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Impacts of Recreational Use on Soil Dynamics in Kastamonu Urban Forest

Beyza Baç[1], Senem Güneş Şen[1*]

Abstract: This study assessed the effects of recreational use intensity on soil compaction and key physical and chemical soil properties in the Kastamonu Urban Forest, Turkey. Soil penetration resistance, bulk density, organic matter pH, electrical conductivity, and soil texture were measured across three land-use types (forest, recreation area, path) at two depths (0–10 cm and 10–20 cm). Results revealed that increasing use intensity significantly elevated soil penetration resistance and bulk density values, while organic matter decreased, particularly in path and recreation areas. Forest soils consistently showed the lowest soil penetration resistance (1.18–1.48 MPa) and bulk density (0.86–0.93 g/cm³) and the highest organic matter (9–12.4%), highlighting their protective role. In contrast, path soils exhibited the highest soil penetration resistance (up to 3.7 MPa), bulk density (1.60 g/cm³), and electrical conductivity (203–205 µS/cm), indicating greater compaction and reduced soil quality. Soil pH ranged from acidic in forest areas (5.5–5.9) to near-neutral in high-use areas. Correlation analyses confirmed strong links between increased compaction and reduced organic matter, along with changes in pH and electrical conductivity. Soil texture differences, with higher sand content in intensively used areas, further contributed to compaction. These findings underscore the critical role of forested areas in maintaining soil health and highlight the need for sustainable management practices to reduce compaction in urban forests. This research contributes to understanding human impacts on urban forest soils and informs strategies to balance recreation and ecosystem conservation.

Keywords: Soil compaction, urban forest, recreational use, soil properties, Kastamonu

Kastamonu Kent Ormanında Rekreasyonel Kullanımın Toprak Dinamiklerine Etkisi

Özet: Bu çalışma, Türkiye'deki Kastamonu Kent Ormanı'nda rekreasyonel kullanım yoğunluğunun toprak sıkışması ve temel fiziksel ve kimyasal toprak özellikleri üzerindeki etkilerini değerlendirmiştir. Toprak penetrasyon direnci, hacim ağırlığı, organik madde, pH, elektriksel iletkenlik ve toprak dokusu; üç farklı kullanım alanında (orman, rekreasyon alanı, patika) ve iki derinlikte (0–10 cm ve 10–20 cm) ölçülmüştür. Sonuçlar, artan kullanım yoğunluğunun toprak penetrasyon direnci ve hacim ağırlığı değerlerini anlamlı şekilde yükselttiğini, organik madde miktarının ise özellikle patika ve rekreasyon alanlarında azaldığını ortaya koymuştur. Orman toprakları, en düşük toprak penetrasyon direnci (1.18–1.48 MPa) ve hacim ağırlığı (0.86–0.93 g/cm³) ile en yüksek organik madde içeriğini (9–12.4%) göstermiş olup; bu durum, orman alanlarının toprak sağlığını koruyucu rolünü vurgulamaktadır. Buna karşılık, patika toprakları en yüksek toprak penetrasyon direnci (3.7 MPa'ya kadar), hacim ağırlığı (1.60 g/cm³) ve elektriksel iletkenlik (203–205 µS/cm) değerlerini sergileyerek daha fazla sıkışma ve azalan toprak kalitesini göstermektedir. Toprak pH'ı, orman alanlarında asidik (5.5–5.9) değerlerden, yüksek kullanım alanlarında nötr değer aralığına kadar değişmektedir. Korelasyon analizleri, artan sıkışmanın azalan organik madde miktarıyla ve pH ile elektriksel iletkenlikteki değişimlerle güçlü bir şekilde ilişkili olduğunu doğrulamaktadır. Ayrıca, kullanım yoğunluğu fazla olan alanlarda daha yüksek kum içeriği gibi toprak doku farklılıklarının da sıkışmayı artırdığı belirlenmiştir. Bu bulgular, orman alanlarının toprak sağlığını korumadaki kritik rolünü ortaya koymakta ve kentsel ormanlarda sıkışmayı azaltacak sürdürülebilir yönetim uygulamalarının gerekliliğine işaret etmektedir. Araştırma, insan etkisinin kentsel orman toprakları üzerindeki etkilerini anlamaya katkı sağlamakta ve rekreasyon ile ekosistem koruma arasında denge kurulmasına yönelik stratejiler geliştirilmesine katkıda bulunmaktadır.

Anahtar Kelimeler: Toprak sıkışması, kent orman, rekreasyonel kullanım, toprak özellikleri, Kastamonu

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1. Introduction

In recent decades, rapid rural-to-urban migration has led to increasing urbanization rates and, consequently, excessive population density in cities. This has resulted in heightened physical and mental pressures on urban residents. To cope with these challenges, individuals seek opportunities for rest, travel, and leisure activities during their limited free time after work (Uzun & Müderrisoğlu, 2010). In this context, recreation areas have emerged as important spaces that fulfill various needs such as relaxation, entertainment, and picnicking. Gottman and Glikson defined recreation as the refreshing of the human mind and the revitalization of life energy, encompassing planned activities that help maintain a healthy life, work efficiently, and cope with adverse environmental conditions (Balcı & İlhan, 2008). Similarly, Mateer et al. (2021) described recreational activities as voluntary leisure pursuits that individuals engage in for relaxation, enjoyment, and personal enrichment.

Recreational activities can be broadly classified into two categories based on their spatial characteristics: "open area" and "indoor" recreation. Open area recreation includes sports such as basketball and volleyball, as well as nature-based activities like hiking, picnicking, and camping. In modern urban environments characterized by intense stress and physical demands, the need for nature-based recreation has grown significantly. Even when individuals do not actively participate, they frequently visit parks, and forests to enjoy natural scenery or breathe fresh air (Karaçar & Göker, 2017). This increasing demand and interest in open area recreation has important implications for natural communities and habitats (Kissling et al., 2009). Urban forests, which provide these free and natural spaces on the periphery of cities, host dynamic interactions between human activities and the surrounding soil, air, and vegetation (Jacsman, 1998; Niemelä, 1999). However, uncontrolled increases in recreational use can disrupt the functioning of these ecosystems and lead to adverse effects (Gathoni et al., 2022; Hubbard et al., 2022; Stachowiak et al., 2022).

