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An Approach to the Key Soil Physical Properties for Assessing Soil Compaction Due to Livestock Grazing in Mediterranean Mountain Areas

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Abstract: The selection of key soil physical properties (SPPs) for studying the impact of livestock treading is an unexplored research topic, especially in studies that analyze the influence of livestock management on the degradation process. The objective of this work was to demonstrate that the key SPPs for studying the impact of livestock treading depend on the objectives of the research and the environmental characteristics of the study site. This work used discriminant analysis to establish the most significant SPPs among the following: bulk density (BD), total porosity (P), field capacity (FC), infiltration capacity (IC), and aggregate stability (AS). Results showed that (1) IC and BD are the key properties for identifying the areas affected (bare patch) and unaffected (vegetated patch) by livestock treading, (2) none of the SPPs are significant under increasing stocking rates, and (3) BD is the key property for analyzing livestock impact with increasing stocking rate, using soil calcium carbonate content, slope exposure, and grass cover. We concluded that the relationship between physical soil degradation and stocking rate is not linear because it depends on environmental factors; therefore, to establish the key SPPs, it is necessary to take this fact into account.

Keywords: soil physical properties; livestock treading; stocking rate; environmental variability; discriminant analysis

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1. Introduction

Soil compaction is the process whereby compression results from a reduction in volume for a given soil mass. In physical terms, this process causes an alteration of the soil structure. Soil compaction causes a reduction in the total volume of soil and an alteration in the pore size distribution because it reduces the proportion of large pores and increases the proportion of smaller ones [1]. The application of pressure or loads causes changes in the soil volume. Pressure applied by livestock's hooves causes degradation of soil physical properties (SPPs). The extent of soil degradation, resulting from compaction, depends on the soil water content and the magnitude of the load applied [2]. The degree of compaction is greater in soils with elevated humidity because a sliding action often accompanies the livestock treading, especially in mountain areas where there is a high slope gradient. The deformation and displacement of the soil is a kind of puddling, which alters the original structure of the soil. The hoof pressure is calculated on the basis of weight per projected unit of contact area. A moving animal will have two or three hooves on the ground at any one time, causing a variation in the pressure exerted on the soil. Also, treading speed, duration of hoof–soil contact, and cattle activity (stationary or walking) are other factors that imply an increase in the pressure applied [3]. Also, soil structure degradation due to livestock treading alters the development of pastures due to changes in their root structure. Specifically, root density is reduced [4], as well as certain morphological characteristics, such as length and diameter [5].

Soil compaction, as a result of livestock treading, has been widely analyzed. This soil degradation process is often characterized in terms of bulk density (BD), total porosity (P), field capacity (FC), infiltration capacity (IC), and aggregate stability (AS). Table 1 shows the SPPs analyzed in 27 selected papers from 1981 to 2021 [2,6–31]. These papers studied soil grazing impact, mainly in mountain regions, and are characterized by the presence of different types of vegetation, especially grassland, and particular herd type (basically cattle herds). Soil IC and BD were the properties most frequently used by researchers studying grazing impact on SPPs. Both properties were used in 67.3% of the total data. The next most used was P, in 20.4% of cases, and finally AS and FC, in 8.2% and 4.1%, respectively. The number of SPPs analyzed per study also varied. A total of 48.2% of the studies analyzed only one soil property, and the remaining 51.8% were divided equally between cases that analyzed two, three, or more properties.

Table 1. Objectives of investigation and physical properties analyzed in the selected articles of soil degradation due to grazing from 1991 to 2021.

Objectives of Investigation	Soil Physical Properties					Papers (Reference Number)
	BD	P	FC	IC	AS	
Grazing influence on soil hydrologic characteristics.				*		[6–10]
		*		*		[11,12]
	*	*		*		[13]
Grazing influence on soil structure.	*					[14–16]
	*			*		[17]
Grazing management influence on SPPs: different stocking rate.	*					[18–20]
			*			[21]
	*			*		[22]
	*	*		*		[23]
	*	*		*	*	[24]
Grazing management influence on SPPs: different grazing systems.	*				*	[25]
	*	*		*		[26]
Grazing management influence on SPPs: different soil moisture contents and cattle weights.	*	*				[2]
Grazing management influence on SPPs: different animals and stocking rate.	*	*	*			[27]
Integrated grazing–crop system influence on SPPs: grazed/ungrazed and conventional tillage/no tillage system.	*			*	*	[28]
Meta-analysis of livestock impacts on soil properties: different stocking rate.	*					[29]
Developing a method for estimating the effects of grazing on the soil physical properties.		*			*	[30]
Developing a geospatial model to measure the impacts of grazing.	*	*		*		[31]
TOTAL CITED	18	10	2	15	4	
%	36.7	20.4	4.1	30.6	8.2	

BD—bulk density; P—total porosity; FC—water content at field capacity; IC—infiltration capacity; AS—aggregate stability; SPPs—soil physical properties. *—SPPs analyzed.

The choice of SPPs for analyzing grazing impacts has not always been adequately justified. In some cases, however, the properties used were appropriated because of the overall intended objectives. For example, a significant group of articles analyzed the impact of grazing on certain previously established soil properties. Some studies analyzed the effects of grazing on the hydraulic characteristics of the soil and therefore measured IC [6–10]. Other studies analyzed the effects of grazing on the soil structure, in which case the property measured was BD [14–16]. In these cases, the different SPPs used were clearly justified. Nevertheless, in some cases, the physical properties used did not correspond directly to the specific objective, as they used indirect measurements, which increased the work effort without providing improved results. For example, papers that aimed to study grazing impact on hydraulic properties not only analyzed IC but also other properties, such as P [11,12] or BD and P [13]. Other works analyzed soil compaction and used BD and also IC [17].

