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Effects of toposequences on soil physicochemical properties and enzyme activities in semi-arid landscapes

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Abstract

This study investigated the influence of landscape position and parent material on soil physicochemical properties and biological functioning along the Çankırı–Acıçay River toposequence. Our objectives were to (i) characterize six representative soil profiles, (ii) quantify the range and spatial variation of key hydrolytic enzyme activities (urease, phosphatase, arylsulfatase, and β-glucosidase), and (iii) evaluate the relationships between soil properties and enzymatic activity. The transect encompasses distinct lithologies: right-bank soils developed on Quaternary alluvial deposits (terraces/floodplains), while left-bank soils evolved from a complex mix including Oligo-Miocene gypsum and rock-salt strata (steep slopes). These differences resulted in classifications as Entisols, Inceptisols, and Mollisols, and distinct variations in particle-size distribution and organic matter (OM) accumulation across the profiles. Results showed that topography-driven erosion and deposition strongly controlled soil OM dynamics, which was the primary regulator of enzymatic activity. OM correlated with all enzymes, r = 0.81** to 0.89**. The old river terrace soils (depositional areas) exhibited the highest enzyme activities due to greater OM and finer texture, confirming their function as biological "hotspots". Conversely, upper-slope and gypsiferous soils displayed minimal enzymatic potential. In conclusion, variations in landscape position and parent material fundamentally alter both soil development and enzyme-mediated nutrient cycling within the semi-arid landscape of the Çankırı–Acıçay River basin.

Keywords: Soil genesis, soil landscape, enzyme activity, toposequence, organic matter.

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Introduction

Soil is an unconsolidated, three-dimensional natural body that forms a continuous mantle over the Earth's surface. Its characteristics and properties arise from a complex interaction of physical, chemical, and biological processes—collectively referred to as pedogenic processes (Ciolkosz et al., 1989). According to the classical Jenny (1941, 1980) formulation, soil formation is governed by the combined effects of climate, organisms, parent material, topography, and time. These factors control the type and intensity of pedogenic processes, thereby determining the structure, composition, and function of soils. Because climate, parent material, and relief simultaneously influence geomorphic evolution, the study of landscapes is intimately linked to the study of soils (McFadden and Knuepfer, 1990). Consequently, soil characteristics vary not only between regions but also across short distances within the same landscape (Birkeland, 1999). This spatial

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variability is not random but reflects the systematic influence of environmental gradients and pedogenic pathways.

In arid and semi-arid regions, numerous studies have shown that soils exhibit pronounced heterogeneity as a result of variations in parent material, geomorphic age, topography, hydrological redistribution, and biological activity (Wierenga et al., 1987; Wang et al., 2025). These factors collectively regulate the degree of weathering, leaching, and organic matter accumulation, leading to distinctive soil patterns along toposequences (Birkeland, 1999; Kussainova et al., 2013).

Soil is also a dynamic biochemical system in which enzymatic processes play a critical role in nutrient cycling and organic matter transformation. Soil enzymes are produced by microorganisms, plant roots, and soil fauna, and their activities serve as sensitive indicators of soil fertility and ecological condition. Several authors have demonstrated that soil biological parameters are among the most responsive indicators of ecological stress, land degradation, or ecosystem recovery (Kennedy and Papendick, 1995; Kızılkaya and Bayraklı, 2005). Measurements of enzymatic activities have thus been widely adopted to evaluate soil biological fertility and quality (Dick and Tabatabai, 1992).

Among the key soil enzymes, urease (EC 3.5.1.5) catalyzes the hydrolysis of urea into carbon dioxide and ammonium (Bremner and Mulvaney, 1978), directly linking the carbon and nitrogen cycles. Similarly, phosphatase (EC 3.1.3.2), arylsulfatase (EC 3.1.6.1), and β-glucosidase (EC 3.2.1.21) are responsible for the mineralization of organic phosphorus, sulfur, and carbon compounds, respectively—processes that sustain microbial growth and plant nutrition (Yertayeva et al., 2019; Muminova et al., 2023). The distribution and activity of these enzymes are highly sensitive to environmental conditions such as organic matter content, soil texture, pH, moisture regime, and topographic position.

The Çankırı–Acıçay River basin represents an ideal setting for investigating these interactions, as it encompasses distinct topographic positions (floodplain, terrace, backslope, shoulder) and contrasting parent materials on either side of the river. These geomorphological variations influence soil formation, vegetation cover, and land use, which in turn affect soil biochemical activity. Therefore, and to address the knowledge gaps mentioned above, the primary objectives of this study were: (i) to determine the physicochemical properties of six representative soils developed under different landscape positions and parent materials; (ii) to measure the range and spatial variation of key enzyme activities (urease, phosphatase, arylsulfatase, and β-glucosidase); and (iii) to evaluate the influence of soil properties and topographic position on the distribution of these enzyme activities across both sides of the Çankırı–Acıçay River.

Material and Methods

Study Area

The study was conducted along a transect spanning both sides of the Çankırı–Acıçay River, a location characterized by a distinct landform sequence, varying parent materials, and diverse vegetation types. The study area is situated near the Çankırı province, specifically located approximately between the UTM coordinates 557733E–4497924N and 557751E–4497889N. The elevation within the study transect ranges from 740 to 800 m above sea level. To capture the full spectrum of geomorphological, topographic, and soil characteristic variations, four representative landscape positions were selected: floodplain, terrace, backslope, and shoulder.

