS

A. glutinosa and F. orientalis wood strands (natural products in Iran) with 4 and 16 cm lengths and 30 and 70% coverages were effective in reducing runoff, soil loss, and sediment concentration. The application of 4-cm strands of both native wood strands at 70% coverage was the most effective treatment, producing 54–78% reductions of runoff as compared to control plots. Furthermore, the incorporation of same treatments into the soil reduced soil loss by 94–99% as compared to control plots. In addition, 90–94% reductions of sediment concentration were obtained for 4-cm strands applied at 70% coverage. The two products were less effective when applied at 30% coverage and/or when longer (16-cm) strands were applied. The 4-cm strands were better, in part, because of their ability to adhere to the soil surface and maintain a non-uniform distribution that blocked water flow and contributed to ponding. In addition, the high surface coverage (70%) probably mitigated rain splash energy. The effect of the wood strands in reducing runoff was not obvious. While both natural products appear to be more suitable for application on accelerated erosion sites in degraded forests of northern Iran, additional research should investigate which coverages and strand dimensions, intermediate of those we tested, are optimal and the most cost effective for mitigating runoff and soil loss. We also recommend that additional tests be performed on longer slopes in the field under natural conditions.

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