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GEOSTATISTICAL ANALYSIS OF THE EFFECTS OF SOIL COMPACTION ON PLANT COMPOSITION IN A SEMI-ARID RANGELAND

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ABSTRACT
Soil compaction is a key factor that shapes the ecological balance of rangelands by altering soil structure and, consequently, influencing plant growth. This research investigates how vegetation is distributed across a semi-arid rangeland and how soil compaction changes from one area to another. To achieve this, 250 soil sampling points were selected, and both composite and undisturbed samples were collected from the top 0–20 cm layer. Penetration resistance was also measured directly in the field. The spatial behavior of soil and vegetation characteristics was examined using semivariogram modeling and ordinary kriging to visualize their spatial structure. Results indicated that areas with lower penetration resistance supported a higher presence of decreaser and increaser species, whereas compacted zones were mostly occupied by invasive plants. These findings emphasize the ecological importance of maintaining low soil compaction to sustain valuable decreaser species and highlight the necessity of grazing management practices that prevent overgrazing and reduce the spread of invasive species in compacted areas.

Keywords: *Penetration, geostatistics, vegetation, composition, kriging.*

INTRODUCTION
Soil compaction remains one of the most persistent physical challenges in semi-arid rangelands, where rainfall is scarce, evaporation is intense, and soil structure is naturally fragile. In these landscapes, the soil is constantly exposed to degradation risks. Continuous trampling by livestock, excessive grazing, and the passage of machinery gradually compress soil aggregates, reduce pore space, and increase bulk density (Yang et al., 2025). As compaction intensifies, soil performance deteriorates—root growth becomes restricted, infiltration slows down, air movement is hindered, and microbial processes decline (Batey, 2009). The likelihood of compaction is highest when the soil approaches field capacity since increased moisture makes the soil more pliable and less able to withstand external forces. Pressures exerted by large grazing animals, ranging between 130 and 250 kPa per hoof, can easily surpass the soil's inherent strength (Di et al., 2001; Głab, 2013;

Roesch et al., 2019). When these physical stresses persist, vegetation gradually adapts. Plant communities begin to favor species that are stress-tolerant or less palatable, leading to reduced overall diversity and a noticeable increase in increaser and invasive types (Hamze & Anderson, 2005). Although the general relationship between compaction and vegetation composition is well recognized, detailed spatial evidence describing these interactions is still limited. Understanding such spatial patterns is essential for developing grazing management strategies that maintain biodiversity and ecosystem stability. In the present study, geostatistical analysis was used to explore how soil compaction—measured through penetration resistance—relates to vegetation structure within a semi-arid rangeland in Türkiye. The aim was to determine how differences in soil mechanical resistance correspond to variations in plant community composition. Ultimately, these insights can guide sustainable rangeland management by providing spatially informed perspectives on soil health and ecological balance.

MATERIALS AND METHODS

This study took place in the semi-arid rangelands of Corum Province, Türkiye (40°43′44″ N, 34°28′31″ E). The region represents a typical open-grazing landscape, making it an ideal setting for rangeland research. The study area covers roughly four hectares at an elevation of about 1,600 meters above sea level. The climate is semi-arid, characterized by annual rainfall between 306 and 431 mm, depending on seasonal variation. Mean annual temperature ranges from 9.1 °C to 10.9 °C (Figure 1).

Figure 1. Location map of the study area

The soils within the study area are generally shallow and rest on calcareous bedrock, most commonly found along sloping hillsides. Due to the arid conditions and limited rainfall, these soils contain only small amounts of organic matter and essential nutrients. According to the USDA Soil Taxonomy, they are classified as Entisols, within the Orthept suborder and Xerorthent great group. More precisely, they correspond to the Lithic Xerorthent subgroup, which describes shallow soils where bedrock occurs roughly 60 cm below the surface. Such soil characteristics are typical of dry highland rangelands and offer a suitable natural setting for examining the relationships between soil properties and vegetation dynamics.