The underlying lithology exhibits significant variation across the transect. On the right bank of the Acıçay River, soils have developed on Quaternary alluvial deposits forming floodplains and terraces. Conversely, the soils on the left bank have evolved from a complex mix of Quaternary alluvium, alluvial–colluvial materials, and Oligo–Miocene gypsum and rock salt strata located at mid- to upper-slope positions. Notably, gypsum appears in crystalline, laminated (foliated), and mixed forms within the left-bank soils.

Vegetation cover also differs markedly along the transect. Lands on the right bank are intensively used for agricultural production, while the left-bank slopes support natural vegetation comprising herbaceous, shrub–grass, and grass communities. The uppermost lands on the left bank are largely barren, primarily due to overgrazing. Based on meteorological data for the region, the mean annual temperature is 11.1 °C and the mean annual precipitation is 417.7 mm. According to the Soil Survey Manual (2017) classification, the area exhibits a mesic soil temperature regime and a xeric moisture regime.

Soil Sampling

This study was designed under the hypothesis that topography, parent material, and vegetation cover are the primary controlling factors governing soil development and biological activity. Six representative soil profiles were excavated along a single transect oriented east–west across both sides of the Acıçay River. Figure 1 illustrates the varying soil formations on different parent materials, slopes, and land covers along the transect.

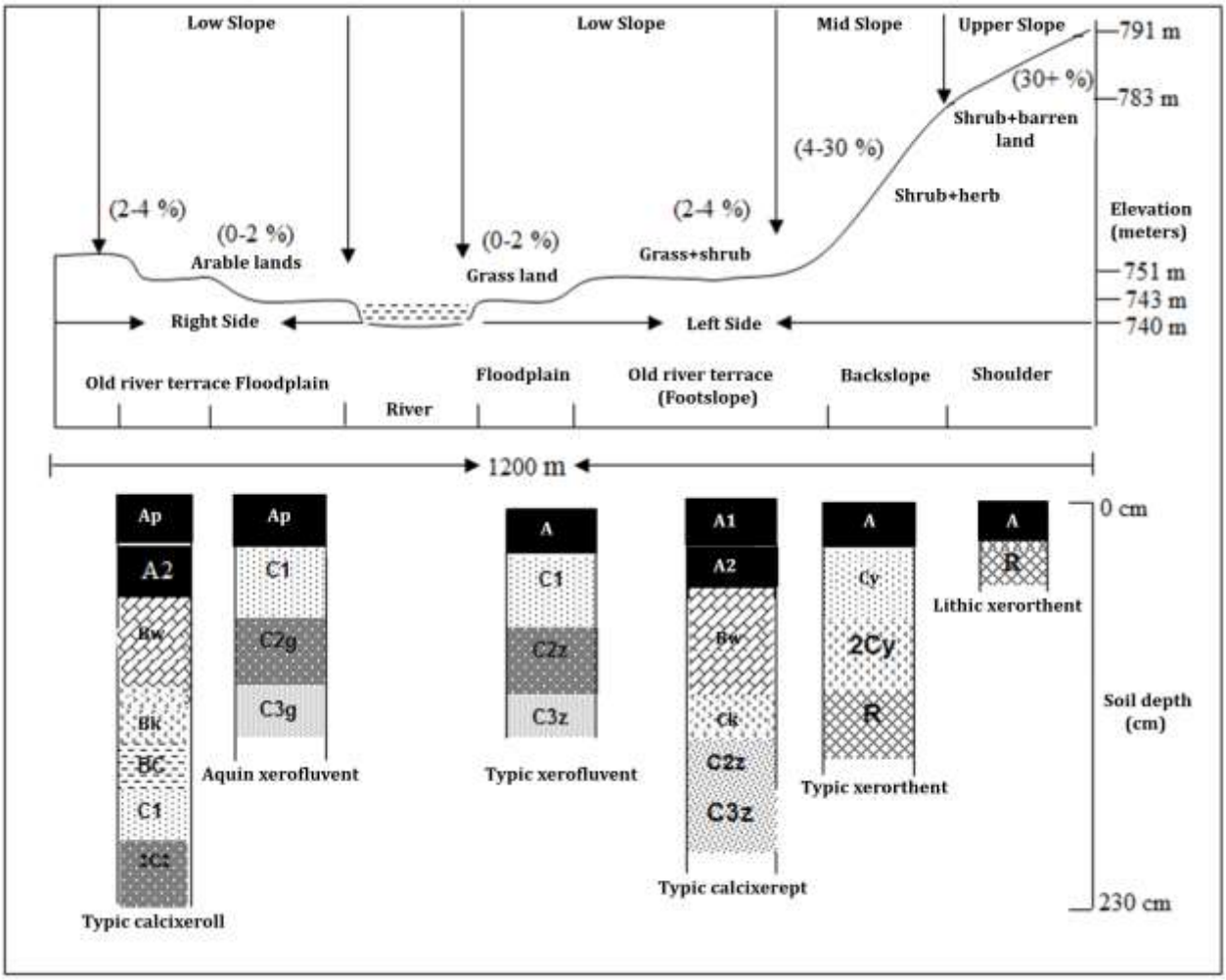


Figure 1. Different soil formations on various parent materials, slopes, and land covers along the transect of both sides of the Acıçay River.