Other approaches to determine the impact of grazing analyzed the influence of different grazing systems, stocking rates, herd types, forage seeding, integrated crop–livestock systems, etc., on the physical properties of the soil. These approaches used different SPPs to measure the effects of grazing, as there was no agreement on which criteria provided reliable measurements. Table 1 reflects very varied combinations: (1) BD [18–20,29]; (2) FC [21]; (3) BD and P [2]; (4) BD and IC [22]; (5) BD and AS [25]; (6) BD, P, and IC [23,26]; (7) BD, P, IC, and AS [24]; (8) BD, P, and FC [27]; (9) BD, IC, and AS [28]. Finally, two works that developed a method to estimate grazing impact also used different SPPs; one used P and AS [30], and the other used BD, P, and IC [31].

The objective of this work was based on the hypothesis that the key SPPs for studying the impact of livestock management are variable and depend on the objectives of the research and the environmental characteristics of the study site. We set the following aims to demonstrate that hypothesis: (1) to determine the most significant key SPPs to differentiate areas affected and unaffected by livestock treading, and (2) to determine the most significant key SPPs to analyze the soil impact with an increasing stocking rate and under different environmental characteristics. These objectives will allow a reliable analysis of this degradation process, at the same time reducing the fieldwork and lab analysis by focusing on the most significant measurements. Furthermore, these objectives are closely in line with achieving sustainable livestock development, because reliably measuring the impacts would facilitate the implementation of actions to control degradation.

2. Materials and Methods

2.1. Site Characteristics

The study site was a goat farm, representative of the grazing systems of the Mediterranean mountains of southern Spain. The farm is located in the Montes de Malaga and has an area of 176 hectares (Figure 1). The study site has an altitude between 650 m and 977 m and an average slope of 40%, with maximum values that rise to 60%. The climate is Mediterranean with topographic features. The average annual precipitation is 701 mm and the average annual temperature is 14.2 °C.

Vegetation was originally a holm oak (*Quercus rotundifolia* L.) and cork (*Quercus suber* L.) forest. However, intensive agricultural activity significantly transformed the original vegetation. Vineyards were the main economic activity in this area from the early 1600s to the end of the nineteenth century. After the phylloxera plague in 1878, the land was put to different use, i.e., it was used for olive groves and extensive animal grazing. The goat farm used in this study came into use in the early twentieth century. Today, the vegetation is mainly composed of different shrub species (*Cistus albidus* L., Ulex parviflorus Pourret, Genista umbellata (L'Her.) Poiret, *Phlomis purpurea* L., *Lavandula stoechas* L., and *Daphne gnidium* L.) and grass species (*Calendula arvensis* L., *Medicago minima* (L.) Bortal, *Trifolium* sp., and *Vicia sativa* L.subsp. *cordata* (Wulfen ex Hoppe) Ascherson and Graebner).

The soils were classified as Calcaric Regosols (dominant soil). They are associated with Eutric/Calcaric Coarsic Leptosols in areas most degraded by water erosion, and with Calcaric Cambisols in areas less affected by erosion [32]. These are largely of loam texture, poor in organic matter content (0.5–2%), with a pH neutral to moderately alkaline (pH water 6.7–8.0). They have a low cation exchange capacity (10.5–15.0 meq 100 g^{-1}) and high base saturation (85–100%). The presence of calcium carbonate in soils varies from non-calcareous to strongly calcareous (20.11%).

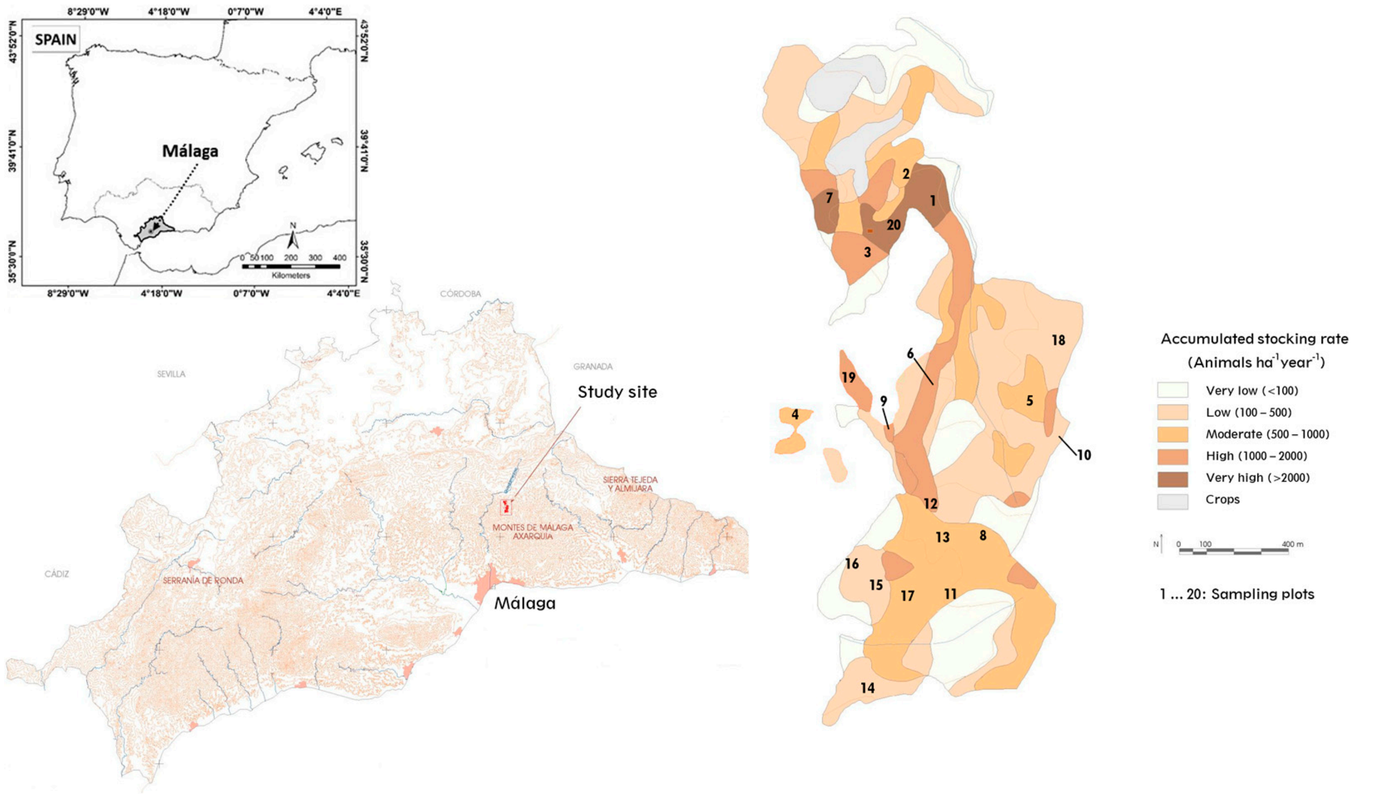

Figure 1. Location and delimitation of the study goat farm. The figure shows the cumulative stocking rate of the goat farm and the location of the sampling plots.

