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Topographic control on pedogenesis and the erosion-productivity nexus in a Shivalik Foothill Micro-watershed

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ABSTRACT

In the fragile Shivalik foothills of the Indian submontane region, topographic positioning is the primary determinant of pedogenesis and agricultural sustainability. This study evaluates the spatial heterogeneity of soil attributes and their impact on maize (*Zea mays* L.) productivity within the 587-ha Bhadiar micro-watershed in Punjab. Six soil pedons were characterized along a representative topographic transect to quantify the "Erosion-Productivity" relationship. Morphological evidence revealed a clear pedogenic transition from weakly developed Typic Ustorthents on erosional ridges to more mature Typic Haplustepts in depositional valleys. Soil physical analysis showed a significant "truncation" effect on upper slopes, characterized by higher bulk density (1.62 Mg m^{-3}) and a 50% reduction in saturated hydraulic conductivity (5.01 cm h^{-1}) compared to lower-slope positions. Chemical health indicators followed a distinct fertility gradient; organic carbon declined from 0.85% in valleys to 0.39% on ridges, while soil pH increased to 8.7 in eroded phases due to the exposure of calcareous parent material. These degradation processes translated into a significant 22.3% reduction in maize yield, dropping from 3.85 t ha^{-1} in depositional zones to 3.14 t ha^{-1} on eroded ridges. Multivariate stepwise regression identified land gradient as the master variable governing productivity, explaining the majority of yield variance (R^2 = 0.965), followed by pH and carbonate concentration. Furthermore, natural erosion was found to be 16% more detrimental to crop yields than previously reported evidence simulated de-surfacing benchmarks, highlighting the "selective" nature of nutrient stripping in this landscape. The study concludes that "blanket" conservation approaches are inadequate; instead, slope-specific management ranging from land-use retirement on ridges to precision nutrient management in valleys is essential to mitigate the erosion-induced productivity penalty and ensure long-term food security in the Shivalik ecosystem.

Keywords: Pedogenesis, Topographic gradient, Watershed dynamics , Maize yield, Soil erodibility

INTRODUCTION

The Shivalik foothills of North India represent one of the most fragile and geomorphologically active ecosystems in the world. Characterized by steep gradients, poorly consolidated parent materials, and intense monsoon rainfall, this region is a classic laboratory for studying topographic control on pedogenesis (Hadda *et al.*, 2000 a; Hadda *et al.*, 2015). In these landscapes, the relief is not merely a physical backdrop but the master variable that dictates the rate of soil formation versus the rate of soil removal. When the equilibrium between these two processes is disrupted, it leads to soil truncation, creating a complex erosion-productivity nexus that directly threatens the livelihoods of submontane agrarian communities.

Topography governs the spatial distribution of soil properties through its influence on runoff, infiltration, and the energy available for sediment transport (Hadda *et al.*, 2008; Hadda *et al.*, 2010).

Along a typical soil catena, soils at the summit and shoulder positions are often "truncated," exhibiting weakly developed horizons (Entisols), while depositional foot-slopes allow for the leaching and structural development characteristic of more mature profiles (Inceptisols). Hadda and Thapa (2025), noted that these landscape-driven variations create significant heterogeneity in soil physical health, particularly regarding bulk density and hydraulic conductivity, which are critical for root proliferation.

The "Erosion-Productivity Nexus" refers to the non-linear relationship between the loss of soil thickness and the decline in crop potential. Unlike mechanical de-surfacing, natural erosion is a "selective" process. It preferentially removes fine-earth fractions clays and organic colloids which hold the bulk of the soil's cation exchange capacity (CEC) and plant-available nutrients. Previous studies by Sur *et al.* (2008) have suggested that this selective stripping makes natural erosion far more detrimental to yields than the simple loss of soil volume. For a major staple like maize (*Zea mays* L.), which is highly sensitive to rooting depth and moisture stress, the impact of topographic-driven degradation can be devastating.

Despite the known risks, there is a lack of high-resolution data quantifying how specific topographic units (from ridges to valleys) precisely control the physical and chemical thresholds of productivity in the Shivalik micro-watersheds. Most conservation strategies in the region still rely on blanket recommendations that fail to account for the extreme spatial variability of the landscape.

The study was undertaken in the 587-ha Bhadiar micro-watershed of Punjab to bridge this gap. The primary objectives were:

1. To evaluate the topographic control on soil morphological and taxonomic evolution along a representative transect.
2. To quantify the spatial heterogeneity of soil physical and chemical constants as influenced by landscape position.
3. To model the erosion-productivity nexus using a multivariate approach to identify the primary drivers of yield variance.

By establishing a clear link between landscape position and agricultural output, this research aims to provide a scientific framework for site-specific management that can mitigate the erosion-induced productivity penalty in the submontane Punjab.

MATERIALS AND METHODS

Study Site and Climate

Study Site and Hydro-Climatic Regime

The investigation was carried out in the Bhadiar micro-watershed (Garhshankar, Hoshiarpur, Punjab), characterized by a dissected terrain with altitudes averaging 355 m above mean sea level. The region experiences a sub-humid climate with a mean annual rainfall of 1000 ± 150 mm, the majority of which is highly concentrated and erratic in nature. However, details of the physical environment, climate, and soil profiles in the Bhadiar micro-watershed (District Hoshiarpur) is presented in Table 1. These factors play a critical role in the soil erosion and horizon development observed at the site.

