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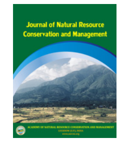

Effect of fencing, slope position (upper, middle and lower) and depth on soil physical characteristics in submontane Punjab

M.S. Hadda[1,*] and K.B. Thapa[1]

Department of Soil Science, Punjab Agricultural University, Ludhiana-141004, Punjab, India
**Corresponding author email: ms_hadda@yahoo.com*

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ABSTRACT

Soil degradation in the fragile Shivalik foothills of Punjab is strongly shaped by grazing pressure and topographic variation. A field study was conducted in the Kandi region to evaluate the effects of fencing (grazing exclusion), slope position (upper, middle, lower), and soil depth (0–5, 5–10, 10–15, 15–30 cm) on soil physical properties. Two adjacent sites-one protected by fencing for five years and the other left open to grazing-was compared. Analyses included bulk density, porosity, aggregate stability, moisture retention, and saturated hydraulic conductivity. Results showed that fencing significantly improved soil physical health: mean bulk density decreased from 1.58 to 1.42 Mg·m^{-3}, porosity increased by 14.2%, aggregate stability improved, and saturated hydraulic conductivity rose by 13.7%. Improvements were most pronounced in surface layers (0–10 cm), where compaction had previously restricted infiltration and root growth. Slope position further moderated soil quality, with lower slopes exhibiting the most favourable properties due to depositional processes, while upper slopes remained degraded. The combined effects of fencing, slope, and depth produced synergistic benefits, particularly in fenced lower slopes where infiltration and moisture storage were highest. These findings highlight the importance of mechanical protection and slope specific management for rehabilitating degraded soils in submontane Punjab.

Keywords: Bulk density, Porosity, Water stable aggregates, Degraded soils

INTRODUCTION

The submontane tract of Punjab, situated at the foothills of the Shivalik range and locally known as the "Kandi" belt, is an ecologically fragile zone characterized by undulating topography, erratic rainfall, and severe soil erosion. This region occupies approximately 9.5% of the total geographical area of the state (Hadda and Sur, 1989). The soils in this region are prone to rapid degradation due to anthropogenic factors, primarily overgrazing and deforestation, which remove the protective vegetative cover.

The removal of vegetation through uncontrolled grazing exacerbates soil compaction, thereby increasing bulk density and reducing porosity. This leads to reduce infiltration rates and increased surface runoff, triggering a vicious cycle of erosion and land degradation (Kukal *et al.*, 1993; Kumar *et al.*, 2021). Previous studies have indicated that topography, specifically slope position, plays a dominant role in governing soil physical properties by influencing the movement of water and sediments (Hadda *et al.*, 2000b). Soils at lower slope positions generally act as sinks for water and nutrients, whereas upper slopes are often subjected to severe loss of topsoil.

While the effects of vegetative barriers and mechanical conservation measures have been documented, there is a knowledge gap regarding the specific quantitative interaction between fencing (complete exclusion of biotic interference) and slope position on fundamental soil physical properties in the surface and sub-surface layers of soils in this specific region. Understanding these dynamics is crucial for designing site-specific watershed management plans. Keeping these points in view, the primary objectives of this study were to evaluate the effect of fencing (protection from grazing) on soil physical properties such as bulk density, porosity, and aggregate stability. The study also aimed to assess the variation in soil physical characteristics across different slope positions, including upper, middle, and lower slopes. Additionally, it sought to determine the interaction effects of fencing and topography on soil moisture retention and infiltration characteristics.

MATERIALS AND METHODS

Study site, climate, and soils

The study was conducted at DR Bhumbla, Zonal Research Station for Kandi Area (ZRSKA), Ballowal-Saunkhri, and district SBS Nagar. It is in agro-climatic zone-I of the state of Punjab. The area has a semi-arid to a sub-humid type of climate according to the classification of Thornthwaite (Singh, 1979). The mean annual rainfall of the area is 1000± 150mm (Table 1). There is high inter-annual and seasonal variability in rainfall, especially during the winter (rabi) season. The rainfall distribution is bimodal with mean monthly rainfall highest in July and lowest in November. The monsoon (summer season) rains are received in 20-30 rainstorms, of which only 8-12 produce runoff and overland flow (Hadda and Sur, 1986). However, only 2 to 3 rainstorms occur with average intensity >120 mm h^{-1} and maximum 15-minutes intensity > 240 mmh^{-1} in the area. The probability of expecting one dry–spell of more than 6 days in an individual month varies between 55 to 99 percent in which dry–spell of longer duration is quite common during the winter season (Sur and Ghuman, 1994). The mean maximum temperature varies from 18.6° C in January to 39.1° C in May and the mean minimum temperature from 5.2° C in December to 24.7° C in June. Due to high temperature and low relative humidity in these months, vegetation cover is very sparse (Hadda *et al*., 2000 a).

