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Slope length effects on microbial biomass and activity of eroded sediments

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Abstract
Purpose Due to climatic and topographic conditions, soil erosion is a major problem in Turkey; approximately 86% of the land is suffering from some degree of erosion. This study investigated the relationship between bare soil slope length and the erosion-induced degradation of soil quality and the loss of carbon (C) and nitrogen (N) from the microbial biomass in eroded sediment in the Western Black Sea Region of Turkey.
Materials and methods Six erosion study plots were constructed at an altitude of 146 m with a mean slope of 30%. Each plot had a width of 1.87 m and two slope lengths (5.5 and 11.0 m) with the long axis oriented downslope. Runoff and sediments were collected in two tanks arranged in series at the base of each plot. Microbial biomass carbon (C_{mic}) and nitrogen (N_{mic}) were estimated using the chloroform-fumigation extraction method. Moreover, basal respiration was determined by quantifying the carbon dioxide (CO_2) released in the process of microbial respiration during 7 days of incubation.
Results and discussion Data from six field runoff plots with two slope lengths (5.5 and 11.0 m) revealed that short slopes had more runoff per unit area than long slopes. In contrast, the total soil loss per unit area increased with increasing slope length. The estimated total annual losses of microbial C and N were 641.72 and 106.90 g ha^{-1} $year^{-1}$, respectively, for short slopes and 814.32 and 153.46 g ha^{-1} $year^{-1}$, respectively, for long slopes. Microbial communities of eroded sediment in long slopes are energetically more efficient (lower qCO_2) with correspondingly higher C_{mic}/C_{org} ratios (increased biomass) compared to short slopes.
Conclusions The present study demonstrated that increased soil loss results in increased C_{mic}/C_{org} percentages and decreased qCO_2. Moreover, the eroded sediment from long slopes exhibited a healthier eco-physiological profile compared to sediment from short slopes.

Keywords C_{mic}/C_{org} percentage · Microbial biomass · qCO_2 · Slope length · Soil erosion

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1 Introduction

Turkey is a mountainous and hilly country with an average altitude of 1,132 m; 62.5% of the total land area has a slope greater than 15%. Due to climatic and topographic conditions, soil erosion is the most serious soil degradation process and has had a severe economic and environmental impact on the country. Almost 86% of the land is suffering from some degree of erosion (Özden et al. 2000).

Soil erosion is a major factor in the depletion of soil fertility and the decline in soil productivity in Turkey. The decline in soil fertility caused by erosion is related to transport of nutrients in water runoff as dissolved load and eroded sediments (Lal 1980). Disruption or breakdown of aggregates exposes carbon (C), previously encapsulated within the aggregates and protected against mineralization, to climatic elements and microbial decomposition (Lal

2001). A reduction in soil organic carbon will have an ecological impact; depending on the degree of anaerobiosis, carbon may be emitted into the atmosphere as CO_2 or CH_4, and the transport of sediment and sediment-borne and dissolved pollutants to streams and reservoirs can increase eutrophication and adversely affect water quality (Steegen et al. 2001).

Soil productivity and nutrient cycling are influenced by the amount and activity of microorganisms, which are key components in maintaining soil fertility (Jenkinson and Ladd 1981). Topsoil acts as a reservoir for microbial biomass and is therefore important for decomposition and nutrient cycling. A loss of soil depth can cause the diverse living organisms comprising the soil microflora to be carried away with the eroding sediments. The loss of soil microflora can have detrimental effects on soil chemical, physical, and biological properties (Milne and Haynes 2004).

The metabolic quotient (qCO_2) is a specific parameter for evaluating how environmental conditions affect the soil microbial biomass; it measures the ratio of respiration to the soil microbial biomass. Soil microorganisms are assumed to generate more CO_2–C per unit microbial biomass per unit time as stress increases, which will result in a higher qCO_2 (Anderson and Domsch 1993; Nannipieri et al. 2003). However, the microbial quotient (C_{mic}/C_{org}), known as substrate availability, is responsive to soil degradation and can be used as an indicator of substrate availability. It increases when readily available organic C input increases and decreases when C input decreases (Anderson and Domsch 1989; Kara et al. 2008). Further, soil degradation due to accelerated erosion causes changes in soil quality (Lal 2001), which might be reflected in microbial indicators such as qCO_2 and the C_{mic}/C_{org} percentage.