Although recreational activities can contribute positively by enhancing environmental awareness and fostering a sense of nature conservation (Cole, 1995; Waltert et al., 2002; Hegetschweiler et al., 2009), they can also have negative environmental impacts on forest ecosystems, particularly soil and vegetation. Problems such as soil compaction, nutrient depletion, loss of organic matter, vegetation damage, biodiversity loss, land degradation, and environmental pollution are frequently reported consequences of intensive recreational use (Ballantyne & Pickering, 2015a; Hakim & Miyakawa, 2018; dos Santos Pereira et al., 2022). Soil compaction caused by recreational use affects bulk density, porosity, and water retention (Grieve, 2001; Andrés-Abellán et al., 2005), reducing plant productivity and altering vegetation structure (Jim, 1987; Kutiel et al., 2000). Additionally, food waste, litter, and ash residues left by visitors can alter key soil properties such as pH, organic matter content, and nutrient composition (Hart et al., 2005; Arocena et al., 2006; Cole & Spildie, 2007), subsequently affecting herbaceous vegetation composition (Zhevelev & Sarah, 2008). Long-term field observations have shown that vegetation cover, plant height, and species diversity decrease in frequently visited recreational areas (Liddle, 1997; Kutiel & Zhevelev, 2001; Malmivaara et al., 2002; Roovers et al., 2004; Rusterholz et al., 2009). The severity of these impacts depends on factors such as visitor frequency, type of recreational activity, soil and vegetation type, and seasonal use (summer or winter) (Cole, 1987; Gallet & Roze, 2001). Consequently, soil compaction has been identified as a priority research topic for developing soil protection strategies in European Union countries (Van-Camp et al., 2004).

Research on the ecological effects of recreational activities in forest ecosystems highlights that these activities directly and indirectly affect ecosystem components. Indirect impacts include habitat alterations due to soil compaction and erosion (Deluca et al., 1998; George & Crooks, 2006). Increased soil bulk density, reduced porosity, and impaired soil aeration and water movement (Kozlowski, 1999) are key physical changes that elevate the importance of soil compaction as a factor in ecosystem health. These changes can hinder plant root development and limit water and nutrient availability, ultimately reducing plant productivity (Whalley, 1995; Gómez et al., 2002; Soane & Van Ouwerkerk, 2013). Studies on soil compaction’s effects on soil organic matter, pH, and nutrient content report varying outcomes, including increases or decreases in organic matter and pH, and mixed results on nutrient composition (Amrein et al., 2005; Andres-Abellan et al., 2005; Güneş Şen & Aydın, 2024). As compaction progresses, soil moisture content typically declines, reducing infiltration capacity and water availability (Xuegang & Haosheng, 1999; Settergren & Cole, 1970). However, in sandy loam soils, compaction can sometimes increase moisture retention due to greater capillary pore space (Hammitt & Cole, 1999; Aydın & Hınıs, 2024).

The degree of soil compaction is influenced by several physical and chemical factors, including soil texture, pH, cation exchange capacity, clay particle size, organic matter content, and the presence of iron oxides and aluminum hydroxides, which affect soil cohesion (Assouline et al., 1997). In urban parks, soil compaction is primarily caused by pedestrian traffic, maintenance activities, and vehicle use. Areas adjacent to paths and roadsides often experience the most severe compaction, sometimes extending to depths of up to 50 cm (Jim, 1998a; 1998b; Toleti, 2008).

The impacts of recreational use on soil moisture are complex, shaped by factors such as compaction level, soil texture, organic matter content, forest canopy density, and exposure to sunlight and wind (Xuegang & Haosheng, 1999; Settergren & Cole, 1970; Aydın & Demirci, 2024). In particularly sensitive environments—such as transitional ecosystems and fragile areas heavily used by visitors (Yıldız et al., 2017)—environmental damage can occur that is difficult to reverse, affecting multiple ecosystem components (Liddle, 1997; Sargıncı et al., 2021).

In light of these findings, this study seeks to address the following research question: Does the intensity of recreational use in the Kastamonu Urban Forest significantly alter key physical and chemical soil properties, bulk density, pH, electrical conductivity, soil texture, and loss on organic matter?

This study aims to fill a critical gap in the literature by providing region-specific empirical data on how recreational pressure alters soil properties in an urban forest ecosystem in Turkey.

2. Materials and Methods

2.1. Study area

The study was conducted in Kastamonu Urban Forest, located approximately 11 km from the central district of Kastamonu Province in the Western Black Sea Region of Turkey (Figure 1). The area covers 29.5 hectares (OGM, 2017) and is situated at latitude 41°16′23″ N and longitude 33°46′43″ E, with an average elevation of 1102 meters. According to data from the nearest meteorological station (Airport Meteorology Station), operational since 2014, the mean annual temperature between 2014 and 2024 is 11.9°C, and the average annual precipitation is 671 mm. The Köppen climate classification categorizes the region as "warm in winter, hot in summer, rainy in all seasons (Cfb)" (Kottek, 2006; Bölük et al., 2023). The area is predominantly composed of Pinus sylvestris L., with little to no significant understory vegetation. The bedrock consists mainly of Eocene neritic limestone, characterized by medium-thick bedding, heavy jointing, and a massive gray-beige structure (Atalay, 2006; Akbaş et al., 2011).