The soils are generally moderate to alkaline in reaction, non-saline in nature; contain low amounts of organic matter, low in nitrogen and phosphorus, but medium to high in potassium content (Thapa, 2003). The pertinent information on the area, climate, and soils is given in Table 1.

Experimental procedure and sample determination

The two contiguous areas were selected (Main treatments) such as fenced: protected from human and animal interference and other without fencing**:** left open to anthropogenic interventions such as grazing and browsing. The landscape was divided into three distinct positions (Sub-treatments) based on elevation and gradient such as Upper Slope: Convex crest, slope gradient > 5%; Middle Slope: Transportation mid-section, slope gradient 3-5% and Lower Slope: Concave toe-slope, slope gradient < 3%.

Since soil depth can be influenced by genetic factors and soil erosion, the sites were selected within the same parent and landscape unit. The soil samples were collected from 0-5, 5-10, 10-15, and 15-30 cm depths from each sub-treatment. The collected soil

Table 1. Area, climate, and soils of Ballowal-Saunkhri

Parameters	Range
Elevation (MSL, m)	355
Area (ha)	150
Average annual rainfall (mm)	1000 ± 150
Mean maximum temperature (°C)	39.1
Mean minimum temperature (°C)	5.2
Average annual evaporation (mm)	1403
Major soil groups	Ustorthents, Ustipsamments, Haplustalfs
Texture	Sandy loam to Loamy sand
pH	7.2-9.2
Organic carbon content (%)	0.47-2.11
Total Nitrogen (kg ha^{-1})	26.7-508.8
Available phosphorous (kg ha^{-1})	7.9-49.4
Available potassium (kg ha^{-1})	53.8-363.2
Cation exchange capacity (c^+ mol kg^{-1})	12.6-23.9
Total soil porosity (m^3m^{-3})	0.30-0.45

Table 2. Methodologies for determining soil physical characteristics

Soil Physical Characteristic	Methodology / Instrument	Reference / Standard Method
Particle Size Analysis	International Pipette Method (after removing organic matter and cementing agents)	Gee and Bauder (1986)
Bulk Density	Core Method	Blake and Hartge (1986)
Aggregate Stability	Wet Sieving Technique (computing Mean Weight Diameter - MWD)	Yoder (1936)
Infiltration Rate	Double Metallic Ring Infiltrometers	Richards (1954)
Soil Moisture Characteristics	Pressure Plate Apparatus	Richards (1947)
Saturated Hydraulic Conductivity	Constant Head Permeameter (using core sampler and Darcy's equation)	Richards (1954) / Darcy's Law
Total Porosity	Computation using Bulk Density and Particle Density	Russel (1949)
Penetration Resistance	Prowine Cone Ring Penetrometer	*Method implied by instrument usage*
Max. Water Holding Capacity (MWHC)	Methods of Soil Analysis	Richards (1954)

samples were analysed for their physical characteristics.

Determining soil physical characteristics

Information w.r.t determining soil physical characteristic, relevant methodology and reference employed are mentioned in Table 2.

Per cent sand, silt and clay

The sand, silt and clay content varied from 71.3 to 92.3, 5.3 to 13.6 and 2.0 to 16.3 per cent in fenced and from 82.3 to 91.6, 5.3 to 9.6 and 1.6 to 11.6 per cent, respectively in the without fencing treatment (Thapa, 2003). There were significant interactions between treatment and depth in case of sand and in treatment and slope position in case of clay. In the case of silt, only the interactions between treatment and depth were significant.

Sand content decreased by 9.9, 5.9, 2.9 and 0.5 per cent whereas clay content increased by 56.0, 63.1, 50.0 and 61.7 per cent at 0-5, 5-0, 10-15 and 15-30 cm soil depths, respectively in fenced compared to without fencing treatments. The overall decrease in sand and increase in clay due to fencing were 4.8 and 56.9 per cent, respectively. As compared to without fencing treatment, silt content increased by 75.7 and 25.7 per cent in 0-5 and 5-10 cm soil depths, respectively whereas, it decreased by 11.5 and 14.8 per cent in 10-15 and 15-30 cm soil depths, respectively (Thapa, 2003).

Statistical Analysis

The data were subjected to Analysis of Variance (ANOVA) appropriate for factorial randomized design was employed with 3- replications. The significance of differences between means was tested using the Critical Difference (CD) at a 5% probability level.