There is a conspicuous lack of scientific data about how erosion–deposition cycles affect soil microbial activity and the transport of microbial biomass of C and nitrogen (N) via sediments. Therefore, this study investigated how slope length affected soil microbial activity and assessed losses in microbial biomass of C and N via sediments.

2 Materials and methods

2.1 Study area

The study site was located near the city of Bartin in northwestern Turkey. The area is located at an elevation of 146 m and has a humid mesothermal climate characterized by warm summers. Based on climatological data from the past 30 years, the annual mean temperature in the province is 12.6°C. July and August are the hottest months, with mean temperatures of 22.4°C and 21.9°C, respectively. Mean annual precipitation is 1,118.6 mm, about 44% of which occurs from October to January. The study area received nearly 1,136.7 mm of precipitation in the observation periods. All vegetation was removed from the plots by hoeing. Native vegetation species (*Quercus robur* L., *Juniperus oxycedrus* L., *Arbutus unedo* L., *Pyrecantha coccinea* L., *Phillyrea latifolia* L., *Ajuga chamaepitys* L., *Bellis perennis* L., *Cistus creticus* L., *Convolvulus arvensis* L., *Dactylis glomerata* L. subsp. *hispanica* (Roth.) Nyman, *Globularia aphyllanthes* Crantz., *Lamium purpureum* L., *Lolium perenne* L., *Medicago lupulina* L., *Melilotus officinalis* L., *Prunella vulgaris* L., *Pteridium aquilinum* (L.) Kuhn (Bracken), *Salvia forskahlei* L., *Sedum stoloniferum* L., *Taraxacum officinale* Weber., *Teucrium polium* L., *Teucrium chamaedrys* L. var. *Chamaedrys*, *Trifolium pratense* L. var. *Pratense*, and *Trifolium repens* L. subsp. *Repens*) of the study area were removed to more clearly determine the relationship of soil loss with slope length without the noise incurred by differences in vegetation distribution among plots. The soil, developed on limestone, is fine-textured, stony, and calcareous. Table 1 presents a detailed description of soil properties in the experimental plots.

2.2 Experimental details and sampling

Six erosion study plots were constructed at an altitude of 146 m. Slope gradient is a very important factor affecting soil erosion intensity. In this study, it was decided that the runoff plots would have average slope gradient of 30% so that the results could be comparable. Each plot had a width of 1.87 m and two surface lengths (5.5 and 11.0 m) with the long axis oriented downslope. The experimental plots were enclosed by metal sheets on all sides to prevent lateral water movement. The edge of the metal sheet was raised approximately 30 cm above the soil surface and extended

Table 1 Some characteristics of the soils in the experimental plots

Sand (%)	32.87 (±5.95)[a]
Silt (%)	20.69 (±3.91)
Clay (%)	46.43 (±5.09)
Soil texture	Clay
Bulk density (g cm^{-3})	1.36 (±0.12)
Particle density (g cm^{-3})	2.70 (±0.08)
Porosity (%)	49.38 (±4.80)
pH in water	8.06 (±0.05)
Electrical conductivity (dS m^{-1})	0.19 (±0.01)
$CaCO_3$ (%)	38.79 (±3.80)
Organic carbon (mg g^{-1})	31.24 (±8.32)
Total nitrogen (mg g^{-1})	2.38 (±0.42)

[a] Values represent the means of 24 samples (±standard deviation)

