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ORIGINAL ARTICLE

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Assessing Agronomic Risk under Altitudinal-Slope Variations in Eastern India: A Conceptual Synthesis of Soil-Water-Productivity Interactions

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ABSTRACT

Topographic heterogeneity is a defining feature of the Eastern Region of India (ERI), where sharp gradients in altitude and slope exert strong control over soil formation processes, hydrological dynamics, vegetation distribution, and agricultural performance. There is an urgent need to synthesize multidisciplinary evidence to evaluate agronomic risks associated with altitudinal–slope variations across ERI's major landscape units—floodplains, piedmonts, undulating uplands, and hilly terrains. Steeper slopes and higher elevations consistently elevates risks due to enhanced runoff generation, severe soil erosion, rapid nutrient loss, reduced soil organic carbon (SOC), and diminished soil moisture retention, collectively heightening susceptibility to crop failure. In contrast, mid-altitude zones with higher vegetation cover tend to exhibit moderated erosion and improved soil stability, while lower elevations face complex risks driven by intensive cultivation, sedimentation, land-use transitions, and expanding urbanization. Comparable evidence from Himalayan and other terrain-complex regions reinforces these topography-driven degradation patterns, particularly regarding erosion rates, nutrient redistribution, and SOC variability. The terrain attributes fundamentally regulate soil physical, chemical, and biological properties, influencing micronutrient availability, infiltration capacity, SOC stocks, and vegetation structure—key determinants of agronomic suitability. With projected increases in rainfall intensity and monsoonal variability under climate change, these topography-linked risks are expected to intensify. Incorporating high-resolution terrain metrics into agronomic risk assessments can substantially strengthen land-use planning, soil conservation strategies, and climate-resilient agricultural management. Thus, there is urgent need for altitude- and slope-responsive interventions including erosion control, vegetative reinforcement, precision nutrient management, and landscape-specific conservation practices to safeguard soil health and ensure sustainable agricultural productivity in the highly diverse and vulnerable eastern region of India.

1 | INTRODUCTION

Agricultural landscapes of the Eastern Region of India (ERI) are characterized by pronounced topographic variability, with steep slopes, dissected uplands, and plateau systems interacting intricately with hydroclimatic and edaphic conditions. Across these altitudinal–slope gradients, agronomic risk emerges from a complex interplay of soil characteristics, climatic variability, and farming practices. The region's heterogeneous terrain strongly regulates hydrological processes—modulating runoff generation, infiltration dynamics, and moisture retention and thereby governs crop productivity, yield stability, and the long-term resilience of agroecosystems (Sarkar *et al*., 2017; Jeet *et al*., 2024).

Topographic heterogeneity further amplifies hydrological extremes, including drought, flooding, and waterlogging, with soil erosion the most pervasive and detrimental process in upland and hilly ecosystems. Globally, soil erosion is recognized as a major driver of land degradation and a key constraint to sustainable agriculture, particularly in regions where farming underpins rural livelihoods. In India, erosion-induced nutrient depletion is estimated to remove approximately 74 million tonnes of essential nutrients from topsoil annually, resulting in economic losses exceeding INR 68 billion (Pal and Jana, 2025). Such nutrient losses diminish soil fertility, impair crop performance, and undermine the long-term sustainability of production systems.

Anthropogenic pressures, including deforestation, unregulated land conversion, overgrazing, and the expansion of cultivation into marginal lands, have accelerated erosion rates to levels 10 to100 times higher than natural background rates (Seifu *et al*., 2021). The urgency to quantify erosion dynamics across altitudinal and slope gradients thus lies at the heart of evaluating agronomic vulnerability and designing sustainable land management interventions. Accurate assessment of current and projected erosion scenarios is indispensable for informed land-use planning, soil fertility conservation, enhanced ecosystem resilience, and sediment management in riverine systems. Altitude and slope are pivotal determinants of erosion processes. Increasing gradient steepness amplifies runoff velocity and erosive energy, promoting the detachment and downslope transport of soil particles. Consequently, the upland and hilly landscapes of ERI exhibit heightened susceptibility to erosion and nutrient depletion (Pal and Jana, 2025). Field-based studies from the Himalayas and other complex terrains further demonstrate the magnitude of erosion risks, reporting soil loss rates ranging from 20 to 25 t ha^{-1} yr^{-1} to as high as 92 t ha^{-1} yr^{-1} (Sharda and Ojasvi, 2016). Climate change projections indicating intensifying rainfall and shifting monsoonal patterns are expected to exacerbate these losses.