RESULTS AND DISCUSSION

Maximum water holding capacity and total porosity

The maximum water holding capacity of soils of the area varied from 22.7 to 46.4 per cent and 23.2 to 39.7 per cent in fenced and without fencing treatments, respectively (Table 3; Fig. 1). Similarly, the total porosity varied from 0.34 to 0.46 m^3m^{-3}in the former and 0.30 to 0.41 m^3 m^{-3} in the latter case. The treatment, depth and slope position had significant effect on maximum water holding capacity. The interactions of treatment × depth and treatment × slope position × depth were highly significant in case of maximum water holding capacity. The MWHC increased by 36.8 and 8.7 per cent for 0-5 and 5-10 cm soil depths, respectively in fenced over without fencing treatment. The overall, MWHC increase by 7.5 percent in fenced treatment than in without fencing treatment.

The higher MWHC in the case of fenced treatment in surface layers of soils from 0-10 cm might have resulted due to more stable aggregation. This might have stemmed due to presence of higher organic matter and clay content. The overall, MWHC was positively and significantly correlated with mean weight diameter (r=0.60) and with geometric mean weight diameter (r=0.54) of aggregates, at Ballowal Saunkhri, Hoshiarpur (Bhardwaj, 2000; Thapa, 2003).

Table 3. The effect of fencing and slope position on depth distribution of maximum water holding capacity and total porosity of soils

Depth (cm)	Position							
	MWHC				Total porosity			
	Upper slope	Middle slope	Lower slope	Mean	Upper slope	Middle slope	Lower slope	Mean
	Per cent				$m^3 m^{-3}$			
Fenced								
0-5	40.00	46.47	36.78	41.1	0.39	0.41	0.46	0.42
5-10	24.99	25.65	38.44	29.7	0.40	0.41	0.44	0.42
10-15	22.79	23.24	31.80	25.9	0.37	0.40	0.41	0.39
15-30	24.26	23.27	30.02	25.8	0.34	0.37	0.37	0.36
Mean	28.01	29.65	34.26		0.37	0.39	0.42	
Without fencing								
0-5	25.83	32.01	32.25	30.0	0.35	0.38	0.41	0.38
5-10	24.22	24.53	33.05	27.3	0.36	0.38	0.38	0.37
10-15	24.72	23.62	39.71	29.4	0.32	0.33	0.35	0.33
15-30	23.88	23.26	34.95	27.4	0.30	0.32	0.36	0.32
Mean	24.66	25.85	34.99		0.33	0.35	0.37	

MWHC			**Total porosity**		
Attributes	**F. Cal**	**L.S.D.(0.05)**	**Attributes**	**F. Cal**	**L.S.D.(0.05)**
TR (Treatment)	5.16*	1.94	TR (Treatment)	99.15**	0.008
DP (Depth)	18.58**	2.75	DP (Depth)	38.21**	0.012
TS (slope position)	29.49**	2.38	TS (Transect)	36.35**	0.01
TR × DP	11.60**		TR × DP	NS	
TR × TS	NS		TR × TS	NS	
TR × DP × TS	3.55**		TR × DP × TS	NS	
CV(%)	24.2		CV(%)	10.43	
SD	7.15		SD	3.95	

