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Research article



Wattle fencing improved soil aggregate stability, organic carbon stocks and biochemical quality by restoring highly eroded mountain region soil

Emre Babur [a], Omer Kara [b], Riyad Abdllah Fathi [c], Yunus Emre Susam [d], Muhammad Riaz [e,*], Muhammad Arif [f], Kashif Akhtar [g]

[a] Department of Soil Science and Ecology, Faculty of Forestry, Kahramanmaraş Sütçü İmam University, Kahramanmaraş, Turkey
[b] Department of Watershed Management, Faculty of Forestry, Karadeniz Technical University, Trabzon, Turkey
[c] College of Environmental Science and Technologies, University of Mosul, Mosul, Iraq
[d] General Directorate of Forestry, Ankara, Turkey
[e] Department of Environmental Sciences and Engineering, Government College University Faisalabad, Pakistan
[f] Department of Agronomy, The University of Agriculture Peshawar, Pakistan
[g] Institute of Nuclear Agricultural Sciences, Key Laboratory of Nuclear Agricultural Sciences of Ministry of Agriculture and Zhejiang Province, Zhejiang University, Hangzhou, 310058, China

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ABSTRACT

Eroded bare land stabilization is important to reduce soil erosion and stimulate soil carbon (C) sequestration for improved soil biogeochemical quality in hillslope soils. This study investigated the effectiveness of wattle fencing as a bioengineering tool to improve soil stabilization, soil physico-chemical properties and soil organic C dynamics and reduce soil erodibility in the Boyabat mountain regions of Turkey with rough and over-steepened slope (50–70%). Wattle fence treatments were developed in the area of 50 ha in the spring season of 2010 and surface (0–20 cm) and subsurface soil (20–40 cm) samples were taken in Spring, 2015. Results revealed that, compared to control with bare slope, wattle fencing significantly improved some soil physico-chemical, and microbial properties and erodibility indices by increasing clay ratio, dispersion ratio and aggregate stability index in surface and subsoils. Wattle fencing enhanced plant available water contents more in surface than in subsoils. Wattle fencing also increased microbial biomass C contents by 55% and 43% in surface and subsurface soils, respectively. Soil organic C followed similar trends; however, they were indifferent between sampling depths for the control soils. Soil organic C stocks and aggregate stability index were significantly positively correlated and seemed to be better predictor of positive effects of wattle fencing on soil structural stability, erodibility and associated properties. We found positive effects of soil organic C contents on microbial biomass C and soil-water relations suggesting restoration of soil biological functions and favorable influence on soil water retention following wattle fencing. Although sparse vegetation was observed in the research area, our study emphasizes performing further research to understand the effects of wattle fencing along with afforestation with native vegetation on soil erosion rates on a long-term basis by considering the variability in edaphic and environmental factors.

1. Introduction

Soil degradation from erosion has become a critical threat to global food security. Soil erosion gradually decreases soil depth, plant available nutrients, soil organic matter and soil productivity (Nearing et al., 2017; Ayubi et al., 2018). According to Pimentel and Kounang (1998), about 75 billion Mg of soils are eroded from terrestrial ecosystems in the world each year, which is similar to estimations from the Global Soil Partnership (GSP, 2017), with losses ranging from 13 to 40 Mg ha^{-1} yr^{-1} in most agricultural fields around the world (Pimentel and Kounang, 1998). The global economic loss from soil erosion has been estimated to be around $400 billion dollars (GSP, 2017). As a result, 10 million ha cropland are lost each year from soil erosion processes, a situation that poses serious implications for food production, global food security and environmental quality (Pimentel, 2006; Pimentel and Burgess, 2013; Battaglia et al., 2020). Therefore, soil erosion has long been recognized

* Corresponding author.
E-mail address: mr548@ymail.com (M. Riaz).

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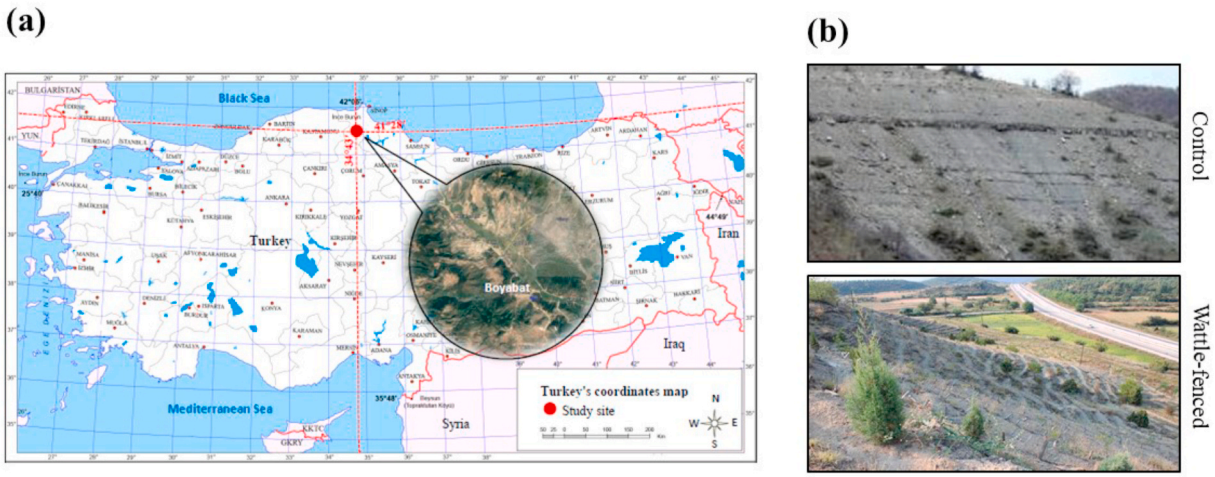

Fig. 1. Location map of a) study site and b) treatment plots under field conditions.

to decrease agricultural production because it leads to loss of the most productive soils.

