Straw Checkerboard Barriers Improve Soil Characteristic and Growth Performance of Winter Cover Crops and Protect Sloping Land

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Abstract

Aims Finding how straw checkerboard barrier technology, as a sustainable and environment-friendly method, may affect soil chemical properties and water status despite wind erosion control directed us to evaluate this technique as a vital component of management plans in sloping lands of semi-arid areas. We were interested to know if it could support the soil capabilities to grow pilot plants and recover some ecological services via alleviate drought stress or amendment of soil attributes.

Methods In order to study soil characteristic and growth performance of winter cover crops, an experiment was carried out in 2018. Checkerboards were setup in a 1×1 m pattern with rice residues. Seeds of sainfoin (*Onobrychis sativa*), rye (*Secale montanum*) and tall wheatgrass (*Agropyron sp*) were sown at the checkerboards and bare ground as the control. Detailed analyses include growth characteristics, physiological attributes i.e. photosynthetic pigment contents, proline and malondialdehyde contents and relative water contents of mentioned crops and the related soil properties during the growing season were carried out in borders and centers of the straw checkerboards and bare ground.

Results Soil covered with straw checkerboard barriers was the most effective for improving vegetation growth and establishing taller plants with higher biomass. Based on the physiological analyses, the rye grown in straw checkerboard plots coped well with dry conditions. Higher proline content and more efficient osmotic adjustment indicates improvements of soil water retention status, which may alleviate drought stress damages and improve cover crop performance in straw checkerboard plots. Photosynthetic pigments also showed higher contents in checkerboards for rye. Soil organic matter, total nitrogen, available phosphorus, potassium and water storage increased in checkerboards too, however, such effects vary with the crop type.

Conclusions straw checkerboards could be deemed as an effective management strategy in semi-arid areas, as an important method for conserving natural resources and sustaining productivity.

Introduction

Successful recovery of soil and vegetation in semi-arid regions is a challenge because water availability severely limits germination, plant establishment, growth and survival (Wilson et al. 2004; Munson and Lauenroth 2012). In bare soil, the evaporation process evacuates water from the soil surface, and microclimate conditions are rarely favorable for the establishment of plants, therefore poorly covered soil can lead to erosion (Hadas 2004). Soil erosion is one of the most important soil problems in arid and semiarid Mediterranean areas, which reduces soil fertility, plant productivity and also environment healthy (Yüksek and Yüksek 2015). Therefore, in arid and semiarid sites, with undesirable seedbeds, field techniques may support soils conserving water, improve seedbed microclimate and seedling establishment, increase soil fertility, reconstruct ecological community and reduce erosion.

Straw checkerboard barrier technique is widely used for controlling of erosion and habitat recovery in arid and semi-arid areas (Li et al. 2006). This technique, as an environmentally-friendly strategy, is cheap and easy to install (Zhang et al. 2018). Straw of wheat, rice, reeds and other plants are installed in the square shape 20 cm buried in the soil and about 20 cm exposed above the soil surface (Wang et al. 2020). The checkerboard barriers can be placed at various dimensions, including 0.5×0.5, 1×1, 1.5×1.5 m and so on (Qu et al. 2007; Zhang et al. 2018). Straw checkerboards reduce the wind speed which decrease water loss through evaporation (Bo et al. 2015; Li et al. 2020).

After the establishment of straw checkerboard barriers, straw can improve soil water holding capacity (Li et al. 2018; Zhang et al. 2018; Li et al. 2006; Li et al. 2020), increase the microorganism numbers (Li et al. 2006), available soil nitrogen and potassium (Li et al. 2018; Zhang et al. 2018), organic matter content (Dai et al. 2019; Lie 2017; Yu Qiu et al. 2004), roughness of the underlying surface (Yu Qiu et al. 2004), and improve the soil structure (Lie 2017). Straw checkerboard barriers have the potential to create favorable conditions for plant establishment, increase the survival rate of shrub and reduce erosion risk (Li et al. 2006). Li et al. (2000) and Williams et al. (1995) showed that cryptogamic crusts have been developed four years after revegetation in squares, which could reduce water and wind erosion. Zhang et al. (2018) reported that application of a straw checkerboard improved soil water content and physicochemical properties; thereby, contributed to the establishment of plant and promoted ecological restoration. Dai et al. (2019) and Sun et al. (2016) showed that the soil particle size decreased after the implement of checkered barriers and the physical properties of the soil improved; thus, a better environment for the growth of plant community was provided.

Winter cover crops are deemed as one of the most effective sustainable land management techniques for reducing soil erosion rates and recovery of degraded land (Marques et al. 2016). Cover crops decrease the kinetic energy of the raindrops on the soil surface, decrease runoff velocity and interception and protect winter rainwater storage in soil rather than reduce evaporation (Sharma et al. 2018; Kairis et al. 2013). Other beneficial effects of cover crops include facilitating nutrient cycling, increasing soil organic carbon sequestration, improving soil structure and reducing wind or water erosion (Ranells and Waggener 1996; Dabney et al. 2001; Palese et al. 2014). The impact of cover crops to reduce erosion varies with the plant species and biomass production (Blanco-Canqui et al. 2011). Numerous studies have indicated that cover crops, such as rye, spring lentils, sainfoin and winter triticale decrease wind erosion by increasing soil cover and carbon build-up, which could catch soil particles together and/or improving soil aggregate stability (Bilbro and Hargrove 1991; Blanco-Canqui et al. 2013). Novara et al. (2019) indicated that, in the sloping area, the cover crop exerts a positive impact on carbon budget by an increase in the C input and a restriction on the C loss.