Erosion processes are inherently spatially and temporally variable, driven by complex interactions among topography, rainfall, soil, vegetation, land-use change, and human activities. For example, micronutrient variations (Fe, Mn, Cu, Zn) along elevation and land-use in the Eastern Himalayas show the need for site-specific nutrient management in acidic, erosion-prone soils. Globally, arid, semi-arid, sub-humid, and mountainous areas are most vulnerable to erosion and land degradation. In tropical hill ecosystems, especially in developing countries, converting forests to agriculture speeds up topsoil loss, depleting nutrients (N, P, K, Fe, Mn, Cu, Zn), reducing fertility, and threatening sustainability (Schroder *et al*., 2024). These patterns are mirrored in the ERI uplands and plateaus, where soil health is vital for sustainable agriculture and livelihoods. In India's Eastern Region—comprising floodplains, plateaus, and hill tracts—slope and altitude create diverse risks: floodplains are prone to waterlogging; piedmonts face runoff and erosion; and plateau and hill areas suffer from droughts and topsoil loss. This heterogeneity highlights the need to consider altitude and slope in risk assessment and management. Given these interlinked biophysical processes, a comprehensive evaluation of agronomic risk across varying altitudinal and slope gradients is imperative to inform effective soil conservation planning, enhance agroecosystem sustainability, and maintain long-term land productivity in this ecologically sensitive landscape.

2 | REVIEW METHODOLOGY

This review synthesizes published evidence on the effects of altitudinal–slope gradients on soil–water–agriculture interactions in the Eastern Region of India (ERI). A systematic search of Scopus, Web of Science, PubMed, CAB Abstracts, and Google Scholar (2000–2025) was conducted using keywords such as “altitude,” “slope,” “soil water,” “soil properties,” “agronomic risk,” “crop productivity,” and “Eastern India.” In the present study, the inclusion criteria were studies from Eastern India or comparable tropical/subtropical regions addressing soil, water, or crop productivity under altitudinal–slope variation. Selected literature was thematically synthesized to highlight soil–water–vegetation dynamics, nutrient gradients, slope-related soil quality, and implications for agronomic risk assessment, providing a structured conceptual overview of productivity variations across altitudinal–slope gradients in ERI.

HIGHLIGHTS

- Eastern Hills and Plateaus feature diverse subsistence farming adapted to fragile slopes.
- Steeper slopes and higher elevations heighten runoff, erosion, nutrient loss, and moisture stress.

This review is constrained by uneven regional data coverage, particularly in high-altitude and remote landscapes of ERI, and the absence of quantitative meta-analysis, which may limit generalizability of some trends. The reliance on analogous studies from Himalayan and comparable tropical/subtropical regions, while methodologically justified, introduces uncertainty regarding direct transferability to all ERI contexts. Additionally, temporal variability in climate, land-use practices, and management interventions may not be fully captured in the synthesized evidence. Future research should prioritize primary field studies across ERI's diverse physiographic zones and employ quantitative synthesis approaches to strengthen evidence-based recommendations.

3 | CONCEPTUAL SYNTHESIS

3.1 | Altitudinal-slope variations

Slope orientation, elevation, and terrain configuration play decisive roles in shaping agronomic risk across the ERI, influencing solar radiation, soil moisture regimes, wind exposure, vegetation cover, soil properties, and hydrological responses. High-altitude and steep-slope areas consistently exhibit greater erosion due to sharp gradients, sparse vegetation, elevated sand and silt content, lower clay fractions, and reduced soil organic carbon (SOC), whereas mid-altitude zones experience lower erosion rates owing to dense vegetation that buffers runoff, and low-elevation floodplains, despite gentle slopes and higher clay content, are prone to moderate degradation from intensive farming and urban expansion. Studies from the North-Eastern Himalayan Region highlight these patterns: Choudhari *et al*. (2014) found higher SOC concentration and stock in non-agricultural land uses (2.20–2.51%, 35.2–42.1 Mg ha^{-1}) compared with agricultural and plantation systems (1.44–1.63%, 27.4–28.4 Mg ha^{-1}), with SOC variability shaped by soil texture and altitudinally driven climatic factors; trends were inconsistent below 1,000 m but became linear above this elevation. Mishra and Francaviglia (2021) observed increasing SOC stocks with elevation in

Nagaland, while nutrient availability (N, P, K) varied with both land use and soil texture, and phosphorus showed the highest concentrations at lower elevations (<500 m), emphasizing local context effects. These studies demonstrate that while erosion and general soil stability follow predictable altitude–slope patterns, SOC and nutrient dynamics are highly context-dependent, reflecting interactions among land use, soil texture, and climate. Consequently, effective agronomic risk assessment in ERI requires integrating broad physiographic patterns with localized land management and soil conservation practices to optimize productivity and sustainability.