Each profile was meticulously described in the field for morphological features following the procedures outlined in the Soil Survey Manual (2017), and subsequently classified according to the Soil Survey Staff (1999). Soil samples were collected by genetic horizon, yielding a total of 25 composite samples used for subsequent laboratory analysis of their physical, chemical, and biochemical properties. Disturbed samples were air-dried, gently crushed, and sieved through a 2 mm mesh prior to all laboratory analyses.

Soil Physicochemical Analyses

Particle size distribution was determined by the hydrometer method (Bouyoucos, 1951). Coarse fragments (2–60 mm) were separated and the mass coarse fraction ratio (CF_m) was calculated. Soil pH and electrical conductivity (EC) were measured in a 1:2.5 soil–water suspension according to Peech (1965) and Rowell, (1996) procedures. Organic matter (OM) was determined by the Walkley–Black wet oxidation method (Walkley and Black, 1934).

Calcium carbonate ($CaCO_3$) was quantified using the Scheibler calcimeter method (Loeppert and Suarez, 1996), and total gypsum was measured by $BaCl_2$ precipitation (Porta, 1998). The cation exchange capacity (CEC) was determined using 1 N ammonium acetate (NH_4OAc) at pH 7.0 (Rowell, 1996). Soil moisture content was determined gravimetrically after oven-drying at 105 °C for 48 h.

Soil Enzyme Activities

To assess the biological activity of the soils, four key extracellular hydrolytic enzymes were analyzed: urease (EC 3.5.1.5), phosphatase (EC 3.1.3.2), arylsulfatase (EC 3.1.6.1), and β-Glucosidase (EC 3.2.1.21).

Urease activity (UA) was determined following Hoffmann and Teicher (1961). One gram of air-dried soil was incubated with 0.25 mL toluene, 0.75 mL citrate buffer (pH 6.7), and 1 mL of 10% urea solution at 37 °C for 3h. The released ammonium (NH_4^+–N) was quantified spectrophotometrically at 578 nm, and results were expressed as μg NH_4^+–N g^{-1} 3 h^{-1} of oven-dry soil.

Phosphatase activity (PA) was assayed according to Tabatabai and Bremner (1969) using p-nitrophenyl phosphate (pNPP) as the substrate. One gram of soil was incubated with 4 mL modified universal buffer (pH

6.5) and 1 mL of 0.05 M pNPP at 37 °C for 1 h. After incubation, 0.5 mL of 0.5 M $CaCl_2$ and 4 mL of 0.5 M NaOH were added to stop the reaction. The released p-nitrophenol (pNP) was measured at 400 nm, and activity was expressed as μg pNP g^{-1} h^{-1}.

Arylsulfatase activity (ASA) was determined using the method of Tabatabai and Bremner (1970). One gram of soil was incubated with 4 mL acetate buffer (pH 5.8) and 1 mL of 0.025 M p-nitrophenyl sulfate at 37 °C for 1 h. The amount of released pNP was measured colorimetrically at 400 nm, and the activity was expressed as μg pNP g^{-1} h^{-1}.

β-Glucosidase activity (BGA) was measured according to Eivazi and Tabatabai (1988) using p-nitrophenyl-β-D-glucopyranoside as the substrate. One gram of soil was mixed with 4 mL Modified Universal Buffer (MUB, pH 6.0) and 1 mL of 25 mM substrate, followed by incubation at 37 °C for 1 h. The released pNP was extracted with 0.5 M $CaCl_2$ and 0.1 M Tris buffer (pH 12), and quantified at 400 nm. Enzyme activity was expressed as μg pNP g^{-1} h^{-1}.

Statistical Analyses

All laboratory measurements were carried out in triplicate. Results are presented as mean ± standard error (SE) on an oven-dry basis. Descriptive statistics and Pearson correlation analyses were performed using the Statistical Package for the Social Sciences SPSS 10.0 software. Significance levels were reported as $P < 0.05$ (*) and $P < 0.01$ (**). The correlation coefficients were used to evaluate the relationships among soil physicochemical parameters (pH, EC, OM, CaCO3, gypsum, clay, silt, sand, and CEC) and the enzyme activities (urease, phosphatase, arylsulfatase, and β-glucosidase).

Result and Discussion

Physicochemical Properties of Soils

The field characteristics and physicochemical data for the six representative soil profiles are detailed in Figure 1 and Table 1. The observed variability in soil physical properties reflects the dynamic interactions among controlling environmental factors: climate, parent material, land use, and topography. Specifically, slope is recognized as a crucial abiotic factor that controls pedogenic processes at the local scale (McDaniel et al., 1992; Boul et al., 2011). Steeper slopes contribute to greater runoff and translocation of surface materials downslope through surface erosion and mass movement (Hall, 1983).