Soil erosion is a function of complex interactions among variables including vegetation, soil properties, parent material, topography, and rainfall amount and intensity (Manyevere et al., 2016; Poesen, 2017; Diatta et al., 2020). While the effects of these factors are well-established (Laker, 2004), changes in land use and management practices are predominantly the main drivers that accelerate soil erosion processes (Govers et al., 2006; Maetens et al., 2012). This, in turn, has resulted in drastic implications for nutrient and C cycling, land productivity and, ultimately, global socio-economic conditions (Borrelli et al., 2013). Over the course of time, the problem of soil erosion has become aggravated in hilly areas because the hillslope soils tend to evolve maintaining a balance between erosion and soil production, which results in developing soil thickness characteristic to particular climatic and geographic regions (Montgomery, 2007). Thus, topographical features in hilly areas are important determinants of soil erosion (Zhang et al., 2015).

Many ecological engineering techniques and strategies are adopted to control soil erosion; however, relative efficiency of these approaches is generally not reported as their success or failure to improve soil and water conservation (Maetens et al., 2012; Haregeweyn et al., 2015). Liu et al. (2011) reviewed different soil erosion control techniques in Northeast China, including a blend of agronomic and bioengineering practices such as tillage practices, terrace and strip farming and soil organic amendments. Alley cropping is an important soil conservation practice in sloping farmlands in hilly areas that can reduce soil erosion risks and enhances soil productivity in mountain ecosystems (Tu et al., 2005). Soil erosion and water runoff can also be sustainably reduced by decreasing the slope and establishing natural terraces on steep slopes through establishment of hedgerows systems. Moreover, hedgerows were reported to have positive effects on soil organic matter and nutrient contents alongside with reductions in water and soil losses (Chaowen et al., 2007; Wen et al., 2013). Growing perennial crops for different uses has been effective to reduce soil erosion while improving soil quality over the long term. Fagnano et al. (2015) found that giant reed (*Arundo donax* L.) improved soil organic matter and fertility and reduced soil erosion on marginal hilly lands in southern Italy. Giant reed has the ability to grow under extreme soil conditions and low water availability on hilly croplands with steep slopes areas facing extended droughts and accelerated erosion in Mediterranean climatic regions (Lewandowski et al., 2003; Diodato et al., 2009; Fiorentino et al., 2010). Results from multistate research conducted on different landscape positions in the US found that the root systems of Switchgrass (*Panicum virgatum* L.) can increase carbon (C) and nitrogen (N) pools in soils over the long term and reduce the risk of N loss (Kumar et al., 2019). Other bioenergy crops with high productivity potential and low nutrient requirements such as *Miscanthus giganteus* could also be used to this end (Battaglia et al., 2019). The relative effectiveness of these techniques is measured from improvements in soil physical (aggregate stability, plant available water, bulk density, aeration and gaseous exchange), chemical (pH, electrical conductivity, cation exchange capacity and nutrient availability) and biological (microbial activity and biomass) indicators of soil quality (Lal, 2015; Babur et al., 2021). Soil organic C is also the most reliable indicator of changes in soil quality from erosion and degradation (Singer and Warkentin, 1996; Rajan et al., 2010).

Wattle fencing or fascines is a soil bioengineering technique aiming to reduce soil erosion on steep slopes (Polster, 2003; Rey, 2009; Liela et al., 2017). By the end of the 19th century, wattle fencing was considered an efficient bioengineering technique to protect soil erosion on steeper naked slopes that were highly susceptible to severe land degradation (Thornes, 2005; Evette et al., 2009). Robichaud et al. (2008) demonstrated a significant reduction in sediment erosion after applying contour felled log, straw wattle, and hand dug contour trench as hillslope erosion barrier treatments. Wattle fences stabilize moisture sensitive soils that are susceptible to sliding by allowing the moisture to drain into steep slopes. While the terracing made by the wattle fences reduces soil erosion, it also provides soil organic matter and nutrients for a dense cover of pioneering woody species on the slope (Polster, 2002; Li et al., 2013a, b). Wattle fences are generally installed perpendicular to prevailing wind or slope to reduce the impact of wind and long slope lengths on soil erosion (Kearley and McCallister, 2000; Rivas, 2006).

Boyabat is the largest city of Sinop Province located in the Middle Black Sea region in Turkey. The topography of this region is characterized by the presence of high and rough mountain ranges with the most over-steepened slopes in Sinop region (Babur et al., 2016). The research area has a Mediterranean climate and is a transition zone between the Middle Black Sea and Central Anatolia (Emberger, 1952; Akman, 1990). The geological structure of the study area is formed by eocene marn, claystone, tufa and quaternary alluvions (Ketin, 1962). Babur et al. (2016) reported severe erosion in the bare area of the study site due to the absence of vegetation and rather high slope. As yet, however, no data are available that demonstrate the use of bioengineering techniques to control soil erosion in the study region. In order to prevent severe erosion in these areas, the General Directorate of Combating Desertification and Erosion of Turkey established the wattle fences in these areas in 2010. We hypothesized that wattle fencing would reduce soil erodibility indices by improving surface and subsoil properties, water relations and soil organic C of highly eroded soil. The objectives of this research were a) to investigate the effects of wattle fencing on soil physico-chemical and biological properties in surface and

Table 1
Soil physico-chemical properties under control and wattle-fenced treatments in surface and subsoil at 0–20 and 20–40 cm depths.