3.1.1 | Terrain-driven agronomic risks

The Eastern Region of India (ERI), which includes the Indo-Gangetic floodplains, undulating plateaus, and hill tracts (Fig. 1), faces a variety of risks driven by altitude and slope. Floodplains are prone to waterlogging, flooding, and lower oxygen levels. Undulating piedmonts experience flash runoff, rill–gully erosion, and soil crusting. Plateau and hill ecosystems are affected by recurring droughts, significant topsoil loss, and quick runoff. This spatial diversity emphasizes the importance of including altitudinal and slope features in agronomic risk assessment models.

3.2 | Topographic controls on soil, water, and vegetation dynamics

Elevation influences temperature, rainfall patterns, solar radiation, and evapotranspiration. Steeper slopes reduce infiltration, accelerate runoff, and enhance erosion risk (Nath *et al*., 2021). The Himalayas and the Northeast Hill Region (NEHR) consistently exhibit accelerated runoff, high sedimentation, and nonpoint source pollution. Soil degradation costs are significantly higher in NEHR due to steep terrain, high rainfall, unscientific cultivation, and anthropogenic activity (Das *et al*. 2021). Similar dynamics characterize high-altitude zones in ERI. Slope, aspect, surface shape, stream power, and topographic wetness index (TWI) all influence erosion pathways. Steep slopes produce faster runoff and less infiltration, causing significant soil detachment (Saha *et al*., 2022). Regions with stripped forest cover, inadequate soil conservation, and shifting land use, such as the Chambal and Mahi basins, illustrate the consequences of terrain–land-use interactions. Topographic steepness is thus a central determinant of hydrological processes, erosion vulnerability, and land-use patterns (Gupta *et al*., 2024).

3.3 | Soil organic carbon (SOC), nutrients, and altitudinal gradients

Altitudinal and slope variations strongly shape SOC distribution, nutrient stocks, and soil physical properties. Studies across the Eastern Himalayas and related ecosystems reveal consistent patterns. Higher elevations generally exhibit higher SOC concentrations and stocks due to cooler temperatures, slower decomposition, and higher silt–clay content (Choudhury *et al*., 2016; Mishra and Francaviglia, 2021). SOC concentration nearly doubles at elevations of 2,500–3,500 msl compared to baseline levels.

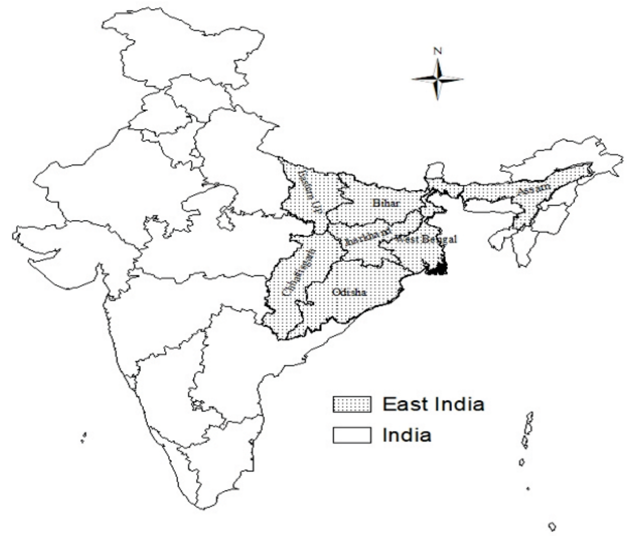

FIGURE 1 Eastern part of India map

Land-use changes, such as upland forest conversion to plantations, lead to 41–60% reductions in micronutrients (Mn, Cu, Zn) (Choudhury *et al*., 2021). Non-agricultural land uses (grasslands, forests) exhibit significantly higher SOC stocks than shifting or settled agriculture (Singh *et al*., 2018). Steep slopes promote soil translocation and downslope redeposition, leading to variability in soil texture and nutrient distribution. In ERI, similar patterns emerge: plain regions show higher SOC stocks (31.81 Mg ha^{-1}), followed by piedmonts and hills (Saini *et al*., 2021), with SOC highest at foot slopes and lowest on upper slopes.