Soil and plant sampling

A total of 250 sampling plots, each measuring 5×5 meters, were randomly distributed throughout the rangeland. From each plot, five disturbed soil samples (0–20 cm depth) were composited, while undisturbed cores were collected to determine bulk density and field capacity. Penetration resistance was measured at five points within each plot using a manual dynamic cone penetrometer (Eijkelkamp, 1990), and all coordinates were precisely recorded using GPS. The collected soil samples were air-dried, passed through a 2 mm sieve, and analyzed for various physical and chemical properties. Particle size distribution was determined by the hydrometer method (Bouyoucos, 1962). Soil pH and electrical conductivity (EC) were measured in a 1:2.5 soil-to-water suspension, $CaCO_3$ content was determined following the procedures of the Soil Survey Staff (1992), and organic matter was analyzed using the modified Walkley–Black method. Aggregate stability was evaluated according to Kemper and Rosenau (1986), while soil water content at field capacity and permanent wilting point was estimated as described by Cassel and Nielsen (1986). Vegetation surveys were carried out in 2021 during the peak flowering period using the loop method. In each plot, dominant species were identified at 100 observation points along a 20-meter wire transect. Species cover and composition were then calculated, and all plant taxa were identified using standard floristic references (Davis et al., 1988). Based on palatability, plant species were categorized into three groups following Heath et al. (1985):

Class I (Decreasers): Highly palatable perennial species that decline under heavy grazing and represent climax vegetation.

Class II (Increasers): Moderately palatable species that initially increase with grazing but decline when grazing pressure becomes intense.

Class III (Invaders): Poorly palatable or unpalatable species that expand under prolonged grazing, often dominating disturbed areas (Arzani et al., 2004).

Descriptive Statistics and Geostatistical Analysis

Descriptive statistics including the mean, range, standard deviation, skewness, kurtosis, and coefficient of variation were computed for all soil and vegetation parameters using the SPSS 23 software package. According to Webster (2001), when the absolute value of skewness falls between 0.5 and 1.0, a square-root transformation is recommended, while values greater than 1.0 generally require a logarithmic transformation. If the skewness is below 0.5, no transformation is needed. Normality of the data was evaluated using the skewness coefficient. Traditional statistical methods assume that observations are independent in both space and time (Mulla, 1998). However, this assumption is rarely met in soil studies, where measurements often exhibit spatial dependence (Hamlett et al., 1986). Because soil variance tends to change with the distance between sampling points, geostatistical methods are generally preferred over classical techniques when analyzing spatially dependent variables (Burrough, 1983). Departures from normality can influence how effectively spatial structures are modeled. Lark (2000) noted that applying suitable data transformations can sometimes improve the accuracy of geostatistical models, particularly when the dataset deviates strongly from normality. On the other hand, Webster and Oliver (2008) argued that transformations do not always lead to significant improvements, as the overall shape of the semivariogram often remains similar. In this study, several transformations were tested following the approach of Webster (2001). Since the resulting semivariogram models showed only minor differences, analyses were performed using the original, untransformed data. For each soil parameter, semivariance values were plotted against lag distance to produce semivariograms describing the spatial variability of the measured properties. In semivariogram modeling, the distance separating two points is referred to as a lag. Lag classes were assigned sequential values (1, 2, 3, and 4), corresponding to distances of 30, 60, 90, and 120 meters between paired samples (Mulla and McBratney, 2001). Lags are typically generated by dividing the maximum sampling distance into equal intervals, but this method can sometimes fail to capture short-range spatial dependence. To improve the accuracy of the experimental semivariogram, variable lag intervals were used, ensuring that each lag class contained at least 30 data pairs (Isaaks and Srivastava, 1989). The most appropriate theoretical model was determined by maximizing the coefficient of determination (R^2) while minimizing both the residual sum of squares (RSS) and the nugget effect, ideally approaching zero (Robertson, 2000). Each semivariance value represents the average squared difference between paired observations separated by distance *h*, as expressed in Equation (1).