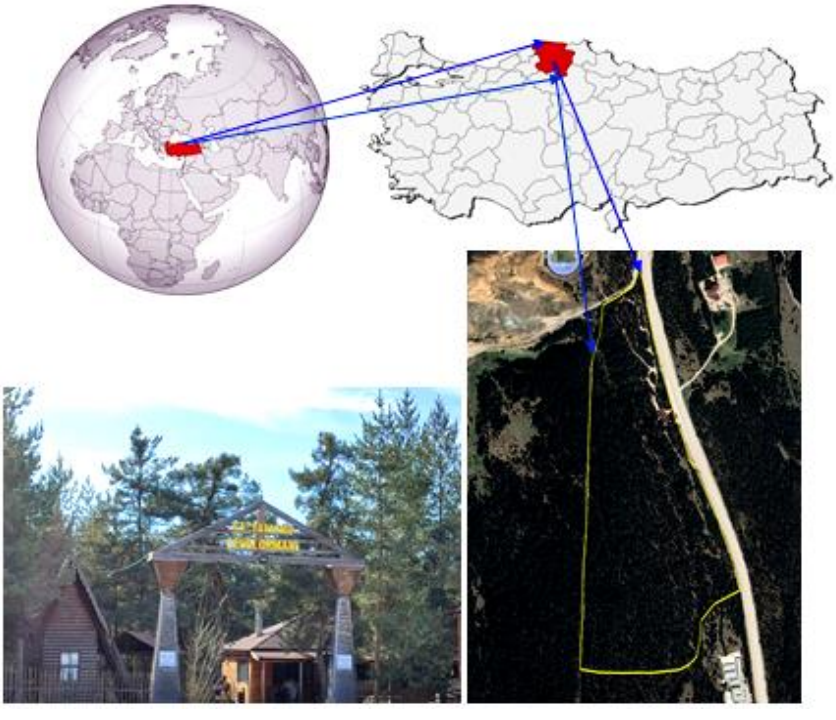

Figure 1. Location of the study area

2.2. Sampling Design and Site Classification

To assess the impact of recreational use intensity, we identified three distinct land-use types within the urban forest: path (walking routes), recreation area (picnic sites with tables and barbecues), and forest area (areas with minimal human activity). Based on field observations, the recreation area was categorized as the most intensively used, followed by path, while forest area represented the least-used areas (Figure 2). Although exact visitor counts were not available, intensity classifications were based on direct field observations, frequency of human activity, and infrastructure presence (e.g., picnic tables, grills, walking trails).

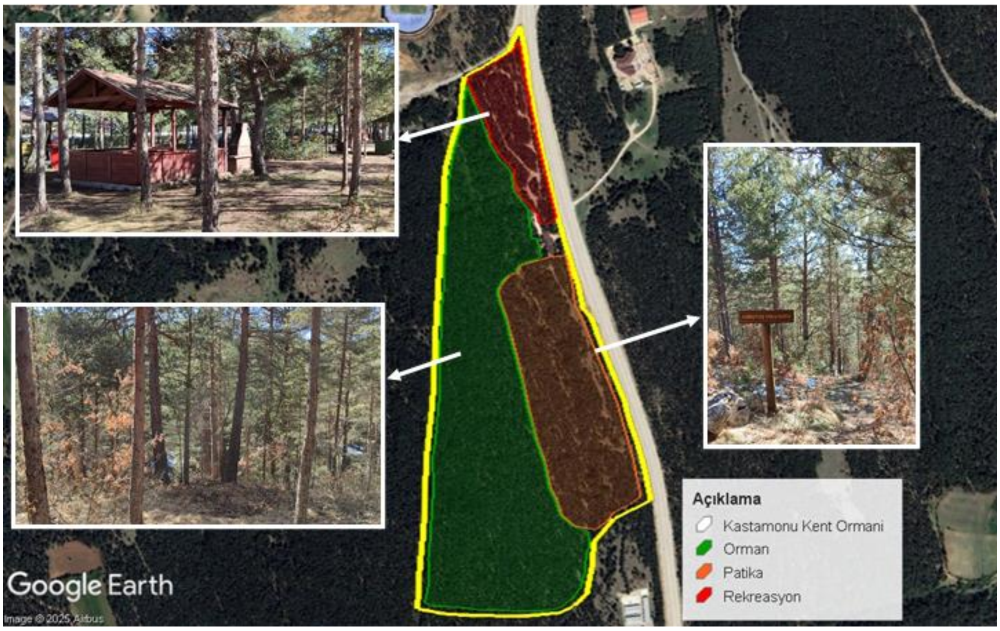

Figure 2. Study area identified according to intensity of use (Red: recreation area, Orange: pathway, Green: forest area)

2.3. Field Data Collection and Soil Analysis

We randomly selected 30 sampling points in each of the three land-use types, totaling 90 sampling sites. At each point, soil compaction was measured using a hand penetrometer set at a 30° angle (Adedokun et al., 2023). A 30° insertion angle was chosen to minimize surface resistance artifacts and ensure consistent depth penetration across varying terrain. Measurements were taken at two depth levels (0–10 cm and 10–20 cm) and classified using the USDA (1993) soil penetration resistance scale (Table 1).

Table 1. Soil penetration resistance classification

Penetration resistance (MPa)	Class
< 0,01	Extremely Low
0,01 – 0,1	Very Low
0,1 – 1,0	Low
1,0 – 2,0	Moderate
2,0 – 4,0	High
4,0 – 8,0	Very High
> 8,0	Extremely High

To analyze physical and chemical soil properties, we collected both disturbed and undisturbed soil samples from each point at both depth levels. In the laboratory, pH and electrical conductivity (EC) were determined by preparing a 1:2.5 soil-to-water suspension and using digital pH and EC meters (Özyuvacı, 1971). Soil texture was analyzed using the hydrometer method (Bouyoucos, 1936; Gülçur, 1974) and classified according to the USDA soil texture triangle (USDA, 1987). Organic matter content was estimated by igniting soil samples in a oven at 800°C for 2 hours and calculating weight loss (Gülçur, 1974).