In the left-bank soils, the clay percentage of surface horizons on low-slope positions is generally higher than on high slopes, with the exception of the floodplain topsoil, which consists of recently deposited coarse alluvium. Conversely, the sand content is higher on slopes with a high gradient. This finding, supported by studies in Iran (Rezaei and Gilkes, 2005), suggests that accumulation processes are dominant on low slopes (2-4%), while runoff and erosional processes prevail on steeper slopes (>30%). This pattern is mirrored by the Coarse Fragment Ratio (CFr). The lowest CFr value (0.44%) is found in the 0-2% slopes, while the highest values (34.52%) steadily increase with slope gradient. Consequently, the right-bank floodplain of the Acıçay River consists of finer-textured soils, whereas the opposite bank typically features sandier and coarser-textured soils (Table 1).

The effect of topography on soil thickness has been widely reported (Power et al., 1981; McIntosh et al., 2000; Rezaei and Gilkes, 2005; Yuan et al., 2021; Zhang et al., 2024). Soils along the left-bank transect exhibit variation in particle distribution and depth in the surface horizon, a clear result of erosional forces. Consequently, surface materials are carried and accumulated from uplands to lowlands, leading to progressively redder, deeper, and finer-textured soils with decreasing elevation. The deepest soils formed on low-slope classes (2-4%) or terraces, while shallow soils cover steep slopes.

Topsoil textural classes, which are influenced by the slope gradient, transition as follows with decreasing elevation: Coarse sandy loam from Clay loam to Clay. This distribution is partially consistent with the results of Kreznor et al. (1989) and Rezaei and Gilkes (2005), who demonstrated the dependence of particle size on landscape attributes. However, an abrupt textural transition to loamy sand is observed from the old river terrace soils to the floodplain soils. Both floodplains contain common pebbles and cobbles within their profiles. Phillips et al. (2001) indicated that soil on terraces generally shows greater development and better drainage compared to floodplain soils, an observation that is consistent with this study, owing to the higher position of terrace soils on the landscape. Furthermore, the effect of parent material on the structure and solum depth of the left-side soils appears to be more significant than the effect of landscape position. Soil profile thickness and clay content are crucial parameters for water retention (Rezaei and Gilkes, 2005; Yuan et al., 2021; Zhang et al., 2024), particularly important for unfertilized rangelands.

Table 1. Selected physicochemical properties for the six typical soil profiles

Horizon	Depth, cm	Particle size C,%	Si, %	S,%	class	CFm >2 mm, %	pH	EC, dS m^{-1}	OM, %	$CaCO_3$, %	Gypsium, %	CEC, cmol kg^{-1}
Right side old river terrace (PI) Typic Calsixeroll												
Ap	0-22	41	37	22	C	1.41	7.28	1.79	2.44	10.61	0.10	15.61
A2	22-53	32	44	24	CL	1.05	7.52	1.70	1.21	12.37	0.13	15.74
Bw	53-113	38	38	24	CL	0.96	7.47	2.61	1.11	13.14	0.24	22.08
Bk	113-149	43	39	18	C	0.54	7.80	3.22	1.05	17.34	0.74	25.08
BC	149-185	36	49	15	SiCL	0.13	7.83	3.85	0.98	12.08	0.66	19.45
C1	185-229	48	37	15	C	0.21	7.78	4.50	0.72	11.64	0.50	22.74
C2	229+	45	43	12	SiC	0.74	7.48	2.80	0.70	12.14	0.34	18.70
Right side floodplain (PII) Aquic Xerofluvent												
Ap	0-14	31	44	25	CL	1.1	7.52	1.90	1.92	12.23	0.18	16.70
C1	14-40	18	46	35	L	23.1	7.53	1.13	0.78	11.53	0.21	15.43
2C2g	40-69	11	9	80	SL	64.6	7.66	1.80	0.33	7.78	0.21	10.75
2C3g	69+	15	24	61	SL	20.3	7.52	2.92	0.65	8.84	0.25	12.45
Left side floodplain (PIII) Typic Xerofluvent												
A	0-6	5	22	73	SL	0.44	7.53	3.50	0.98	15.73	0.53	9.04
C1	6-15	9	53	38	SiL	1.33	7.77	4.71	0.72	15.19	0.62	9.35
C2z	15-26	9	43	48	L	2.16	7.93	9.32	0.78	14.66	1.33	11.65
C3z	26+	8	39	54	SL	5.31	7.82	8.71	0.59	14.66	1.44	10.62
Right side old river terrace (P IV) Typic Calsixerept												
Ap	0-22	41	37	22	C	1.41	7.28	1.79	2.44	10.61	0.10	15.61
A2	22-53	32	44	24	CL	1.05	7.52	1.70	1.21	12.37	0.13	15.74
Bw	53-113	38	38	24	CL	0.96	7.47	2.61	1.11	13.14	0.24	22.08
Bk	113-149	43	39	18	C	0.54	7.80	3.22	1.05	17.34	0.74	25.08
BC	149-185	36	49	15	SiCL	0.13	7.83	3.85	0.98	12.08	0.66	19.45
C1	185-229	48	37	15	C	0.21	7.78	4.50	0.72	11.64	0.50	22.74
C2	229+	45	43	12	SiC	0.74	7.48	2.80	0.70	12.14	0.34	18.70
Left side back slope (PV) Typic Xerorthent												
A	0-20	28	39	41	CL	26.90	7.45	7.52	0.78	11.31	1.76	18.16
Cy	20-44	26	33	51	SCL	15.30	7.56	5.11	0.52	13.29	13.43	16.11
2Cy	44-120	23	42	36	L	10.25	7.75	16.62	0.33	10.61	21.71	16.30
R	120+	-	-	-	-	-	-	-	-	-	-	-
Left side shoulder (PVI) Lithic Xerorthent												
A	0-18	14	24	62	SL	34.52	7.42	9.79	0.46	6.36	20.13	18.09
R	18+	-	-	-	-	-	-	-	-	-	-	-