Treatment	$pH_{1:2.5}$ (H_2O)		EC (dS m^{-1})		Sand (%)		Silt (%)		Clay (%)		Soil texture		BD (g cm^{-3})		Aggregate stability index		Colloidal moisture	
	0–20 cm	20–40 cm	0–20 cm	20–40 cm	0–20 cm	20–40 cm	0–20 cm	20–40 cm	0–20 cm	20–40 cm	0–20 cm	20–40 cm	0–20 cm	20–40 cm	0–20 cm	20–40 cm	0–20 cm	20–40 cm
Control	7.58 ± 0.03 bc	7.54 ± 0.03 c	0.75 ± 0.13 c	1.30 ± 0.18 b	31.1 ± 1.94 a	31.1 ± 2.27 a	37.1 ± 1.20 b	37.3 ± 1.32 b	31.8 ± 0.92 a	31.6 ± 1.12 a	Clay loam	Clay loam	1.62 ± 0.04 b	1.71 ± 0.04 ab	0.77 ± 0.70 b	0.76 ± 0.02 b	1.70 ± 0.04 ab	1.65 ± 0.04 ab
Wattle-fenced	7.69 ± 0.04 a	7.67 ± 0.04 ab	1.64 ± 0.17 ab	2.02 ± 0.16 a	26.5 ± 1.61 a	32.8 ± 1.73 a	41.3 ± 0.74 a	37.8 ± 0.99 b	32.2 ± 1.21 a	29.4 ± 1.32 a	Clay loam	Clay loam	1.77 ± 0.02 a	1.76 ± 0.03 a	0.91 ± 0.70 a	0.89 ± 0.01 a	1.78 ± 0.06 a	1.59 ± 0.07 b
F-values	T = 10.01**; D = 0.65^{ns}; T × D = 0.025^{ns}		T = 25.39***; D = 8.34**; T × D = 0.29^{ns}		T = 0.54^{ns}; D = 2.76^{ns}; T × D = 2.80^{ns}		T = 4.59*; D = 2.24^{ns}; T × D = 3.03^{ns}		T = 0.64^{ns}; D = 1.79^{ns}; T × D = 1.26^{ns}		N/A		T = 10.59**; D = 1.42^{ns}; T × D = 2.52^{ns}		T = 126.6***; D = 1.29^{ns}; T × D = 0.09^{ns}		T = 0.02^{ns}; D = 5.16*; T × D = 1.48^{ns}	

Values are means of 30 data points and followed by standard errors of means (n = 30). Means of each variable with different letters differ significantly from each other. EC = Electrical conductivity, BD=Bulk density; *$P < 0.05$, **$P < 0.01$, ***$P < 0.001$, ns = Non-significant; T = Treatment, D = Depth, N/A = Not applicable.

subsoil, and b) to study if wattle fencing reduce soil erodibility indices and improve soil-water relations by enhancing aggregate stability and soil organic C stocks.

2. Materials and methods

2.1. Study site characteristics

The study area is located at 20 km from west Sinop-Boyabat, in Northwestern Black Sea mountain region of Turkey (Fig. 1). The altitude ranges between 350 and 450 m and has dominant hill slope of 40–60% with southern aspect. According to the long-term weather data from the 1985–2015 period collected from the Turkish State Meteorological Service (*www.*mgm.gov.tr/), annual mean temperature in the area is 12.9 °C with a maximum of 21.7 °C in July and a minimum of 4.0 °C in January. The long-term annual precipitation is 620 mm and maximum rain occurring in December (75 mm) and minimum in July (30 mm). The region falls within the arid and humid zone under a temperate oceanic climate. Steeper slope (50–70%) topography has moderate soil depths between 50 and 90 cm. The rugged topography basically consists of volcanic sedimentary bedrock (MTA, 2000). The soil of the study site is young and horizons have begun to form, and classified as Inceptisol by U.S. Soil Taxonomy (Soil Survey Staff, 2010). The dominant vegetation species in the close proximity to the research area are larch (*Larix decidua*), scotch pine (*Pinus sylvestris*) and oak (*Quercus robur*). The study site vegetation is in Euro-Siberian zone öksin-provens part (Davis, 1965; Anşin, 1983).

2.2. Development of wattle-fenced treatments

The area was established in the spring season of 2010 by the General Directorate of Combating Desertification and Erosion of Turkey, because the soils become soft during rainy season at the site. Wattle fences were used to treat the over-steepened slopes at the study site after preparing the site with a handheld mechanical excavator. Wooden poles having a diameter of 4–6 cm and a length of 100 cm were used to construct wattle fences and they were kept at 30–40 cm distance from each other. Two-third length of the poles were driven into the ground with hammer.

2.3. Soil sampling and preparation

In April 2015, the soil sampling was conducted in the wattle-fenced and control treatment plots. Soil samples were collected using a randomized sampling design that covered a total of 50 ha land area. Thirty sampling points were chosen in each of the wattle-fenced and control plots within interior of the terrace made for the wattle fence. The bulk and intact core soil samples were taken from surface (0–20 cm) and subsurface (20–40 cm) to make 120 samples in total. Litter layer, stones, and root debris were first removed from the sampling area, and then bulk surface and subsurface soil samples were taken with an augur from the interior of the terrace made for the wattle fence for determination of selected physico-chemical properties (pH, EC, particle size, aggregate stability, soil-water relations and soil organic C) and intact samples were taken using a stainless-steel ring (8 cm diameters, 10 cm height) for bulk density analysis. The bulk and intact samples were transferred into hermetic plastic bags before taking them to laboratory. For the analysis of microbial biomass C, 50-g subsamples from bulk samples were adjusted to 50–60% of water holding capacity, put into the separate hermetic plastic bags and kept at 4 °C until analysis. The remaining bulk soil samples were air-dried, ground, sieved through a 2.0-mm mesh and stored into plastic bags until analyses for physico-chemical properties.

2.4. Laboratory analysis

Soil pH in distilled water was measured in a 1:2.5 (soil/water) mixture with a pre-calibrated digital pH meter, whereas electrical