Although the herd is made up of approximately 400 Malagueña dairy goats, the number of animals that go out to pasture oscillates between 200 and 400 goats throughout the year due to the fact that during gestation periods the animals do not go out to graze. This variation in the size of the herd has been taken into consideration when calculating the stocking rate. The farm bases its feeding strategy on the availability of forage resources, and also uses supplementary feeding resources such as concentrates, oat grain, and crop residues, such as wheat straw. Grazing is based on a continuous year-long but very-short-duration grazing system, where the livestock graze on a specific area of land for a short time period (generally a few minutes) followed by a few days of rest. This grazing system favors the existence of paths created by livestock treading (bare patch), which are clearly distinguishable from the vegetated patches, i.e., those areas not affected by continuous livestock trampling (Figure 2).

The stocking rate was calculated using the concept "cumulative stocking rate", established by Blanco [33], which is defined as the number of animals per unit of surface area and unit of time that the soil supports. Scholefield and Hall [34] showed that one of the mechanisms that influences soil compaction is the duration and number of times that livestock treading occurs in the same place. These arguments suggest that it is necessary to take into account the frequency of grazing; for this reason, we used the concept of cumulative stocking. The estimate of the cumulative stocking rate of the farm was based on the observation of livestock grazing routes during four one-week periods (one for each season of the year). The observations were based on the number of animals grazing, delimitation of the land grazed, and length of time that the animals remained on each land unit. The cumulative stocking rates of the farm ranged from very low to very high: very low (<100 animals ha^{-1} year^{-1}) on 10.1% of the grazing land, low (100–500 animals ha^{-1} year^{-1}) on 43.92%, moderate (500–1000 animals ha^{-1} year^{-1}) on 36.53%, high (1000–2000 animals ha^{-1} year^{-1}) on 3.42%, and very high (>2000 animals ha^{-1} year^{-1}) on 6.02% (Figure 1).

Figure 2. Grazing plot with paths created by livestock treading (bare patch) and areas not affected by continuous livestock trampling (vegetated patch).

2.2. Data Collection and Analysis

Twenty sampling plots located in the described goat farm were selected (Figure 1). They represented the different environmental conditions and the stocking rate in the study area. The sampling was performed on transects that were picked at random. Two transects were established for each unit (one for the bare patch (paths created by livestock treading) and another for the vegetated patch (area covered with vegetation between paths)). The effects of the treading on the latter varied depending on the type of vegetation. Clearly, it was impossible for the animals to tread on thickly covered vegetation, like areas of scrub formation, where the SPPs remained unaltered. In herbaceous areas, although there was some impact as a result of animal treading, in general, the physical properties of this soil were well maintained because of the sporadic nature of the trampling and the cushioning effect of the plant cover. Consequently, we considered that the difference between the two patches showed the soil response to the impact of grazing.

Soils were sprinkled with water and covered with vegetation in order to keep the surface water conditions constant up until the time of the sampling. Previous water levels of the soil could vary according to the different environmental conditions of the land units, which may have influenced the results. This error factor was avoided by making the soil moisture levels uniform at the time of the sampling. After the soils were drained to FC (approximately 24 h), IC was measured, and undisturbed soil samples (0 to 5 cm) were collected using a ring of 100 cm^3 to determine BD, P, and FC. Triplicate samples of SPPs were taken in each patch. Sampling was performed in the summer of 2017. Soil BD was determined using the core method [35]. It was calculated from the oven dry weight and the known volume of each cylinder (100 cm^3). P was calculated from the relationship between the pore volume and the total volume of the cylinder, following the approach of Guitian and Carballas [36]. Pore volume equaled the volume of water drawn from the saturated cylinders. Soil FC was determined according to the method proposed by Cassel and Nielsen [37], known as in situ FC. Soil IC was calculated in situ using a simple ring infiltrometer (diameter 21 cm) with a constant load, following the approach of Youngs [38]. Mean infiltration rates were determined after a period of thirty minutes. Soil AS was determined in the laboratory using disturbed soil samples and following the structural instability index of Henin, Grass, and Monnier [39].

2.3. Statistical Analysis

The soil sampling results were analyzed using discriminant analysis. This statistical technique allowed us to quantify the weight of each soil physical property in the discrimination; thus, we were able to determine the key SPPs for analysis of the compaction due to grazing. The objective was to establish a linear combination of the independent variables, which allowed reclassification of the cases within the previously established groups. This linear combination is the discriminant function. The optimal function is one that provides a classification rule minimizing the probability of errors. The discriminant linear equation (D), in unstandardized coefficients, is expressed in the following way:

$$D = B0 + B1\ X1 + B2\ X2 + \ldots + Bn\ Xn \quad (1)$$

where B0 is the constant; Bn is the estimated coefficients; Xn is the independent variables.

Statistical analysis was performed using IBM SPSS Statistics 25.0, and discriminant analysis was carried out using the stepwise method.

3. Results and Discussion

Table 2 shows the results obtained from the SPP sampling. As expected, the impact of the treading on the trampled soil (bare patch) compared with less or untrampled patches (vegetated patch) caused an increase in BD and AS. The BD was 1.41 g cm^{-3} in the bare patch and decreased to 1.28 g cm^{-3} in the vegetated patch. AS was 3.08 and 2.61 in the bare and vegetated patches, respectively.