Sainfoin (*Onobrychis sativa*), rye (*Secale montanum*) and tall wheatgrass (*Agropyron sp*) were selected in this study as pilot plant, because of properties such as highly tolerant to drought, good source of animal feed, unique adaptation to poor soils and well-developed root system (Sancak et al. 2003; Kaspar and Bakker 2015; Oelke et al. 1990; Bayat et al. 2016). Previous studies have shown that legumes act as pioneer plants to enhance poor soil and have useful effects on soil fertility (Agbenin and Adeniyi, 2005). Sainfoin could provide a large amount of organic material and nitrogen content by fixing atmospheric nitrogen that improves the physico-chemical characteristics of the soil (Mohajer et al. 2012; Beyaz et al. 2011).

This study was designed for a sloping land that is prone to features of water and wind erosions, high velocity of runoff with low infiltration and poor biodiversity in a semi-arid area, Shahrekord, Iran. We were interested in studying the influence of straw checkerboard barriers on growth and performance of rye, sainfoin, and tall wheatgrass as pilot cover crops. Checkerboards capability to alleviate the drought effects caused by deficiency of precipitation, improve soil chemical properties, water storage change in the soil, stabilizing the slope surface and ecological restoration were the theoretical basis we want to understand. The aims of this study were therefore 1) to evaluate effects of straw checkerboards on soil water status. 2) to study the effects on soil properties and attributes. 3) to evaluate if the changes for water availability or soil amendments could support establishment of pilot plants in the soil and/or improve their performance.

Materials And Methods

Site Description and Experimental Set up

This experiment was performed at Shahrekord University, Chaharmahal and Bakhtiari Province, Iran (50° 49′ E, 32° 21′ N; 2050 m a.s.l). A Mediterranean semiarid area, with warm, dry summer and cold winters. The mean annual precipitation is approximately 316 mm and average monthly temperature is 12.12°C. The mean annual wind velocity is 2.6 m/s. The soil is classified as Entisol and the slope ranges from 10 to 14%. The ground-water table depth was below 80 m, which cannot be used by the plant. At the beginning of the study, 10 soil samples were randomly collected from 0–30 cm depth using a soil auger. The samples were then mixed together. Three replications for each mixed sample were obtained. The mixed samples were air dried and then below characteristics of the soil were measured (Table 1).

Table 1
Physical and chemical properties of the studied soils.

Characteristic	Unit	Value
Ec	$\mu\text{S cm}^{-1}$	153.4
pH	-	7.72
Organic matter	mg kg^{-1}	9228
TN	mg kg^{-1}	903
AP	mg kg^{-1}	14.8
AK	mg kg^{-1}	500.6
Bulk density	g cm^{-3}	1.3
Sand	%	36
Silt	%	44.56
Clay	%	19.44

The experiment was conducted in a weakly structure soil with slope 14% and no plant materials or litter on the surface, prone to erosion. 1×1 m square grids of rice straw barriers were established in January, 2018 as the checkerboards pattern, covering a 35×20 area of approximately 700 m². A bare ground with the same area was also intended as control in the adjacent to the straw checkerboard barriers. The straw was buried in the soil to a depth of 20 cm and protruded 20 cm above the soil. (Fig. 1). Sainfoin (*Onobrychis sativa*), rye (*Secale montanum*), and tall wheatgrass (*Agropyron sp*) were seeded separately within each square in four 1m long rows manually at 2–4 cm depth in November 2018 at three replication. The distance between two plants on the rows was 8cm, which apply 50 plant m⁻² for all. No irrigation or other operations were done. The same seeding operation was performed in bare ground area as control. Each 1×1 m seeded square at checkerboards were divided into two areas, the inner 50×50 cm area intended as center of barriers and approximately 25 cm marginal as borders of barriers, compared with seeded area in bare ground as control.

Measurements

Plants Growth Parameters

Plant growth parameter measurements were taken at the end of the growing period. Five plants were randomly selected from the borders of barriers, centers of barriers, and the bare ground separately by cutting them at the ground level at 1st June. Afterward, the plants’ height and above-ground biomass of the samples were assessed. The aerial parts were then oven-dried at 70°C for 48 h and weighed to determine the dry weight.

Physiological Traits

Chlorophyll a, chlorophyll b, and carotenoids contents were determined for selected plants according the methodology described by Lichtenthaler and Buschman (2001). At first, 100 mg fresh leaf sample collected from matured leaves were ground with 5 ml of 80% acetone. After filtration, extracts were adjusted to 10 ml with 80% acetone solution and the absorbance of the solution was recorded at 646.8, 663.2, and 470 nm with a spectrophotometer (HACH Company, DR 6000, Germany). Pigment contents were calculated by the following equations:

$$\text{Chl a (mg g}^{-1} \text{ FW)} = (12.7 \times \text{abs}_{663.2}) - (2.6 \times \text{abs}_{646.8}) \text{ mL acetone mg}^{-1} \text{ (1)}$$

$$\text{Chl b (mg g}^{-1} \text{ FW)} = (22.9 \times \text{abs}_{646.8}) - (4.68 \times \text{abs}_{663.2}) \text{ mL acetone mg}^{-1} \text{ (2)}$$

$$\text{Carotenoids (mg g}^{-1} \text{ FW)} = [(100 \times \text{abs}_{470}) - (1.82 \times \text{Chl a}) - (85.02 \times \text{Chl b})] / 198 \text{ (3)}$$