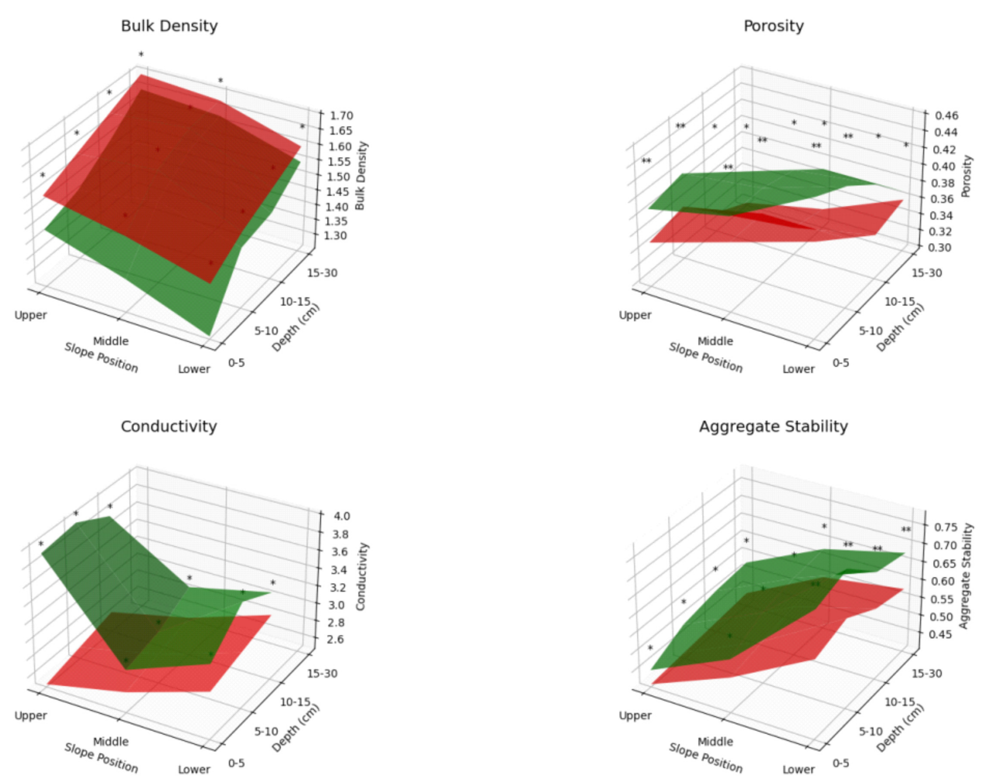

Fig. 1. Spatial and vertical variation of soil physical properties across slope positions and depths

The overall, total porosity increase by 14.2 percent in fenced treatment than in without fencing treatment. This showed that collapse of macro-pores resulted in lower porosity in without fencing treatment in the area. Also, the total porosity values in top few centimeters were observed to be 17 per cent lower in grazed sites compared to un-grazed sites in semi-arid areas of Argentina (Villamil *et al.,* 2001). The total porosity varied from 0.34 to 0.46 m^3m^{-3}in the former and 0.30 to 0.41 m^3 m^{-3} in the latter case. The interactions of treatment x depth, treatment x slope position and treatment x depth x slope position effect were, however, non-significant in case of total porosity. The total porosity increased by 10.5, 13.5, 18.1 and 12.5 per cent for 0-5, 5-10, 10-15 and 15-30 cm, of soil depths, respectively in fenced than that over without fencing treatment. Greater porosity in upper slopes suggests better aeration and water movement, beneficial for plant growth. Porosity decreases with depth, inversely related to bulk density. The upper slopes show higher porosity, especially in surface layers.

Bulk density and saturated hydraulic conductivity

The bulk density (BD) of soils varied from 1.26 to 1.65 Mg m^{-3} and 1.37 to 1.70 Mg m^{-3} in fenced and without fencing treatments, respectively (Table 4; Fig.1). The overall decrease in bulk density by 3.8 per cent and increase in saturated hydraulic conductivity by 13.7 per cent was observed in fenced treatment compared to without fencing treatment.

The BD showed significant reduction across all slopes and depths under fencing, strongest in surface layers. Bulk density increases with depth across all slope positions. The mean bulk density in the fenced area was 1.42Mg m^{-3}compared to 1.58 Mg m^{-3} in the unfenced area. The bulk density values were lower by 6.8, 2.6, 3.7 and 2.4 per cent in fenced compared to without fencing treatments through the soil depths of 0-5, 5-10, 10-15 and 15-30 cm, respectively.

This reduction is attributed to the restoration of vegetative cover and root proliferation, which loosens the soil, and the cessation of animal trampling (hoof pressure). Slope position also significantly influenced bulk density. A significant

Table 4. Effect of fencing and slope position on depth distribution of bulk density and saturated hydraulic conductivity of soils under fenced and without fencing

Depth (cm)	Position							
	Bulk density				Saturated hydraulic conductivity			
	Upper slope	Middle slope	Lower slope	Mean	Upper slope	Middle slope	Lower slope	Mean
	Mg m^{-3}				cm h^{-1}			
Fenced								
0-5	1.44	1.36	1.26	1.35	3.95	2.95	3.30	3.40
5-10	1.48	1.52	1.45	1.48	4.00	3.05	3.65	3.5
10-15	1.56	1.60	1.47	1.54	3.80	3.25	3.45	3.5
15-30	1.65	1.63	1.55	1.61	—	—	—	—
Mean	1.53	1.52	1.43		3.91	3.08	3.46	
Without fencing								
0-5	1.41	1.58	1.37	1.45	3.05	3.30	2.55	2.9
5-10	1.53	1.59	1.45	1.52	3.25	3.25	2.58	3.1
10-15	1.59	1.65	1.57	1.60	3.00	3.00	3.35	3.1
15-30	1.69	1.70	1.58	1.65	—	—	—	—
Mean	1.55	1.63	1.49		3.10	3.18	2.91	

Bulk density			**Saturated hydraulic conductivity**		
Attributes	**F. Cal**	**L.S.D. (0.05)**	**Attributes**	**F. Cal**	**L.S.D. (0.05)**
TR (Treatment)	6.71*	0.048	TR (Treatment)	32.09**	0.15
DP (Depth)	17.34**	0.598	DP (Depth)	NS	
TS(Slope position)	8.38**	0.069	TS (Transect)	9.77**	0.19
TR × DP	NS		TR × DP	NS	
TR × TS	NS		TR × TS	13.34**	
TR × DP × TS	NS		TR × DP × TS	NS	
CV (%)	8.07		CV (%)	12.52	
SD	0.12		SD	0.41	

difference was observed between fenced and without fencing treatment in their bulk density values. Higher bulk density in lower slopes may indicate compaction due to runoff or sediment accumulation, potentially reducing root penetration and water infiltration. In general, there was a tendency for increase in bulk density with increase in depth due to the compaction by human and livestock interventions in without fencing treatments. The higher content of organic matter in fenced treatment might have contributed to more microbial activities that made soil more porous in nature.

