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Effect of bioengineering treatments on reduction of soil erosion from road cut slope and fill slope

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Abstract: The efficiency of different conservation practices on soil loss from road side slopes is scarcely identified in the Hyrcanian forests of Iran, which could retard the implementation of these management practices. Sediment of 48 plots on the cut slopes and fill slopes of forest roads were collected to explore their responses to soil conservation practices, including straw bale (SB), living hedge (LH), dead hedge (DH), geo-cell (GC), geotextile (GT), and bare soil (BS). Moreover, the efficiency of conservation practices was evaluated to find a cost-effective approach. Sediment traps were installed at the toe of side slopes in the ditch and end of each treated plot. Sediment volume was measured monthly for six months. The results demonstrated that the lowest soil loss occurred in autumn and fill slopes treated with GC (5.05 $g \cdot m^{-2}$) and the highest in winter and cut slopes treated with SB (41.81 $g \cdot m^{-2}$). In all cases, soil loss from BS (126.74 $g \cdot m^{-2}$) was significantly higher than in plots treated with conservation practices. GC performed well under certain circumstances due to two-dimensional protections of contiguous wooden lumbers. Moreover, it was found that in a short time there were not any significant differences between LH (28.78 $g \cdot m^{-2}$), DH (36.01 $g \cdot m^{-2}$), and GT (30.61 $g \cdot m^{-2}$) in soil loss control ability. Regarding implementation and installation costs, GC (USD 16.67 per plot) was the most expensive, while LH (USD 3.33 per plot) was the cheapest. Regarding GC, it is necessary to conduct long-term research to determine economic efficiency, durability, maintenance, and repair costs. Until then, it is possible to use affordable treatments such as LH, which have yielded favourable results in efficiency.

Keywords: geo-cell; Hyrcanian region; road side slopes; season; sediment

Water erosion is the process of washing and transporting soil particles by runoff and deposition of sediment in gentle slopes. Removal of vegetation, disturbance of topsoil, creation of steep slopes, and compaction due to road construction are the reasons for erosion (Nguyen et al. 2020; Su et al. 2020). This process can destroy road structures, downstream water quality, and aquatic habitats (Ramos-Scharrón et al. 2022). Moreover, soil erosion can have serious consequences as it causes

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severe nutrient loss (Gholami et al. 2021). Nutrient loss through runoff and soil erosion is an essential threat to soil nutrient depletion in forests, bringing about high costs because of the need for restoration practices to enhance the sustainability of forest systems (Akay et al. 2020; Chen et al. 2020).

Forest road side slopes are critical resources of sediment production, especially in landslide-prone areas (Parsakhoo et al. 2014). Therefore, conservation practices should be used, mainly when the forest road construction occurs in steep and unstable topography (Kumar et al. 2021). Soil conservation practices are a series of biological and mechanical engineering approaches such as terraces, geosynthetic mats, reforestation, geo-cell, geotextile, living hedge, dead hedge, erosion control blankets, hydro mulch, and water absorption bale which can be used to protect erosive slopes (Gilley et al. 2000; Bhattacharyya et al. 2010; Hytiris et al. 2015; Acharya 2020; Wang et al. 2022). Most of them are designed to minimise contact between water and soil by absorbing the kinetic energy of rainfall and runoff flow. Conservation practices effectively reduce the erosive power of surface runoff and mitigate the development of erosion (Grace 2000).

Many studies have emphasised the importance of conservation practices against soil loss. For example, Song et al. (2021) used geo-cell-containing wheat straws to control soil erosion and provide suitable conditions for vegetation growth. The results showed that soil erosion increased with increasing rainfall intensity and cell dimensions. Grace (2000) showed the most significant erosion control potential of native and exotic vegetative species as compared to wood excelsior mat. The effects of geotextile, vetiver grass, and a combination of geotextile and vegetation on soil loss control were studied on 45° side slopes with lateritic soil. The results revealed that the geotextile prevented erosion immediately after installation, but vetiver grass exhibited good erosion control after six months (Likitlersuang et al. 2020). Gholami et al. (2021) investigated the effect of straw bale, dead hedge, and geo-cell on the sedimentation rate of forest road side slopes under rainfall events. Results showed that the straw bale treatment is more efficient than the other two treatments. In a study in northern China, Fang (2021) showed that the annual soil loss rate significantly decreased on the terraced field as compared to the plot with no soil conservation. In a study about slope stabilisation in Nepal, Kumar et al. (2021) proved the beneficial effects of geo-cell, geo-grid and micropile on increasing soil resistance against erosion. Paz et al. (2018) indicated the positive performance of coconut, geo-mat, and geo-cell in reduction of soil erosion from road cut slopes. Geo-cell had a significantly high efficiency due to its special structure.