Values represent mean ± standard deviation (n = 3) on an oven-dry basis

Soil chemical properties on different slope positions and parent materials were significantly affected by the degree of soil development and leaching processes (Table 1). Gerrard (1981) also noted that water movement and distribution on slopes are primary reasons for differences in soil properties across landscapes. Soil pH and EC are generally higher at depth than at the soil surface. This pattern was particularly evident in the left-side terrace soil, which exhibits significantly high pH values (7.80–8.75), whereas the pH of the right-side terrace soil varies between 7.28–7.83. This variation in pH appears to significantly influence the distribution of land uses and plant patterns on both sides of the Acıçay River.

Numerous studies have correlated soil properties with landscape positions, slope, and parent material. Brubaker et al. (1993) found that properties like sand, silt, pH, EC, and $CaCO_3$ generally increased downslope, while clay content, OM, and CEC generally decreased. In contrast, this study found that clay content, OM, and CEC generally increased from upper-slope to low-slope lands. Soil organic matter (OM) content depends on the complex interaction of litter fall, climate, soil properties (especially clay type and amount), and erosion (Dahlgeren et al., 1997).

Soils on both sides of the Acıçay River exhibit consistently low organic matter (0.46% to 2.61%), with the highest concentration consistently found in the surface horizon, decreasing sharply in the subsoil (Table 1). The low OM content in the study area is attributed to the rapid decomposition and mineralization of organic matter (due to intensive agricultural activities on the right bank), and to overgrazing and soil erosion (due to high slope on the left bank).

Cation exchange capacity (CEC) ranged from 9.04 to 27.18 cmol kg^{-1}. CEC values were strongly related to clay content (r=0.901**), due to the generally low OM content, particularly in subsurface horizons. Nonetheless, a statistically significant correlation was found between OM and CEC (r=0.596*). Gypsum content, which is relatively high in the fresh parent material (13.43% to 21.71%), remains relatively low (0.10% to 1.76%) in most surface horizons.

Soil Enzyme Activities

Beyond their physicochemical variability, soils differ fundamentally in their biochemical potential, which governs nutrient transformation and ecosystem productivity. Enzymes act as catalysts of these transformations, mediating the mineralization of organic carbon, nitrogen, phosphorus, and sulfur compounds. Because enzymatic activity closely reflects microbial abundance, organic substrate availability, and micro-environmental stability, it serves as a sensitive indicator of pedogenic intensity and soil quality. Therefore, the spatial and vertical distributions of four major hydrolytic enzymes—urease, phosphatase, arylsulfatase, and β-glucosidase—are presented to evaluate the effects of landscape position and parent material on the biological functioning of soils (Table 2).

Table 2. Activities of urease, phosphatase, arylsulfatase, and β-glucosidase enzymes in different landscape positions and soil horizons along the Çankırı–Acıçay River toposequence

Landscape Position	Profile ID	Horizon	Depth (cm)	UA	PA	ASA	GA
Right side old river terrace	PI	Ap	0–22	53.2 ± 3.1	172 ± 10.5	81 ± 5.3	210 ± 11.5
		A2	22–53	39.6 ± 2.4	132 ± 8.1	56 ± 3.8	148 ± 9.6
		Bw	53–113	28.7 ± 2.0	120 ± 8.0	49 ± 3.8	132 ± 7.9
		Bk	113–149	22.4 ± 1.5	98 ± 6.3	41 ± 3.4	103 ± 6.4
		BC	149–185	17.5 ± 1.3	84 ± 5.5	37 ± 2.9	92 ± 5.8
		C1	185–229	12.6 ± 1.1	61 ± 4.2	30 ± 2.5	65 ± 4.9
		C2	229+	9.8 ± 0.8	52 ± 3.7	27 ± 2.2	58 ± 4.3
Right side floodplain	PII	Ap	0–14	47.3 ± 2.8	165 ± 9.8	72 ± 4.5	190 ± 12.3
		C1	14–40	31.5 ± 1.7	108 ± 6.4	45 ± 3.2	128 ± 8.4
		2C2g	40–69	18.4 ± 1.2	65 ± 4.1	31 ± 2.7	72 ± 5.0
		2C3g	69+	10.6 ± 0.9	42 ± 3.6	25 ± 2.2	54 ± 4.3
Left side floodplain	PIII	A	0–6	32.4 ± 2.2	138 ± 7.2	57 ± 4.1	156 ± 9.2
		C1	6–15	25.9 ± 1.6	104 ± 6.8	49 ± 3.6	122 ± 7.4
		C2z	15–26	21.1 ± 1.5	92 ± 5.6	42 ± 3.4	108 ± 6.8
		C3z	26+	12.3 ± 1.1	65 ± 4.1	35 ± 2.8	81 ± 5.2
Left side backslope	PIV	A	0–20	25.2 ± 1.9	95 ± 6.3	51 ± 3.5	103 ± 6.8
		Cy	20–44	15.7 ± 1.2	76 ± 5.1	43 ± 3.1	86 ± 5.5
		2Cy	44–120	9.4 ± 0.7	52 ± 3.8	30 ± 2.6	61 ± 4.2
Left side shoulder	PV	A	0–18	11.8 ± 0.8	61 ± 4.0	39 ± 2.8	85 ± 5.3
Left side gypsic slope	PVI	A	0–14	17.5 ± 1.1	79 ± 5.2	46 ± 3.4	95 ± 6.1
		Cy	14–46	11.9 ± 0.9	64 ± 4.6	36 ± 2.9	72 ± 5.0