The depth and slope had significant effect in affecting bulk density values both in fenced and without fencing treatments. The highest bulk density was observed in the upper slope positions, indicative of erosion and exposure of denser subsoil layers. Lower slope positions tend to have higher bulk density, especially at deeper layers. The statistically significant differences, suggesting that slope position and depth meaningfully affect soil compaction. However, all interactions were observed to be non-significant both in fenced and without fencing treatments. The lower slope recorded the lowest bulk density (1.43Mg m^{-3}), likely due to the deposition of finer particles and organic matter eroded from upper slopes.

The saturated hydraulic conductivity (Ksat) ranged from 2.9 to 4.0 cm h^{-1} in fenced plots and 2.5 to 3.3 cm h^{-1} in unfenced plots. On average, fencing increased Ksat by 13.7% compared to unfenced treatments. Depth-wise improvements were most pronounced in the surface layers: 0–5 cm: +14.8%; 5–10 cm: +14.4%; 10–15 cm: +12.5%. However, the slope position significantly influenced Ksat. Lower slopes consistently exhibited higher conductivity values due to depositional processes and greater organic matter accumulation, while upper slopes showed the lowest values, reflecting erosion and compaction. Statistical analysis confirmed that both treatment (fencing) and slope position had significant effects on Ksat, whereas depth effects were less pronounced beyond 15 cm. The increase in Ksat under fencing reflects the restoration of soil structure through reduced trampling, enhanced root proliferation, and organic matter accumulation. These factors promote the formation and stability of macro-pores, which facilitate water transmission. Higher conductivity in lower slopes highlights the role of depositional environments in improving infiltration capacity. Conversely, upper slopes remain vulnerable to compaction and reduced pore continuity, limiting hydraulic conductivity. Improvements in Ksat were strongest in the upper 0–15 cm, where grazing pressure had previously collapsed macro-pores. At deeper layers, differences between treatments narrowed, suggesting that fencing primarily benefits surface horizons. Enhanced Ksat under fencing translates into better infiltration, reduced runoff, and improved soil moisture regimes. This is critical for erosion control and vegetation recovery in fragile Shivalik foothills. The observed 13–15% increase aligns with findings from semi-arid rangelands, where exclusion of grazing similarly improved infiltration and hydraulic conductivity. This underscores fencing as a practical intervention for soil rehabilitation in degraded landscapes.

Aggregate size distribution (water stable aggregates)

The mean weight diameter (MWD) varied from 0.40 to 0.75 mm in fenced and 0.41 to 0.62 mm in without fencing treatments, respectively (Table 5; Fig. 1). Fencing significantly improved the MWD from 0.45 mm (Unfenced) to 0.82 mm (Fenced). The accumulation of organic matter in the protected

Table 5. Effect of fencing and slope position on depth distribution of aggregate size distribution (MWD) of soils

Depth (cm)	Transect			
	Upper slope	Middle slope	Lower slope	Mean
	MWD (mm)			
		Fenced		
0-5	0.62	0.62	0.72	0.65
5-10	0.57	0.60	0.75	0.64
10-15	0.47	0.53	0.57	0.52
15-30	0.40	0.42	0.51	0.44
Mean	0.51	0.54	0.63	
		Without fencing		
0-5	0.60	0.62	0.61	0.61
5-10	0.56	0.59	0.62	0.59
10-15	0.47	0.51	0.52	0.50
15-30	0.41	0.41	0.41	0.41
Mean	0.51	0.53	0.54	