Electrolyte leakage (EL) value, specified for assessing the degree of drought tolerance was measured according to the method of Lutts et al. (1996). To this end, cleaned and freshly collected leaf samples were put into test tubes containing 10 ml distilled water and incubated for 2 h at 25 °C. Subsequently, the electrical conductivity of the solution was measured (EC1). The samples were autoclaved at 15 psi for 15 min and the second electrical conductivity (EC2) was determined. Electrolyte leakage (EL) was estimated according to the following formula:

$$\text{EL (\%)} = (\text{EC1/EC2}) \times 100 \text{ (4)}$$

Considering the accumulation of proline as a criterion for physiological stress in plants and its key role in plant stress adaptation, the variations in proline accumulation were studied accordingly. The proline content was estimated by the method of Bates et al. (1973). The leaf fresh samples were ground with 3% salicylic acid. After adding ninhydrin and glacial acetic acid in tubes containing portions of the ground samples, tubes were kept in a 100°C water bath. After cooling, 4 mL toluene was added. The absorbance was measured by spectrophotometer (HACH Company, DR 6000, Germany) at 520 nm using the calibration curve.

Since malondialdehyde concentration is also determined as a criterion for degree of oxidation damage occurring under stress conditions, MDA concentration was estimated. The malondialdehyde (MDA) concentration was determined based on the 2-thiobarbituric acid (TBA) test proposed by Draper and Hadley (1990).

For relative water content (RWC), three leaves per plant of a similar age were detached and weighed freshly (FW). Afterward, the leaf fresh samples were immersed in distilled water in sealed vials for 24 h at 4°C in dim light. After 24 h, the leaves were weighed to obtain the turgid weight (TW). Dry weight (DW) was then determined after oven drying at 70°C for 48 h. The RWC was calculated using the following formula (Turner 1981).

$$\text{RWC (\%)} = [(FW-DW) / (TW-DW)] \times 100 \text{ (5)}$$

In order to determine the protein content, dried samples of aerial parts of plants were passed through a 1-mm sieve and analyzed for total nitrogen concentration based on Kjeldahl method. The protein contents then were estimated using the following equations (Tessta et al. 2011):

$$\text{Protein (\%)} = N \times 6.25 \text{ (6)}$$

Determination of Soil Water Storage

The volumetric soil water content was measured at 5, 15, and 25 cm depths in border and center of each square as well as at the different places of bare ground randomly during the growing season of rye, sainfoin, and tall wheatgrass (on 22.04.2019, 4.05.2019, 16.05.2019, and 29.05.2019). Volumetric soil water content was measured with a soil moisture meter (model SM01, Azar-Khak-Ab urmia) through walking in each mentioned places at the squares. Soil Water Storage (SWS), to a depth of 25 cm, was calculated as follows (Ren et al. 2008):

$$\text{SWS} = \sum_{i=1}^n h_i \times \text{SWC}_i \times 10/100 \text{ (7)}$$

where SWS (mm) is the soil water storage; h_i (cm) is the soil layer depth; SWC_i is the volumetric soil water content of soil layer i ; n is the number of soil layers, $i = 1, 2, \dots$ etc.

Soil Measurements

After the plants harvest, soil samples were collected along a vertical line in the borders and also the centers of each square as well as at different places of bare ground randomly using a soil auger in 0–25 cm soil layer. Three points per treatment were taken to collect soil samples and then pooled together. Three replications for each mixed sample were obtained. The mixed samples were air dried and then sieved through a 2 mm sieve. The soil organic carbon (SOC) content was measured by Walkley-Black, potassium dichromate oxidation method (Lu 2000). Total nitrogen (TN) content was determined using the Kjeldahl digestion (Bremner and Mulvaney 1982). Soil available phosphorus (AP) was measured using the method provided by Olsen et al. (1954). Soil available potassium (AK) content was extracted with 1 N ammonium acetate and using flame photometry (Lu 2000).

Data analysis

Since having three pairs of data from each replicate and several fixed factors, GLM was run. Repeated-measures analyses of variance (RM-ANOVAs) were performed on the plant traits and soil chemical properties data (confidence level of 95%), because the factors were brought in pairs, were not independent in place. In these traits, distances from barriers were pairs and repeated parameter. The between-subject factors were the cover crops while the within-subject factor was the distance from barriers. Moreover, soil water storage data, were not independent in place and time and distance from barrier and time were repeated parameters. Therefore, between-subject factors included cover crops while the within-subject factor included distance from barriers and time.

Repeated-measures analyses of variance were performed using the STATISTIX 12.0 software. The differences between the mean values were compared using the least significant difference (LSD) at $P < 0.05$.

Results

Weather Conditions

Daily precipitation and air temperature during the growing period are given in Fig. 2. The rainfall during the growing periods amounted to 300 mm and the daily mean of air temperature varied from -5.1 to 20.4°C (Fig. 2).

Plant Growth Parameters

Plant height, biomass, and shoot dry weight were significantly affected by the cover crop type ($p < 0.01$), the distance from barriers ($p < 0.01$) and their interaction (Table 2). It was observed that border of barrier with value of 40.11 cm and center of barrier with value of 36.27 cm were superior to the bare ground in terms of plant height (Table 2). For example, the height of rye in the border and center of the barriers was on average 22 and 16% higher than the bare ground respectively (Table 3). In the border of barriers, the higher shoot fresh weight belonged to the rye, followed by the sainfoin and tall wheatgrass (Table 3). Also, the border of the barriers contributed positively to higher shoot fresh weight of the rye (105%), sainfoin (133%) and tall wheatgrass (167%) compared to the bare ground (Table 3). The rye plant grown in the border of barriers showed around 60% higher shoot dry weight compared to the bare ground (2.7 vs. 1.7 g) (Table 3). Generally, the rye showed higher amounts of biomass, shoot dry weight, and plant height than that of other cover crops.