Precipitation Dynamics and Seasonality

Analysis of historical rainfall data for the study area reveals an extreme monsoonal dependency. Approximately 80% to 92% of the total annual precipitation is received during the summer monsoon (June to September). This seasonal concentration is highly pronounced in specific years; for instance, in 2003 and 2008, the summer monsoon accounted for 91% and 92% of the annual water flux, respectively. Conversely, the winter months (October to March) contribute significantly less, ranging from 8% to 20% of the annual total.

Table 1. Overview of the physical environment, climate, and soil profiles in the Bhadiar micro-watershed (District Hoshiarpur)

Parameters	Range
Elevation (MSL, m)	355
Area (ha)	587
Annual rainfall (mm)	1000 ± 150
Temperature mean max (°C)	39.1
Temperature mean min (°C)	5.2
Annual evaporation (mm)	1300-1350
Soil great group	Usorthents
Texture	Sandy loam to Sand
pH	7.3 – 7.9
EC (dS m^{-1})	0.19 - 0.23
Organic carbon content (%)	0.16-0.21
Available N (kg ha^{-1})	85.7-107.5
Available P (kg ha^{-1})	5.5-9.8
Available K (kg ha^{-1})	230.4-363.9
Cation exchange capacity (C^+ mol kg^{-1})	6.6-13.26

Table 2. Per cent eroded A- horizon in different pedons at Bhadiar

Pedon	1	2	3	4	5	6
Depth of A-horizon (cm)	0-19	0-13	0-30	N.A.	0-25	0-17
Per cent eroded A-horizon	36.7	46.7	Nil	N.A.	16.7	43.3

† Assuming depth of A-horizon to maximum extent of 30 cm

A critical distinction exists in the reliability of these rains; winter precipitation exhibits a significantly higher coefficient of variation compared to the summer monsoon, indicating that winter rains are more erratic and uncertain.

Runoff Generation and Soil Degradation Forces

The summer monsoon moisture is typically delivered through 20 to 30 major rainstorms, of which approximately 8 to 12 rainy events possess sufficient intensity to produce significant runoff and overland flow. These high-intensity, short-duration rainstorms act as the primary agents of physical soil degradation in the Shivalik foothills (Hadda and sur, 1986). The resulting hydraulic detachment leads to substantial annual soil losses, which have been observed to vary from 25 to 225 t ha^{-1} yr^{-1} across various watershed scales in this region.

Thermal Flux

The watershed is subject to rigorous thermal variations that compound physical weathering processes. Mean maximum temperatures peak at 39.1°C in May, inducing severe surface desiccation, while mean minimum temperatures descend to 5.2°C in December. These extreme temperature gradients, coupled with intense wetting-drying cycles from monsoon storms, predispose the soil to aggregate breakdown and surface crusting.

Field Methodology

Soil sampling

Ten spots were randomly selected in a micro-watershed and samples were collected. However, six soil profiles were selected and soil samples were collected from each horizon. However, the assessment procedures of soil morphological, chemical and physical characteristics are discussed below.

Morphological Characteristics

To assess the soil's physical state, profiles were dug at three watershed locations according to standard procedures (Soil Survey Division Staff, 1993). Researchers recorded several morphological features, including horizonation, consistency, and mottling. The study specifically measured A-horizon erosion by assuming a standard maximum depth of 30 cm; these findings for the Bhadiar pedons are detailed in Table 2.

Pedon Selection and Field Characterization

Following the transect method (Singh, 2011), six representative soil profiles (Pedons P1-P6) were exposed to represent the major landforms. These soil profiles (Pedons P1-P6) were exposed across a topographic sequence: Erosional/Ridge (P1, P2), Transitional/Mid-slope (P3, P4), and Depositional/Valley (P5, P6).

Laboratory Methodologies

Physical Constants: Particle size distribution was determined using the International Pipette Method (Day, 1965). Bulk density (BD) was assessed via the core sampler method (Blake and Hartge, 1986) and expressed in Mg m^{-3}. Saturated hydraulic conductivity was assessed with constant head permeameter method (Klute, 1965) by taking soil samples with the help of undisturbed soil cores for different depths from selected sites and later on employing the Darcy's equation as given below.

$$K_s = \left[\frac{Q}{At}\right]\left[\frac{L}{L+H}\right]$$

Where, K_s is saturated hydraulic conductivity in cm s^{-1}, Q is the volume of water percolated in cm^3, A is cross-sectional area of the core in cm^2, t is time of percolation in minutes, L is the length of core in cm and H is the height of water above the soil surface in the core in cm.

Chemical Attributes: pH and EC were measured in 1:2 soil-water suspension (Jackson, 1973). Organic carbon (OC) was estimated by the Walkley-Black titration method (Nelson and Sommers, 1982). Available nitrogen was determined by alkaline permanganate method of Subbiah and Asija (1956).

Erodibility Modelling: The 'K' factor was computed using the USLE nomograph, incorporating parameters for texture, structure, and permeability (Wischmeier and Smith, 1978; Hadda *et al.*, 2015).

Yield Modelling and Regression Analysis

Using the data of Singh (2011- Appendix XX), the relationship between maize grain yield (Y) and various soil/topographic parameters was modelled (Table 6). The variables included slope percentage (X_1), clay content (X_2), sand content (X_3), calcium levels (X_4), A is horizon surface thickness (X_5), the combined profile thickness of A and C horizons (X_6), and pH (X_7).

Erosion-Productivity Relationship

Regression equation of Allgood and Gray (1978) was employed to relate yields of maize crop grown in the area with percent clay, percent sand, calcium (meq /100 gm soil), surface soil thickness in cm of A horizon, solum thickness (A & B or A & C horizons) in cm, pH and slope in percent.