Attributes	**F. Cal**	**L.S.D. (0.05)**
TR(Treatment)	24.66**	0.014
DP (Depth)	179.78**	0.02
TS (slope position)	39.05**	0.018
TR × DP	NS	
TR × TS	17.47**	
TR × DP × TS	NS	
CV (%)	17.62	
SD	0.09	

plots enhanced the binding of soil particles. The MWD were affected significantly by treatments, slope and depth. Whereas, only the interaction of treatment x slope was significant on MWD. The overall increase in MWD by 5.6 per cent was observed in fenced treatment compared to without fencing treatment. With increase in depth, 6.5, 8.4, 4.0 and 7.3 per cent increase in MWD 0-5, 5-10, 10-15 and 15-30 cm soil depths, respectively was observed in case of fenced over without fencing treatments. Stability tends to be higher in upper layers and decreases with depth. Upper slopes exhibit greater aggregate stability, especially at deeper layers. However, significant, differences, especially between upper and lower slope. Higher stability in upper slopes suggests better soil structure and resistance to erosion. The increase in size of aggregates in fenced treatment may be due to cementing action displayed by organo-clay complexes and higher content of organic matter contributed by dense vegetation than that in without fencing. However, the higher proportion of sand, which is more erodible, may be one of factors responsible to poor aggregation in without fencing treatment (Kolarkar *et al.,* 1974). The capacity of a soil to protect and accumulate soil organic matter (SOM) in organo-mineral particles is not always positively related to the clay and silt content per se but rather to the degree to which this capacity level is filled (Hassink and Whitemore 1997). Once the clay plus silt is saturated with organic matter, additional SOM would be found in macro aggregates (Franzluebbers and Arshad 1996), probably as sand sized macro-organic matter.

Penetration resistance

The penetration resistance of the soils varied from 6.15 to 29.95 kg cm^{-2} and 10.3 to 30.95 kg cm^{-2} in fenced and without fencing treatments, respectively (Table 6; Fig. 1). The treatment, depth and slope significantly affected the penetration resistance of soil. Significant interactions of treatment × depth, treatment × slope and treatment × depth × slope were observed. The resistance to penetration values decreased by 32.9, 24.8 and 19.7 per cent in 0-5, 5-10 and 10-15 cm of soil depths, respectively in fenced as compared to without fencing treatment. The overall decrease in penetration resistance value was observed to be 24.2 per cent in the fenced treatment. The higher penetration resistance in case of without fencing condition may be due to compaction of surface soil layers by human and livestock interferences followed by, less vegetation and low microbial activities in surface soil layers.

Table 6. Effect of fencing and slope position on depth distribution of penetration resistance of soils

Depth (cm)	Position			
	Upper slope	Middle slope	Lower slope	Mean
	kg cm^{-2}			
	Fenced			
0-5	9.10	6.80	6.15	7.35
5-10	17.85	9.75	9.35	12.31
10-15	29.95	17.70	22.75	23.46
Mean	18.9	11.4	12.7	
	Without fencing			
0-5	11.80	10.30	10.80	10.96
5-10	18.50	14.45	16.20	16.38
10-15	30.95	27.80	29.00	29.25
Mean	20.4	17.5	18.6	

Attributes	F. Cal	L.S.D.(0.05)		
TR (Treatment)	: 315.06**	0.54	CV(%)	: 49.07
DP (Depth)	: 1535.95**	0.66	SD	: 8.18
TS (Slope position)	: 140.50**	0.66		
TR × DP	: 6.07**			
TR × TS	: 37.28**			
TR × DP × TS	: 12.44**			

Infiltration Characteristics

The cumulative infiltration was highest in the Fenced + Lower Slope treatment (Thapa, 2003). The final steady infiltration rate was observed to be: I (fenced) > I (unfenced). Specifically, the infiltration rate in fenced at lower slopes was 2.4 (cm hr^{-1}), whereas it was only 0.8 (cm hr^{-1}) in the unfenced at upper slopes. The compaction in unfenced areas reduced the continuity of macro-pores, thereby restricting water entry.

General Discussion

Fencing and Soil physical characteristics

The "Unfenced Struggle," where physical hardness is the primary bottleneck (Fig. 1: Without Fencing). The vector for penetration resistance and likely bulk density will be very prominent and dominant. It pointed in the opposite direction (negative correlation) to vectors for porosity and hydraulic conductivity. However, the data shows that penetration resistance is the "absolute gatekeeper" in this system (r = -0.91 to -0.99). This plot shows a system defined by compaction, where,