Table 2 Effects of cover crop types and distance from barrier on growth characteristics, concentrations of leaf photosynthetic pigments, RWC, Electrolyte leakage, MDA, Proline and Crude Protein and their average contents.											
Source of variation	Plant height (cm)	Shoot fresh weight /plant (g)	Shoot dry weight /plant (g)	Chlorophyll a (mg g ⁻¹ FW)	Chlorophyll b (mg g ⁻¹ FW)	Carotenoids (mg g ⁻¹ FW)	RWC (%)	Electrolyte leakage (%)	Malondialdehyde (μmol. g ⁻¹ FW)	Proline (μmol. g ⁻¹ FW)	Crude Protein (%)
Cover crop (C)	**	**	**	**	**	**	*	**	**	**	**
Rye	82.44 a	4.40 a	2.17 a	0.626 a	0.191 a	0.280 a	63.18 a	70.71 c	0.038 a	3.14 a	9.18 b
Sainfoin	11.16 b	0.98 b	0.37 b	0.311 b	0.109 c	0.154 c	55.56 b	72.72 b	0.039 a	2.095 b	10.77 a
Tall wheatgrass	13.66 b	0.68 c	0.25 b	0.334 b	0.151 b	0.182 b	54.44 b	79.32 a	0.029 b	2.30 b	8.44 b
Distance from barrier (D)	**	**	**	**	**	**	**	**	**	**	**
Border of barriers	40.11 a	2.91 a	1.2 a	0.504 a	0.181 a	0.245 a	63.22 a	69.16 c	0.033 b	3.04 a	10.55 a
Center of barriers	36.27 b	1.81 b	0.9 b	0.408 b	0.141 b	0.200 b	56.49 b	75.38 b	0.036 a	2.67 a	9.43 ab
Bare ground	30.88 c	1.34 c	0.68 c	0.360 c	0.128 b	0.173 c	53.46 b	78.22 a	0.037 a	1.82 b	8.41 b
C × D	*	**	*	NS	NS	NS	NS	NS	NS	**	NS
p (Sphericity test)	0.06	0.038	0.007	0.362	0.162	0.451	0.224	0.869	0.975	0.329	0.008
Huynh-Feldt Epsilon	0.909	0.868	0.780	1	1	1	1	1	1	1	0.784
** and * indicate, respectively, differences at $P \leq 0.01$ and $P \leq 0.05$ probability level, ns indicates not significant difference. Means with same letter in each column are not significantly different according to the LSD test ($P < 0.05$).											

Table 3
Average contents of plant height, shoot fresh weight, shoot dry weight and proline affected by interactions of cover crop types and distance

Distance from barrier	Plant height (cm)			Shoot fresh weight /plant (g)			Shoot dry weight /plant (g)			Proline
	Rye	Sainfoin	Tall wheatgrass	Rye	Sainfoin	Tall wheatgrass	Rye	Sainfoin	Tall wheatgrass	Rye
Border of barriers	89.3±3.71 a	14± 0.57 cd	17±1.52 c	6.24±0.02 a	1.44±0.11 d	1.05±0.09 de	2.7±0.17 a	0.51±0.03 d	0.37±0.03 de	4.29±0. a
Center of barriers	85± 2.08 a	10.83±1.48 d	13±0.57 cd	3.93±0.13 b	0.90±0.03 ef	0.59±0.03 ef	2.08±0.1 b	0.41±0.04 de	0.23±0.003 de	3.82±0. a
Bare ground	73±2.64 b	8.66±0.88 d	11±1.52 d	3.03±0.4 c	0.61±0.04 ef	0.39±0.05 f	1.7±0.15 c	0.20±0.02 de	0.15±0.01 e	1.32±0.16 d
Values are mean ± SE. Means with same letters in the same column are not significantly different according to the LSD test (P < 0.05).										

Physiological Attributes

Leaf Photosynthetic Pigments

Leaf chlorophyll a, b and carotenoids contents were significantly different for the cover crops ($p < 0.01$) and the distance from barriers ($p < 0.01$; Table 2) while the interaction effect of the cover crops and distance from the barriers was not significant (Table 2). The content of the rye chlorophyll a was significantly higher than sainfoin and tall wheatgrass (Table 2). Plants grown in the borders (0.504 mg g^{-1}) indicated higher chlorophyll a contents compared to the bare ground (0.36 mg g^{-1}) (Table 2). Among the different cover crops, higher chlorophyll b was also recorded for rye plants (Table 2). The border of the straw barriers led to a significant increase in the chlorophyll b of leaves with a value of 0.181 mg/g , while no significant differences were detected between the center of the barriers and bare ground (Table 2). The same trend was observed for the carotenoid contents. The carotenoid contents of the cover crops in a descending order were as follows: rye > tall wheatgrass > sainfoin (Table 2). In addition, the border of the barriers increased the carotenoid content by 22% and 41% relative to the center of the barriers and bare ground, respectively (Table 2).

Relative Water Content (RWC)

In terms of relative water content, there were significant effects of the cover crops ($p < 0.05$) and distance from the barrier ($p < 0.01$), but not their interaction (Table 2). The rye plants maintained the highest RWC among the crops (Table 2). The relative water content of sainfoin was not significantly different from that of tall wheatgrass (Table 2). Higher RWC was recorded in the border of the barriers by increasing 18% as compared to the bare ground (63.22 vs. 53.46%) (Table 2). However, no significant differences were detected between the plants grown in the center of the barriers and bare ground (Table 2).