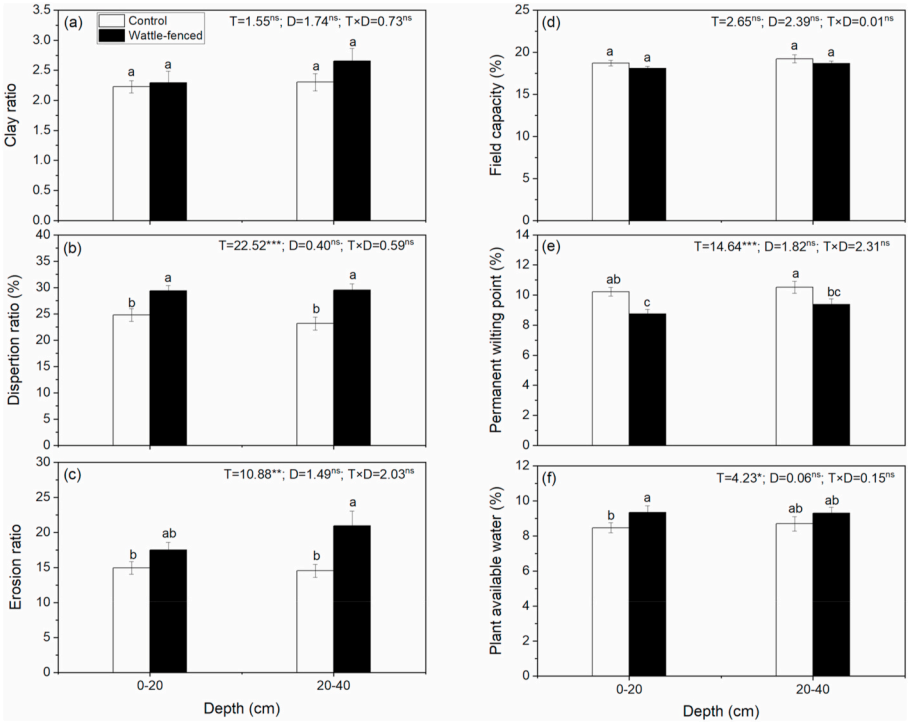

Fig. 2. Changes in a) clay ratio, b) dispersion ratio, c) erosion ratio, d) field capacity, e) permanent wilting point and f) plant available water under control and wattle-fenced treatments in surface and subsoils at 0–20 and 20–40 cm depths, respectively. Each bar shows mean values of 30 samples and contains standard errors of means (n = 30). Different letters on bars show significant differences between mean values. $^{*}P < 0.05$; $^{**}P < 0.01$; $^{***}P < 0.001$; ns = Non-significant. T = Treatment, D = Depth.

conductivity (EC) was measured in the same suspension with a digital EC meter (Rowell, 1994). Particle size distribution was determined by using the hydrometer method (Bouyoucos, 1935). Soil water relations, i.e. field capacity (FC), permanent wilting point (PWP) and plant available water content (PAWC) were determined by following the method of Karaöz (1989). Field capacity and PWP were measured with a ceramic plate at 33 kPa and 1500 kPa, respectively (Klute, 1986). The PAWC was estimated as the difference between FC and PWP. Soil bulk density (BD) was estimated using the intact core samples taken with a stainless-steel core-sampling cylinder of known volume (Karaöz, 1989).

Erodibility indices such as clay ratio, dispersion ratio, colloid/moisture equivalent and erosion ratios were determined to measure relative susceptibility of soils to erosion (Singh and Khera, 2008). Dispersion ratio was calculated from the amount of silt and clay in calgon-dispersed and water-dispersed samples using Bouyoucos hydrometer method of particle size described (Eq. (1)) by Gee and Bauder (1986); clay ratio with the equation suggested by Bouyoucos (Eq. (2)) (Neal, 1938); colloid/moisture equivalent by the soil clay ratio divided by the FC moisture; erosion ratio by dividing the dispersion ratio with colloid/moisture equivalent (Eq. (3)) (Middleton, 1930; Singh and Khera, 2008). Specific equations used for the erodibility indices were as follows:

$$\text{Dispersion ratio} = \frac{\text{Suspension percentage}}{(\text{Silt} + \text{Clay}) \text{ under dispersed conditions}} \quad (1)$$

$$\text{Clay ratio} = \frac{\%\ (\text{Silt} + \text{Clay})}{\%\ \text{Clay}} \quad (2)$$

$$\text{Erosion ratio} = \frac{\text{Dispersion ratio}}{\text{Clay/moisture equivalent ratio}} \quad (3)$$

Aggregate stability is the measure of the ability of soil aggregates to withstand when broken down into smaller fragments under moist conditions and is an effective soil erosion indicator. The aggregate stability index was determined following the wet sieving method of Kemper and Rosenau (1986).

Total organic C contents were analyzed with potassium dichromate wet oxidation method (Walkley and Black, 1934). The soil organic C stocks in surface and subsoil were calculated by the following equation (Eq. (4)) (Tolunay and Çömez, 2008; Li et al., 2013a, b; Abdalmoula et al., 2019).

$$\text{SOC} = \sum_{i}^{k} \text{C}i\ x\ \ \text{BD}i\ x\ \text{D}i \quad (4)$$

SOC is the amount of soil organic C (t ha^{-1}), C*i* is the soil organic C content (g kg^{-1}) in a soil depth, BD*i* is the bulk density (g cm^{-3}) of a soil depth, and D*i* is the soil depth (cm).

Soil microbial biomass C (MBC) was estimated using the chloroform fumigation extraction method (Anderson and Ingram, 1996). Briefly, 20 g dry weight equivalents moist soil samples were weighed into 250 mL–capacity glass beakers and incubated with ethanol-free chloroform for 24 h in vacuumed desiccators. The fumigated and non-fumigated soil samples were extracted with 0.5 M K_2SO_4 (1:4 w/v) after shaking in an oscillator for 60 min at 150 rpm. The solutions were filtered through Whatman No.42 filter paper and kept at 4 °C prior to analysis. Total organic C contents in fumigated and non-fumigated sample extracts were determined by titration against 0.033 M acidified ferrous ammonium sulphate after dichromate oxidation (Walkley and Black, 1934). MBC contents were then calculated using the following expression (Eq. (5)):

$$\text{MBC} = \left(\text{C}_{\text{fumigated}} - \text{C}_{\text{non-fumigated}}\right)/\text{K}_{\text{EC}} \quad (5)$$

Where K_{EC} was used as an efficiency factors for MBC and we used 2.64 as K_{EC} (Vance et al., 1987; Kara and Baykara, 2014).

2.5. Statistical analysis

Data was first analyzed for normality as a pre-requisite for analysis of variance (ANOVA) test and, when required, data were log-transformed before analysis. Two-way ANOVA was applied to test the effects of treatment and depth on soil physico-chemical properties, soil organic C, soil-water relations and erodibility indices. Tukey's post-hoc test was used to compare multiple means. Pearson's correlation coefficients were calculated for the relationships between soil erodibility indices and soil