In the mountainous forests of the Hyrcanian zone, where road construction is costly and complex, it is necessary to apply environmentally friendly procedures and a successful method to protect unstable slopes. Soil conservation practices are still rare in some regions, especially in developing countries (Wu et al. 2020). A lot of theoretical reports show that different soil stabilisation methods have a good reinforcement effect, but they still lag behind the engineering practical experience, and the soil conservation practices under natural forest and slope conditions need to be further studied. So, selecting soil conservation materials with adequate price, ability and persistence is necessary to obtain maximum soil stability. The specific aims of this study were to (*i*) study the soil loss from cut slopes and fill slopes under different soil conservation measures, and (*ii*) identify the cost of conservation practices in a mountainous forest road in the Hyrcanian zone.

MATERIAL AND METHODS

Description of study area. Bahramnia forest with 1 713 ha and an altitude range of 100 m a.s.l. to 1 000 m a.s.l. is located in Golestan province on a lime and sandstone bedrock (36°43'27'' to 36°48'6''N and 54°21'26'' to 54°24'57''E; Figure 1). This mixed deciduous forest with mean stock growth of 247 $m^3 \cdot ha^{-1}$ has brown soil with mostly silty-loam-clay texture. The climate of the region is Mediterranean with mean annual precipitation of 562 mm. In Bahramnia forest, 30.3 km of forest roads were constructed in 1989. Some segments of roads in this forest are susceptible to erosion and in rainy seasons water erosion occurs there.

Sampling plan and initial evaluations. Forty-eight erodible road side slopes with gradients of 45–60° were selected for this study. The dimensions of plots were 3 m in height, and 10 m in length (area: 30 m^2). Six soil conservation treatments, each of four replications in two blocks (cut slopes and fill slopes), formed a complete

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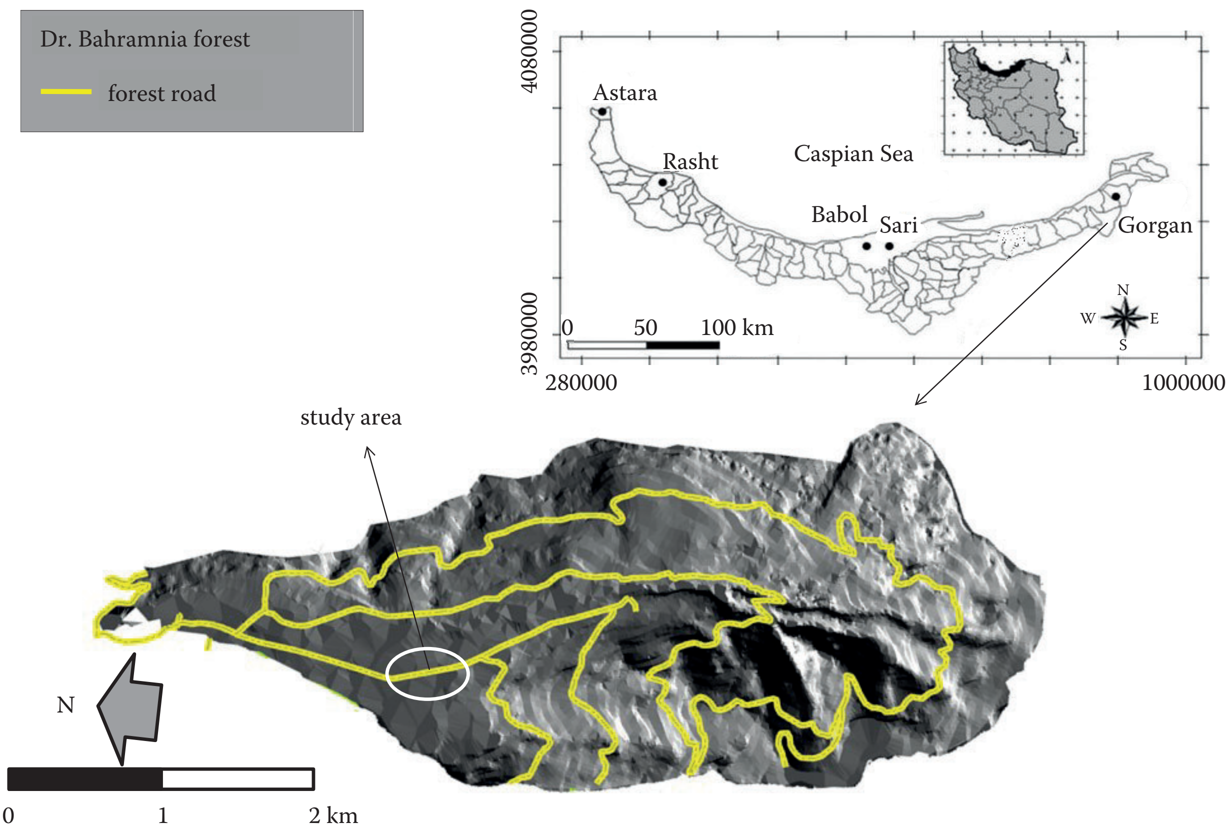