UA: Urease, μg NH_4^+-N $g^{-1}3h^{-1}$; PA: Phosphatase, μg pNP $g^{-1}h^{-1}$; ASA: Arylsulfatase, μg pNP $g^{-1}h^{-1}$; GA : β-Glucosidase, μg pNP g^{-1} h^{-1}
Values represent mean ± standard deviation (n = 3) on an oven-dry basis

Urease Activity

Urease (EC 3.5.1.5) catalyzes the hydrolysis of urea into ammonium and carbon dioxide, a crucial step in nitrogen mineralization. Urease activity (UA) exhibited marked spatial and vertical variability across the toposequence (Table 2). The activity was highest in surface horizons, particularly in the old river terrace (PI) on the right bank (53.2 μg NH_4–N g^{-1} 3 h^{-1}), followed by the floodplain soils (PII) (47.3 μg NH_4–N g^{-1} 3 h^{-1}). Conversely, the lowest activities were detected in the shoulder (PV) and gypsic slope (PVI) profiles on the left bank, ranging between 11.8 and 17.5 μg NH_4–N g^{-1} 3 h^{-1}.

Within each profile, UA decreased progressively with soil depth, reflecting the sharp reduction of microbial biomass, root exudation, and organic carbon availability. Topographically, higher UA in foot-slope and terrace positions indicates depositional enrichment of organic matter and fine particles, which provide both substrate and protection sites for enzyme stabilization. The lower activity on steep slopes and gypsiferous parent materials may stem from limited organic inputs, higher erosion rates, and inhibitory effects of soluble salts and gypsum. UA was positively correlated with organic matter and clay content in depositional areas (r=0.89**) as also reflected in Table 3. This spatial variability confirms that nitrogen transformation is highly dependent on landscape position and soil development stage (Fu et al., 2004; Aşkın and Kızılkaya, 2006).

Phosphatase Activity

Phosphatases (EC 3.1.3.2) mediate organic phosphorus mineralization. Phosphatase activity (PA) displayed a strong dependence on both soil depth and landscape position (Table 2). The highest activity was recorded in the Ap horizon of the old river terrace (PI), with a mean of 172 μg pNP g^{-1} h^{-1}, followed closely by the floodplain soils (PII) (165 μg pNP g^{-1} h^{-1}). The left-side shoulder (PV) showed the lowest activity (61 μg pNP g^{-1} h^{-1}), correlating with its low organic matter (0.46%) and coarse-textured substrate.

Depth-wise trends revealed that PA decreased sharply below the Ap horizon in all profiles, reflecting the predominance of microbial and root-derived enzyme sources in the biologically active surface layer. The low activity in gypsiferous and eroded uplands can be attributed to restricted root biomass, moisture limitation, and possible inhibition by Ca^{2+} and SO_4^{2-} ions. PA showed a highly significant correlation with organic matter (r=0.85**), indicating that carbon input and microbial activity are primary regulators of phosphorus cycling. The high activity in the right-bank terrace soils supports the notion that depositional environments promote higher biochemical turnover by retaining fine particles, moisture, and accumulated plant residues (Amador et al., 1997).

Arylsulfatase Activity

Arylsulfatase (EC 3.1.6.1) is crucial in sulfur mineralization. The results indicated that Arylsulfatase activity (ASA) varied widely among landscape positions and soil depths (Table 2). Maximum activity occurred in the Ap horizon of the old river terrace (PI) (81 μg pNP g^{-1} h^{-1}), followed by the floodplain soils (PII) (72 μg pNP g^{-1} h^{-1}). The lowest activities were found in the shoulder (PV) (39 μg pNP g^{-1} h^{-1}) and gypsic slope (PVI) (46 μg pNP g^{-1} h^{-1}).

ASA generally declined with depth, corresponding closely to the distribution of organic matter and microbial abundance. Reduced ASA in the gypsic slope and shoulder profiles likely reflects lower microbial biomass and the adverse effects of salinity and gypsum content. The significant correlation observed between ASA and organic matter (r=0.81**) underscores its potential as a sensitive indicator of soil biological fertility. The distribution of ASA shows that terrace and floodplain positions act as active sulfur transformation zones (Speir and Ross, 1978).