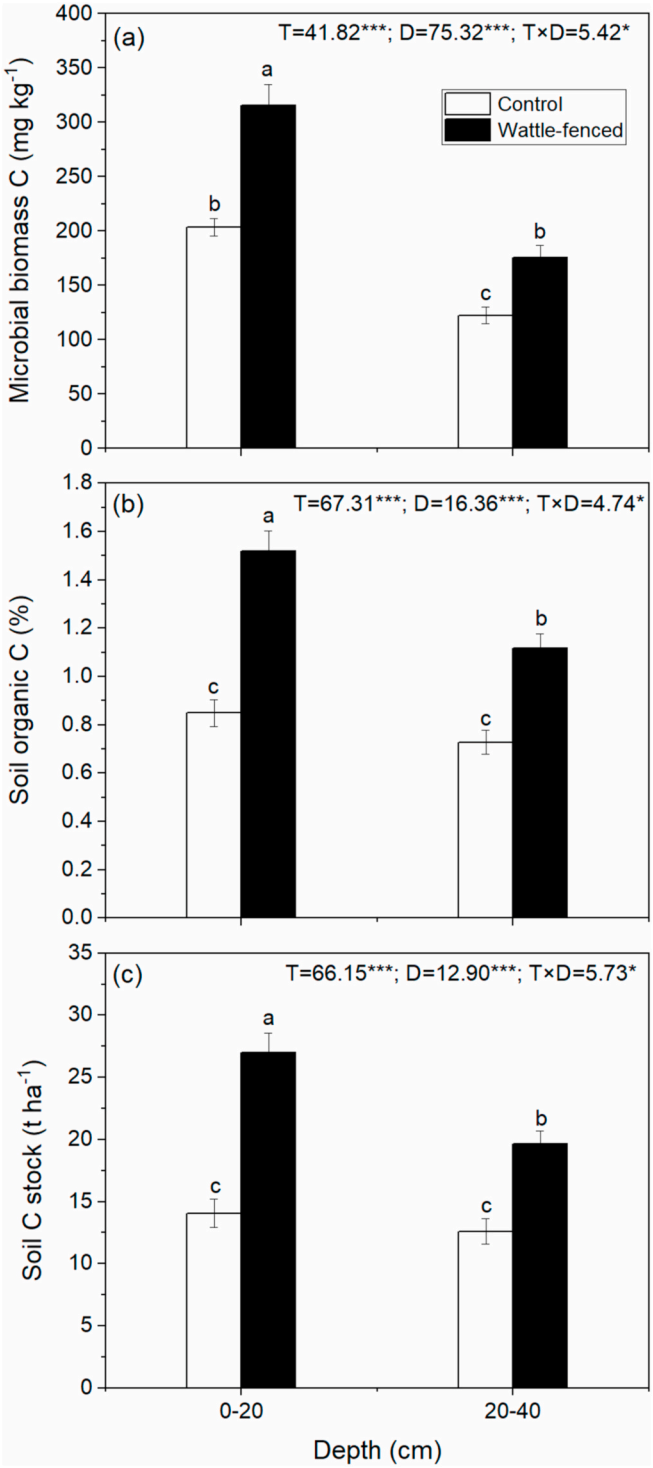

Fig. 3. Changes in a) microbial biomass C, b) soil organic C and c) soil C stocks under control and wattle-fenced treatments in surface and subsoils at 0–20 and 20–40 cm depths, respectively. Each bar shows mean values of 30 samples and contains standard errors of means (n = 30). Different letters on bars show significant differences between mean values. $^{*}P < 0.05$; $^{**}P < 0.01$; $^{***}P < 0.001$; ns = Non-significant. T = Treatment, D = Depth.

properties. The scatter plots along regression analysis were used for the relationships between soil organic C stocks, bulk density, aggregate stability and soil-water relationships. Statistical analyses were performed using SPSS for Windows software v. 19.

3. Results

3.1. Effects on soil properties

Soil physico-chemical, particle size fractions and textural properties, aggregate stability index and colloidal moisture at two soil profile depths under the control and wattle-fenced treatments are listed in Table 1. In both surface and subsoil, the wattle-fenced treatment significantly increased soil pH and EC compared to control; however, depth had significant effects on EC only. Compared with control, the wattle-fenced treatment increased soil pH by 1.45% and 1.72% at the 0–20 cm and 20–40 cm soil depths. Soil EC were significantly higher in the wattle-fenced treatments, with increase of 119% and 55% in surface and subsoil compared to control, respectively. Despite of some variations in sand, silt and clay contents in surface and subsoil, soil texture was clay loam under both depths and treatments (Table 1).

We found that wattle fencing had significant effects on BD and aggregate stability index whereas depth only affected colloidal moisture (Table 1). Wattle-fencing increased BD in surface soil more than in subsoil and, under the control treatment, subsoil had higher BD compared to the surface soil. Wattle-fencing resulted in significant positive effects on aggregate stability index in surface (18% higher than control) and subsoils (17% higher than control). Colloidal moisture contents in wattle-fenced treatments were higher than control and remained higher in surface than subsoil.

3.2. Changes in soil erodibility indices and water relations

Treatment and depth showed non-significant effects on clay ratio, although clay ratio in subsoil at the 20–40 cm depth for wattle-fenced soil was 15% higher than control treatment (Fig. 2a). Wattle fencing significantly enhanced dispersion ratio in surface and subsoils without significant changes between soil depths (Fig. 2b). Similar treatment effects were observed for erosion ratio and an increase of 20% was found under wattle-fenced treatment at the 20–40 cm depth compared to the 0–20 cm depth (Fig. 2c). Wattle fencing decreased FC values in both surface and subsoil (Fig. 2d). In contrast, wattle fencing significantly decreased PWP in surface and subsoil by 15% and 11% when compared to the control treatment, respectively (Fig. 2e). At the 0–20 cm depth, wattle fencing significantly improved PAW contents by 10% versus control (Fig. 2f).

3.3. Effects on soil organic C dynamics

Changes in microbial biomass C, soil organic C and soil C stocks at the two profile depths after wattle fencing are presented in Fig. 3. Compared to control, application of wattle fences increased microbial biomass C by 55% and 43% at the 0–20 cm and 20–40 cm depths, respectively (Fig. 3a). In wattle-fenced treatments, there was a nearly 2-fold decrease in the microbial biomass C contents in subsoil compared to surface soil. Similarly, wattle fencing increased soil organic C from 0.85% to 1.52% at the 0–20 cm depth, and from 0.73% to 1.12% at the 20–40 cm depth (Fig. 3b). Soil organic C contents under the control treatment varied very little between depths, while under wattle fencing, soil organic C contents significantly decreased by 26% in subsoil compared to surface soil. Because soil organic C stocks were calculated using the soil organic C contents, therefore, treatment and depth effects on soil organic C stocks were similar to those on soil organic C contents (Fig. 3c).