Bulk density was determined using 5 cm steel cylinders for undisturbed soil samples. The bulk density was calculated by dividing oven-dry soil weights by the volume of the cylinder (Özyuvacı, 1976). All laboratory analyses were conducted at the Watershed Management Laboratory, Faculty of Forestry, Kastamonu University.

2.4. Statistical Analysis

We first evaluated whether the data followed a normal distribution by examining skewness and kurtosis coefficients, considering values within ±1.5 (Tabachnick & Fidell, 2013) and ±2 (George & Mallery, 2010) as acceptable. When normality was confirmed, we applied one-way ANOVA or Welch ANOVA to assess differences between land-use types. Post-hoc tests were used to identify specific group differences. For non-normally distributed data or variance was not homogeneous, we used the Kruskal-Wallis test. Finally, we conducted Spearman correlation analyses to assess the strength and direction of associations between soil compaction and other measured soil properties.

3. Results and Discussion

The mean values of soil compaction and some soil properties measured according to different usage densities and depths in Kastamonu Urban Forest are given in Table 2.

Table 2. Soil properties in different land uses (0–10 cm and 10–20 cm depths)

Depth (cm)	Land Use	SPR (MPa)	OM (%)	BD (g/cm³)	pH	EC (µS/cm)	Sand (%)	Silt (%)	Clay (%)
		Mean ± SD	Mean± SD	Mean ± SD	Mean± SD	Mean± SD	Mean ± SD	Mean ± SD	Mean± SD
0–10	Forest Area	1.10 ± 0.34	12.36 ± 2.30	0.93 ± 0.26	5.90 ± 0.41	132.8± 24.397	44.6 ± 6.10	33.4 ± 5.31	21.9 ± 2.51
	Recreation Area	2.33 ± 0.54	7.76 ± 1.37	1.25 ± 0.13	7.38 ± 0.40	137.1± 24.19	61.36 ± 9.53	22.21 ±10.86	16.44 ± 4.91
	Path	2.81 ± 0.65	5.10 ± 1.07	1.52 ± 0.35	7.70 ± 0.44	205.6± 60.893	49.6 ±10.78	34.5 ± 7.44	15.9 ± 5.08
10–20	Forest Area	1.48 ± 0.44	8.96 ± 1.44	0.86 ± 0.10	5.45 ± 0.17	142.4± 29.431	48.72 ± 7.78	27.28 ± 7.38	23.99 ± 6.12
	Recreation Area	2.23 ± 0.39	6.46 ± 0.99	1.23 ± 0.15	7.82 ± 0.57	128.1± 21.435	58.14 ± 6.11	22.26 ± 3.95	19.59 ± 5.32
	Path	3.70 ± 0.72	5.40 ± 0.84	1.60 ± 0.32	6.70 ± 0.48	203.2± 59.775	48.8 ± 7.29	30.4 ± 5.59	20.9 ± 7.88

The statistical analysis results demonstrated significant differences in topsoil properties (0–10 cm depth) among the various land-use types ($p < 0.01$). Effect sizes (η^2) were generally high, ranging from 0.29 to 0.78, suggesting a strong differentiation in soil characteristics between the groups. Post-hoc comparisons indicated that the most pronounced differences occurred between the forest (F) and recreation (R) areas. The Kruskal-Wallis test for electrical conductivity (EC) further confirmed that EC values varied significantly across the groups. Overall, the findings highlight that land use intensity significantly influences soil quality. Forest areas (F) maintained superior soil structure, characterized by higher organic matter content and lower bulk density (BD) and soil penetration resistance (SPR), compared to the recreation (R) and path (P) areas. In contrast, the recreation and path areas exhibited more pronounced soil compaction and greater organic matter depletion, reflecting the impact of intensive human activity (Table 3).

Table 3. Statistical test results (ANOVA, Welch ANOVA, Kruskal-Wallis) for topsoil (0–10 cm) soil properties across different land-use intensities

	One Way ANOVA					Post-Hoc Test				
	Levene's Test p	**Test Used**	**$F(df_1, df_2)$ / H**	**p-value**	**η^2**	**Test**	I-J	**Mean Diff. / H**	**Std. Err.**	**p-value**
SPR	0.007	W	75.27(2, 87)	<0.001	0.63	Th	F – R	-1.146	0.117	0.000
							F – P	-1.631	0.135	0.000
							R – P	-0.485	0.155	0.009
OM	0.000	W	147.45(2, 87)	<0.001	0.77	Th	F – R	4.598	0.489	0.000
							F – P	7.291	0.462	0.000
							R – P	2.693	0.317	0.000
BD	0.000	W	38.16(2, 87)	<0.001	0.47	Th	F – R	-0.323	0.053	0.000
							F – P	-0.596	0.080	0.000
							R – P	-0.273	0.069	0.001
pH	0.585	A	154.05(2, 87)	<0.001	0.78	T	F – R	-1.430	0.107	0.000
							F – P	-1.780	0.107	0.000
							R – P	-0.350	0.107	0.005
Sand	0.001	W	27.32(2, 87)	<0.001	0.39	Th	F – R	-16.774	2.066	0.000
							R – P	11.783	2.628	0.000
Silt	0.001	W	17.97(2, 87)	<0.001	0.29	Th	F – R	5.537	1.006	0.000
							F – P	6.029	1.034	0.000
Clay	0.004	W	20.71(2, 87)	<0.001	0.32	Th	F – R	11.239	2.207	0.000

EC	—	KW	H = 41.631	<0.001	0.46		F – R	-3.983	6.744	0.555
							F – P	-39.517	6.744	<0.001
							R - P	-35.533	6.744	<0.001

Note: p < 0.05 significant differences, η² values are effect size. I–J: Pairwise group comparison KW: Kuruskall-Wallis, W: Welch test, A: ANOVA, Th: Tamhane, T: Tukey, F: Forest area, R: recreacional area, P: path, SPR: Soil Penetration Resistance (MPa); OM: Organic Matter (%); BD: Bulk Density (g/cm3); EC: Electrical conductivity; Electrical Conductivity (µS/cm), Sand (%), Silt (%), Clay (%)

The results indicate that usage intensity exerts significant and statistically robust effects on subsoil properties at the 10–20 cm depth ($p < 0.001$). The effect sizes (η²) were generally high, ranging from 0.07 to 0.83, highlighting strong differentiation in soil characteristics between the land-use types. The findings reveal that soil degradations, including compaction, organic matter loss, increased pH, and dissolved salt accumulation, are particularly pronounced in path and recreation areas compared to forested areas. The protective and ameliorative role of forest cover in maintaining soil quality was clearly demonstrated. Overall, intensive human activity in recreation and path areas has led to substantial soil degradation (Table 4).