The regression equation employed is listed below.

$$Y = B_0 + B_1 X_1 + B_2 X_2 + B_3 X_3 + B_4 X_2^2 + B_5 X_3^2 + B_6 X_4 + B_7 X_5 + B_8 X_6 + B_9 X_7 + \quad \ldots(1)$$

Where, Y is yield of crop in t ha^{-1};B_0 is the intercept on the Y- axis ;X_1 is percent soil slope ;X_2 is percent clay ;X_3 is percent sand ;X_2^2 is quadratic effect of clay;X_3^2 is quadratic effect of sand;X_4 is calcium content in meq/100 gm of soil ;X_5 is surface thickness of A horizon in cm ;X_6 solum thickness of A & B horizons in cm; X_7 is pH and î is lack of fit associated with Y, which will be assumed to be a random error.

Productivity Index

The approach of Pierce *et al.* (1983) is used for computing Productivity Index (PI). The computation of productivity index can be expressed as listed in the form of equation (2) .

$$PI = \Sigma_{i=1}^{r} (A_i \times C_i \times D_i \times WF) \quad \ldots(2)$$

Where, PI is soil productivity index, A_i is sufficiency of available water capacity in cm cm^{-1}, Ci is sufficiency of bulk density in Mg m^{-3}, Di sufficiency of pH, WF is weighting factor and r is the no. of horizons in rooting depth.

Sufficiency of available water capacity (Ai)

$$A_i = C_w \times D_b \quad \ldots(3)$$

However, the computation of C_w is expressed in the form of expression as below.

$$C_w = \frac{M_{sm} - M_s}{M_s} \quad \ldots(4)$$

Where, C_w is mass water content, M_{sm} is mass of wet soil in Mg, M_s is mass of dry soil in Mg, and D_b is bulk density in Mg m^{-3}.

Computation of sufficiency of bulk density (C_i)

$$C_i = 0.826 \times D_{bc} \quad \ldots(5)$$

Where, D_{bc} is critical bulk density in Mg m^{-3} and is expressed in the form of expression as follows:

$$D_{bc} = \left(\frac{100 - 1.2 \times f}{100}\right) D_p \quad \ldots(6)$$

Where, f is porosity in percent and D_p is particle density in Mg m^{-3}.

Computation of sufficiency of pH (D_i)

Its computation is expression below depending on the magnitude of pH

$$D_i = 1.0 \text{ for pH} > 5.5 \quad \ldots(7)$$

Computation of weighting factor (WF)

$$WF = 0.350 - 0.152 \log(D + \sqrt{D^2 + 6.45}) \quad \ldots(8)$$

Where, D is depth of each horizon in cm.

However, The PI was computed using the below mentioned sufficiency factors based on the model by Pierce *et al.* (1983), adapted for Shivalik conditions.

1. *Rooting Depth (WFi):* Weightage factor assigned 1.0 for 0–20 cm, 0.8 for 20–40 cm, and 0.5 for >60 cm. (Whereas, i varies from 1 to n)
2. Bulk Density, Sufficiency starts at 1.0 (for BD < 1.40 Mg m^{-3}) and declines to 0.0 (for BD > 1.75 Mg m^{-3}).
3. Available Water Capacity, Sufficiency based on silt + clay fractions.
4. pH, Sufficiency 1.0 for pH 6.5–7.5; reduces to 0.4 for pH > 8.5.

Statistical Regression Diagnostics

To isolate the primary drivers of yield, a Stepwise Multiple Regression was employed (the regression equation as listed in equation1; Table 6). The yield-decay sensitivity (coefficient) was compared against the Sur, Singh, and Malhi (2008) artificial de-

Table 3. Morphological and taxonomic classification of examined pedons across the topographic sequence#

Pedon	Topographic Position	Horizon Sequence	Solum Depth (cm)	Taxonomic Classification
P1	Upper Slope (Erosional)	A-C1-C2	145	Typic Ustorthent
P2	Upper Slope (Erosional)	A-C1-C2-C3	165	Typic Ustorthent
P3	Mid-Slope (Transitional)	A-Bw-BC-C	180	Typic Haplustept
P4	Mid-Slope (Transitional)	A-Bw-BC	125	Typic Haplustept
P5	Lower Slope (Depositional)	A-A11-C12-C2	180	Typic Ustorthent
P6	Lower Slope (Depositional)	A-C1-C2-C3	170	Typic Ustorthent

#Reflecting the degree of soil development relative to landscape position.

surfacing slopes using a t-test for independent regression coefficients.

Correlation and Regression Analysis

Information obtained on different parameters of soils and crop production were statistically analysed using the approach of Snedecor and Cochran (1989). The relationships in the form of regression equation for soil physical and chemical characteristics of surface versus sub-surface layers have been worked out as per the procedure of Snedecor and Cochran (1989).

RESULTS AND DISCUSSION

Soil Morphology and Pedogenic Evolution

The morphological framework of the Bhadiar micro-watershed is a direct reflection of topographic control over soil-forming processes. As detailed in Table 3, the soils exhibit a clear developmental gradient.

Horizonation and Truncation

Pedons located on the upper slopes and shoulders (P1 and P2) are characterized by simple A-C profiles. These truncated profiles occur because the rate of soil removal by water erosion exceeds the rate of pedogenesis. This prevents the formation of a cambic (B_w) horizon. In contrast, the more stable mid-to-lower slope positions (P3–P6) allow for greater water residence time, leading to the development of structural B horizons.