3.4. Correlations between soil properties, soil-water relations and erodibility indices

Relationships of erodibility indices and colloidal moisture contents with soil physico-chemical properties are shown in Table 2. Clay ratio was positively correlated with BD and negatively with FC and PAW

Table 2
Pearson's correlation coefficients of clay ratio, dispersion ratio, erosion ratio and colloidal moisture with other physico-chemical properties of soil under control and wattle-fenced treatments.

Erodibility indices	$pH_{1:2.5}$ (H_2O)	EC	BD	Aggregate stability index	FC	PWP	PAW	Soil organic C	Microbial biomass C	Soil C stock
Clay ratio	−0.24**	0.18*	0.18*	0.10^{ns}	−0.35**	-0.13^{ns}	−0.21*	-0.14^{ns}	-0.14^{ns}	-0.12^{ns}
Dispersion ratio	0.05^{ns}	0.27**	0.16^{ns}	0.24**	0.16^{ns}	0.02^{ns}	0.14^{ns}	0.14^{ns}	0.21*	0.15^{ns}
Erosion ratio	-0.13^{ns}	0.35**	0.13^{ns}	0.19*	0.16^{ns}	0.09^{ns}	0.06^{ns}	-0.05^{ns}	0.01^{ns}	-0.03^{ns}
Colloidal moisture	0.32**	−0.31**	-0.10^{ns}	-0.03^{ns}	-0.11^{ns}	-0.13^{ns}	0.01^{ns}	0.32**	0.21*	0.29**

*$P < 0.05$; **$P < 0.01$; ns = non-significant; n = 120. EC = Electrical conductivity, BD=Bulk density, FC=Field capacity, PWP=Permanent wilting point, PAW=Plant available water.

contents. Dispersion ratio showed negative correlation with EC and positive correlations with aggregate stability index and MBC contents. Erosion ratio was also positively correlated with EC and aggregate stability index, and negatively with pH. Colloidal moisture contents were, however, significantly positively correlated with pH, microbial biomass C and soil organic C contents, but significantly negatively with EC (Table 2).

The correlation plots showed that soil organic C stock had a significant positive correlation with aggregate stability index (Fig. 4a) and microbial biomass C (Fig. 4b) whereas the correlation between BD and soil C stock was also significant and positive (Fig. 4c). Effects of soil C stocks on soil water relations showed that soil C stock was significantly negatively correlated with FC (Fig. 5a) and PWP (Fig. 5b), but significantly positively correlated with PAW (Fig. 4c).

4. Discussion

The effects of wattle fencing on soil physico-chemical, biological and erodibility indices in our study suggested that wattle fencing can reduce soil erosion by improving soil aggregate stability, soil water relations and soil organic C, similar to previous studies who found that bioengineering techniques including wattle fencing might stabilize soil and promote vegetation restoration in eroded areas (Wu et al., 2010; Deng et al., 2014; Zhang and Zhao, 2015; Punetha et al., 2019). In addition, such bioengineering techniques can improve soil slope stability, reduce soil erodibility, promote soil-plant interactions and enhance hydrological flows (Freer, 1991; Gao et al., 2007). Wattle fences are particularly effective in slope stabilization as they promote mechanical stabilization against erosion (Prescot et al., 2021). While reviewing global strategies to tackle soil erosion in mountain regions, Patel (2012) viewed wattle fencing as an effective tool to reduce and mitigate soil erosion in hilly areas. In another study, Wu et al. (2010) observed that nine-year of fencing significantly enhanced vegetation cover and above-ground biomass and, hence, improved soil properties. Therefore, wattle fencing can stimulate natural vegetation cover which could increase organic matter inputs and improve soil physico-chemical properties including soil stabilization, nutrient and water retention in surface and subsurface soils (An et al., 2013; Wang et al., 2019). Hevia et al. (2014) reported that construction of wattle fences reduced erosion, improved infiltration rates and promoted vegetation recovery in badlands of the Saldaña region, Spain.

We found that wattle fencing improved soil-water relations which may enhance soil structural stability. Soil structure influences vegetation growth, water retention and, C and nutrient cycling in eroded soils. Soil aggregate stability is a fundamental soil property closely associated with soil water cycle, soil erodibility and soil nutrient cycling (Zádorová et al., 2011). Quijano et al. (2019) showed that the management of aggregate stability was crucial for productivity of Mediterranean agroecosystems facing erosion problem and reduction in aggregate stability frequently results in high soil erosion risks in these ecosystem (Cantón et al., 2009). Barthès et al. (1999) also demonstrated that topsoil aggregate stability and soil erodibility were strongly linked in hillslopes of Aveyron, France under Mediterranean climatic conditions. Our results indicated that wattle fencing promoted soil aggregate stability and, hence, improved soil physico-chemical properties. The measurement of soil physico-chemical properties can facilitate deep understanding of the factors regulating erosion and the effectiveness of erosion control measures (Masoodi et al., 2017; Ayoubi et al., 2018). Ouyang et al. (2018) used soil physical and water-relation properties to report the extent of soil erosion in an intensively-cultivated paddy landscape.

The reduction in soil erodibility indices after wattle fencing in our study may have resulted from the changes in physico-chemical properties like soil structure and/or retention of soil moisture (Nwankwo, 2001; Cornelis, 2006). The higher clay ratio under wattle-fenced surface and subsoil, and a significant positive relationship between dispersion ratio and aggregate stability index in this study also provides evidence of the role of clay particles in soil aggregation because clay particles with their organo-mineral complexes and soil organic matter are the main binding agents of soil aggregate stability (Six et al., 2002). Dispersion ratio, clay ratio and erosion ratio have been used conjunctively to estimate soil erodibility (Sharma and Bhatia, 2003; Singh and Khera, 2008; Parwada and Tol, 2017). However, dispersion ratio sometimes cannot differentiate between the soils that are highly erodible or highly resistant to erosion because of its inability to evaluate the complex factors affecting erosion (Wahler and Arulanandan, 1976). Favorable soil structure and higher aggregate stability are the significant factors for enhancing soil porosity and decreasing erodibility (Thomaz and Luiz, 2012).