Figure 1. The geographical position of the study area

randomised block design. In each plot, three soil samples (0–20 cm depth) were taken during the preparation of treatments to determine the physical and chemical properties of the soil. Soil texture was measured using the hydrometer 1200 (ALLA, France). The organic matter content was calculated by Walkley and Black method (Table 1). The soil conservation treatments including geo-cell (GC), geotextile (GT), straw bale (SB), living hedge (LH), dead hedge (DH), and bare side slope as control plots (BS) were located in places with the highest concentration of precipitation and the most severe soil erosion (Figure 2).

Implementation of conservation treatments. Wheat straw bales were installed on road side slopes in parallel directions with a distance of 1.5 m. The diameter, length and mass of each straw bale used in this study were 0.3 m, 3 m, and 2 000 $g \cdot m^{-1}$, respectively. Geo-cells are two-dimensional systems with a cellular structure. In this study, the depth of the geo-cells, as well as the size of each cellular unit, was 10 cm and 0.25 m^2 (50 cm × 50 cm). Wooden lumbers with a length of 3 m and a width of 0.3 m were used to create geo-cells. Cotton geotextile with a thickness of two mm and mass per square meter of 220 g was installed on road side slopes. Dead hedges are piles of branches and twigs arranged to form a barrier on 0.4-m terraces on road side slopes. This treatment was installed by placing the stakes (with a diameter of 50 cm and length of 100 cm) at one-meter distances in parallel directions with a distance of 1.5 m among directions. Thin twigs with a maximum diameter of 3 cm were installed among stakes. Pussy willow living hedges in a cut consist of a row of cuttings (40 cm to 50 cm long by 2–3 cm in diameter)

Table 1. Characteristics of the study road side slopes

Block	Slope direction	Bulk density ($g \cdot cm^{-3}$)	Silt (%)	Clay (%)	Sand (%)	Organic matter (%)
Cut slope	northeast	1.12	47.1	24.9	27.0	3.5
Fill slope		0.92	46.3	24.9	28.9	6.7

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Block 1 Cut slope	R1 BS	R1 SB	R1 GC	R1 GT	R1 LH	R1 DH	R2 BS	R2 SB	R2 GC	R2 GT	R2 LH	R2 DH
Block 2 Fill slope	R1 BS	R1 SB	R1 GC	R1 GT	R1 LH	R1 DH	R2 BS	R2 SB	R2 GC	R2 GT	R2 LH	R2 DH
Block 1 Cut slope	R3 BS	R3 SB	R3 GC	R3 GT	R3 LH	R3 DH	R4 BS	R4 SB	R4 GC	R4 GT	R4 LH	R4 DH
Block 2 Fill slope	R3 BS	R3 SB	R3 GC	R3 GT	R3 LH	R3 DH	R4 BS	R4 SB	R4 GC	R4 GT	R4 LH	R4 DH

Figure 2. Sampling plan and experimental design of research

BS – bare soil (control plot); SB – straw bale; GC – geo-cell; GT – geo-textile; LH – living hedge; DH – dead hedge; R1 – replication 1; R2 – replication 2; R3 – replication 3; R4 – replication 4

placed in a trench excavated along the slope contour. The width of the trenches and the internal gradient of the trench bed were 0.4 m and 20%, respectively. The three nodes of cuttings are planted deeply so that only 30% of their length protrudes from the slope (Figure 3).