Electrolyte Leakage (EL)

The effects of the cover crops and distance from the barrier were significant on electrolyte leakage ($p < 0.01$; Table 2). The interaction effect of the cover crops × distance from the barrier was not significant on the EL value (Table 2). Among the different cover crops, the lowest EL value was obtained for the rye plant (70.71%) (Table 2). The measurement of electrolyte leakage in the leaves of the plants grown in the straw checkerboard and bare ground showed that on average 13% and 3% lower EL value is in the border and center of the barriers respectively, compared to the bare ground (Table 2).

Malondialdehyde (MDA)

MDA content was significantly affected by the cover crops and distance from the barrier ($p < 0.01$) but, no interaction effect was found (Table 2). Among the different cover crops, sainfoin and rye recorded the highest malondialdehyde content (Table 2). Malondialdehyde content ranged between $0.033 \mu\text{mol g}^{-1}$ for the plant grown in the borders to $0.037 \mu\text{mol g}^{-1}$ for the plant grown in the bare ground (Table 2). The border plants had significantly the lowest MDA as compared to the bare ground plants (0.033 vs. $0.037 \mu\text{mol g}^{-1}\text{FW}$). No significant differences were observed between the center of the barriers and bare ground (Table 2).

Proline

Proline content was significantly affected by the cover crops, the distance from the barrier and their interaction ($p < 0.01$; Table 2). The highest values of proline were obtained for the rye grown in the border and center of the barriers, while the lowest value was recorded for the rye grown in the bare ground (Table 2).

3). The tall wheatgrass also showed higher amounts of proline content in the border of the barriers but the proline content of sainfoin was the only case that was not affected by the distance from the barriers (Table 3).

3.4.6. Crude Protein

Statistical analysis carried out on crude protein content revealed a significant difference between the cover crops and distance from the barrier ($p < 0.01$) but not for their interaction (Table 2). The crude protein content of the shoots was significantly higher for sainfoin (10.77%) (Table 2). The crude protein content of the plant grown in the straw checkerboard was also significantly greater than the ones on the bare ground (Table 2).

Soil Water Storage

During the growing seasons of the rye, sainfoin and tall wheatgrass, the soil water storage was monitored. Analysis of the soil water storage dynamic within a 0-25cm depth under the three mentioned crops at different distances from the barriers showed that a higher value of soil water storage was observed in the checkerboard plots (Fig. 3A). At the borders, plants consumed the water so that the plot without plants had higher soil water storage (Fig. 3A). The rye consumed more water than the other cover crops that may be due to the higher biomass produced. In the center of the barriers, water status was more stable (Fig. 3A). In other words, although there was no more water consumption in a plot without plants, but there was more evaporation resulted from bare soil and may lead to lower water storage.

The soil water storage dynamics showed variations in the straw barriers and bare ground during the growing season (Fig. 3B). During the growing season of crops, the border and center of the barriers invariably retained higher soil moisture than the bare ground and significant differences among the straw barriers and bare ground were observed. The soil water storage fell dramatically over time and changed moderately during the late growth period (Fig. 3B).

Soil Chemical Properties

Total N

Soil total N was affected by cover crops ($p < 0.01$), distance from barrier ($p < 0.01$) and their interaction ($p < 0.05$) (Table 4). Soil total nitrogen content was increased with the establishment of straw barriers compared with the bare ground, especially at the border of barriers (Table 5). In the border of the barriers, higher levels of total N were detected in soil with sainfoin (1184.3 mg kg⁻¹), tall wheatgrass (1031.7 mg kg⁻¹) and the soil with no plant (1156.7 mg kg⁻¹). Also, lower total N content detected in the soils after rye harvest (868.3 mg kg⁻¹), may relate to higher biomass of the rye produced near the borders (Table 5).

Table 4
Chemical parameters of soil as influenced by cover crop types and distances from barriers at harvest stage.

Source of variation	TN (mg kg ⁻¹)	AP (mg kg ⁻¹)	AK (mg kg ⁻¹)	SOM (mg kg ⁻¹)
Cover crop (C)	**	**	NS	**
Rye	879.1 b	17.2 ab	619.4 a	10821.2 a
Sainfoin	966.2 a	16.8 bc	630.6 a	9751.9 b
Tall wheatgrass	867.4 b	16 c	670.3 a	8290.6 d
Straw checkerboard and bare ground without plant	968 a	18.3 a	623.3 a	8724.3 c
Distance from barrier (D)	**	**	**	**
Border of barriers	1060.2 a	19.1 a	720.8 a	11567.7 a
Center of barriers	922.8 b	16.4 b	623.05 b	8888.5 b
Bare ground	777.5 c	15.6 c	563.9 c	7734.8 c
C × D	*	**	NS	*
p (Sphericity test)	0.001	0.449	0.036	0.910
Huynh-Feldt Epsilon	0.798	1	0.952	1
** and * indicate, respectively, differences at $P \leq 0.01$ and $P \leq 0.05$ probability level, ns indicates not significant difference. Means with same letter in each column are not significantly different according to the LSD test ($P < 0.05$).				

Table 5
Average contents of chemical parameters of soil at harvest stages as influenced by interaction effects of cover crop types and distance from barriers

Distance from barrier	TN (mg kg ⁻¹)				AP (mg kg ⁻¹)				SOM (mg kg ⁻¹)
	Rye	Sainfoin	Tall wheatgrass	WP	Rye	Sainfoin	Tall wheatgrass	WP	Rye
Border of barriers	868.3±60.3 _{cd}	1184.3±60.3 _a	1031.6±60.38 _{ab}	1156.6±60.3 ^a	20.3±0.88 _a	18.4±0.5 _b	16.9±0.87 _{cd}	21±0.2 _a	12745.8±491.2 ^a
Center of barriers	994±38.01 _{bc}	911.6±38.01 _{bcd}	875.6±38.01 _{bcd}	910±38.01 _{bcd}	16.3±0.5 _{cde}	16.7±0.1 _{cd}	15.1±0.31 _f	17.5±0. _{bc}	10156.6±385.1 ^e
Bare ground	775±29.9 _{de}	802.6±29.9 _{de}	695±29.9 _e	837.3±30 _{cde}	14.9±0.01 _f	15.3±0.38 _{ef}	15.8±0.15 _{def}	16.5±0.32 _{cde}	9561.4±211.3 _f
WP: Straw checkerboard and bare ground with no plant, Values are mean ± SE. Means with same letters in the same column are not significantly different according to Duncan's multiple range test (p < 0.05).									