On the contrary, P (46.54% in the bare patch vs. 50.68% in the patch with vegetation), FC (30.36% in the bare patch vs. 37.80% in the patch with vegetation), and IC (18.98 cm h^{-1} in the bare patch vs. 53.41 cm h^{-1} in the vegetated patch) decreased in the bare patches.

3.1. Discriminant Analysis Using the Sampling Areas as Grouping Variables: Bare Patch and Vegetated Patch

The most significant variables introduced to discriminate in the model were IC and BD. The variable selection process is shown in Table 3. At step zero, IC was introduced because it had the lowest value of Wilks' Lambda and the highest F-value. At step one, BD was included, following the same rule. No other variables satisfy the stepwise method criteria; hence P, FC, and AS were not included. The discriminant linear equation (D), in unstandardized coefficients, is the following:

$$D = 11.292 - 9.39BD + 0.037IC \quad (2)$$

This explains the 100% model variability, with a canonical correlation of 0.792. In the case of discriminant analyses of two groups, the canonical correlation is equivalent to the Pearson correlation. The discriminant function presents a Wilks' Lambda of 0.373 and a Chi-square value of 36.536 ($p < 0.001$).

Once the discriminant function was known, each case was classified in the best group according to its discriminant scores. Table 4 shows the results of the new classification, indicating both correctly and incorrectly classified cases. Of the original groups, 85% of cases were classified correctly, including 80% of cases in the bare patch and 90% of cases in the vegetated patch. Of a total of forty cases, six were incorrectly classified (four in the bare patch and two in the vegetated patch). The analysis showed that 85% of the results obtained from the five SPPs originally selected could be explained using only IC and BD. Thus, these two SPPs were the most significant for differentiating the areas affected and those not affected by livestock treading.

Table 2. Results of the soil physical properties analyzed in the bare and vegetated patches of the sampling plots.

Land Unit Sampling		BD (g cm^{-3})		P (%)		FC (%)		IC (cm h^{-1})		AS	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
1	Bare patch	1.36	0.031	48.36	3.89	29.32	3.22	10.01	2.60	4.17	0.39
	Vegetated patch	1.26	0.007	50.25	2.65	43.77	0.67	35.58	8.00	2.19	0.19
2	Bare patch	1.39	0.033	47.28	1.68	32.09	1.28	34.19	4.68	2.41	0.28
	Vegetated patch	1.25	0.034	51.46	2.51	38.94	2.67	76.73	1.89	2.09	0.43
3	Bare patch	1.34	0.012	51.40	1.05	36.63	2.01	8.34	3.57	2.99	0.37
	Vegetated patch	1.28	0.049	52.98	1.95	40.07	2.85	28.19	10.56	1.89	0.30
4	Bare patch	1.30	0.055	51.29	1.15	37.72	1.51	32.52	2.96	1.90	0.29
	Vegetated patch	1.24	0.028	52.57	1.02	40.73	1.37	63.39	11.30	1.73	0.30
5	Bare patch	1.52	0.045	42.63	1.40	26.57	1.73	18.90	10.10	2.61	0.19
	Vegetated patch	1.30	0.12	50.93	4.44	38.44	6.27	37.25	3.52	2.19	0.11
6	Bare patch	1.46	0.079	42.72	3.03	27.10	3.27	8.34	3.57	4.21	0.32
	Vegetated patch	1.31	0,04	50.14	1.71	36.90	2.75	42.53	2.48	2.52	0.44
7	Bare patch	1.49	0.047	42.16	1.60	25.80	1.46	24.18	2.70	2.54	0.13
	Vegetated patch	1.25	0.079	51.75	3.72	37.73	4.24	80.07	15.45	2.77	0.47
8	Bare patch	1.43	0.15	44.02	4.86	30.07	5.91	7.42	3.27	3.01	0.16
	Vegetated patch	1.27	0.029	49.19	1.17	36.91	1.77	30.02	5.05	3.66	0.12
9	Bare patch	1.45	0.059	43.54	2.39	27.08	1.74	8.34	3.57	2.22	0.10
	Vegetated patch	1.32	0.066	45.24	3.50	27.05	2.26	46.7	12.40	3.26	1.05
10	Bare patch	1.41	0.034	47.07	1.38	31.27	1.29	20.56	9.53	2.38	0.048
	Vegetated patch	1.16	0.01	52.42	1.15	42.25	0.96	41.14	4.64	2.37	0.064
11	Bare patch	1.50	0.04	45.95	2.09	28.58	2.54	15.01	4.15	5.97	1.69
	Vegetated patch	1.38	0.034	46.80	1.95	32.02	1.83	19.45	2.84	3.65	0.86
12	Bare patch	1.35	0.07	47.42	3.56	31.74	3.40	41.70	3.90	2.37	0.12
	Vegetated patch	1.30	0.041	50.23	0.89	35.78	1.92	75.06	2.73	1.66	0.13
13	Bare patch	1.49	0.039	42.63	3.66	25.79	1.46	16.67	3.09	2.87	0.50
	Vegetated patch	1.23	0.044	50.64	2.81	40.04	1.06	53.38	7.37	2.34	0.22
14	Bare patch	1.54	0.045	41.74	2.50	24.54	2.34	9.45	2.24	4.34	0.19
	Vegetated patch	1.41	0.028	46.52	0.58	28.94	1.53	35.02	3.70	4.01	0.86
15	Bare patch	1.32	0.014	50.54	1.28	35.37	1.27	13.89	1.76	3.92	0.55
	Vegetated patch	1.28	0.041	53.15	1.76	41.08	4.40	84.23	10.85	3.17	0.48
16	Bare patch	1.31	0.018	50.86	1.54	35.65	0.87	32.24	11.29	2.34	0.64
	Vegetated patch	1.27	0.019	53.59	2.32	41.41	4.78	70.06	7.39	2.41	0.023
17	Bare patch	1.33	0.009	46.57	1.60	32.34	0.42	38.36	3.19	2.36	0.20
	Vegetated patch	1.27	0.025	50.75	2.09	38.01	3.83	80.07	13.32	1.99	0.21
18	Bare patch	1.47	0.023	46.70	1.88	28.46	2.73	20.01	4.02	2.79	0.18
	Vegetated patch	1.29	0.17	49.93	5.37	36.59	8.18	77.56	23.64	3.07	0.35
19	Bare patch	1.40	0.013	49.75	1.67	32.91	1.38	6.67	1.95	3.01	0.03
	Vegetated patch	1.22	0.076	52.90	2.45	41.37	5.29	55.88	8.93	1.97	0.22
20	Bare patch	1.39	0.058	48.09	2.78	28.11	1.28	12.78	5.54	3.19	0.60
	Vegetated patch	1.29	0.051	52.06	0.72	37.94	1.94	35.86	3.82	3.33	0.076
Mean bare patch		1.41	0.04	46.54	2.25	30.36	2.06	18.98	4.38	3.08	0.35
Mean vegetated patch		1.28	0.05	50.68	2.24	37.80	3.03	53.41	7.99	2.61	0.35