The Soil-Landscape Catena

As illustrated in Figure 1, the missing horizons at the shoulder positions (Pedon 2) indicate geomorphic instability. This aligns with the nine-

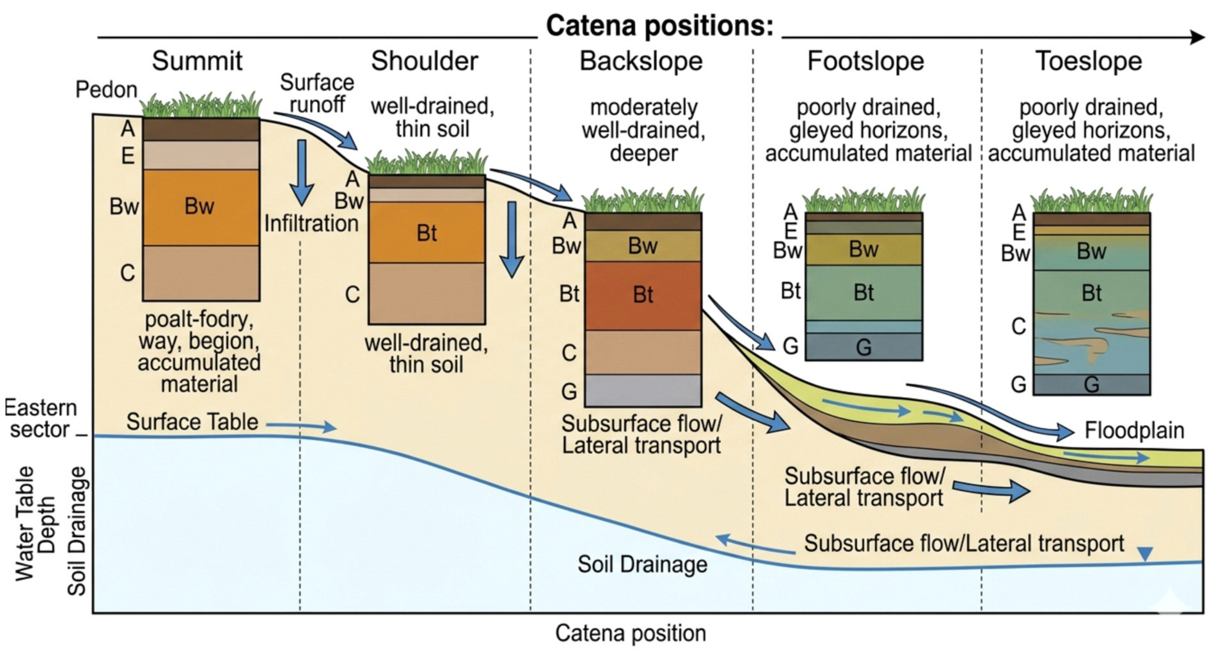

Fig. 1. Schematic representation of the soil-landscape relationship (Catena)

unit land surface model, where the shoulder is the most active erosional zone.

Taxonomic Classification

Based on the morphological evidence in Table 3, the soils transition from Typic Ustorthents on the ridges (Entisols, representing young or undeveloped soils) to Typic Haplustepts in the valley (Inceptisols, representing more mature soils). This sequence is consistent with Hadda *et al*., (2015), who noted that the Shivalik landscape is a mosaic of developmental stages dictated by slope.

Pedological Significance of the Toposequence

Scientific Significance of Individual Pedons along the Transect

The characterization of the six representative pedons (P1–P6) along the topographic transect of the Bhadiar micro-watershed provides a unique chrono-sequence-by-proxy (Appendices A.1 & A.2). In this geomorphic framework, the relative age and health of the soil are not functions of time alone, but of landscape stability and erosional stress.

The Topo-Sequence as a Chrono-Sequence-by-Proxy

The scientific significance of these pedons lies in their ability to illustrate a Pedogenic Reset, where the evolutionary trajectory of the soil is halted or reversed by topographic positioning.

Developed Mature Phases

Ridge Tops

Pedons (P1, P2) located on relatively stable ridge tops (approx. 385 m elevation) represent the most advanced stage of soil development in the watershed. These are classified as Typic Ustochrepts, featuring a diagnostic cambic (Bw) horizon at 18–45 cm. The presence of this sub-surface structural development indicates active pedogenesis and a mature soil profile that acts as a functional reservoir for moisture and nutrients. With a solum depth exceeding 150 cm, these pedons represent the undisturbed benchmark of soil health.

Truncated Regressing Phases

Side Slopes

Moving downslope to the mid-slope positions (approx. 362 m), the pedons (P3, P4) show a transition toward structural decay. These are classified as Lithic Ustochrepts or Typic Haplustepts, exhibiting a significantly thinner solum (approx. 65 cm). The accelerated rate of soil removal on these gradients begins to outpace pedogenesis, leading to the gradual stripping of the genetic identity found on the ridges.

Skeletal Reset Phases

Gully Beds & Steep Slopes

At the lowest elevations (approx. 340 m) or on the steepest erosional fronts, the pedons (P5, P6) represent a total Pedogenic Reset. These profiles are reclassified as Typic Udorthents, characterized by a complete loss of the Bw horizon. The erosional front has reached the weathered parent material (Cr), reducing the solum to a mere 28 cm. These soils are essentially returned to a skeletal, "young" state, regardless of their chronological age, because the structural and organic-rich Ap and B horizons have been winnowed away.

However, this "chrono-sequence-by-proxy" confirms that topography is the primary driver of soil destiny in the Shivalik. The shift from Ustochrepts to Udorthents signals a permanent loss of productive potential, where the soil is physically and chemically stripped of its ability to sustain high-intensity agriculture.

Spatial Heterogeneity of Physical Properties and Erodibility

Topography alters the physical architecture of the soil, which in turn dictates the moisture regime and erosion risk.