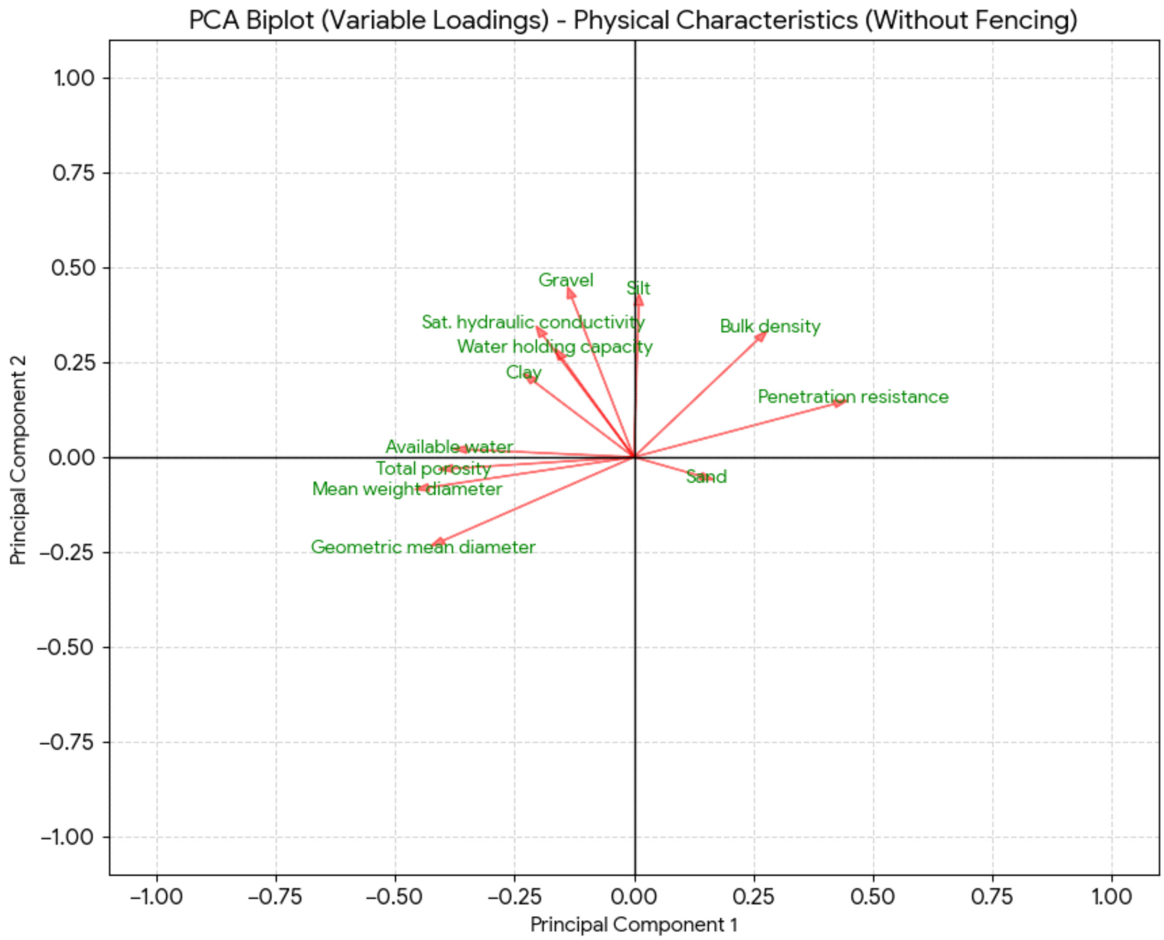

Fig. 2. PCA Biplot (variable loadings) –Physical characteristics (Without fencing)

the hard physical state of the soil physically prevents root growth and water infiltration, regardless of nutrient status. (Fig.2;Without-fencing). However, the restoration of soil structure is referred to The "House". The vectors for total porosity and saturated Hydraulic conductivity will be long and positively correlated (pointing together). The influence of penetration resistance will be significantly diminished (shorter vector or less opposed to productivity). This shift corresponds to the finding that porosity increased by 14.2% and conductivity by 13.7%. The bi-plot confirms that the soil has transitioned from a "suffocated" state to an "aerated" state, allowing the "house" to support deep root growth and water storage (Fig. 3; Fenced). However, in unfenced areas, animal trampling

Table 7. Summary of impact of fencing on soil physical structure parameters and land productivity

Parameter	Change (Fenced vs. Unfenced)	Impact on land productivity
Penetration Resistance	-24.2%	Primary Success Factor: Softer soil allows roots to grow deeper and stabilize the ground.
Gravel Content	-53.1%	Erosion Control: Fencing keeps fine, fertile soil from washing away, leaving less rocky debris.
Total Porosity	+14.2%	Better Breathing: More air pockets in the soil prevent "suffocation" of plant roots.
Hydraulic Conductivity	+13.7%	Water Management: Rain soaks into the ground instead of running off and causing floods.