SD—standard deviation; BD—bulk density; P—total porosity; FC—water content at field capacity; IC—infiltration capacity; AS—aggregate stability (>AS > structural instability).

Table 3. Variable selection in a stepwise regression. IC is selected at step zero and BD is selected at step one. No other variable at step two is included in the model because the minimum partial F is 3.84 and no variables reach this value.

Step		Tolerance	F to Enter	Wilks' Lambda
0	Bulk Density (BD)	1.00	41.68	0.48
	Total Porosity (P)	1.00	21.54	0.64
	Field Capacity (FC)	1.00	32.91	0.54
	Infiltration Capacity (IC)	1.00	**42.41**	**0.47**
	Aggregate Stability (AS)	1.00	2.97	0.93
1	**Bulk Density** (BD)	0.90	**9.94**	**0.37**
	Total Porosity (P)	0.92	3.90	0.43
	Field Capacity (FC)	0.93	8.05	0.39
	Aggregate Stability (AS)	0.86	0.28	0.47
2	Total Porosity (P)	0.35	0.53	0.37
	Field Capacity (FC)	0.33	0.19	0.37
	Aggregate Stability (AS)	0.74	2.48	0.35

Table 4. Classification results. Each case is classified in the best group according to its discriminant scores. Of the originally grouped cases, 85% are correctly classified, 80% of cases in the bare patch, and 90% of cases in the vegetated patch.

	Group	Predicted Group Membership		Total
		1 Bare Patch	2 Vegetated Patch	
Count	1 Bare Patch	16	4	20
	2 Vegetated Patch	2	18	20
%	1 Bare Patch	80.0	20.0	100
	2 Vegetated Patch	10.0	90.0	100

3.2. Discriminant Analysis Using the Cumulative Stocking Rates as Grouping Variables: Low, Moderate, High, and Very High Cumulative Stocking Rates

The independent variables were the SPPs analyzed in the bare patches (i.e., trampled areas). Statistical analysis showed that none of the variables used were significant to identify the groups previously established because the cases studied were not well classified. None of the variables satisfied the criteria of the stepwise method. In this discriminant analysis, the Wilks' Lambda values were very high, correlating with low F-values (Table 5).

Table 5. Variable selection in a stepwise regression. No variables are included in the model because none satisfy the criteria of the stepwise method (the minimum partial F to enter is 3.84).

Step		Tolerance	F to Enter	Wilks' Lambda
0	Bulk Density (BD)	1.00	0.25	0.95
	Total Porosity (P)	1.00	0.43	0.92
	Field Capacity (FC)	1.00	0.44	0.92
	Infiltration Capacity (IC)	1.00	0.20	0.96
	Aggregate Stability (AS)	1.00	0.35	0.94

These results showed that, surprisingly, a linear relationship could not be established between the degradation of soil properties and the stocking rate. This was because the study was carried out at a farm located in a mountainous region, where environmental conditions vary from one area to another. Therefore, the impact of grazing on SPPs depends on other parameters, not solely on the stocking rate. In other words, the different soil response to degradation depends on environmental factors.

This is in close agreement with the results of other works. Blackburn [13] indicated that hydrological effects of livestock grazing were a consequence of the interactions of climate, vegetation, soil, intensity and duration of livestock use, and the type of grazing livestock and the land management influence on SPPs. Manono et al. [40] observed a lower bulk density and a higher water volumetric content in the soils under sheep grazing than under dairy grazing due to the greater impact of the cows' hooves. In addition, applications of irrigation water and organic effluents in the grasslands increased the organic carbon content and improved the structure and the soil hydrological characteristics. The relief, soil texture, and plant cover deserve special attention with respect to environmental factors. Blanco and Nieuwenhuyse [41] observed that slope gradient was correlated with bulk density in tropical mountain cattle farms. This result was used to establish the livestock carrying capacity based on this environmental factor. Van Haveren [14] showed that the effect of grazing intensity on soil compaction depended greatly on soil texture and, particularly, on the clay content of the soil [42]. Ess et al. [43] indicated that compaction depended on the amount of plant residue on the soil surface. Blanco [44] established in studies carried out in the Mediterranean mountains that compaction also depended on vegetation cover, to which was added the calcium carbonate content of the soil and the slope exposure (north, south, east, and west). Therefore, the impact of grazing on SPPs depends on certain environmental factors, not only on the stocking rate. As a result, soils with the same stocking rate may have different levels of impact.

3.3. Discriminant Analysis Using Stocking Rates and Calcium Carbonate Content, Slope Exposure, and Grass Cover Factors as Grouping Variables

A new discriminant analysis used three environmental factors (soil calcium carbonate content, slope exposure, and grass cover) and the stocking rate as grouping variables (Table 6). The three groups were a combination of these factors, which were based on the conclusions reached by Blanco [44] for the same area studied in this article. Group 1 covered an area of 85.5 ha (48.7% of the total farm) and was represented by 10 sampling plots. Group 2 extended over an area of 58.7 ha (33.4%) and had seven sampling plots. Finally, Group 3 was the smallest unit (31.5 ha, 17.9%) and was represented by three sampling plots.

Table 6. Group characteristics. These groups were established by Blanco [44] based on calcium carbonate content, slope exposure, and grass cover factors because these influence the vulnerability of soil physical properties to the impact of animal trampling in the study area.