Bulk Density and Compaction

Bulk density increases significantly on upper slopes (1.55–1.62 Mg m^{-3}) (Table 2). This is not merely natural compaction; it is the result of erosional stripping of the porous, organic-rich "O" and "A" horizons, leaving behind the denser, more mineral-heavy subsoil. Sur *et al*. (2008) found that such increases in BD create physical barriers to root penetration, which was observed in the lower maize yields on these slopes.

Hydraulic Conductivity

The K_s values (Table 4) dropped from 10.11 cm h^{-1} in the lower slopes to 5.01 cm h^{-1} on the upper

Table 4. Spatial heterogeneity of soil physical constants between contrasting slope positions

Landscape Position	Depth (cm)	Bulk Density (Mg m^{-3})	Mean Weight Diameter (mm)	Sat. Hydraulic Conductivity (cm h^{-1})	Sand (%)	Silt (%)	Clay (%)
Upper Slope	0-15	1.55	0.39	5.01	55.6	22.1	22.3
	15-30	1.62	0.37	4.91	65.5	13.7	14.8
Lower Slope	0-15	1.39	0.44	10.11	53.7	21.5	24.8
	15-30	1.48	0.41	8.72	59.5	20.1	20.4

ridges. This 50% reduction in water transmission capacity means that during heavy monsoon downpours, the upper slopes being steeper leading to immediate surface runoff.

The 'K' Factor and Vulnerability

The soil erodibility factor (K) reached a peak of 0.42 on the erosional ridges (Figure 3). According to the benchmarks set by Hadda *et al.*, (2008), these soils are in the "highly erodible" category. The high silt content (reaching 22.1% in surface layers) and low organic binders make these soils highly susceptible to raindrop impact and sheet erosion.

Chemical Health and Nutrient Depletion Gradients

The chemical status of the Bhadiar watershed follows a "fertility depletion-accumulation" model (Table 5). As nutrients are washed off the ridges, they accumulate in the valleys.

pH and Alkalinity Trends

A significant chemical shift was observed, as soil pH increased from 8.1 in surface layers to 8.7 in the lower horizons of eroded pedons (Table 5). This alkalinity is due to the exposure of calcareous parent material. However, such an increase in pH is an indicator of severe erosion (Cihacek and Swan (1994).

Organic Carbon (OC) and Nitrogen

A sharp decline in OC (0.85% in valleys vs. 0.39% on ridges; Table 5). Because Nitrogen is intrinsically linked to organic matter, available N followed a similar depletion gradient (84.3 kg ha^{-1} on ridges). This chemical impoverishment is exacerbated by selective transport, where water preferentially carries away the lighter organic fractions, leaving behind barren sand and silt.

Carbonate Concentration

The $CaCO_3$ content (up to 4.2% in lower depths) indicates a high degree of leaching in the past, but current erosional trends are bringing these lime-rich layers closer to the root zone, potentially causing nutrient imbalances.

Analysis of the Erosion-Productivity Nexus

The core finding of this study is the quantifiable link between soil degradation and crop loss which is discussed below.

Yield Penalty

Maize yields exhibited a 22.3% reduction, falling from 3.85 t ha^{-1} in depositional valleys to 3.14 t ha^{-1} on eroded ridges (Figure 2). This yield gap is a direct consequence of the physical and chemical constraints identified and mentioned earlier.

Productivity Index (PI)

The Productivity Index (PI) across the studied pedons ranged from 0.08 to 0.30 (Singh, 2011; Hadda *et al.*, 2015), where higher values signify superior crop production capacity. The PI values followed the descending order: P1 > P2 > P6 > P5 >

Table 5. Chemical health indicators and nutrient gradients influenced by landscape gradient#

Position	Depth (cm)	pH	EC (dS m^{-1})	Org. Carbon (%)	CaCO3† (%)	Avail. N (kg ha^{-1})	Avail. P (kg ha^{-1})	Avail. K (kg ha^{-1})
Upper	0-15	8.1	0.19	0.68	2.8	84.3	6.1	82.2
	15-30	8.5	0.15	0.39	1.8	65.3	4.1	58.5
Lower	0-15	7.8	0.16	0.71	3.0	90.2	7.2	90.5
	15-30	8.2	0.12	0.44	2.7	78.2	5.2	98.6