$$\gamma(h) = \frac{1}{2N\,(h)} \sum_{i=1}^{N} [z(x_i + h) - zx_i]^2 \qquad (1)$$

In this context, *z(xi+h)* refers to the observed value at a point located a distance *h* from location *xi*, while *z(xi)* represents the observed value at location *xi*. The term *N(h)* denotes the total number of paired observations separated by the lag distance *h* (Webster and Oliver, 2008). Ordinary Kriging (OK) was applied for spatial interpolation because it provides the most reliable linear and unbiased estimates by minimizing prediction variance. This approach accounts for spatial autocorrelation by assigning weights to sample points based on their proximity and the strength of spatial dependence (Isaaks and Srivastava, 1989). After the semivariogram model was optimized, its accuracy was evaluated through cross-validation, and spatial predictions for unsampled locations were then generated using Equation (2).

$$z_0 = \sum z_i \times \mathrm{w} \qquad (2)$$

where z_0 is the estimated value at an unknown location, while z_i refers to the observed value at a known sampling point.

RESULTS AND DISCUSSION

Descriptive statistics for the measured soil and vegetation properties—including the mean, standard deviation, minimum, maximum, and skewness—are presented in Table 1. The mean soil pH recorded in this study (7.67) was lower than the value reported by Khosravi et al. (2017), who found a pH of 8.96. This difference likely reflects variations in parent material, land management, or local microclimatic conditions. The coefficient of variation (CV) was used to evaluate the degree of variability in soil and vegetation parameters.

Table 1. Descriptive statistics of soil and plant properties

Properties	Min	Max	Mean	SD	Skew.	Kurt.	CV %
DP (%)	9.00	72.00	35.81	13.71	0.21	-0.60	38.29
IP (%)	0.00	68.00	13.04	12.24	0.93	1.26	93.91
IV (%)	0.00	76.00	31.52	15.01	0.09	-0.31	47.62
BG (%)	2.00	54.00	19.66	8.30	0.76	1.01	42.23
BD (g/cm^3)	1.00	1.62	1.20	0.10	-0.41	0.43	8.16
$CaCO_3$ (%)	5.91	19.42	11.82	2.27	0.68	0.20	19.20
OM (%)	0.39	3.03	1.61	0.50	0.16	1.07	30.77
ASI (%)	0.13	0.55	0.47	0.05	-3.43	17.37	11.45
f (%)	39.31	62.97	55.21	3.65	0.30	0.33	6.61
pH	7.04	8.74	7.67	0.35	1.03	0.88	4.60
EC (μS/cm)	31.70	480.30	110.31	60.17	2.87	11.00	54.55
FC (%)	8.79	39.90	20.75	5.61	1.06	1.41	27.04
PWP (%)	0.66	23.79	11.14	3.14	1.25	4.22	28.17
AWC (%)	0.16	25.79	9.68	4.48	0.90	1.46	46.35
Sand (%)	23.90	63.90	42.26	6.27	0.50	0.16	14.84
Clay (%)	3.60	43.60	32.93	4.87	-0.66	4.20	14.78
Silt (%)	6.60	49.10	24.80	5.75	-0.28	1.59	23.17
PR (MPa)	0.12	4.65	1.81	0.82	0.62	0.67	45.37

SD-Standard deviation. Skew.- Skewness. Kurt.- Kurtosis. CV-Variation of coefficient. DP- Decreaser plant. IP- Increaser plant. IV- İnvader plant. BG-Bare ground. BD- Bulk density. OM- Organic matter. ASI- Aggregate stability index. f: Soil porosity. EC- Soil electrical conductivity. FD- Field capacity. PWP-Permanent wilting point. AWC- Available water content. PR- Penetration resistance