Available P

Soil available P was influenced by the cover crop type, distance from barriers and interaction between the cover crops and distance from the barrier ($p < 0.01$) (Table 4). Higher concentrations of available P were recorded in the border of barriers especially for the ones with no plant and after the rye harvest (Table 5). Generally, P content of the border of the barriers was averagely higher by 22% than the bare ground (19.1 vs 15.6 mg kg⁻¹). The P content in the soil with rye was averagely lower by 24% and 36% in the center of the barriers and bare ground, respectively, compared with the borders (16.3 and 14.9 vs 20.3 mg kg⁻¹) (Table 5).

Available K

In terms of soil available K, there were effects only by the distance from the barriers ($p < 0.01$) (Table 4). The straw checkerboards increased available K averagely 27% near the borders and 10 % at the centers, respectively, compared to the bare ground (Table 4).

Organic Matter

The soil organic matter content was significantly affected by the cover crop type ($p < 0.01$), the distance from barriers ($p < 0.01$) and the interaction between them ($p < 0.05$) (Table 4). Higher soil organic matter content was recorded for the border of the barriers (11567.7 mg kg⁻¹) (Table 4). The rye has been left more organic matters in the borders compare to sainfoin (9%) and tall wheatgrass (23%) (Table 5). Higher organic matter observed for the border of barriers with no plant indicates the effect of straw materials on organic matter. The rye (9561.4 mg kg⁻¹) and sainfoin (8859.6 mg kg⁻¹) grown in the bare ground improved the soil organic matter compared to a soil without cover crops (6359.7 mg kg⁻¹) (Table 5).

Principal Component Analysis

The analysis of the principal components of the morphophysiological properties of plants (Chlorophyll a, chlorophyll b, carotenoids, RWC, EL, MDA, proline, protein, plant height, shoot fresh weight and shoot dry weight) showed 75.77% variation explained by PC1 and PC2 (Table 6). The highest eigenvectors were related to the chlorophyll a, carotenoids, shoot fresh weight and shoot dry weight for PC1. Moreover, MDA and protein had a positive correlation with the PC2 and the EL had a negative correlation with the PC2 (Table 6). As shown in Fig. 4, the points related to the rye plant were located on the left side of the PC1 and the points related to the tall wheatgrass and sainfoin plant were located on the right side of the PC1. Therefore, the rye had higher shoot fresh weight, shoot dry weight, chlorophyll a and carotenoids compare to sainfoin (Fig. 4). The protein variable had the highest positive correlation with the PC2 and has caused the separation of sainfoin from the tall wheatgrass.

Table 6
Eigenvector of morphophysiological characteristics of cover crops and soil chemical properties, eigenvalues and variance in PCA axes

crop	Trait	Eigenvector	
		1	2
	Chlorophyll a	-0.3673	-0.1006
	Chlorophyll b	-0.3220	-0.2269
	Carotenoids	-0.3573	-0.1548
	Relative water content	-0.3165	0.2006
	Electrolyte leakage	0.2723	-0.4786
	Malondialdehyde	-0.0543	0.2846
	Proline	-0.2650	-0.0007
	Protein	-0.0531	0.7326
	Plant height	-0.3460	-0.1525
	Plant fresh weight	-0.3654	-0.0228
	Plant dry weight	-0.3608	-0.0599
	Eigenvalue	6.987**	1.569
	Variance (%)	63.51	14.26
soil	Total N	-0.4392	0.4762
	Available P	-0.4622	0.1556
	Available K	-0.4118	-0.8381
	Soil organic matter	-0.4378	-0.0761
	Soil water storage	-0.4818	-0.2022
	Eigenvalue	3.987**	1.569
	Variance (%)	65.93	11.10

The PCA on soil characteristics (total N, available P, available K, soil organic matter and soil water storage) showed that PC1 and PC2 explained the 63.95% and 11.10% data variability, respectively (Table 6). The highest eigenvectors were related to the available P and the soil water storage, which have negative correlations with this principle component. The total nitrogen had a positive correlation and the available potassium had a negative correlation with the second principal component (Table 6). The results showed that the points related to the border of barriers were located on the left side of the PC1 and the points related to the bare ground were located on the right side of the PC1 (Fig. 5). In the present research, it could be noticed that PC1 represents the changes both in different plants and between the border of the barriers, center of the barriers and bare ground.

Discussion

In the semiarid areas, large amounts of carbon lose through high mineralization rates and soil erosion; thus, cover crops are vital to preserve the soil organic carbon stock (Fernandez-Romero et al. 2016). In this study, since the highest SOM content was found in the rye grown in the border of the barrier, so straw checkerboards act as an efficient technique via facilitating cover crop establishment and performance in sloping lands. Residue incorporation in soils with high C:N ratio may increase C mineralization and have positive priming effect which accelerate native SOC decomposition (Zhang et al. 2013). Soil microbes have the ability to decompose old recalcitrant SOM by using fresh straw carbon as a source of energy *i.e.*, the phenomenon called the priming effect (PE) (Kuzakov et al. 2000).