Measuring of soil loss from road side slopes. A sediment collection trap was placed at the

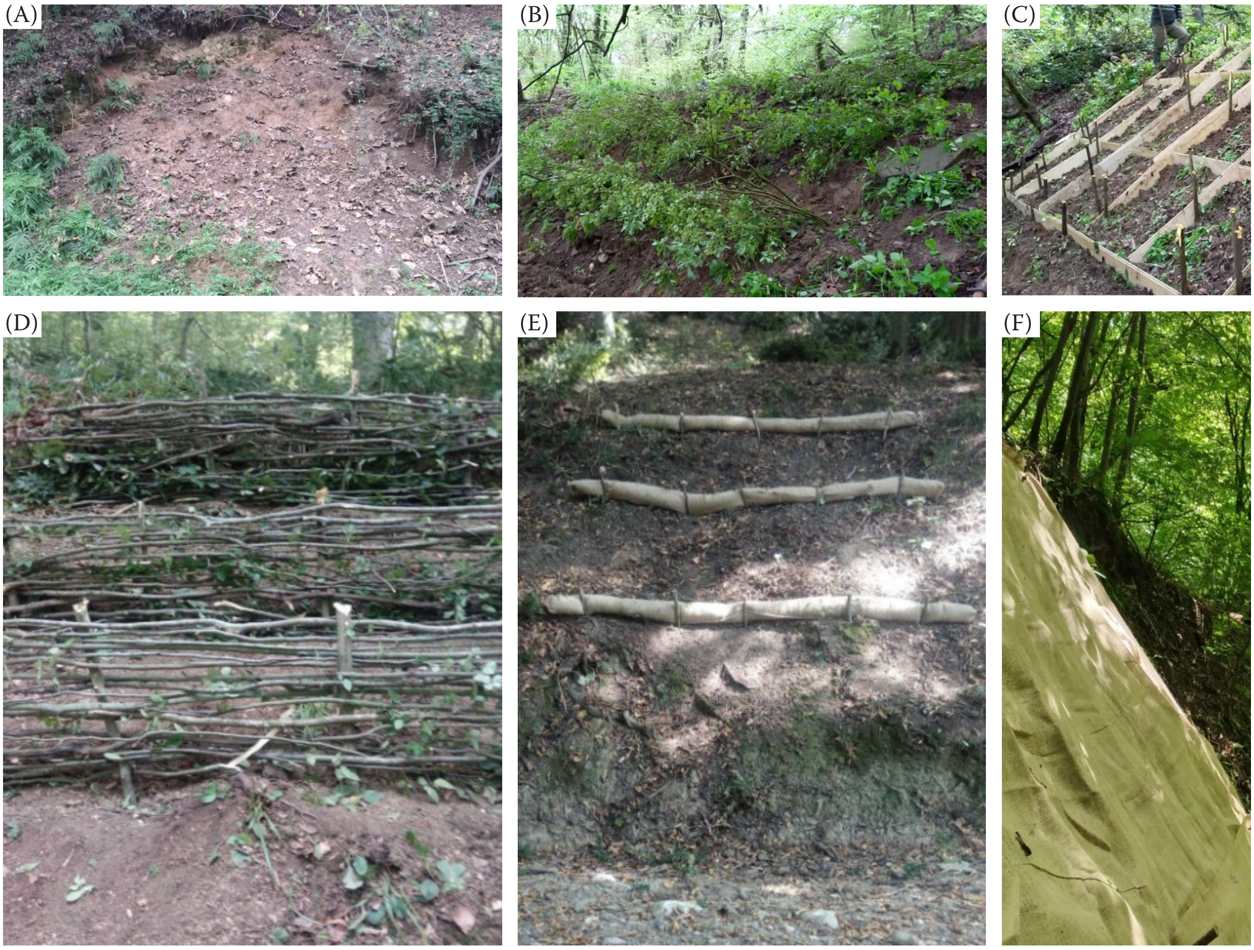

Figure 3. Soil conservation practices applied on road side slopes: (A) bare soil, (B) living hedge, (C) geo-cell, (D) dead hedge, (E) straw bale, and (F) geo-textile

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Table 2. Meteorological characteristics during the study period