According to Cambardella et al. (1994), variables with CV values $\geq$ 35% are considered highly variable, those between 15% and 35% show moderate variability, and those $\leq$ 15% exhibit little variability. In this dataset, CV values ranged from 4.60% for pH indicating low variability to 54.55% for electrical conductivity, which showed a high degree of variation (Table 1). The small variation in pH is likely due to its logarithmic nature, as also observed by Usowicz and Lipiec (2017a). In contrast, the larger variability in soil electrical conductivity and available water capacity seems to be mainly influenced by differences in soil texture, rainfall distribution, and topography (Hillel, 2004; Mulla, 2013). Soil properties that are primarily controlled by parent material and pedogenic processes such as $CaCO_3$ content, organic matter, silt fraction, field capacity, and wilting point exhibited relatively low spatial variability (Brady and Weil, 2008; Usowicz and Lipiec, 2017b). The mean organic matter content was 1.61%, ranging from 0.39% to 3.03%, indicating notable depletion, which was most likely caused by intensive grazing and reduced vegetation cover. Continuous livestock activity limits litter accumulation and decreases aboveground biomass, both of which reduce organic matter inputs to the soil. Penetration resistance (PR) varied considerably across the rangeland, ranging from 0.12 to 4.65 MPa, with an average value of 1.81 MPa (Table 1). Bowen et al. (1994) suggested that optimal root growth typically occurs between 0.9 and 1.5 MPa, while Leao and Silva (2006) reported that values near 2.0 MPa can restrict root elongation. In this study, the mean PR slightly exceeded that optimal range, and localized peaks above 4 MPa clearly indicated severe compaction in certain areas. These findings are consistent with those of Ludvíková et al. (2014), who also observed higher penetration resistance under trampled conditions. Overall, the results suggest that soil compaction is unevenly distributed and may significantly constrain root growth and development in parts of the rangeland.

Table 2. Semivariogram parameters of soil and plant properties

Variables	Model	Nugget Co	Sill Co C+	Range Ao (m)	RSS	R^2	Nugget effect (%)	CVr
DP	Gaussian	0.000001	0.002	10.56	1.48E-07	0.96	0.05	0.40
IP	Gaussian	90.50	207.20	243.00	188.00	0.96	43.68	0.52
IV	Exponential	111.00	222.1	54.6	668.00	0.80	49.98	0.41
PR	Spherical	0.001	0.55	15.30	0.05	0.87	0.18	0.14

RSS- Residual sum of squares, CVr- Coefficient of cross validation, SE- Standard error, DP- Decreaser plant. IP- Increaser plant. IV- İnvader plant. BG-Bare ground. BD- Bulk density. OM- Organic matter. ASI- Aggregate stability index. f: Soil porosity. EC- Soil electrical conductivity. FD- Field capacity. PWP-permanent wilting point. AWC- Available water content. PR- Penetration resistance

Spatial variation in penetration resistance (PR) appears to be influenced by heterogeneity in soil texture, rainfall patterns, and microtopography, which together create irregular moisture distributions across the rangeland (Western et al., 2004). These variations alter soil structure at small spatial scales, ultimately affecting root growth and plant community composition. The results highlight the need to consider localized compaction effects when evaluating vegetation dynamics in semi-arid environments. The semivariogram parameters for the analyzed variables are presented in Table 2. Penetration resistance is commonly modeled using exponential semivariogram functions (Barik et al., 2014a; Veronese Junior et al., 2006), although spherical models can provide a better fit at certain soil depths (Medina et al., 2012). In the present study, the spherical model was found to best represent PR, aligning with results reported in previous studies. A comparison between soil penetration resistance and plant group distribution showed that increaser species were generally associated with less compacted soils, while decreaser and invasive species occurred more frequently in moderately to highly compacted areas. These relationships suggest that excessive soil compaction caused by heavy grazing alters vegetation composition and reduces the ecological stability of rangelands. The findings highlight the importance of considering localized compaction effects when evaluating vegetation dynamics in semi-arid ecosystems.