Table 4. Statistical test results (ANOVA, Welch ANOVA, Kruskal-Wallis) for subsoil (0–10 cm) soil properties across different land-use intensities

	One Way Anowa					Post- Hoc test				
	Levene's Test p	**Test Used**	**F(df_1, df_2) / H**	**p-value**	**η²**	**Test**	**I-J**	**Mean Diff./H**	**Std. Err.**	**p-value**
SPR	0.000	W	103.590 (2, 87)	<0.001	0,75	Th	F – R	-0,75	0,139	0.000
							F – P	-2,221	0,139	0.000
							R – P	-1,471	0,139	0.000
OM	0.003	W	68.729 (2, 87)	<0.001	0,65	Th	F – R	2,504	0,289	0.000
							F – P	3,587	0,289	0.000
							R – P	1,083	0,289	0,001
BD	0.000	W	118.073 (2, 87)	<0.001	0,68	Th	F – R	-0,374	0,055	0.000
							F – P	-0,747	0,055	0.000
							R – P	-0,373	0,055	0.000
pH	0.000	W	303.814 (2, 87)	<0.001	0,83	Th	F – R	-2,369	0,114	0.000
							F – P	-1,300	0,114	0.000
							R – P	1,069	0,114	0.000
Sand	0.532	A	17.522 (2, 87)	<0.001	0,28	T	F – R	-9,418	1,831	0.000
							F – P	-0,061	1,831	0.999
							R – P	9,357	1,831	0.000
Silt	0.211	A	3.597 (2, 87)	<0.001	0,07	T	F – R	4,404	1,686	0,028
							F – P	3,089	1,686	0,165
							R – P	-1,314	1,686	0,716
Clay	0.038	W	22.134 (2, 87)	0<0.001	0,25	T	F – R	5,023	1,500	0,003
							F – P	-3,104	1,500	0,102
							R – P	-8,127	1,500	0.000
EC		KW	H=34.856	<0.001	0.38		F – R	13,300	6,744	1,972
							F – P	-39,150	6,744	-5,805
							R - P	-25,850	6,744	-3,833

Note: p < 0.05 significant differences, η² values are effect size. I–J: Pairwise group comparison KW: Kuruskall-Wallis, W: Welch test, A: ANOVA, Th: Tamhane, T: Tukey, F: Forest area, R: recreacional area, P: path, SPR: Soil Penetration Resistance (MPa); OM: Organic Matter (%); BD: Bulk Density (g/cm3); EC: Electrical conductivity; Electrical Conductivity (µS/cm), Sand (%), Silt (%), Clay (%)

The correlation analysis revealed that soil penetration resistance (SPR) is directly associated with a decrease in organic matter content and an increase in bulk density. Organic matter acts as a mitigating factor, reducing compaction by enhancing soil structure. Conversely, high visitor density in areas such as paths and recreation areas contributes to increased bulk density, thereby exacerbating soil compaction. Soil pH and electrical conductivity (EC) showed slight to moderate correlations with compaction, suggesting that compaction can influence soil chemistry and potentially alter plant growth conditions. Additionally, the proportions of sand, clay, and silt, which define soil texture, indirectly influence compaction. Specifically, soils with higher clay content exhibit a greater tendency for compaction, whereas sandy soils maintain a more permeable and less compacted structure (Table 5).

Table 5. Correlation of soil compaction and other soil properties

	Mean	SD.	SPR	OM	BD	pH	EC	Sand	Silt	Clay
SPR	2,29	0,99	1							
OM	7,67	2,86	-,641**	1						
BD	1,23	0,36	,640**	-,583**	1					
pH	6,84	0,99	,419**	-,552**	,439**	1				
EC	158,19	51,86	,400**	-,436**	,344**	0,120	1,000			
Sand	51,86	9,94	0,020	-,149*	0,116	,305**	-0,044	1		
Silt	19,81	6,18	-0,113	,192**	-,230**	-,305**	-0,087	-,522**	1	
Clay	28,35	8,55	0,057	0,040	0,043	-0,142	0,100	-,770**	-0,129	1

** p < 0.01 * p < 0.05

Soil penetration resistance (SPR) ranged from 1.18 MPa to 1.48 MPa in forest areas, 2.23 MPa to 2.33 MPa in recreation areas, and 2.81 MPa to 3.70 MPa in path areas. The lowest SPR values were consistently observed in forest areas at both depth levels. Welch test results indicated that the most significant difference in SPR occurred between forest and path areas (-2.221 ± 0.139; $p < 0.001$). Overall, soil penetration resistance increased in direct proportion to usage intensity. According to the USDA (1993) classification, soils in recreation and path areas exhibited high compaction levels, whereas forest soils exhibited only moderate compaction (Figure 3). A strong negative correlation was found between SPR and organic matter content ($r = -0.641$, $p < 0.01$), indicating that organic matter mitigates compaction. Moderate positive correlations were observed between SPR and both pH and EC ($r = 0.419$, $p < 0.01$), suggesting that compaction influences soil chemical properties and may affect plant growth. A strong positive correlation was also observed between SPR and bulk density ($r = 0.640$, $p < 0.01$), confirming that higher compaction is associated with increased soil density. Collectively, these findings demonstrate that higher usage intensity significantly increases soil compaction, as reflected in elevated penetration resistance values. These results are consistent with previous studies (Liddle & Thyer, 1986; Coder, 2000; Talbot et al., 2003; Lei, 2004; Mingyu et al., 2009; Kissling et al., 2009; Adedokun et al., 2023; Savacı & Abodkar, 2024), which also identified a linear relationship between usage intensity and soil penetration resistance. Furthermore, soil loss has been reported to accompany soil compaction in recreational and intensively used areas (Marion & Cole, 1996; Pimentel & Kounang, 1998; Güngör, 2018).