Groups	Land Units	Sampling Plots
1	Calcareous slopes (all slope exposures) and non-calcareous slopes with northern exposure (grass cover > 10%).	**1–4, 12, 15–17, 19, 20.**
2	Non-calcareous slopes with eastern and western exposure and mountain summits (grass cover > 25%).	**5, 7, 8, 10, 11, 13, 14.**
3	Non-calcareous mountain summits (herbaceous cover < 25%) and non-calcareous slopes with northern and southern exposure (grass cover < 10%).	**6, 9, 18.**

Land units with a cumulative stocking rate of 1 (500–1000 animals ha^{-1} $year^{-1}$); 2 (100–500 animals ha^{-1} $year^{-1}$); 3 (<100 animals ha^{-1} $year^{-1}$).

These factors were the most relevant to evaluate soil vulnerability to degradation caused by extensive grazing on the farm used for this study. Calcium carbonate content plays a fundamental role in SPPs. Dietze et al. [45] observed that the soil calcium carbonate increased structural stability and improved the water infiltration times into the soil. Calcium ion favored the formation of a stable structure because it produced flocculation of the soil ions [46]. Slope exposure was a factor of microclimatic variability because it determined how the soil received different levels of solar radiation, especially between north-facing and south-facing slopes. The review by Singh [47] showed that these microclimatic differences influenced vegetation and SPPs. North-facing slopes were more protected from the evapotranspiration processes and therefore had a higher moisture balance throughout the year than soils that had a different type of slope exposure. These conditions favored the growth of vegetation, crop production, and good soil properties and improved the soil structure, infiltration rate, water holding capacity, hydraulic conductivity, and aeration. Grass cover has beneficial effects on the SPPs, through the incorporation of organic matter. This fact improves the stability of soil aggregates [48] and protects the soil from the impact of rainfall, thus reducing hillside erosion [49]. Also, grass cover absorbs and reduces part of the impact of the animal trampling, which in turn reduces the effects of this trampling on the SPPs [44].

In Blanco [44], there is a detailed analysis of the research performed to determine the extent to which these factors influence the SPPs. The purpose was to reduce the initial variations caused by environmental factors in the SPPs in order to specifically analyze the impact of animal treading on those properties. The independent variables were the SPPs analyzed in the bare patch areas.

The most significant variable used to discriminate in the model was BD. Table 7 shows the variable selection process. The discriminant lineal equation (D), in unstandardized coefficients, is the following:

$$D = -36.767 + 26.030BD \tag{3}$$

Table 7. Variable selection in a stepwise regression. BD is selected at step zero and no other variable at step one is included in the model because the minimum partial F is 3.84 and no variables reach this value.

Step		Tolerance	F to Enter	Wilks' Lambda
0	**Bulk Density** (BD)	1.00	**27.54**	**0.24**
	Total Porosity (P)	1.00	18.36	0.32
	Field Capacity (FC)	1.00	10.84	0.44
	Infiltration Capacity (IC)	1.00	1.73	0.83
	Aggregate Stability (AS)	1.00	2.88	0.75
1	Total Porosity (P)	0.70	1.12	0.21
	Field Capacity (FC)	0.47	0.13	0.23
	Infiltration Capacity (IC)	0.97	0.21	0.23
	Aggregate Stability (AS)	0.90	2.35	0.18

The canonical function explains the 100% variability rate of the model, with a canonical correlation of 0.874. The discriminant function presents a Wilks' Lambda of 0.236 and a Chi-value of 24.557 ($p < 0.001$). Once the discriminant function was known, each case was classified into the best group according to its discriminant scores. Table 8 shows the results of the new classification where the correctly and incorrectly classified cases are shown. Of the original groups, 70% of the cases were correctly classified, including 100% of the cases in Group 1 and 40% in Groups 2 and 3. Of a total of twenty cases, six were incorrectly classified (three in Group 2 and another three in Group 3). The conclusion is that 70% of the results obtained from the five SPPs can be explained using only BD. Thus, this soil physical property is the key variable for analysis of the impact of animal treading on the bare patch.

Table 8. Classification results. Each case is classified in the best group according to its discriminant scores. Of the originally grouped cases, 70% are correctly classified, 100% of cases in Group 1, 60% of cases in Group 2, and 60% of cases in Group 3.

	Group	Predicted Group Membership			Total
		1	2	3	
Count	1	10	0	0	10
	2	0	2	3	5
	3	0	3	2	5
%	1	100.0	0.0	0.0	100
	2	0.0	40.0	60.0	100
	3	0.0	60.0	40.0	100

4. Conclusions

The results obtained showed that IC and BD were the key SPPs for evaluating soil compaction as a consequence of goat trampling in Mediterranean mountain areas. These were the two most relevant properties to take into account when distinguishing soils with treading impact (bare patch) and those without (vegetated patch).

It has traditionally been accepted that a linear relationship exists between soil physical degradation and the stocking rate. However, this fact takes into consideration only part of the phenomenon of the grazing impact on the SPPs, because soil compaction is a complex relationship between the type of grazing livestock, the stocking rate, and certain environmental factors. This work has demonstrated that, in the study area, where there are the same livestock types and different environmental conditions, the soil physical degradation versus stocking rate relationship is not linear because soil degradation resulting from livestock treading depends on the environmental variability. In our opinion, this is one of the main findings of the work.

Factors that influence soil vulnerability to degradation due to livestock treading in the study area, in Mediterranean mountain conditions, are calcium carbonate content, slope exposure, and grass cover. Within this context, BD is the key variable for analyzing the physical impact of grazing on the bare patches of the study area. For practical purposes, it is of special interest for future research to determine the environmental factors that influence soil degradation due to trampling that are adapted to each ecosystem.