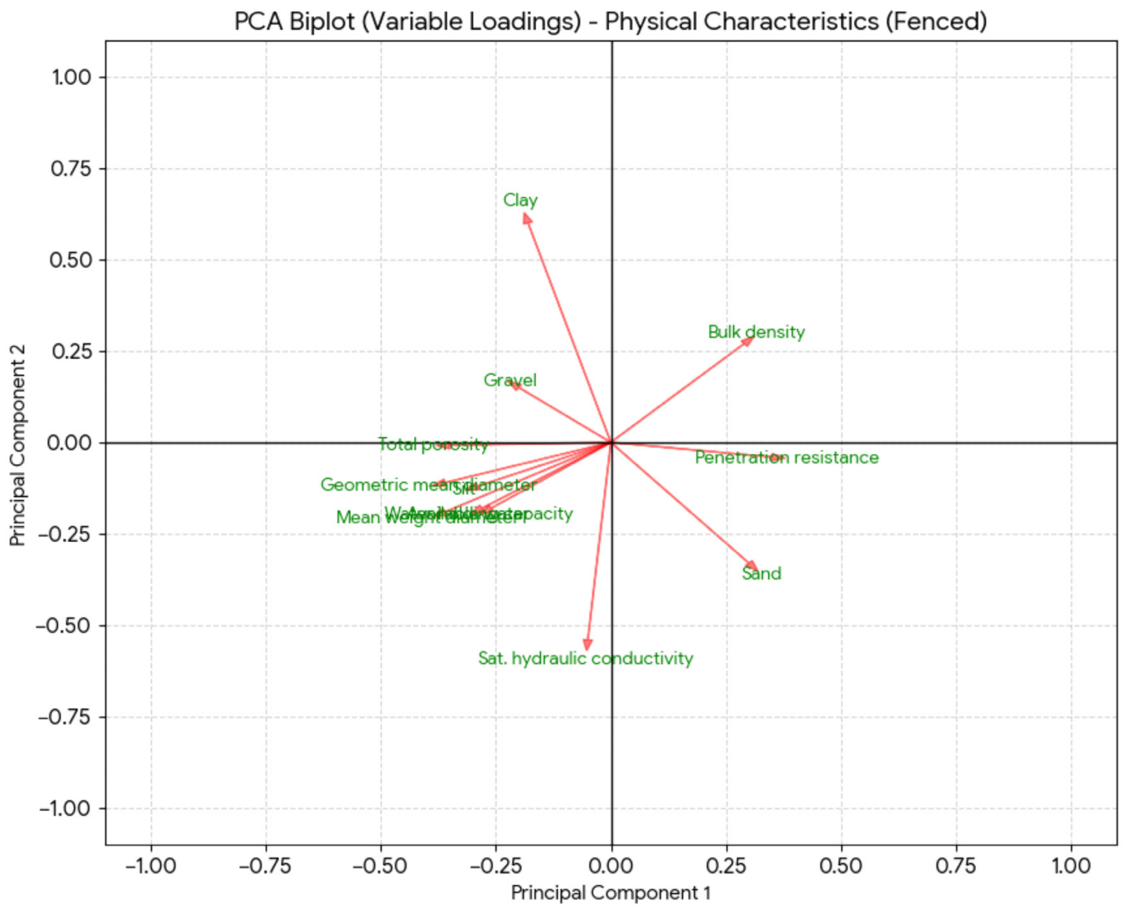

Fig. 3. PCA Biplot (variable loadings) –Physical characteristics (Fenced)

causes soil compaction, which squeezes out air and water. Fencing reverses this degradation. In unfenced areas, animal trampling creates a "compacted layer". This mechanical pressure forces soil particles together, collapsing the macrospores necessary for air.

CONCLUSION

This study demonstrates that soil physical degradation in the Shivalik foothills is strongly influenced by fencing (TR), slope position (TS), and soil depth (DP). Fencing significantly improved soil structure by reducing bulk density (–10%), increasing porosity (+14.2%), enhancing aggregate stability (+14.2%), and lowering penetration resistance (–24.2%). These improvements were most pronounced in the surface layers (0–10 cm, DP), where compaction from grazing had previously restricted infiltration and root growth. Slope position played a critical role: lower slopes (TS) exhibited naturally better physical properties due to depositional processes, and when combined with fencing, they showed the highest infiltration rates and moisture storage. Conversely, upper slopes (TS) remained the most degraded, highlighting the urgent need for protective measures in these areas. However, fencing reversed compaction, slope position moderated baseline conditions, and depth controlled magnitude of improvement. However, slope position matters such as upper slopes generally show better soil health indicators (lower bulk density, higher porosity and stability). The Soil properties degrade with depth, emphasizing the importance of topsoil management. However, conservation practices should focus on lower slopes and deeper layers to mitigate compaction and erosion.

Soil recovery was most effective in fenced lower slopes at shallow depths. The interaction of fencing, slope position, and depth produced synergistic benefits, particularly in fenced lower slopes at shallow depths, where soil recovery was most evident. These findings confirm that mechanical protection through fencing, coupled with slope specific and depth sensitive management strategies, is essential for rehabilitating degraded soils in submontane Punjab.

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