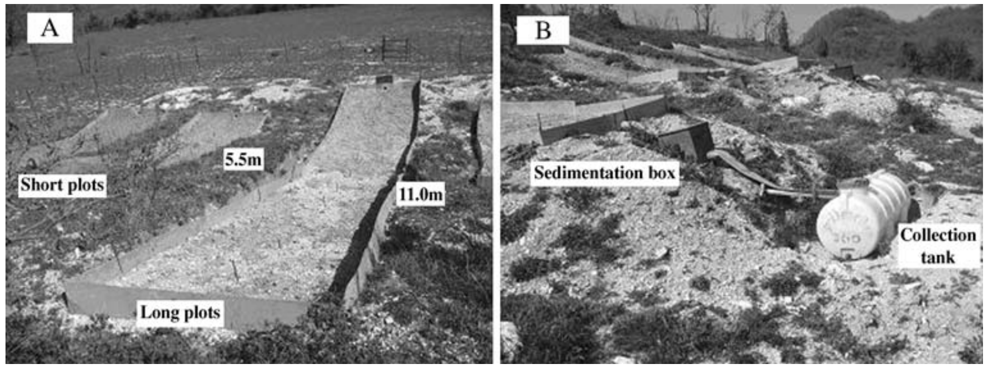

Fig. 1 Layout of erosion plots (**a**) with a sediment and runoff collection system (**b**) for two slope lengths

20 cm below the soil surface. Figure 1a shows the soil erosion plots.

To measure runoff and soil loss, each plot had an installation consisting of a sedimentation box and a collection tank. Runoff and sediments were collected in two tanks arranged in series at the base of each plot (Fig. 1b). At each of the six experimental plots, the amount of water and sediments collected in each tank was measured after each major rainfall event during 2007. Sediment samples were air-dried and weighed. Aliquot samples of runoff were centrifuged at 2,500 rpm for 30 min to separate sediments from liquid. Settled sediments were air-dried and weighed to calculate concentration (g L^{-1}). Soil weight was converted to sediment yield (kg ha^{-1}). In addition, 18 soil core samples representing the uppermost 0–10 cm of each plot were collected to estimate soil physicochemical parameters.

2.3 Soil and sediment analysis

Soil samples were air-dried, ground, and sieved (<2 mm). Soil particle size distribution was determined using the hydrometer method. Soil pH in a 1:2.5 soil/water suspension was determined using a pH meter. Electrical conductivity (EC) in a 1:5 soil/water suspension was determined using an electrical conductivity meter. The total organic C content was estimated using potassium dichromate oxidation, and the total N content was estimated using Kjeldahl digestion (Rowell 1994).

Sediment samples were sieved (<2 mm) and stored at 4°C before microbial analyses were conducted. Microbial biomass carbon (C_{mic}) was estimated using the chloroform-fumigation extraction method described by Brookes et al. (1985) and Vance et al. (1987); both oven-dried fumigated and unfumigated sediment equivalent to 30-g field-moist sediment were extracted with 0.5 M K_2SO_4 (1:4 *w*/*v*). The organic C content of K_2SO_4 extract was determined after oxidation with 0.4 N $K_2Cr_2O_7$ at 150°C for 30 min, followed by back-titration with ferrous ammonium sulfate. C_{mic} was calculated using the following relationship: $C_{mic}=2.64\ E_C$, where E_C is the difference in extractable organic carbon between the fumigated and unfumigated treatments, and 2.64 is the proportionality factor for microbial biomass C released by fumigation extraction (Vance et al. 1987).

The Kjeldahl digestion–distillation–titration method was used to determine the total nitrogen extracted from K_2SO_4. A 15-mL sample of each extract was digested with 10 mL 95% H_2SO_4 after the addition of 0.4 mL 0.2 M $CuSO_4$ to promote organic matter breakdown. This mixture was digested at 380°C for 3 h until all organic compounds were decomposed. The solution was then brought to a volume of 250 mL in deionized water. A 50-mL subsample was steam-distilled in 10 M NaOH; the distillate was collected in a boric acid-mixed indicator solution, and the solution was back-titrated (Anderson and Ingram 1993). Microbial biomass N (N_{mic}) was calculated using the following equation: $N_{mic}=F_N/0.54$, where F_N is the total N from fumigated soil minus the total N from unfumigated soil, and 0.54 is the proportionally factor for microbial biomass N released by fumigation extraction (Brookes et al. 1985).