3.4 | Biodiversity, vegetation, and soil-plant interactions along altitudinal gradients

Vegetation structure, diversity, and community composition vary with altitude in the Eastern Region of India (ERI). Low-altitude forests typically exhibit high species diversity, whereas high-altitude forests support larger biomass and basal area (Bhutia *et al*., 2019). Climatic variables such as temperature, precipitation, wind, and radiation interact with soil characteristics to shape adaptive plant traits (Gupta *et al*., 2019). Increased soil organic carbon (SOC), higher moisture content, improved infiltration, and reduced bulk density at higher elevations favor the growth of woody shrubs and other resilient species (Mangral *et al*., 2023). The extent of water savings and yield improvement under different altitudinal gradients and agronomic soil and water conservation practices is shown in (Table 1).

Agronomic soil and water conservation practices demonstrate altitude- and slope-dependent effects on crop productivity and water use efficiency. For instance, ridge and furrow methods on slight slopes enhanced water savings by ~27% and increased yields by 8–24% in crops such as soybean, cotton, maize, cowpea, and colocasia (Basediya *et al*., 2018), while broad-bed furrow and contour farming on gentle to moderate slopes improved yields by 33–81% in soybean and sorghum (Kumari *et al*., 2020). Practices such as conservation furrows, sub-soiling, plastic mulching, rice-straw mulching, and trench-cum-bunding showed variable water savings (4.7–45%) and yield improvements (7.5–60%) depending on slope and crop type (Bhardwaj, 2013; Chaudhry *et al*., 2004; Rajkumar and Satishkumar, 2014), and laser leveling in level to slight slopes enhanced water efficiency and yields in rice–wheat systems (Jat *et al*., 2009; Rudragouda Chilur *et al*., 2016). Vegetation patterns and agronomic responses are largely influenced by the combined effects of altitude, slope, soil, and climate, yet the magnitude of water savings and yield gains remains context-specific, underscoring the importance of tailoring soil and water management practices to local physiography and crop requirements.

Table 1. Extent of water savings and yield improvement under different altitudinal gradients and agronomic practices

Practices	Slope variations (Range)	Crop	Average water saving (%)	Average increase in crop yield (%)	Reference
Ridge and furrow method	0.15-0.5%	Soyabean, cotton, maize, cowpea, colocassia	27	8-24	Basediya *et al*. (2018)
Broad bed furrow	< 3%	Soyabean	-	81	Kumari *et al*. (2020)
Sowing across the slope (Contour farming)	2-10%	Soyabean	-	33	Kumari *et al*. (2020)
Compartmental bunding	up to 6%	Sorghum	-	52	Kumari *et al*. (2020)
Conservation furrow	0.2-0.5%	Cotton, pigeon pea	-	8-60	Kumari *et al*. (2020)
Sub soiling	up to 12%	Groundnut	-	11	Kumari *et al*. (2020)
Plastic mulching	2-4%	-	4.7-4.5	7.5-22	Bhardwaj (2013)
Rice straw mulching	9 to up to 30%	-	30	-	Chaudhry *et al*. (2004)
Trench cum bunding	2-7%	-	15	-	Rajkumar, and Satishkumar (2014)
Laser levelling	upto 0.2%	Rice-wheat, rice	2.5	2.5	Jat *et al*. (2009); Rudragouda Chilur *et al*. (2016)

*Note: Values represent reported ranges from individual studies or reviews as cited. Variations reflect differences in crop type, slope gradient, soil conditions, and management practices across different agro ecological contexts.**

3.5 | Slope position and soil quality

Slope position strongly influences soil nutrients, cation exchange capacity, moisture content, and bulk density, with most soil properties declining from lower to upper slopes due to erosion-driven loss of clay and organic matter (Debisa *et al*., 2025). Assessments across different land uses in the Eastern Himalaya and Northeastern Himalaya reveal consistent patterns: lower slope and valley positions under forest or perennial vegetation exhibit higher SOC, nutrient stocks, and better soil structure, whereas upper slopes and hilltops under shifting cultivation or intensive cropping show reduced fertility and higher susceptibility to degradation (Singh *et al*., 2013; Mishra *et al*., 2017, 2019). These variations are strongly mediated by land-use type, vegetation cover, and microtopography, indicating that slope position alone does not fully determine soil quality. Although lower slope positions reliably provide higher soil fertility and reduced erosion risk, the interplay of slope, land use, and vegetation cover creates site-specific variability; therefore, agronomic risk assessment and management strategies in ERI's hilly and plateau regions must integrate slope position with local land-use and conservation practices to sustain soil productivity.