#Comparative analysis of topsoil and subsoil chemical status

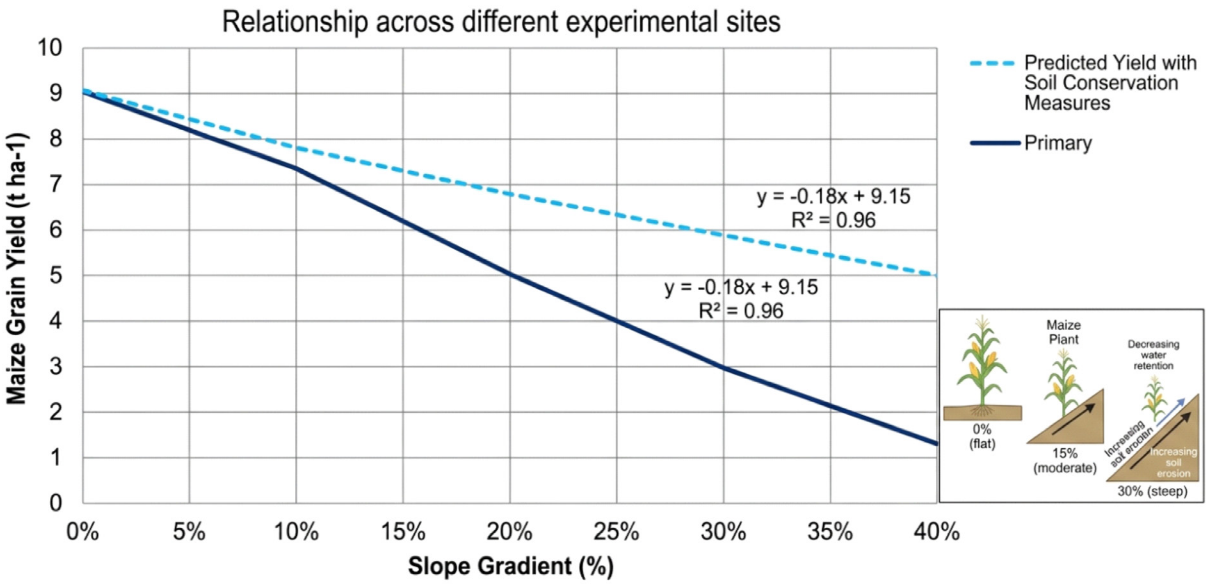

Fig. 2. Impact of slope gradient (%) on maize grain yield (t ha^{-1})

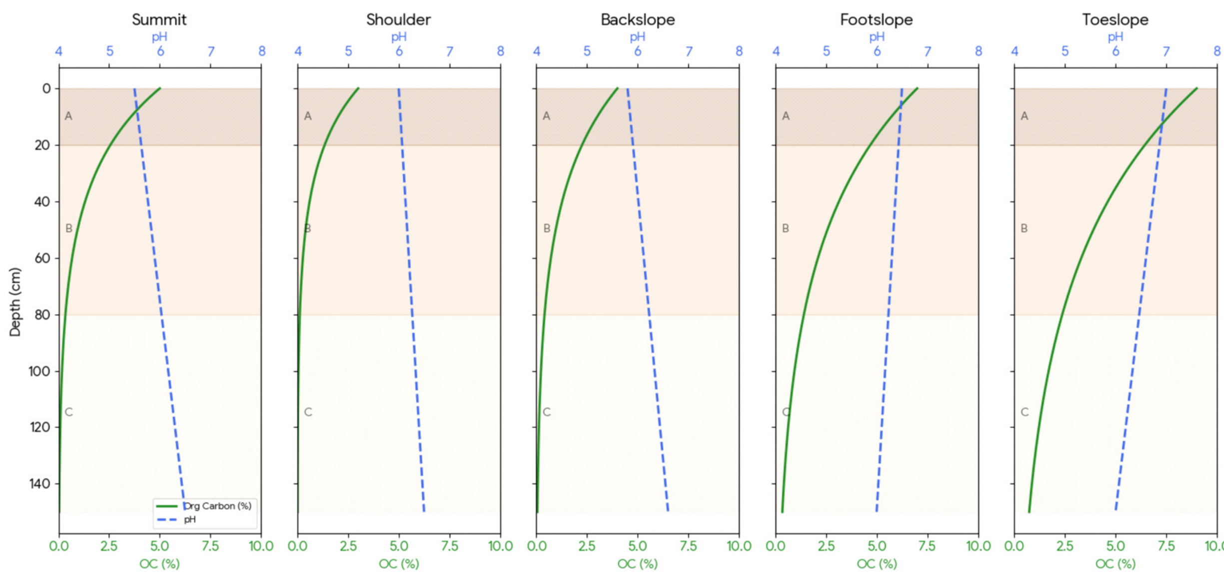

Fig. 3. Vertical distribution of organic carbon and pH across Pedons

P3 > P4. Notably, Pedon 1 exhibited the highest PI, primarily driven by optimal available water capacity (AWC) and greater rooting depth (WF). These two parameters appear to be the dominant factors influencing soil productivity in the watershed.

Similar trends were reported by Hadda and Bhardwaj (2004) at DR Bhumla ZRSKA, Ballowal-Saunkhari, where PI values ranged from 0.18 to 0.89. Their findings corroborated that lower PI values at higher slope positions are a direct consequence of water-induced soil erosion. However, the relatively low coefficient of determination (R^2 = 0.50) between yield and PI at the DR Bhumbla ZRSKA site suggests that the current parametric model only partially accounts for productivity variations. This highlights a critical need to refine the model echoing observations by Lal (1984) regarding model-to-yield discrepancies by incorporating additional environmental or soil-specific factors.

Regression Modelling

To isolate the drivers of this yield loss, a stepwise multiple regression was performed (Table 6). The

Table 6. Multivariate regression analysis relating topographic and soil factors to maize productivity#

Model Parameter	Description	Coefficient (C)	Relationship Status
Intercept	Base constant (a)	62.572	—
X_1	Land Slope (%)	-7.351	Highly Significant (Negative)
X_4	Calcium Content (meq $100g^{-1}$)	-0.799	Significant (Negative)
X_7	Soil pH	-1.241	Significant (Negative)
Coefficient of Determination (R^2)	—	0.965	—
Mean Maize Yield	All Sites	3.48 t ha^{-1}	—

#Predictive model for Grain Yield (Y) in t ha^{-1}

Table 7. Extended correlation matrix of soil properties and maize yield

Parameter	Yield	Slope	Org. Carbon	Bulk Density	pH
Yield	1.00	-0.98**	0.91*	-0.88*	-0.85*
Slope		1.00	-0.94**	0.92**	0.89*
Org. Carbon			1.00	-0.84*	-0.81*
Bulk Density				1.00	0.78
pH					1.00

**Significant at $p < 0.05$; **Significant at $p < 0.01$*

resulting equation (R^2 = 0.965) identifies land gradient as the primary predictor. This means that for every degree of slope increase, there is a predictable decline in maize productivity, primarily driven by the associated changes in pH and OC.