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References

1. Nawaz, M.F.; Bourrie, G.; Trolard, F. Soil compaction impact and modelling. A review. *Agron. Sustain. Dev.* **2013**, *33*, 291–309. [CrossRef]
2. Herbin, T.; Hennessy, D.; Richards, K.G.; Piwowarczyk, A.; Murphy, J.J.; Holden, N.M. The effects of dairy cow weight on selected soil physical properties indicative of compaction. *Soil Use Manag.* **2011**, *27*, 36–44. [CrossRef]
3. Di, H.J.; Cameron, K.C.; Milne, J.; Drewry, J.J.; Smith, N.P.; Hendry, T.; Moore, S.; Reijnen, B. A mechanical hoof for simulating animal treading under controlled conditions. *N. Z. J. Agric. Res.* **2001**, *44*, 111–116. [CrossRef]

4. Pulido, M.; Schnabel, S.; Contador, J.F.L.; Lozano-Parra, J.; Gómez-Gutiérrez, A.; Brevik, E.C.; Cerdà, A. Reduction of the frequency of herbaceous roots as an effect of soil compaction induced by heavy grazing in rangelands of SW Spain. *Catena* **2017**, *158*, 381–389. [CrossRef]
5. Mousel, E.M.; Schacht, W.H.; Zanner, C.W.; Moser, L.E. Effects of summer grazing strategies on organic reserves and root characteristics of big bluestem. *Crop Sci.* **2005**, *45*, 2008–2014. [CrossRef]
6. Wood, M.K.; Blackburn, W.H. Grazing systems: Their influence on infiltration rates in the Rolling Plains of Texas. *J. Range Manag.* **1981**, *34*, 331–335. [CrossRef]
7. Gamougoun, N.D.; Smith, R.P.; Wood, M.K.; Pieper, R.D. Soil, vegetation and hydrologic responses to grazing management at Fort Stanton, New Mexico. *J. Range Manag.* **1984**, *37*, 538–541. [CrossRef]
8. McCalla, G.R.; Blackburn, W.H.; Merrill, L.B. Effects of livestock grazing on infiltration rates, Edwards Plateau of Texas. *J. Range Manag.* **1984**, *37*, 267–269. [CrossRef]
9. Takar, A.A.; Dobrowolski, J.P.; Thurow, T.L. Influence of grazing, vegetation life-form and soil type on infiltration rates and interrill erosion on a Somalian rangeland. *J. Range Manag.* **1990**, *43*, 486–490. [CrossRef]
10. Bari, F.; Wood, M.K.; Murray, L. Livestock grazing impacts on infiltration rates in a temperature range of Pakistan. *J. Range Manag.* **1993**, *46*, 367–372. [CrossRef]
11. Zhang, J.H.; Li, Y.; Yang, M.J.Z. Soil water properties in a recently established forest as affected by grazing in a semiarid valley. *Soil Use Manag.* **2000**, *16*, 234–235. [CrossRef]
12. Marquart, A.; Eldridge, D.J.; Travers, S.K.; Val, J.; Blaum, N. Large shrubs partly compensate negative effects of grazing on hydrological function in a semi-arid savanna. *Basic Appl. Ecol.* **2019**, *38*, 58–68. [CrossRef]
13. Blackburn, W.H. Impacts of grazing intensity and specialized grazing systems on watershed characteristics and responses. In *Developing Strategies for Rangeland Management*; National Research Council/National Academy of Sciences: Washington, DC, USA; Westview Press: Boulder, CO, USA, 1984; pp. 927–983.
14. Van Haveren, B.P. Soil bulk density as influenced by grazing intensity and soil type on a short grass prairie site. *J. Range Manag.* **1983**, *36*, 586–588. [CrossRef]
15. Taboada, M.A.; Lavado, R.S. Grazing effects on soil bulk density in the flooding Pampa of Argentina. *J. Range Manag.* **1988**, *41*, 497–503. [CrossRef]
16. Chanasyk, D.S.; Naeth, M.A. Grazing impacts on bulk density and soil strength in the foothills fescue grasslands of Alberta, Canada. *Can J. Soil Sci.* **1995**, *75*, 551–557. [CrossRef]
17. Krzic, M.; Newman, R.F.; Broersma, K.; Bomke, A.A. Soil compaction of forest plantations in interior British Columbia. *J. Range Manag.* **1999**, *52*, 671–677. [CrossRef]
18. Stephenson, G.R.; Veigel, A. Recovery of compacted soil on pastures used for winter cattle feeding. *J. Range Manag.* **1987**, *4*, 46–48. [CrossRef]
19. Steffens, M.; Kölbl, A.; Totsche, K.U.; Kögel-Knabner, I. Grazing effects on soil chemical and physical properties in a semiarid steppe of Inner Mongolia (P.R. China). *Geoderma* **2008**, *143*, 63–72. [CrossRef]
20. Bakhshi, J.; Javadi, S.A.; Tavili, A.; Arzani, H. Study on the effects of different levels of grazing and exclosure on vegetation and soil properties in semi-arid rangelands of Iran. *Acta Ecol. Sin.* **2020**, *40*, 425–431. [CrossRef]
21. Mapfumo, E.; Chanasyk, D.S.; Baron, V.S.; Naeth, M.A. Grazing impacts on selected soil parameters under short-term forage sequences. *J. Range Manag.* **2000**, *53*, 466–470. [CrossRef]
22. Willat, S.T.; Pullar, D.M. Changes in soil physical properties under grazed pastures. *Aust. J. Soil Res.* **1983**, *22*, 343–348. [CrossRef]
23. Hiernaux, P.; Bielders, C.H.L.; Valentin, C.H.; Bationo, A.; Fernández, S. Effects of livestock grazing on physical and chemical properties of sandy soils in Sahelian rangelands. *J. Arid Environ.* **1999**, *41*, 231–245. [CrossRef]
24. Rauber, L.R.; Sequinatto, L.; Kaiser, D.R.; Bertol, I.; Baldissera, T.C.; Garagorry, F.C.; Sbrissia, A.F.; Pereira, G.E.; Pinto, C.E. Soil physical properties in a natural highland grassland in southern Brazil subjected to a range of grazing heights. *Agric. Ecosyst. Environ.* **2021**, *319*, 107515. [CrossRef]
25. Warren, S.D.; Nevill, M.B.; Blackburn, W.H.; Garza, N.E. Soil response to trampling under intensive rotation grazing. *Soil Sci. Soc. Am. J.* **1986**, *50*, 1336–1340. [CrossRef]
26. Southorn, N.J. The soil structure component of soil quality under alternate grazing management strategies. In *Sustainability Land Management-Environmental Protection: A Soil Physical Approach*; Pagliai, M., Jones, R., Eds.; Advances in GeoEcology; Catena Verlag: Reiskirchen, Germany, 2002; Volume 35, pp. 163–170.
27. Tuohy, P.; Fenton, O.; Holden, N.M.; Humphreys, J. The effects of treading by two breeds of dairy cow with different live weights on soil physical properties, poaching damage and herbage production on a poorly drained clay-loam soil. *J. Agric. Sci.* **2015**, *153*, 1424–1436. [CrossRef] [PubMed]
28. Franzluebbers, A.J.; Stuedemann, J.A. Soil physical responses to cattle grazing cover crops under conventional and no tillage in the Southern Piedmont USA. *Soil Till Res.* **2008**, *100*, 141–153. [CrossRef]
29. Lai, L.; Kumar, S. A global metaanalysis of livestock grazing impacts on soil properties. *PLoS ONE* **2020**, *15*, e0236638. [CrossRef]
30. Roesch, A.; Weisskopf, P.; Oberholzer, H.; Valsangiacomo, A.; Nemecek, T. An Approach for Describing the Effects of Grazing on Soil Quality in Life-Cycle Assessment. *Sustainability* **2019**, *11*, 4870. [CrossRef]
31. Donovan, M.; Monaghan, R. Impacts of grazing on ground cover, soil physical properties and soil loss via surface erosion: A novel geospatial modelling approach. *J. Environ. Manag.* **2021**, *287*, 112206. [CrossRef]