Treatment	Rainfall (mm)	Temperature (°C)	Relative humidity (%)	Wind ($m \cdot s^{-1}$)
September 2021	51.8	22.3	65	
October 2021	56.7	15.3	76	
November 2021	10.2	10.7	78	2
December 2021	77.2	15.3	76	
January 2022	9.7	9.8	70	
February 2022	84.4	9.5	72	

downslope end of each treated plot. The diameter and depth of the trap were 0.4 m and 0.6 m, respectively (75 L). The field study lasted for six months, from September 2021 to February 2022, and in this period, 26 rains occurred. The characteristics of rainfalls were recorded by a portable station (Table 2). Sediment measurements were performed monthly according to the ruler within the sediment trap. The height of deposited sediment (m) was multiplied by depositional area (m^2) to calculate sediment volumes (m^3). Then, sediment volume was multiplied by soil bulk density (soil core method) to identify sediment mass.

Statistical analysis. Data analysis with the GLM procedure (factorial test) was done to assess the effect of independent variables including conservation treatments in six levels and side slopes in two levels on sediment mass. Totally, 100 sediment samples were collected during the study period. LSD test was used to compare means between treatments in the SAS program (Version 9.4, 2013).

RESULTS AND DISCUSSION

Conservation treatments, season and the road side slopes and their pairwise interactions had significant effects on soil loss. The interactions of season, road side slope, and conservation treatment on soil loss were not meaningful (Table 3). Soil loss presented large variations over months due to uneven distribution and intensities of rainfalls. The trend of changes in the amount of soil loss in different months shows that the highest amount of soil loss from treated plots was obtained in February. These values were 49.95 $g \cdot m^{-2}$, 21.19 $g \cdot m^{-2}$, 113.12 $g \cdot m^{-2}$, 40.40 $g \cdot m^{-2}$, 24.98 $g \cdot m^{-2}$, and 20.20 $g \cdot m^{-2}$ for the treated cut slopes by SB, LH, BS, DH, GT, and GC, respectively. In addition, 27.75 $g \cdot m^{-2}$, 12.47 $g \cdot m^{-2}$, 62.84 $g \cdot m^{-2}$, 22.44 $g \cdot m^{-2}$, 14.69 $g \cdot m^{-2}$, and 10.63 $g \cdot m^{-2}$ of soil were washed and eroded from the treated fill slopes by SB, LH, BS, DH, GT, and GC, respectively. The lowest amount of soil loss from the treated cut slopes and fill slopes occurred in September, November, and Janu-

Table 3. Analysis of variance for the effects of different treatments on soil loss (R^2 = 0.976; adjusted R^2 = 0.968)

Source	Sum of squares	*df*	Mean square	*F*	Sig.
Corrected model	133 854.701[a]	71	1 885.277	124.100	0.000
Intercept	179 737.096	1	179 737.096	1.183E4	0.000
Treatment	96 676.254	5	19 335.251	1.273E3	0.000
Season	7 393.282	5	1 478.656	97.334	0.000
Block	14 286.416	1	14 286.416	940.415	0.000
Treatment × block	8 028.001	5	1 605.600	105.690	0.000
Treatment × season	6 349.848	25	253.994	16.719	0.000
Season × block	602.714	5	120.543	7.935	0.000
Treatment × season × block	518.186	25	20.727	1.364	0.123
Error	3 281.389	216	15.192	–	–
Total	316 873.186	288	–	–	–
Corrected total	137 136.090	287	–	–	–

[a] significant difference at probability level of 5% based on LSD test; *df* – degree of freedom; *F* – Fisher test; Sig. – significance

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ary, and it is impossible to specify a specific month for this issue. The lowest amount of soil loss was 27.17 g·m^{-2}, 12.47 g·m^{-2}, 64.64 g·m^{-2}, 12.65 g·m^{-2}, 13.58 g·m^{-2}, and 6.33 g·m^{-2} for the treated cut slopes by SB, LH, BS, DH, GT, and GC, respectively. In addition, 15.09 g·m^{-2}, 7.33 g·m^{-2}, 35.91 g·m^{-2}, 7.03 g·m^{-2}, 7.99 g·m^{-2}, and 3.33 g·m^{-2} of soil were washed and eroded from the treated fill slopes by SB, LH, BS, DH, GT, and GC, respectively (Figure 4). This result was in agreement with the findings of Akgul et al. (2019), who indicated that the degradation on forest road side slopes is related to rainfall duration and intensities. In the study area, severe rains occurred in winter and they contributed to high runoff flow (Fidelus-Orzechowska et al. 2020). Water will enter the soil, or wash the top layer and cause