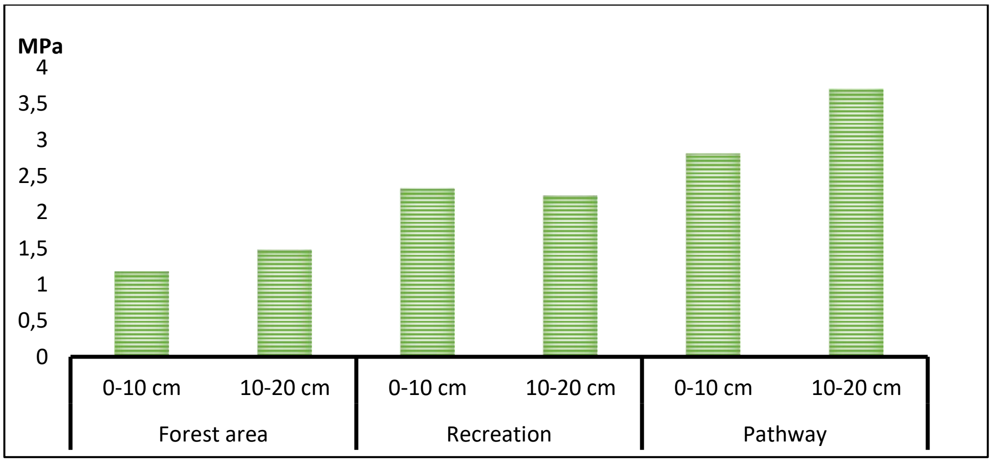

Figure 3. Variation in soil penetration resistance across land-use types (0–10 cm and 10–20 cm)

Bulk density (BD), a key indicator of soil compaction, ranged from 0.86 g/cm³ to 0.93 g/cm³ in forest areas, 1.23 g/cm³ to 1.25 g/cm³ in recreation areas, and 1.52 g/cm³ to 1.60 g/cm³ in path areas. Forest soils consistently exhibited lower BD values compared to soils in recreation and path areas. The most pronounced difference in BD was observed between forest and path areas ($p < 0.001$). These results highlight that intensified human activity in recreation and path areas substantially increases bulk density and, consequently, soil compaction. A strong negative correlation was found between BD and organic matter ($r = -0.583$, $p < 0.01$), indicating that higher organic matter content leads to reduced bulk density and mitigates compaction. Furthermore, a strong positive correlation between SPR and BD ($r = 0.640$, $p < 0.01$) reinforces the link between soil density and compaction. In recreational and path areas with high visitor density, bulk density increased significantly, limiting soil porosity and restricting root development, while low bulk density in forest areas reflected better soil structure (Figure 4). Previous studies (Kozlowski, 1999; Coder, 2000; Lei, 2004; Kissling et al., 2009; Korkanç, 2014; Adedokun et al., 2023) similarly demonstrated that recreational activities significantly increase bulk density and compaction while reducing porosity. According to Çelik and Erkmen (1999), very high bulk density reduces infiltration rates and nitrogen cycling and increases surface runoff in soils.

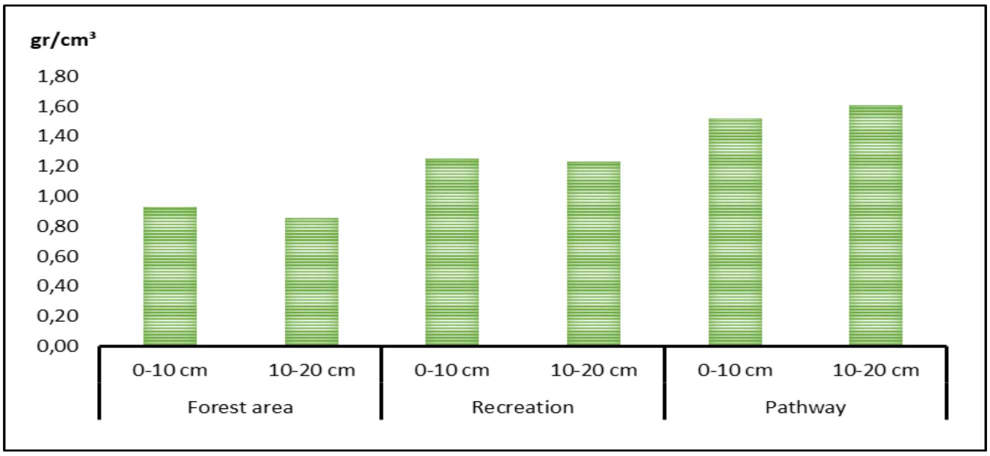

Figure 4. Variation in bulk density across land-use types (0–10 cm and 10–20 cm)

Organic matter (OM) content, a key indicator of soil water retention capacity, fertility, and microbial activity, was highest in forest areas (12.4% and 9% at both soil depths). In contrast, the lowest OM values were consistently observed in the path areas (5.1% and 5.4%). While forest areas maintained high OM content, significant reductions were noted in recreation and path areas. The forest-path comparison revealed substantial differences in OM, with a 7.291 ± 0.462 ($p < 0.001$) difference in topsoil and a 3.587 ± 0.289 ($p < 0.001$) difference in subsoil, underscoring the vital role of forest ecosystems in the organic matter cycle. Conversely, intensive use in path areas accelerated OM loss (Burden & Randerson, 1972). Overall, OM content decreased in parallel with increasing usage intensity. Strong negative correlations were observed between OM and both bulk density ($r = -0.583$, $p < 0.01$) and pH ($r = -0.552$, $p < 0.01$). Higher OM content improves soil structure and reduces bulk density, thereby mitigating compaction. Increased OM also contributes to the production of organic acids and microbial activity, leading to decreased pH, which may negatively impact soil fertility and biological processes (Figure 5). These results align with previous studies (Grieve, 2001; Yüksek, 2009; Çakır et al., 2010; Korkanç, 2014), which reported lower OM levels in recreational areas with high usage intensity.