Fencing techniques have been very effective for ecological restoration on the Loess Plateau of China having complex terrain, extreme drought conditions and severe soil erosion (Deng et al., 2014). Similarly, wattle fencing was predominantly used to reduce erodibility in the mountainous Mediterranean climate agroecosystems (Rey, 2009). The basic unit of soil structure is aggregate stability, which is sensitive indicator of the soil quality (Lynch and Bragg, 1985). In our experiment, wattle fencing improved soil structure by increasing aggregate stability and improved soil water retention. In previous studies, wattle fencing also stimulated aggregation by stabilizing soil particles and promoted soil water retention to decrease soil erosion on steeper slopes (Tisdall and Oades, 1982; Annabi, 2017). The infrequent and/or high intensity rainfall causes soil erodibility by depleting surface and subsurface soil particles on sloping lands (Akhtar et al., 2019). (Liu et al., 2019a, b) argued that comprehensive approaches considering the slope, rainfall and topography could reduce soil erosion and water run-off. Similarly, Olsen et al. (2012) found slope-dependent effects of straw wattles on slope stabilization and suggested that wattle fences could have limited scope on soil stabilization under much steeper slopes. However, they still recommended the use of wattles as an effective slope stabilization technique. When soils on steep slopes are bare and not-protected, soil water retention dramatically decreases, and heavy and infrequent rainfall might lead to increased erosion by detaching soil particles (Akhtar et al., 2018). Water erosion is the result of soil detachment, mainly by rainfall, followed by soil transport by runoff; therefore, soil aggregate stability is linked with soil erodibility or the susceptibility of soil to erosion. Mulumba and Lal (2008) showed that application of mulches as bioengineering technique increased soil porosity, soil water

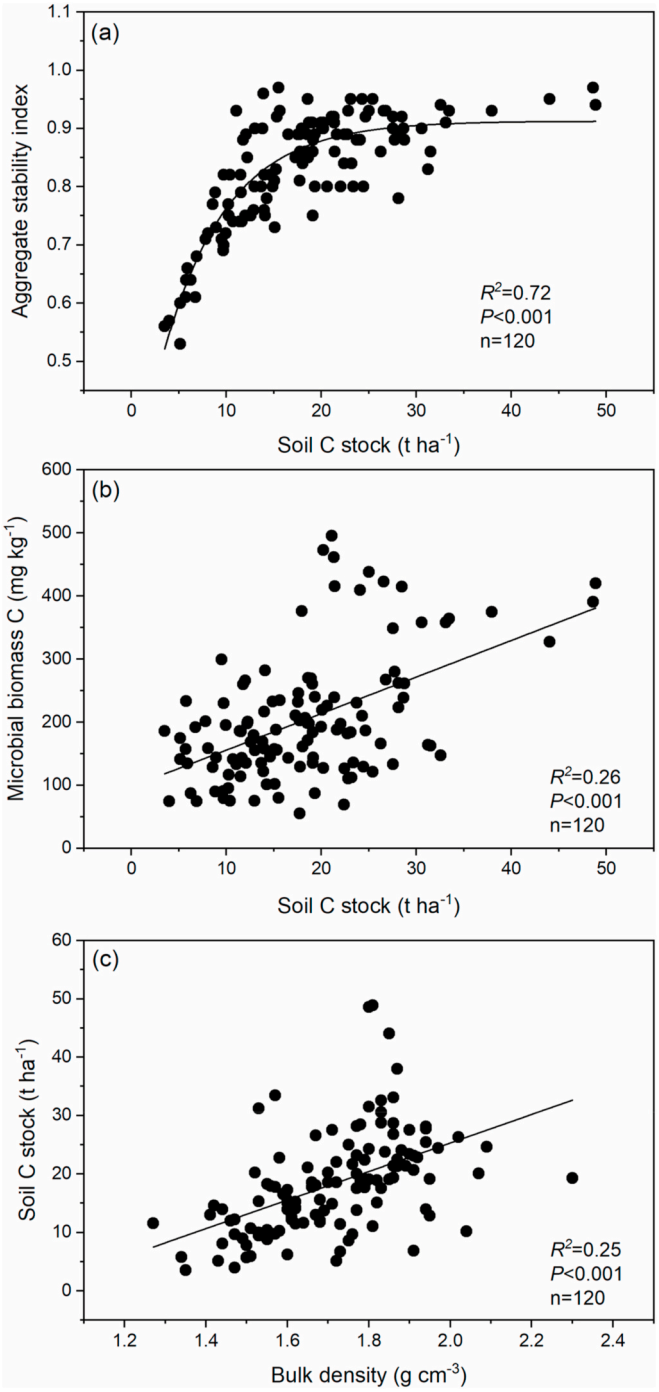

Fig. 4. Relationships of soil C stock with a) aggregate stability index, b) microbial biomass C and c) bulk density with soil C stock in surface and subsoil under control and wattle-fenced treatments.