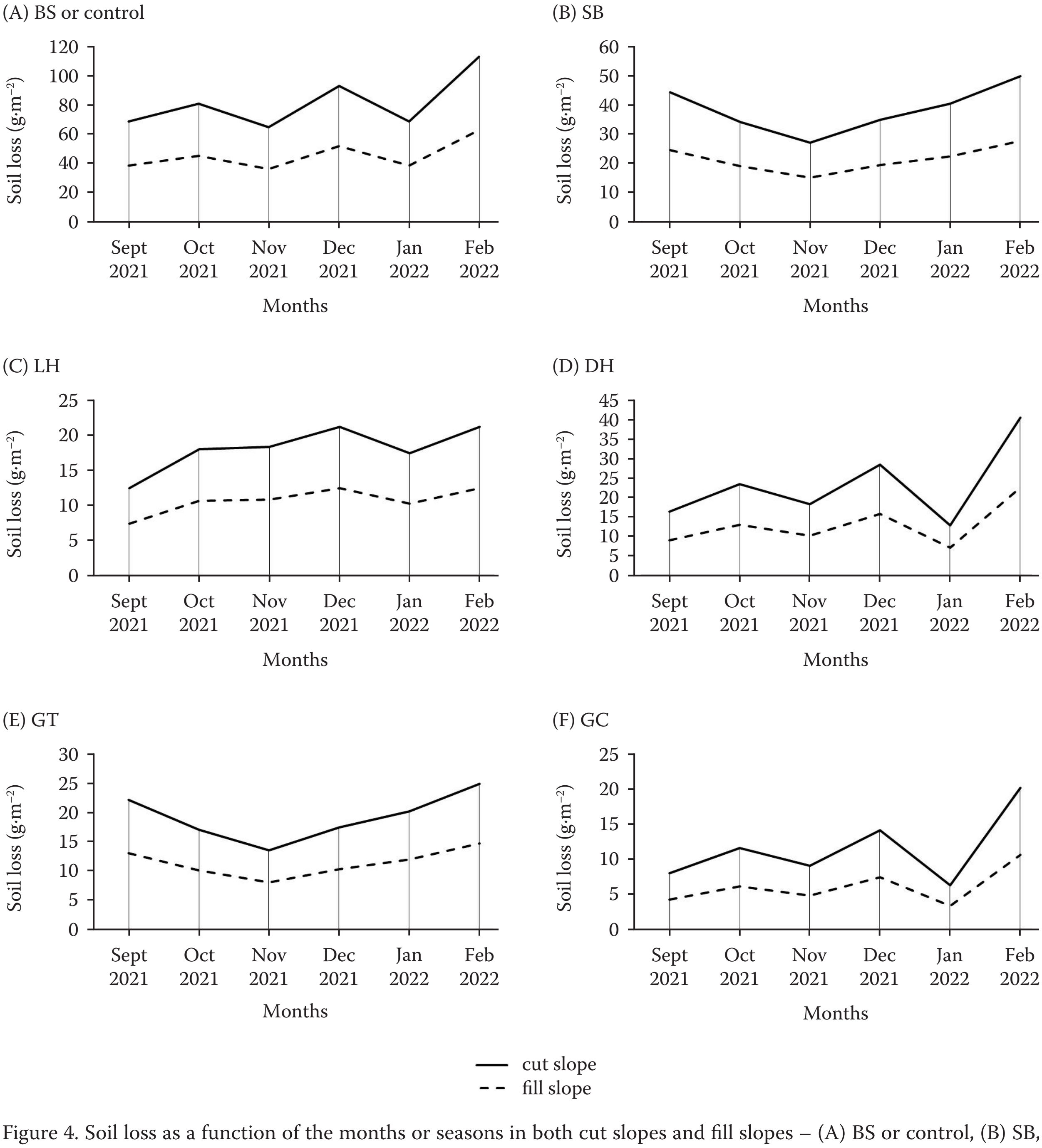

Figure 4. Soil loss as a function of the months or seasons in both cut slopes and fill slopes – (A) BS or control, (B) SB, (C) LH, (D) DH, (E) GT, and (F) GC

BS – bare soil; SB – straw bale; LH – living hedge; DH – dead hedge; GT – geotextile; GC – geo-cell

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a rapid loss of surface condition (Akgul et al. 2017; Shao et al. 2017).