Several studies in different climatic conditions have reported that cover crops such as rye, ryegrass, pea and oats significantly improve soil organic carbon contents relative to plots without cover crops (Olson et al. 2014; Sainju et al. 2002). Additionally, soils treated with cover crops may decrease SOC loss through reducing soil erosion (Blanco-Canqui et al. 2015). Fast growing cover crops increase soil organic material at greater depths of soil. Their extensive roots penetrate soil particles to form a porous network, which enhance water holding capacity (Dabney et al. 2001; Adetunji et al. 2020). Roots, as one of the most important sources of carbon and nitrogen in soil, help to stabilize carbon and nitrogen in the topsoil through their exudates and labile carbon compounds (Jackson et al. 2017). Our results proved that after the establishment of straw checkerboard barriers, the border of the barriers had significantly higher SOM content; that is, the straw buried into the soil acts as a main source of organic matter and soil organic carbon to overcome the lack of SOM. Some cover crops like rye act more efficient in the way. This coincides with Li et al. (2018) who showed that the rice straw checkerboard barriers have useful effect on the soil organic carbon build-up. Straw barriers provide enough carbon for soil microbes and stimulate soil microbial growth and activity (Li et al. 2020; Karhu et al. 2014). Li et al. (2020) observed that the mineralization rate of soil increased by 155% after the implement of straw checkered barriers.

Soil organic matter improves the ability of soil to store macronutrients such as potassium and magnesium by increasing the soil cation exchange capacity (Newman et al. 2007). In this study, establishment of straw checkerboard enhanced NPK content compared with the bare ground. However, the rye absorbed more total nitrogen from soil than the other cover crops. This trend may be stimulated near the borders due to fast rates of growth. Because of N-scavenging capacity of rye, it may assimilate and recycle substantial amounts of residual soil nitrogen during the quick establishment (Staver and Brinsfield 1998; Sadeghpour et al. 2014; Thorup-Kristensen 2006). Nielsen et al. (2015) reported that rye and canola have better potentials to mine residual soil NO_3^- compared to legume cover crops. Based on field experiments, Kaspar and Singer (2011) observed that oats, rye, ryegrass and hairy vetch as cover crops decreased NO_3^- leaching by 6–94%. Sainfoin increased the soil total N which may be attributed to biological N fixation (O'Reilly et al. 2012). On the other hand, higher nutrients released after the establishment of straw checkerboard barriers may be due to the decomposition and mineralization of straw (Li et al. 2020; Kasteel et al. 2007). Carbon rich straw materials of rice provide high levels of energy for microorganism which accelerate the mentioned processes. Gaihre et al. (2013) reported that rice stubble contains many elements such as nitrogen (N), phosphorus (P), potassium (K) and sulfur (S). Almost 40% of N, 30–35% of P and 80–85% of K uptake by rice remain in the straw at maturity stage (Dobermann and Fairhurst 2002). Previous studies have shown that straw checkerboard barriers can increase the soil nitrogen, available phosphorus and available potassium content (Li et al. 2018; Zhang et al. 2018; Lie 2017). After the straw decomposition and mineralization, generated adhesive substances will aid to soil aggregates (Xiu et al. 2019), followed by more water infiltration and higher water storage, etc. that are important topics in semi-arid sloping lands. The rye was more effective in enhancing P availability. The well-developed root system has been nominated in previous studies as a P-mobilizing species (Kamhet al. 1998). Cover crops can decrease the P loss caused by erosion, leaching and runoff (Maltais-Landry and Frossard 2015), which are the main concepts in sloping lands. On the other hand, organic acids released during the straw decay can activate organic phosphorus, leading to an increase in the soil nutrient availability (Shan et al. 2008). Higher available P content in the border of the barriers with no plant indicates the stimulant role of straw checkerboard to enhance available P; however, it may have been consumed in the squares with the plants. Some of plants may be more efficient in this way.

Soil water storage is a crucial parameter for plant establishment and growth, particularly in water-limited endangered conditions (Ren et al. 2008). The lack of sufficient precipitation during mid- to late-growth season (Fig. 2) led to a decrease in the soil water storage especially in the bare ground. Cover crops can improve the soil moisture storage through water conductivity by root channels, enhancing aggregate stability, and reducing soil compaction (Williams and Weil 2004; Soane et al. 2012). Higher soil water storage over plots with straw checkerboard barriers (Fig. 3), indicating their beneficial impacts on the stored soil moisture. The buried straw makes the top layer more porous which lead to more infiltration of water (Yang et al. 2016) to underneath layer. The soil exhibited higher porosity and lower bulk density near the borders. Wu et al. (2016) reported that this may lead to greater water conductivity and infiltration. The rice residue improved the rainwater preservation in carrying over extra soil water content during the growth and development of winter plants (Das et al. 2014). The border of barriers enhanced the soil water storage, and plants can benefit from the stored soil water content originated from winter and spring rainfall during the vegetative development stage. Fungal hyphae, which increase through straw material decomposition may promote the soil aggregation and improve the soil structure; therefore, reduce soil bulk density and alter the soil hydrothermal processes (Peng et al. 2013; Lenka and Lal 2013). Straw checkerboard barriers could effectively weaken the wind velocity (Bo et al. 2015) and provide the most shaded conditions which have a significant effect on microclimate near the ground result in a decreased evaporation while improving the water retention in the soil (Reicosky et al. 1995).