Semivariogram parameters for soil and vegetation variables are summarized in Table 2, providing insight into their spatial structure. The Gaussian model best represented the spatial variability of decreaser (DP) and increaser (IP) plant groups, with high coefficients of determination (R^2 = 0.96 for both), indicating strong spatial autocorrelation. In contrast, the exponential model was most suitable for invasive (IV) species, with a lower R^2 value of 0.80, reflecting a moderate degree of spatial dependence. Penetration resistance (PR) was best described by a spherical semivariogram model (R^2 = 0.87), demonstrating spatial continuity up to a range of approximately 15.3 m. This result aligns with the observations of Medina et al. (2012), who also reported that spherical models effectively represent soil resistance data. Depending on their structural characteristics, other variables were most accurately fitted using exponential or Gaussian models. Nugget effects differed among variables. Penetration resistance (0.18%) and decreaser species (0.05%) exhibited very low nugget values, indicating minimal measurement error and limited microscale variation. In contrast, increaser and invasive plant groups showed considerably higher nugget effects (43.68% and 49.98%), suggesting that fine-scale environmental variability and patchiness strongly influence their spatial distribution. Range values also varied markedly: increaser species showed the widest spatial correlation distance (243 m), followed by decreasers (10.56 m) and penetration resistance (15.30 m).