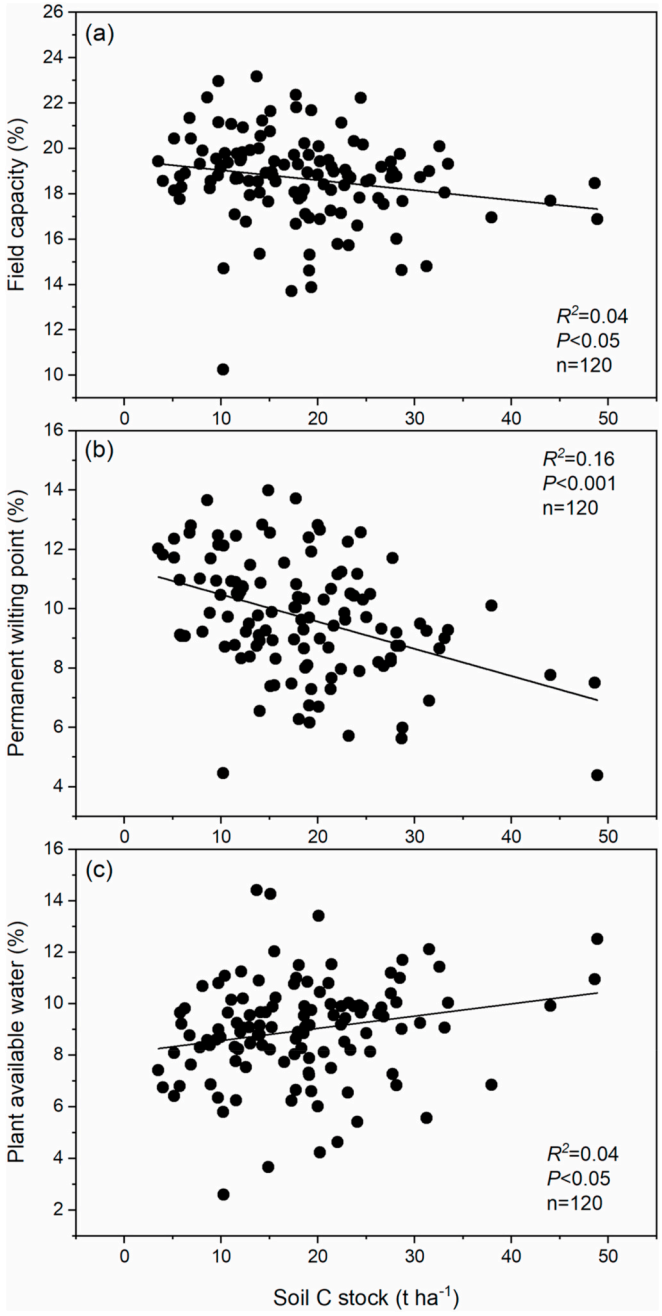

Fig. 5. Relationships of soil C stock with a) field capacity, b) permanent wilting point and c) plant available water in surface and subsoil under control and wattle-fenced treatments.

retention capacity and aggregate stability.

Our study reported significant positive relationships of soil properties and soil aggregate stability with soil organic C stocks. Our results are in agreement with those from Mekonnen et al. (2015) and Brevik et al. (2015) that soil structure improvements strongly increase soil stabilization and C sequestration. Hence, the soil C stability is dependent on favorable soil structure (Mao et al., 2007; Gelaw et al., 2013). Our results showed strong positive relationship between aggregate stability and soil organic C stocks whereas soil organic C stocks correlated significantly positively with BD. These observations were similar to those reported by Garcia-Orenes et al. (2005) who found that increases in aggregate stability were related to an increase in soil organic C contents in two degraded soils. Further, Abu-Hamdeh et al. (2005) and Liu and He (2009) reported that the stability and storage of soil organic C contents was associated with soil aggregate stability and soil structure. In addition to influencing soil organic C and soil physico-chemical properties, wattle fencing also improved soil biological functions reflected from their significant positive effects on soil microbial biomass C contents in surface and subsoil and also significant positive correlations between soil organic C stocks and microbial biomass C contents. Therefore, the higher microbial biomass C in subsoil was primarily due to higher soil organic C contents. However, the better edaphic conditions around the wattle fences can also result in higher biological activity in surface and subsoil (Lovreglio et al., 2020). This also suggests positive influences of soil restoration practices on soil biological

functions and nutrient cycling in eroded soils (Liu et al., 2019a, b).

Soil organic C is the basis for soil fertility and source of energy for soil microorganisms that regulates climate and microbial biodiversity (Lal, 2004, 2014; Li et al., 2013a, b; Dou et al., 2016). Vegetation succession with fencing significantly affects soil biogeochemical properties (Oduor et al., 2018). Upon re-establishment, plants without external disturbance can grow rapidly and require many nutrients that can momentarily reduce soil organic matter contents; however, the plant cover and above-ground biomass continuously increase, which can increase soil organic C and nutrient contents. In our study, we found that wattle fencing significantly increased soil organic C contents probably due to regeneration of vegetative cover as the soil organic C contents increase alongside with the vegetation regrowth and biomass inputs (Zhou et al., 2011; Medina- Roldán et al., 2012; Deng et al., 2014; Kara et al., 2016). Effective soil erosion control measures improve soil organic C and results in net C sequestration (Nie et al., 2017; Ran et al., 2018; Hancock et al., 2019). Moreover, in addition to catch surficial rolling soil, the decomposition of wattle logs can stabilize soil by adding organic matter and slowly releasing moisture during the decomposition (Harmon and Sexton, 1995). Our observations regarding the positive effect of wattle fencing on soil water contents are consistent with results from Thomaz and Luiz (2012) who found that fencing altered hydrological dynamics in the eroded area. Our study reported the effects of wattle fencing on soil physico-chemical and erodibility indices after five-year of treatment development; however, the effects of such erosion-control measures are time-dependent and their effectiveness generally increases with time (Hann and Morgan, 2006).

5. Conclusions

Our field study aimed to find the potential of wattle fencing to reduce erosion on over-steepened hillslopes in the mountain regions of the Boyabat in Turkey. We tested that the hypothesis that wattle fencing would reduce the soil erodibility by affecting the soil aggregate structure, physiochemical properties and soil-water relations. Results indicated the positive influence of wattle fencing on soil physico-chemical properties and erodibility indicators. Increase in aggregate stability index in surface and subsoil under wattle fencing enhanced soil organic C stocks in surface and subsoil. Significant positive relationships were observed between aggregate stability and soil organic C stocks that explained the improved soil water contents and soil biological functions at both soil depths. Our study utilized wattle fencing as the sole bioengineering technique to stabilize the hillslope soils and this technique showed a remarkable potential to reduce soil erodibility. However, more long-term research is required to understand with the effects of wattle fencing and other soil-erosion control techniques that include both the edaphic and environmental conditions. We also emphasize that the restoration of eroded landscapes can provide opportunities for soil and water conservation, C sequestration and climate change mitigation.

Credit author statement

Emre Babur: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Visualization, Writing – review & editing, Funding acquisition. **Omer Kara**: Conceptualization, Resources, Writing – review & editing. **Riyad Abdllah Fathi**: Methodology, Resources, Writing – review & editing. **Yunus Emre Susam**: Writing – review & editing. **Muhammad Riaz**: Formal analysis, Visualization, Writing – original draft, Writing – review & editing. **Muhammad Arif**: Writing – review & editing. **Kashif Akhtar**: Writing – review & editing.

Declaration of competing interest

The authors declare no conflict of interest.

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