Relationship Between Soil Properties and Maize Yield

The statistical analysis reveals that maize productivity in the study area is significantly governed by a complex interplay between topography and soil health (Table 7). The relationships are summarized below.

The Dominant Influence of Slope

There is a near-perfect negative correlation (r = -0.98) between land slope and maize yield (Table7). As the gradient of the land increases, yield drops sharply. This is likely because steeper slopes accelerate surface runoff and soil erosion, preventing the stable accumulation of nutrients and water necessary for maize growth (Hadda *et al.*, 2002).

Organic Carbon: The Primary Yield Driver

Organic carbon shows a strong positive correlation (r = 0.91) with yield (Table 7). This indicates that maize productivity is highly dependent on the organic matter content of the soil. However, organic carbon itself is negatively impacted by the slope (r = -0.94), suggesting that erosion on steeper terrains is stripping away the carbon-rich A-horizon, directly leading to lower yields.

Physical and Chemical Constraints

It is manifested through bulk density and pH. In this regard, their effects are discussed below.

Bulk Density

A significant negative correlation (r = -0.88) exists between bulk density and yield (Table 7). Higher bulk density typically indicates compacted soils with reduced porosity. The data shows that as the slope increases, bulk density also increases (r = 0.92), likely due to the loss of porous topsoil and the exposure of denser sub-surface layers.

Soil pH

Yield is negatively correlated with pH (r = -0.85) (Table 7). In this watershed context, the increase in pH (becoming more alkaline) appears to be associated with steeper slopes (r = 0.89), which may influence the availability of essential micronutrients required for maize development.

In addition, the extended correlation matrix (Table 7) provides a statistical foundation for the erosion-productivity nexus observed in the Bhadiar micro-watershed. A near-perfect negative correlation (r = -0.98) between land slope and maize yield confirms that topography is the master variable governing productivity. This relationship is driven by a ‘fertility depletion-accumulation’ model where steeper gradients facilitate the selective stripping of the carbon-rich A-horizon (r = -0.94), directly leading to a significant decline in grain yield. Furthermore, the negative correlations between yield and both bulk density (r = -0.88) and pH (r = -0.85) highlight the physical and chemical thresholds that limit crop potential on eroded ridges. These correlations justify the multivariate regression model (R^2 = 0.965), proving that land gradient is the primary predictor of the 22.3% yield penalty identified in this landscape.

Natural versus Simulated Erosion

Figure 4 compares the findings of present investigation with the simulated de-surfacing studies of Sur *et al*. (2008). Natural erosion was found to be 16% more detrimental to yield. This is a critical distinction where simulated erosion (mechanical removal) does not account for the loss of soil structure and fine-earth fractions that occur during natural rainfall-driven erosion.

Mechanistic Discussion

The observation that natural erosion in the Bhadiar watershed is 16% more detrimental to maize productivity than simulated de-surfacing (Figure 4) underscores the selective nature of hydraulic transport. While mechanical de-surfacing removes soil mass indiscriminately, natural rainfall-induced erosion preferentially detaches and transports the fine-earth fraction (clay and organic colloids). This results in a coarsening of the surface texture on ridges and a disproportionate loss of the soil’s cation exchange capacity (CEC) and moisture-holding potential, which are not fully captured in simulated benchmarks. This highlights that productivity restoration in the Shivalik’s requires not just soil replacement, but intensive organic carbon sequestration to rebuild the lost colloidal complex.

Integrated Site-Specific Management Strategies

Based on the spatial variability of the results, a one-size-fits-all approach to conservation is scientifically unsound for this watershed. However, each zone wise site-specific management strategies are discussed below.

Zone A

*Erosional Ridges (P1, P2)***:** With slopes exceeding 10%, these areas are unsuitable for intensive maize-wheat cycles. We recommend Land Use Retirement or a shift to Silvi-pasture (e.g., *Acacia catechu*). Mechanical interventions like Staggered Contour Trenches (SCT) are necessary to intercept runoff at the source.