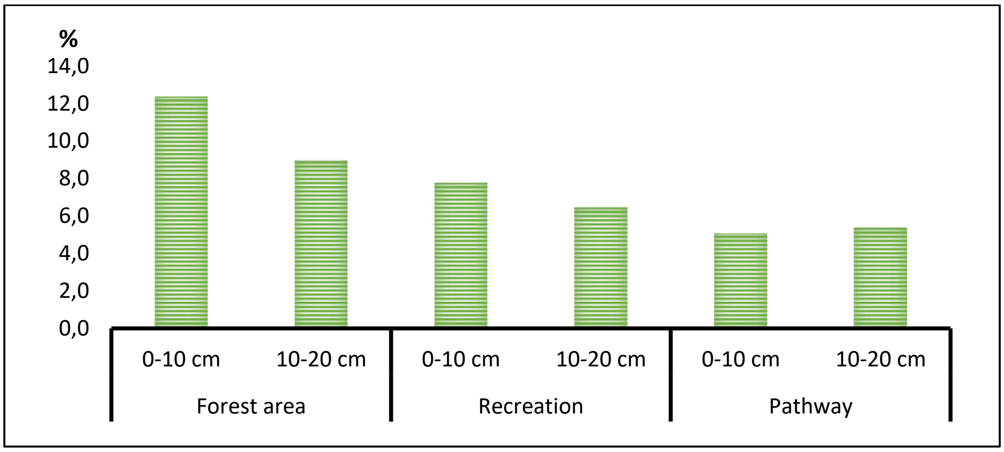

Figure 5. Variation in organic matter across land-use types (0–10 cm and 10–20 cm)

In forest areas with low usage intensity, soil pH ranged from 5.5 to 5.9, indicating an acidic environment. In contrast, recreation areas with the highest usage intensity exhibited neutral to near-neutral pH values, ranging from 7.38 to 7.82. Path areas displayed neutral pH values between 6.7 and 7.7. Significant differences in soil pH were observed across the groups, with the path area showing particularly high pH differences in both topsoil and subsoil ($p < 0.001$). These patterns suggest that topsoil loss and alkaline soil reactions are dominant in path areas. In high-use areas, enhanced organic matter mineralization and increased soil base content contributed to elevated pH (Figure 6). Conversely, pH values decreased in areas with lower usage intensity and reduced compaction. The strongest negative correlation was found between pH and organic matter (r = -0.552, p < 0.01), while the strongest positive correlations were observed with bulk density (r = 0.439, p < 0.01) and soil penetration resistance (r = 0.419, p < 0.01). Soil pH is closely linked to soil structure (loose versus compact), organic matter content, and textural properties. Consistent with the present findings, several studies have reported pH increases with usage intensity (Kutiel et al., 2000; Sarah & Zhevelev, 2007). However, other studies have found no significant changes in pH (Lei, 2004; Kissling et al., 2009; Korkanç, 2014), while some suggest that compacted soils may exhibit more acidic conditions due to organic matter loss (Burden & Randerson, 1972; Monti & Mackintosh, 1979).

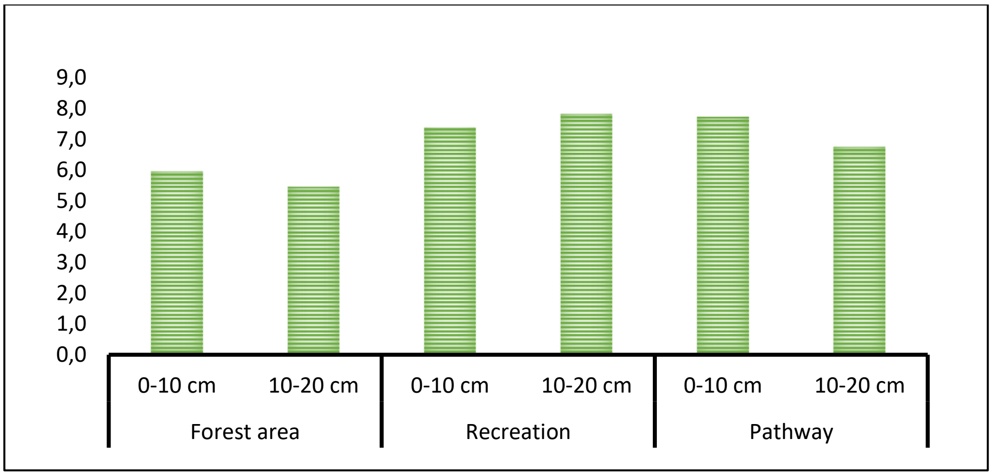

Figure 6. Variation in pH across land-use types (0–10 cm and 10–20 cm)densities

Electrical conductivity (EC) values ranged from 132 µS/cm to 142 µS/cm in forest soils, 128 µS/cm to 137 µS/cm in recreation area soils, and 203 µS/cm to 205 µS/cm in path soils (Figure 7). Kruskal-Wallis test results indicated that the highest EC values were consistently observed in path areas (H = 41.631 and H = 34.856; p < 0.001). Elevated EC levels in path areas suggest increased dissolved salt concentrations, likely resulting from intensive use and topsoil loss. This is particularly important given the implications for soil fertility and plant nutrient uptake (Sarah et al., 2016). A moderate negative correlation was observed between EC and organic matter (r = -0.436, p < 0.01), indicating that organic matter can mitigate salt accumulation. Conversely, a moderate positive correlation between EC and soil compaction (r = 0.400, p < 0.01) suggests that compaction can enhance soil salinity by restricting ion movement.