Among conservation treatments, the lowest soil loss was detected in autumn and on treated fill slopes by GC, and the highest in the winter season and on treated cut slopes by SB. In all cases, soil loss from BS was significantly higher than on plots treated with conservation practices (Table 4; $P < 0.05$). This result agreed with the findings of Paz et al. (2018), who indicated that bare soil (BS) had the highest erosion. Moreover, they found that GC can support vegetation growth in openings of the cellular matrix. In the present study, it was detected that GC performed well under certain circumstances due to two-dimensional protections of contiguous wooden lumbers. GC reduces the runoff velocity and consequently the soil loss, in other words, GC reinforces the modified slope by holding the soil in position against erosion (Sato, Kojma 2018; Arvin et al. 2019; Song et al. 2021). This structure allows more time for infiltration and sediment deposition in each cell.

In this study, it was found that in a short time, there were not any significant differences between LH (28.78 g·m^{-2}), DH (36.01 g·m^{-2}), and GT (30.61 g·m^{-2}) in soil loss control ability. Indeed, the soil loss control performance of these treatments was acceptable when compared to the amount of soil loss from BS. This was in agreement with the findings of Grace (2000) and Likitlersuang et al. (2020), who indicated the high efficiency of LH and GT in soil loss control.

Table 4. Group comparison of soil loss for all treatments

Treatment	Block	Time (season)	Mean soil loss (g·m^{-2}) ± standard deviation
BS	cut slope	autumn	71.37^{b} ± 18.66
		winter	91.58^{a} ± 15.47
	fill slope	autumn	39.65^{e} ± 10.37
		winter	50.88^{c} ± 8.54
SB	cut slope	autumn	35.29^{e} ± 8.10
		winter	41.81^{d} ± 6.98
	fill slope	autumn	19.61^{g} ± 4.50
		winter	23.22^{f} ± 5.74
LH	cut slope	autumn	16.29^{g} ± 3.20
		winter	19.95^{g} ± 3.95
	fill slope	autumn	9.58^{h} ± 1.88
		winter	11.73^{h} ± 2.34
DH	cut slope	autumn	19.19^{g} ± 5.78
		winter	27.11^{f} ± 10.07
	fill slope	autumn	10.66^{h} ± 3.24
		winter	15.06^{gh} ± 5.59
GT	cut slope	autumn	17.64^{g} ± 4.05
		winter	20.90^{g} ± 6.42
	fill slope	autumn	10.38^{h} ± 2.38
		winter	12.30^{h} ± 3.11
GC	cut slope	autumn	9.60^{h} ± 2.65
		winter	13.55^{h} ± 5.03
	fill slope	autumn	5.05^{i} ± 1.54
		winter	7.13^{i} ± 2.21

$^{a–i}$ significant difference at probability level of 5% based on LSD test; BS – bare side slope; DH – dead hedge; GC – geo-cell; GT – geotextile; LH – living hedge; SB – straw bale