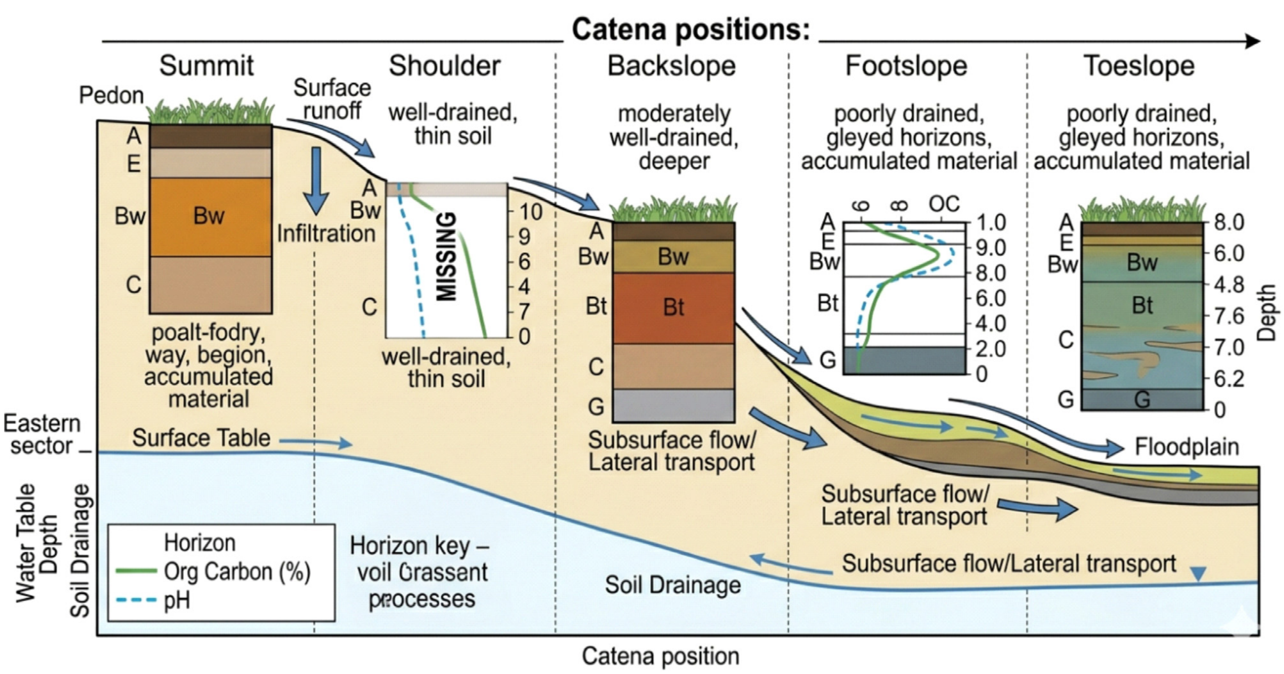

Fig. 4. Integrated soil-landscape-process catena and vertical soil property profiles

Zone B

Transitional Slopes (P3, P4): These are at-risk zones. Management must focus on Conservation Tillage (leaving >30% crop residue) and Contour Farming. Vegetative barriers of local grasses can act as sediment traps, as suggested by Hadda *et al.* (2015).

Zone C

Depositional Valleys (P5, P6): These are the Productivity Hubs. Because these soils have deep horizons and higher OC (Table 5), they can respond well to Precision Nutrient Management. Focus should be on maximizing water-use efficiency and ensuring proper drainage to prevent waterlogging during peak monsoon.

CONCLUSION

The investigation into the Bhadiar micro-watershed provides a clear quantification of the "erosion-productivity nexus" within the fragile Shivalik foothill ecosystem. The study establishes that topography is the master variable governing soil morphology, chemical health, and agricultural output. A distinct pedogenic transition was observed from weakly developed Typic Usorthents on erosional ridges to more mature Typic Haplustepts in depositional valleys.

The results highlight a significant "truncation" effect on steeper gradients, where natural erosion selectively strips the porous, organic-rich A-horizon. This degradation is manifested physically through a 50% reduction in hydraulic conductivity and chemically through a sharp decline in organic carbon (from 0.85% in valleys to 0.39% on ridges). These environmental shifts culminated in a 22.3% reduction in maize yield on eroded ridges compared to depositional zones.

Statistical modelling further confirms that land gradient is the primary predictor of this yield variance ($R^2 = 0.965$), with natural erosion proving to be 16% more detrimental to productivity than indiscriminate mechanical de-surfacing benchmarks. This underscores the "selective" nature of hydraulic transport which preferentially removes the soil's vital colloidal complex.

Ultimately, this study concludes that traditional "blanket" conservation strategies are insufficient for such a heterogeneous landscape. Sustainable land management in the Shivalik region must be slope-specific, integrating land-use retirement on vulnerable ridges with precision nutrient management in productive valleys. By adopting these targeted interventions, the erosion-induced productivity penalty can be mitigated, ensuring long-term food security and geomorphic stability in this sensitive agro-ecosystem.

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Appendix A: Supplemental Data and Morphological Inventories

A.1. Comprehensive Morphological Description of All Pedons (P1–P6) #

Pedon	Position	Horizon	Depth (cm)	Color (Moist)	Structure	Consistence
P1	Ridge	Ap	0–14	10YR 4/3	Weak, fine granular	Friable
		C	14–45+	10YR 5/4	Massive/Single grain	Loose
P2	Shoulder	Ap	0–12	10YR 4/3	Weak, granular	Friable
		Cr	12–35+	10YR 5/6	Weathered Bedrock	Hard
P3	Mid-Slope	Ap	0–15	10YR 4/2	Moderate, granular	Friable
		Bw	15–42	10YR 4/4	Sub-angular blocky	Firm
		C	42–100+	10YR 5/3	Massive	Loose
P4	Lower Mid	Ap	0–16	10YR 4/3	Moderate, granular	Friable
		Bw1	16–48	10YR 4/4	Med. sub-ang. blocky	Firm
		Bw2	48–95+	10YR 5/4	Weak blocky	Firm
P5	Foot-slope	Ap	0–18	10YR 3/3	Strong, granular	Very friable
		Bw1	18–52	10YR 4/3	Strong blocky	Sticky
		Bw2	52–120+	10YR 4/4	Strong blocky	Sticky
P6	Valley	Ap	0–20	10YR 3/2	Strong, granular	Very friable
		Bw1	20–60	10YR 4/3	Med. angular blocky	Very firm
		Bw2	60–140+	10YR 4/4	Strong blocky	Very firm

#This inventory provides the field-level observations supporting the taxonomic transition from Entisols (Upper) to Inceptisols (Lower).

A.2. Summary of Spatio-Vertical Soil Evolution

Pedon	Position	Solum Depth	Horizon Sequence	Soil Taxonomy	Pedogenic Status
P1, P2	Ridge Top	>150 cm	Ap—Bw1—Bw2—BC	Typic Ustochrepts	Developed/Stable
P3, P4	Side Slope	65 cm	Ap—Bw—BC—Cr	Lithic Ustochrepts	Transitional
P5, P6	Gully Bed	28 cm	Ap—Cr		