Table 2 Annual runoff, soil loss, and sediment load in runoff from sample plots

Plot length (m)	Runoff (mm)	Soil loss (kg ha^{-1})	Sediment load in runoff (gl^{-1})
5.5	17.93* a	1,113.09 a	17.42 a
11.0	13.57 b	1,353.21 b	23.35 b

Within each column, values with different letters are significantly different

*$p=0.05$

Table 3 Biochemical properties of eroded sediments from runoff plots

Plot length (m)	C_{mic} (μgCg^{-1})	N_{mic} (μgNg^{-1})	MRbasal (μgCO$_2$–Cg^{-1}h^{-1})	qCO$_2$ (gCO$_2$–Ch^{-1}kg$C_{mic}$$^{-1}$)	C_{mic}/C_{org} (%)
5.5	579.39* a	98.82 a	0.436 a	0.761 a	1.95 a
11.0	618.60 b	116.20 b	0.403 a	0.663 b	2.41 b

Within each column, values with different letters are significantly different (n=3)

C_{mic} microbial biomass carbon, N_{mic} microbial biomass nitrogen, *MRbasal* microbial basal respiration, qCO_2 metabolic quotient, C_{mic}/C_{org} microbial quotient

*p=0.05

Basal respiration was determined by placing 50-g sediment samples into 50-mL beakers and incubating them in the dark at 25°C in 1-l airtight, sealed jars along with 25 mL 0.05 M NaOH. After 7 days, the generated CO_2 was measured by titration of excess NaOH with 0.05 M HCl (Alef 1995). The metabolic quotient (qCO2) was calculated as the basal respiration rate (μg CO_2–C h^{-1}) mg^{-1} of microbial biomass C (Dilly and Munch 1998).

2.4 Statistical analyses

Data for microbial biomass, microbial activity, and losses in the microbial biomass of C and N were subjected to independent sample t tests to determine significant differences between the long and short slopes. A correlation analysis was conducted to investigate the relationships between microbial quotient (C_{mic}/C_{org}) and metabolic quotient (qCO$_2$).

3 Results and discussion

Table 2 summarizes runoff, soil loss, and sediment load data collected during the study period. Runoff volume, soil loss, and sediment amount differed between the different slope lengths. Runoff volume declined with increased slope length; the annual runoff was 32.19% less for longer slopes than shorter slopes. A number of previous field studies also have demonstrated that runoff per unit area decreases as slope length increases (Lal 1997; Van de Giesen et al. 2000). The lower values for runoff per unit area for long slopes can be attributed to the longer time of concentration and the increased surface detention in comparison with short slopes. However, soil loss was significantly greater for long slopes compared to short slopes in the study plots. Mean soil loss were 1,113.09 kg ha^{-1}year^{-1} for 5.5-m plots and 1,353.21 kg ha^{-1}year^{-1} for 11.0-m plots (Table 2). Increased erosion on longer slopes may be caused by increased runoff velocity on longer slope lengths (Lal 1982; Rejman and Brodowski 2005). Similarly, runoff from long slopes had a greater sediment load (23.35 g l^{-1}) than did runoff from short slopes (17.42 g l^{-1}); this was primarily caused by an increased runoff velocity due to the greater slope length. This interaction has been observed in both laboratory and field experiments (Kinnell 2000).

The C_{mic} and N_{mic} content of eroded soils was approximately 18% greater in long than short slopes (Table 3). For long slopes, C_{mic} values ranged from 438 to 803 μg C g^{-1}; the corresponding range for short slopes was 446–669 μg C g^{-1}. N_{mic} content of eroded soils varied from 84 to 139 μg N g^{-1} in long slopes and from 68 to 111 μg N g^{-1} in short slopes. The soil microbial biomass analysis revealed that eroded sediment from long slopes contained the highest microbial biomass of C and N. Clearly, slope length had a significant impact on the C and N content of microbial biomass in eroded sediment.