β-Glucosidase Activity

β-Glucosidase (EC 3.2.1.21) is a key enzyme in the degradation of cellulose and other carbohydrates, reflecting the intensity of carbon cycling and organic matter turnover (Birol and Günal, 2024). Among the enzymes studied, β-glucosidase exhibited the highest activity levels overall (Table 2). The maximum value was observed in the Ap horizon of the right-bank old river terrace (210 μg pNP g^{-1} h^{-1}), followed by the floodplain soils (190 μg pNP g^{-1} h^{-1}).

In all profiles, β-Glucosidase activity (GA) decreased progressively with depth—from over 200 μg pNP g^{-1} h^{-1} in surface soils to roughly 60 μg pNP g-1 h-1 in deep horizons, mirroring the decline in organic matter and microbial biomass (Leirós et al., 2000; Zaman et al., 2002). The close association between GA and organic carbon content (r=0.87**) confirms that enzyme production is primarily driven by microbial decomposition.

Spatially, the highest GA on the terrace and floodplain positions reflects the accumulation of fine materials and stable moisture regimes. Low activities in the shoulder and gypsic slope soils are indicative of strong erosional losses, limited vegetation cover, and restricted substrate supply. The presence of gypsum may also inhibit enzyme activity by altering pH and ionic strength. These findings collectively indicate that β-glucosidase is a reliable biochemical marker of soil organic carbon dynamics, showing that lower slope and terrace positions function as active centers of carbon mineralization and nutrient turnover.

Relationship Between Enzyme Activities and Soil Properties

The functional relationships between soil enzymes and physicochemical parameters are essential for understanding how biological activity responds to pedogenic conditions. Enzyme activities are influenced by a combination of factors such as organic matter content, clay minerals, cation exchange capacity, soil reaction, and salinity. To elucidate these linkages, Pearson's correlation coefficients were calculated among the measured soil properties (pH, EC, organic matter, $CaCO_3$, gypsum, CEC, and particle-size fractions) and the activities of the four major hydrolytic enzymes. The correlation matrix (Table 3) reveals the degree and direction of these associations, highlighting the key variables that regulate soil biochemical processes along the Çankırı–Acıçay toposequence.

The correlation matrix (Table 3) confirms that soil biological functioning is primarily regulated by the amount and quality of organic matter (OM), clay content, and cation exchange capacity (CEC), while pH, salinity (EC), and gypsum content exert secondary or inhibitory effects.

Table 3. Correlation coefficients (r) among soil physicochemical and biochemical properties (n = 25)

	pH	EC	OM	$CaCO_3$	Gypsum	CEC	Clay	Silt	Sand	UA	PA	ASA	GA
pH	1	0.38	−0.24	0.46*	0.41*	−0.43	−0.38	0.12	0.55*	−0.31	−0.28	−0.34	−0.29
EC		1	−0.18	0.32	0.44*	−0.29	−0.26	0.16	0.41	−0.22	−0.19	−0.21	−0.20
OM			1	−0.21	−0.33	0.60*	0.48	0.26	−0.62*	0.89*	0.85**	0.81**	0.87**
$CaCO_3$				1	0.55*	−0.48	−0.42	0.31	0.44	−0.27	−0.23	−0.25	−0.28
Gypsum					1	−0.45	−0.38	0.22	0.36	−0.34	−0.28	−0.30	−0.33
CEC						1	0.75**	0.39	−0.64**	0.67**	0.59*	0.52*	0.64**
Clay							1	0.41	−0.72**	0.55*	0.49	0.46	0.53*
Silt								1	−0.83**	0.41	0.37	0.33	0.40
Sand									1	−0.63**	−0.58*	−0.56*	−0.61**
UA										1	0.94**	0.89**	0.96**
PA											1	0.88**	0.92**
ASA												1	0.90**
GA													1

Significance levels: *P < 0.05; *P < 0.01.

Influence of Organic Matter and Texture

Organic matter (OM) showed highly significant positive correlations with all four enzymes: urease (r=0.89**), phosphatase (r=0.85**), arylsulfatase (r=0.81**), and β-glucosidase (r=0.87**). These strong associations emphasize that organic substrates serve as both energy and carbon sources for microbial growth and as stabilizing agents for extracellular enzymes within soil aggregates. Enzyme activities were also positively correlated with clay content (r values ranging from 0.46 to 0.55) and CEC (r values from 0.59* to 0.67**), suggesting that clay–humus complexes provide adsorption sites that protect enzymes from degradation and enhance their persistence.

The textural control of enzymatic behavior is particularly evident across slope gradients. Fine-textured soils on terraces and floodplains, which possess higher clay and CEC values, support more stable enzymatic systems. Conversely, coarse sandy soils on upper slopes and gypsic formations exhibited low enzyme activities (Table 2), likely due to reduced organic matter retention and rapid desiccation. These findings are consistent with the conceptual model proposed by Tabatabai (1994), where both clay and humic colloids act as enzyme stabilizers by forming organo-mineral complexes that maintain catalytic integrity. The significant negative correlations between Sand content and all enzyme activities further support this link (r =-0.63** to -0.56*).