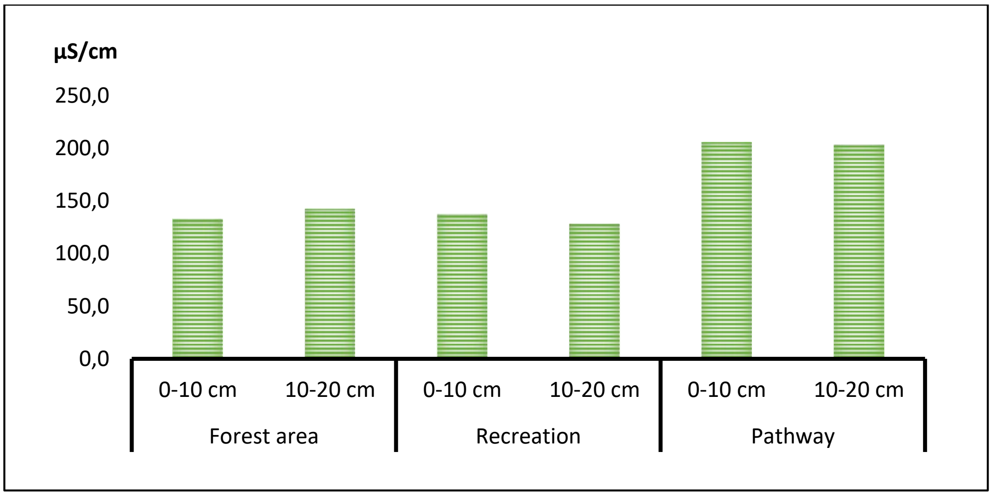

Figure 7. Variation in EC across land-use types (0–10 cm and 10–20 cm)

The soil texture for the 0–10 cm and 10–20 cm depth is presented in Figure 8. Based on international grain size classification, the soils in all three land-use types were classified as sandy clay loam (Çepel, 1996). In the topsoil, the sand content in recreation areas—where use intensity is highest—was approximately 1.5 times greater than in forest and path areas. Soil texture analysis revealed that forest areas had a more balanced and stable structure, with a significantly lower sand ratio compared to recreation areas (p < 0.001). The forest soils also exhibited higher silt and clay contents, underscoring the erosion prevention and soil stabilization functions of forest cover. In the subsoil, the recreation area again had the highest sand content, while the lowest clay content was observed in recreation areas at both depth levels. Silt content was consistently lowest in recreation and path areas. A strong negative correlation was found between sand and clay content ($r = -0.770$, $p < 0.01$). Overall, sand and clay densities were shown to vary according to land-use type; in high-use areas, clay content decreased while sand content increased. Previous research suggests that when clay content drops below 35%, soil becomes more susceptible to compaction, negatively affecting plant root development (McKyes, 1985).

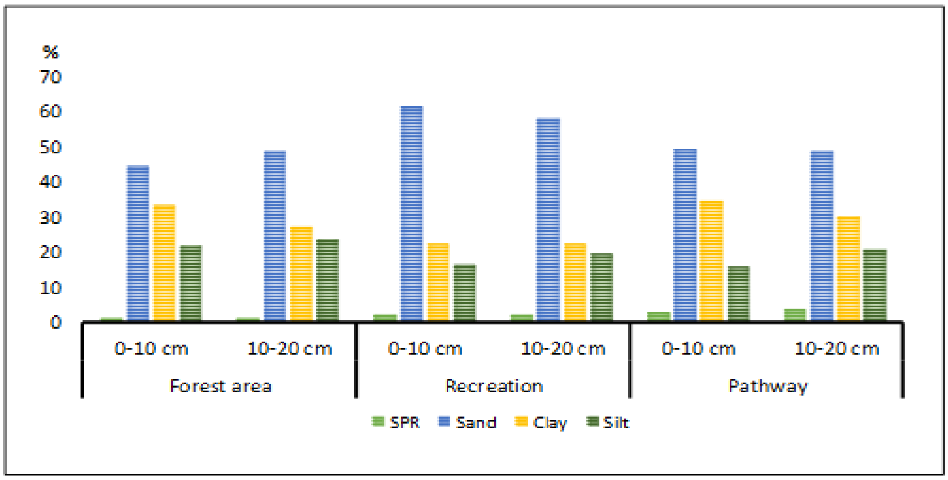

Figure 8. Variation in soil texture across land-use types (0–10 cm and 10–20 cm)

4. Conclusion

This study reveals that recreational activities significantly affect soil properties in the Kastamonu Urban Forest, with the most intense usage in path and recreation areas. The increased visitor density in these areas led to substantial soil compaction, reflected in higher soil penetration resistance and bulk density, alongside a decrease in organic matter and changes in pH and electrical conductivity. These findings underscore the importance of regulating human activity to maintain soil health. Future studies should explore the comparative effectiveness of biological, chemical, and physical soil improvement methods to inform sustainable management strategies and long-term planning for urban forest ecosystems.

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6. Compliance with Ethical Standard

a) Author Contributions

1. SGŞ .: Conceptualization, process, software, verification, formal analysis, research, materials, authoring the first draft, composing the review, and editing, visualization, and oversigh,
2. BB.: Process, materials, data curation, authoring the first draft. The published version of the manuscript has been read and approved by both authors.

b) Conflict of Interests

There is no conflict of interest, according to the authors.

c) Statement on the Welfare of Animals

Not relevant

d) Statement of Human Rights

There are no human subjects in this study.

e) Funding

This study was supported by TÜBİTAK with the application number of 1919B012326521.

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