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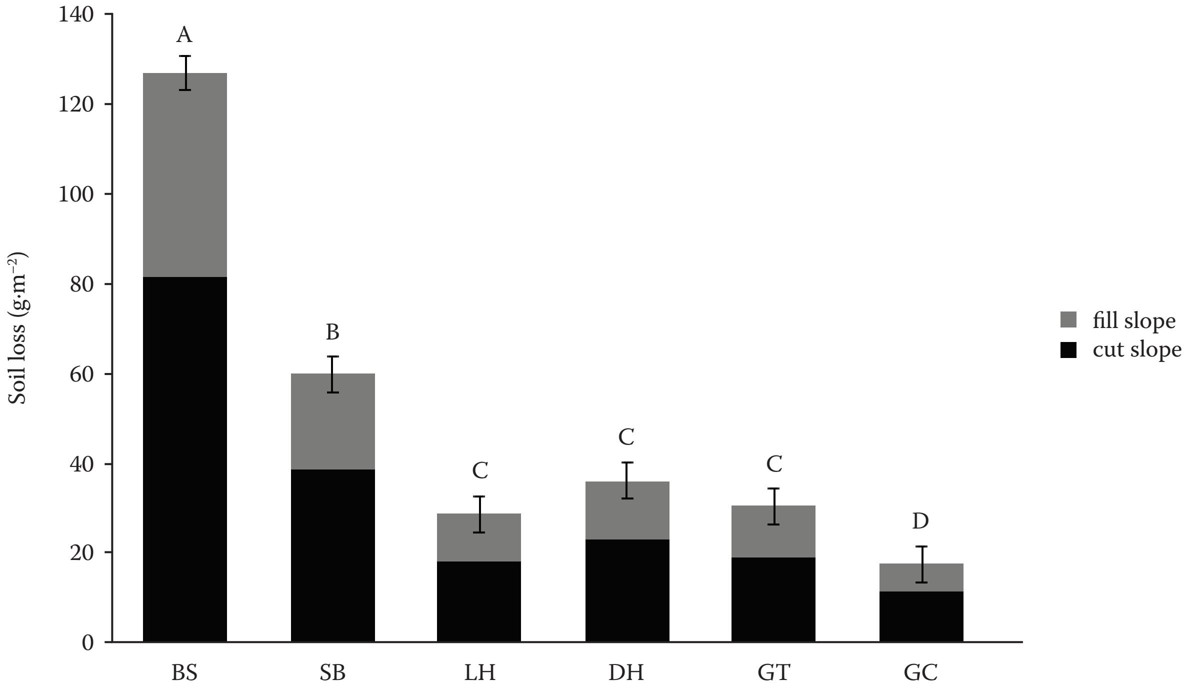

Figure 5. Comparison of the soil loss between different conservation treatments

BS – bare soil; SB – straw bale; LH – living hedge; DH – dead hedge; GT – geotextile; GC – geo-cell

LH barriers control soil loss mainly by increasing the infiltration (Kiepe 1995). Frequent leaf fall and decay in part of the root system increase the chance of a higher permeability of the soil beneath the LH. Gilley et al. (2000) indicated that the plots with grass hedges averaged 52% less runoff and 53% less soil loss than similar plots without grass hedges. The amount of soil loss from treated plots by SB was 59.96 $g \cdot m^{-2}$, which was more than the amount of eroded soil from GC (17.67 $g \cdot m^{-2}$; Figure 5). This means the SB has the best water absorption capacity in the early rainfall phase (Yin et al. 2019). In this phase, the decayed straw materials could quickly absorb the rainwater. With the elapse of time, the materials gradually became saturated (Zhang et al. 2021). This is close to the findings of Zhang et al. (2006) about forest litter. Yadav et al. (2014) reported that the use of GC is suitable from the stability as well as economic point. Field investigations of the present study showed that the establishment speed of GT (0.8 h per plot) was faster than in the other treatments, while GC took more time (3.5 h per plot). It should be noted that in terms of implementation and installation costs, GC (USD 16.67 per plot) was the most expensive and the LH (USD 3.33 per plot) treatment was the cheapest (Table 5). Guo et al. (2021) indicated that LH contributes to a 50% reduction in sediment and runoff. In northeast China, the runoff and sediment reduction by plant stems (LH) was 7.5% and 64%, respectively (Kiepe 1995; Li et al. 2021).

Table 5. Cost evaluation of the establishment of different soil conservation treatments

Treatment	Time to establishment (h per plot)	Establishment cost (USD per plot)
SB	1.5	10.00
LH	1.5	3.33
DH	2.5	5.00
GT	0.8	8.33
GC	3.5	16.67

SB – straw bale; LH – living hedge; DH – dead hedge; GT – geotextile; GC – geo-cell

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CONCLUSION

The results of this study showed that surface runoff and soil erosion were closely related to season, road side slopes, and type of conservation treatment. Soil loss presented significant variations over months due to uneven distribution of rainfall and rainfall erosivity. Compared with bare slopes, the reduction rates were 53–86% for soil loss under conservation treatments in this study. GC has apparent effects on reducing soil loss. It showed an 86% reduction in soil loss compared to control (BS). GC consists of three-dimensional, wooden square structure cells. Due to the confinement effect of the structure, geo-cell spreads the loads over its larger area, thus increasing the load-bearing capacity of the soil. Regarding the GC treatment, it is necessary to conduct more research in the long term to determine its economic efficiency in terms of durability and maintenance and repair costs. Until then, it is possible to use affordable treatments such as LH, which have yielded favourable results in terms of efficiency. The results of this study can be used to assess soil loss, support small watershed management, and preserve road side slopes of erosive areas.

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