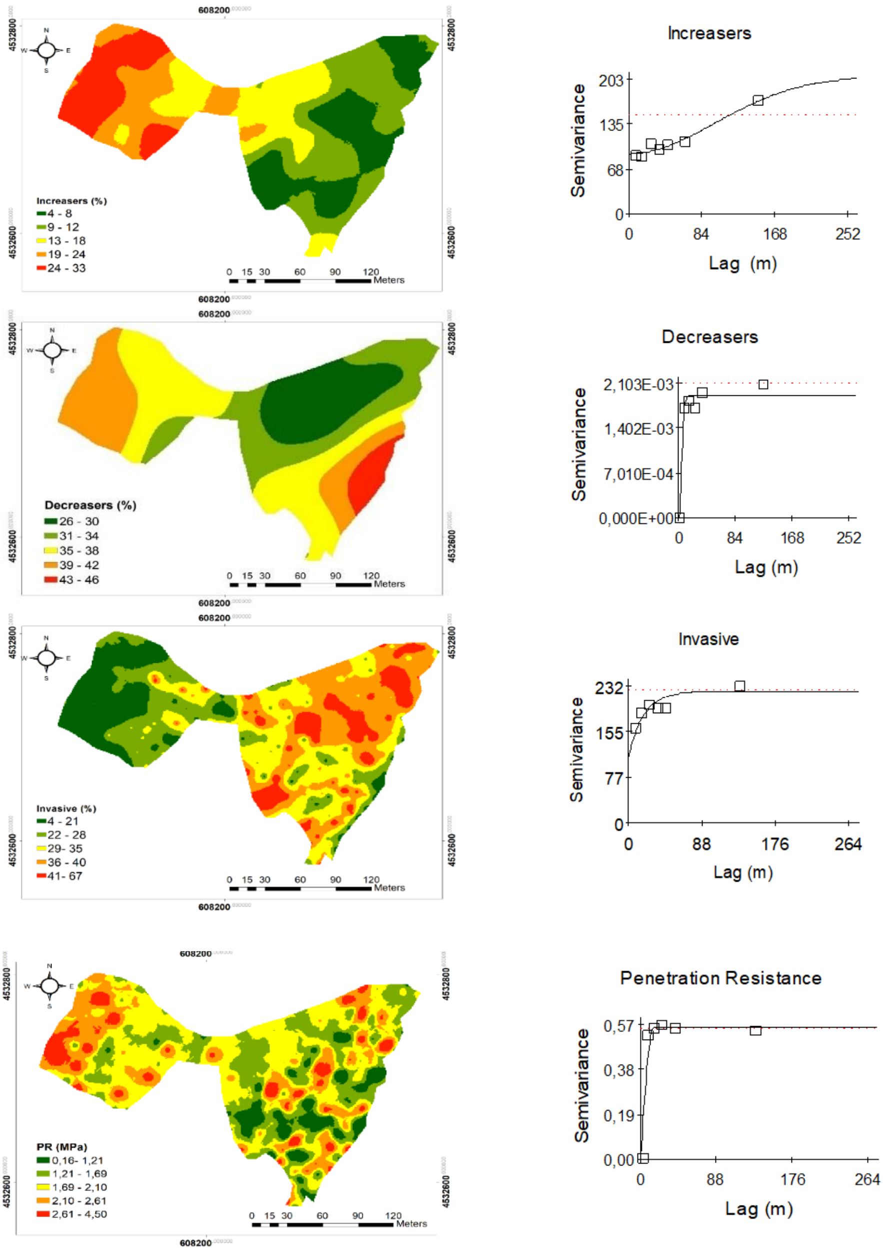

Figure 2. Semivariogram graphs and kriging maps

The spatial interpolation maps generated through ordinary kriging (Figure 2) illustrate clear patterns in both penetration resistance and plant group distribution across the rangeland. Areas with high PR values correspond to compacted zones, where decreaser and invasive species were more abundant. In contrast, increaser species dominated regions characterized by lower compaction and looser soil structure, where root development and water movement were more favorable. These spatial trends highlight the strong sensitivity of plant community composition to changes in soil physical conditions. Zones subjected to intense compaction act as ecological stress sites, reducing overall plant diversity and facilitating the spread of stress-tolerant or invasive species. Although decreaser plants can withstand moderate stress, their abundance declines sharply under prolonged compaction and grazing pressure. The greater presence of invasive species in compacted zones likely reflects their capacity to quickly colonize disturbed soils and outcompete native vegetation. The pronounced spatial association between penetration resistance and plant distribution suggests that soil compaction can serve as a reliable indicator of rangeland condition and ecological integrity. Overall, the results point to a highly heterogeneous spatial pattern of soil compaction and vegetation structure in semi-arid rangelands. This heterogeneity indicates that uniform management approaches may be ineffective. Instead, management strategies tailored to local site conditions especially in severely compacted areas are needed to reduce adverse impacts, restore plant diversity, and enhance the ecological resilience of these fragile ecosystems.

CONCLUSION

Intensive grazing pressure remains one of the main drivers of soil compaction in semi-arid rangelands. The findings of this study clearly show that grazing intensity and trampling significantly alter soil physical structure, which in turn shapes plant community composition. Maintaining soil productivity and preserving plant diversity require controlling overgrazing and adopting grazing management strategies that are adapted to local site conditions.

The spatial maps generated through ordinary kriging provided a detailed picture of how soil compaction and vegetation characteristics vary across the landscape. Variables exhibiting strong spatial dependence were modeled with high accuracy, offering a solid basis for precision-oriented rangeland management. For soil and vegetation properties with weaker or moderate spatial relationships, increasing sampling density or employing alternative interpolation techniques could further improve prediction reliability. A key outcome of this research is the clear spatial correspondence between penetration resistance and plant community patterns. Highly compacted areas were dominated by invasive and stress-tolerant species, whereas less compacted zones supported a greater abundance of decreaser species—plants that are crucial for maintaining ecosystem stability and grazing value. These patterns underscore soil compaction as a sensitive and integrative indicator of ecosystem health and productivity. Overall, this study provides valuable insights into soil–vegetation interactions in semi-arid rangelands and offers practical guidance for sustainable management. Strategies that focus on reducing soil compaction, promoting plant diversity, and enhancing the ecological resilience of degraded rangelands can contribute significantly to the long-term stability of these fragile ecosystems.

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