3.6 | Implications for agronomic risk assessment in ERI

The evidence collectively underscores that altitude and slope serve as fundamental determinants of agronomic risk. Their influence cascades through soil formation, erosion processes, hydrological responses, vegetation patterns, and nutrient dynamics. In the context of ERI:

- Steeper slopes increase exposure to erosion, drought, and nutrient loss.
- Mid-altitude landscapes benefit from favorable vegetation cover and reduced erosion.
- Lowlands face waterlogging, sedimentation, and anthropogenic pressures.

With climate change amplifying rainfall extremes, altering evapotranspiration, and modifying vegetation composition, a systematic assessment of altitudinal–slope risks is critical for sustainable agriculture, resource conservation, and food security in the Eastern Region of India.

4 | CONCLUSIONS

Agronomic risk in the ERI is profoundly intertwined with the region's altitudinal and slope-driven heterogeneity, which shapes soil properties, hydrological behavior, vegetation patterns, and agricultural performance. Evidence from ERI and comparable mountain ecosystems demonstrates that variations in altitude and slope critically influence soil stability, nutrient distribution, organic carbon dynamics, and erosion susceptibility. Steeper, higher-altitude terrain consistently exhibits accelerated runoff, severe soil loss, reduced SOC, and nutrient depletion —factors that collectively undermine crop productivity and long-term soil resilience. In contrast, mid-altitude and gentle-slope landscapes support denser vegetation and more favorable soil conditions, although intensive cultivation and land-use pressures can introduce new vulnerabilities.

The review highlights that agronomic risks in ERI are spatially stratified: floodplains face waterlogging and sedimentation, piedmonts experience rill and gully erosion, and upland hills and plateaus tracts are prone to recurrent drought, severe soil erosion, and nutrient translocation. Climatic variability and increases in rainfall intensity under climate change further exacerbate topography-mediated risks, increasing the likelihood of soil degradation, productivity decline, and livelihood instability. The strong altitudinal influence on SOC, micronutrient distribution, soil moisture, bulk density, and vegetation composition underscores the need for location-specific soil and water conservation measures. Due to known complexity of soil-water-plant interactions, assessing agronomic risk through the lens of altitude and slope provides a scientifically robust foundation for designing sustainable land management strategies. Integrating terrain parameters into risk assessment allows for better targeting of interventions such as contour farming, agroforestry, check-dams, and nutrient management tailored to slope positions and elevation zones. Future efforts must also incorporate climate projections, remote sensing tools, and process-based erosion models to anticipate emerging risks and support resilient agricultural planning.

Strengthening research–extension linkages, promoting community-based watershed management, and integrating indigenous traditional knowledge (ITK) with modern technologies will be essential to safeguarding land resources, stabilizing crop yields, and ensuring long-term agricultural sustainability in the ERI. Overall, altitude and slope are not only physical features but critical determinants of agroecosystem functioning in ERI, and addressing associated agronomic risks requires a holistic strategy that combines soil and water conservation, climatic adaptation, sustainable farming practices, community-based watershed management, and the integration of indigenous knowledge with modern technologies to safeguard soil and water resources, stabilize productivity, and ensure long-term agricultural sustainability.

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CONFLICT OF INTEREST

The author declare there is no conflict.

DATA AVAILABILITY STATEMENT

The data generated or analysed during this study are available from the corresponding author upon reasonable request.

AUTHOR'S CONTRIBUTION

Conceptualization, P.J. and A.K.; data collection, P.J., P.K.S. and A.K.; methodology, P.J., A.U. and P.K.S.; resources, A.D. and A.U.; investigation, P.J. and A.K.; validation, P.J. and S.S.M.; writing-original draft preparation, P.J. and P.K.S.; writing-review and editing, P.J., A.U., A.K., S.S.M and P.K.S.; visualization, P.K.S. and A.D.; supervision, P.J.; project administration, A.D. and A.U. All authors have read and agreed to the published version of the manuscript.

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