Increased plant height, aerial biomass, and shoot dry weight at checkerboard (Table 3) may be attributed to a greater availability of macronutrients and an increase in the soil moisture storage in the root zone and reasonable soil structure (Hallidri 2001). Zhao et al. (2014) and Clarke et al. (2015) reported that the straw returned into the soil reduces the moisture evaporation, increases the soil water content and soil temperature that enhance physiological metabolism in root systems, and also improve the nutrient mineralization and plant uptake. Zhang et al. (2018) showed that straw checkerboards created a suitable eco-environment for establishment of *Agriophyllum squarrosum*. Reducing bulk density and improving soil infiltration rate and soil ecological processes after the establishment of barriers (Zhang et al. 2018) may lead to an increase of root proliferation and extend deeper into the profile which increase the growth and reduce the risk of plant damages arising from drought (Payne et al. 1995). Cover crops with fibrous root system such as rye, oats and ryegrass were more efficient in decreasing the soil erosion than cover crops with thick roots (De Baets et al. 2011).

The leaf chlorophyll contents are good indicators of the photosynthesis activity, nutritional state and abiotic constraints (Marcu et al. 2013). High level of chlorophyll a, chlorophyll b and carotenoids in leaves of rye (Table 2), besides its drought tolerant characteristic, may be considered for their cultivation in this situation more than other ones (Hlavinka et al. 2009).

At the border of barriers, significant higher chlorophyll contents were observed. Enhanced soil moisture storage (Fig. 3A) and supply of nutrients especially nitrogen (Table 5) may increase the chlorophyll contents which coincide with other studies (Das et al. 2019; Silva et al. 2007). Chlorophyll depletion in leaves of plants grown in bare ground can be attributed to the continuously increasing soil moisture deficit and sensitivity of this pigment to drought stress. Carotenoids have a powerful antioxidant role in plants by scavenging reactive oxygen species; thereby, one of the main responsibilities of carotenoids is to protect the photosynthetic system against free radical stress (Ozsoy et al. 2009). The straw checkerboard barriers also increased the carotenoids content in leaves to prevent chlorophyll destruction. Therefore, straw checkerboard barriers can have the ability to prevent plants facing the adverse effect of drought.

Evaluation of RWC revealed better results for rye (Table 2) which may be due to its highly developed root system and can take full advantage of the soil water at the beginning of the growing season. Various studies have shown that grass species maintaining high amounts of RWC can exhibit more cellular hydration under stress conditions (Chai et al. 2010). Maintaining RWC at 67% in the rye grown on borders should allow the rye to retain minimal cell turgidity and represent a high capacity of osmotic adjustment.

Electrolyte leakage has been widely used as an indicator of the oxidative stress (Trabelsi et al. 2019). The rye had the lowest electrolyte leakage among the three cover crops (Table 2). Significant increase in EL on the bare ground plants may be due to water deficit and confirms that these plants are more vulnerable to border plants.

Malondialdehyde (MDA) concentration is the final product of membrane lipid peroxidation (Anjum et al. 2011). MDA content, as an indicator of oxidative damage, reflects the extent of the membrane injury caused by reactive oxygen species (Stajner et al. 2009). Our findings showed that the MDA content was decreased when the rye and sainfoin were grown in the straw checkerboards (Table 2). The straw checkerboards provided better protection from oxidative damages and higher tolerance to drought was created by improving the soil water storage.

As a nitrogenous compound, proline is the main amino acid that plays a major role in plants under drought conditions and is responsible for osmotic adjustment in plants (Hazrati et al. 2017). Higher proline accumulation, occurred in the rye grown on the borders, may be attributed to the increase in soil total nitrogen content (Azcón and Tobar 1998). Increased soil available potassium may induce proline accumulation. It may be attributed to starvation effect of K on amino acids and proline metabolism (Bahrami-Rad and Hajiboland 2017). In this study, the rye plants showed the highest proline concentration (Table 3), and the least-injuries by drought in terms of plants growth; Plants grown in the bare ground suffered more (Table 3). High proline contents were in line with maintaining protein structures; preserve the integrity of cell membranes and antioxidant protective roles in cover crops (Zhang et al. 2009).

Conclusion

Straw checkerboard barriers improved initial vegetation recovery in steep dry lands. As an effective management practice, this technique significantly has improved soil macronutrient, organic matter content and soil water storage which further creates ideal conditions for growth performance of plants. As a result, the improved plant growth leads to soil preserve and reduced erosion. Cover crops, especially the rye, improved organic matter contents of the soil, which may be important as a carbon sequestration approach. Most of the physiological parameters evaluated herein indicate that for the mentioned cover crops, rye had a better ability to survive during drought stress, can be used in such a dry condition effectively. Superior drought tolerance in rye, compared to other cover crops, was associated with increased proline content and more efficient osmotic adjustment. Based on this field experiment, it could be concluded that implement of straw checkerboards will protect cover crops more efficient to conserve natural resources and sustaining productivity. These amazing effects are more evident near the checkerboard stands because of higher water storage, NPK availability; organic carbon, etc. It seems 1×1 straw checkerboards stands provide an ideal set of conditions that support cover crops to establish efficiently.

Declarations

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Conflict of interests

The authors declared no conflict of interests.

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Figures

Figure 1

Straw checkerboards and sampling points

Figure 2

Daily mean air temperature and rainfall in the study area after the establishment of straw checkerboard barriers (a) and during the cover crops growing seasons (b)

Figure 3

Dynamic of soil water storage under cover crops type and straw checkerboard (A) and under straw checkerboard during growing season (B). Bars indicate S.E. Different letters indicate significant differences at $P < 0.05$ by LSD test.

Figure 4

Principal component analysis (PCA) of morphophysiological characteristics of different cover crops under straw checkerboard