Long slopes had a significantly higher annual loss in microbial C than short slopes: 814±73 versus 642±65 SD g ha^{-1}year^{-1}, respectively. Similarly, long slopes had a significantly higher annual loss in microbial N than short slopes, averaging 153±32 and 106±21 SD g ha^{-1} year^{-1}, respectively. The large amount of soil loss might be associated with the transport of microbial C and N bound to the fine soil fraction and its transport via runoff. The relatively high loss of microbial C and N at the study plots

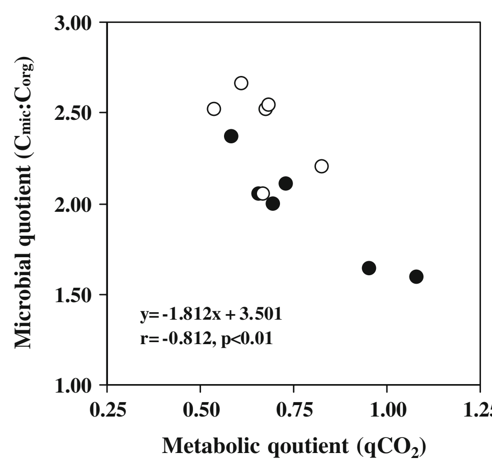

Fig. 2 Relation between microbial quotient and metabolic quotient in eroded sediment of short (*filled circles*) and long slopes (*empty circles*)

with long slopes is therefore likely related to increased runoff velocity and aggregate movement.

Metabolic quotient (qCO_2) can be obtained based on the rate of soil respiration per unit microbial biomass per unit time. Increases in qCO2 have been related with environmental stress (Killham 1985), while decreases in qCO2 have been associated with plant succession (Insam and Haselwandter 1989). It can be used to investigate soil development and substrate quality, as well as ecosystem development and response to stress (Anderson and Domsch 1993). Microbial quotient (C_{mic}/C_{org}) has been widely used as a sensitive indicator of changes in a soil ecosystem, for example due to heavy metal pollution (Renella et al. 2007), land use change (Sharma et al. 2004; Kara and Bolat 2008), management practices (Shannon et al. 2002), reclamation (Insam and Domsch 1988), and forest fire (Kara and Bolat 2009). Table 3 summarizes the experimental data on the fraction of microbial C to total organic C (C_{mic}/C_{org} percentage) for long and short slopes, which together with qCO_2 can be used as an indicator of land degradation. Metabolic quotients (qCO_2) were significantly higher for short slopes than long slopes, ranging from 0.584 to 1.081 and 0.538–0.826 g CO_2–C $h^{-1}kg\,C_{mic}{}^{-1}$, respectively.

The mean microbial quotient (C_{mic}/C_{org}) for long slopes was 23% greater than for short slopes (Table 3), with the range in these values being 2.28–2.59% and 1.84–2.06%, respectively. These results indicate that microbial communities in eroded sediment from long slopes are energetically more efficient (lower qCO_2) with a corresponding higher C_{mic}/C_{org} percentage (increased biomass) compared to those in short slopes. C_{mic}/C_{org} percentages were negatively correlated ($r=-0.812$, $p<0.01$) with qCO_2 (Fig. 2). The decline in C_{mic}/C_{org} in eroded sediment from the short slope may have been caused by the relatively small loss in microbial biomass C that may have been bound to the fine soil fraction. However, less available C may increase microbial respiration in the eroded sediment from the short slope due to the higher energy requirements for the maintenance of soil microorganisms, as indicated by elevated metabolic quotients (qCO_2). Anderson and Domsch (1986) reported similar findings; they observed that when the metabolic quotient (qCO_2) is high, less carbon is available for biomass production, which is reflected in a low microbial quotient (C_{mic}/C_{org}).

4 Conclusions

This study demonstrated that the loss of soil microbial biomass per unit area increases as the slope length increases. This can be attributed to increased soil loss from long slopes compared to short slopes. Microbial communities in sediment from long slopes were energetically more efficient (had a lower qCO_2) with a higher C_{mic}/C_{org} compared to those in sediment from short slopes. It is possible that the increases in C_{mic}/C_{org} percentages with increasing slope length reflect increasing substrate availability and quality for microbial synthesis, with increasing eroded sediment but decreasing respiration. In sum, this study found that increased slope length has an adverse effect on the microbial biomass and activity of the original soil, by altering natural soil properties and removing topsoil microflora.

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