Effects of pH, Electrical Conductivity, and Gypsum

Soil reaction (pH) exhibited weak negative correlations with the studied enzymes (-0.28 to -0.34), indicating that the observed slight alkalinity (ranging up to 8.7 in gypsic strata) may reduce enzymatic efficiency, especially for urease and phosphatase, which typically show optimum activity closer to neutral pH (6.5–7.0). This pH elevation, coupled with ionic interference from soluble salts, likely inhibited enzyme function by altering protein conformation and substrate affinity.

Electrical conductivity (EC) and gypsum content were also negatively related to enzyme activities, albeit less strongly (-0.19 to -0.34). The suppressive influence of gypsum was particularly evident in the left-side gypsic slope soils (PVI), where elevated Ca^{2+} and SO_4^{2-} concentrations coincided with reduced urease and phosphatase activities (Table 2). High gypsum levels may restrict microbial colonization, alter osmotic potential, and precipitate essential nutrients, thereby constraining microbial metabolism. The same inhibitory mechanisms were reported by Kızılkaya et al. (2004), who found that elevated salt concentrations and heavy metal ions decreased enzymatic activity through protein denaturation and oxidative stress on microbial communities.

Inter-Enzyme Relationships

The correlation coefficients among the four enzymes were exceptionally high (r values ranging from 0.88** to 0.96**), revealing a coherent biochemical network within the soil system (Table 3). This strong co-variation implies that these enzymes—though functionally distinct—share common controlling factors such as microbial biomass, organic matter content, and moisture status. The synchronous decline of all enzyme activities with depth, and their concurrent increase in depositional zones, confirms that enzyme systems operate synergistically under similar ecological and pedological conditions.

For instance, β-glucosidase, which catalyzes the decomposition of cellulose, provides the carbon substrates that fuel microbial synthesis of urease and phosphatase enzymes. Similarly, urease-mediated nitrogen mineralization promotes microbial proliferation and thus enhances the synthesis of other hydrolases. These mutual feedback mechanisms highlight the integrated nature of soil biochemical functioning across

toposequences. Such strong enzyme–enzyme correlations also suggest that these parameters can be used collectively as indicators of soil biological quality, as proposed by Doran and Parkin (1994), who recommended that multiple enzyme indices provide a more reliable measure of soil quality than single enzyme assays.

Role of Landscape Position and Soil Development

The spatial patterns in enzyme–soil relationships clearly reflect the interaction of topographic and pedogenic processes. In the right-side terrace soils, well-developed structure, moderate alkalinity, and higher organic matter accumulation favor both enzyme stabilization and microbial colonization, leading to the highest biochemical activities (Table 2). Conversely, the steep and gypsic slopes on the left bank, characterized by thin profiles, low organic matter, and coarse textures, display the lowest enzymatic potential.

These differences are directly linked to erosional and depositional dynamics within the landscape. Erosion on upper slopes removes fine particles and organic residues, while deposition on lower slopes enriches soils with reactive surfaces and organic substrates—creating biochemical "hotspots" of nutrient cycling. Such spatial heterogeneity has been emphasized by Bergstrom et al. (1998) and Fu et al. (2004).

The study therefore supports the hypothesis that landscape position, through its control on organic matter accumulation and soil texture, is a primary determinant of enzymatic activity and soil fertility. It also underscores the potential of enzyme activity profiling as a diagnostic tool for evaluating soil quality across geomorphologically diverse terrains. These findings demonstrate that soil biochemical functioning across the toposequence is primarily governed by organic matter dynamics and clay–humus interactions, rather than by pH or salinity constraints

Conclusion

The comparative evaluation of soils from both sides of the Acıçay River clearly demonstrated that landscape position and parent material are the dominant factors shaping soil formation, physicochemical characteristics, and enzymatic activity. The pronounced contrasts observed between the right- and left-bank soils indicate distinct pedogenic pathways arising from differences in geomorphology, lithology, and erosion–deposition dynamics.

Across the transect, soil chemical and physical properties—such as texture, organic matter (OM), pH, calcium carbonate, gypsum, and cation exchange capacity (CEC)—varied systematically with topographic position:

• The old river terrace (located at the footslope) exhibited the highest OM and clay contents, reflecting depositional accumulation of fine particles and organic residues.

• Upper slopes and gypsiferous zones were characterized by coarser textures, lower fertility, and shallower profiles as a result of continuous erosion and limited vegetation cover.

The biochemical analyses further revealed that urease, phosphatase, arylsulfatase, and β-glucosidase activities differed markedly among landscape positions and soil depths. These enzymes were concentrated in the surface horizons and showed strong positive correlations with soil organic matter and clay content. Such relationships confirm that microbial activity and enzyme synthesis are primarily governed by the availability of mineralizable substrates and the presence of stable microhabitats for enzyme stabilization. The old river terrace soils consistently exhibited the greatest enzymatic activity, confirming that depositional environments function as biochemical hotspots within the landscape.

Overall, this study demonstrated that variations in landscape position can significantly alter the spatial distribution of soil enzyme activities within the soil profile. The interaction of erosion, deposition, and parent material composition produces pronounced heterogeneity in both soil fertility and microbial functioning. Therefore, the Acıçay River toposequence serves as a valuable natural laboratory for understanding the integrated relationships among soil formation processes, organic matter dynamics, and enzyme-mediated nutrient cycling in semi-arid landscapes.

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