32. IUSS Working Group—WRB. *World Reference Base for Soil Resources. International Soil Classification System for Naming Soils and Creating Legends for Soil Maps*, 4th ed.; International Union of Soil Sciences (IUSS): Vienna, Austria, 2022.
33. Blanco, R. The treatment of the concept "Stocking Rate" in the land evaluation systems for cattle grazing. *Estud. Geogr.* **2004**, *254*, 143–150. (In Spanish)
34. Scholefield, D.; Hall, D.M. A recording penetrometer to measure the strength of soil relation to the stresses exerted by a walking cow. *J. Soil Sci.* **1986**, *37*, 165–172. [CrossRef]
35. Blake, G.R.; Hartge, K.H. Bulk density. In *Methods of Soil Analysis. Part I. Physical and Mineralogical Methods*, 2nd ed.; Agronomy Monograph 9; Page, L., Miller, R.H., Keeney, D.R., Eds.; American Society of Agronomy, Inc.: Madison, WI, USA; Soil Science Society of America, Inc.: Madison, WI, USA, 1986; pp. 363–375.
36. Guitian, F.; Carballas, T. *Soil Testing Techniques*; Pico Sacro: Santiago de Compostela, Spain, 1976. (In Spanish)
37. Cassel, D.K.; Nielsen, D.R. Field capacity and available water capacity. In *Methods of Soil Analysis. Part I. Physical and Mineralogical Methods*, 2nd ed.; Agronomy Monograph 9; Page, L., Miller, R.H., Keeney, D.R., Eds.; American Society of Agronomy, Inc.: Madison, WI, USA; Soil Science Society of America, Inc.: Madison, WI, USA, 1986; pp. 901–926.
38. Youngs, E.G. Estimating hydraulic conductivity values from ring infiltrometer measurements. *J. Soil Sci.* **1987**, *38*, 623–632. [CrossRef]
39. Henin, S.; Gras, R.; Monnier, G. *The Cultural Profile. The Physical State of the Soil and Agronomic Consequences*; Mundi-Prensa: Madrid, Spain, 1972. (In Spanish)
40. Manono, B.O.; Moller, H.; Morgan, R. Effects of irrigation, dairy effluent dispersal and stocking on soil properties of the Waimate District, New Zealand. *Geoderma Reg.* **2016**, *7*, 59–66. [CrossRef]
41. Blanco, R.; Nieuwenhuyse, A. Influence of topographic and edaphic factors on vulnerability to soil degradation due to cattle grazing in humid tropical mountains in northern Honduras. *Catena* **2011**, *86*, 130–137. [CrossRef]
42. Gupta, S.C.; Sharma, P.P.; DeFranchi, S.A. Compaction effects on soil structure. *Adv. Agron.* **1989**, *42*, 311–338.
43. Ess, D.R.; Vaughan, D.H.; Perumpral, J.V. Crop residues and root effects on soil compaction. *Trans. ASAE* **1998**, *41*, 1271–1275. [CrossRef]
44. Blanco, R. Land evaluation for extensive grazing by Estimating Soil Vulnerability to Degradation: A Case Study in a Goat Farm in Southern Spain. In *Sustainability of Agro-Silvo-Pastoral Systems*; Schnabel, S., Ferreira, A., Eds.; Advances in GeoEcology; Catena Verlag: Reiskirchen, Germany, 2004; Volume 37, pp. 365–376.
45. Dietze, M.; Bartel, S.; Lindner, M.; Kleber, A. Formation mechanisms and control factors of vesicular soil structure. *Catena* **2012**, *99*, 83–96. [CrossRef]
46. Baver, L.D.; Gardner, W.H.; Gardner, W.R. *Soil Physics*; John Wiley Sons: New York, NY, USA, 1991.
47. Singh, S. Understanding the role of slope aspect in shaping the vegetation attributes and soil properties in Montane ecosystems. *Trop. Ecol.* **2018**, *59*, 417–430.
48. Yu, Z.; Zhang, J.; Zhang, C.; Xin, X.; Li, H. The coupling effects of soil organic matter and particle interaction forces on soil aggregate stability. *Soil Tillage Res.* **2017**, *174*, 251–260. [CrossRef]
49. Prosdocimi, M.; Tarolli, P.; Cerdà, A. Mulching practices for reducing soil water erosion: A review. *Earth-Sci. Rev.* **2016**, *161*, 191–203. [CrossRef]