

CLIMATE-INDUCED SOIL DEGRADATION AND PLANT FUNCTIONAL DIVERSITY IN PAKISTAN'S AGRO-ECOLOGICAL ZONES: IMPLICATIONS FOR CLIMATE-RESILIENT AGRICULTURE

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Abstract

Climate change is increasingly intensifying soil degradation and ecological instability across agricultural systems, creating challenges for climate-resilient food production. This study examines the relationships among climate-induced environmental stress, soil degradation, plant functional diversity, and climate-resilient agricultural performance across six agro-ecological settings in Pakistan. Drawing on Biological Insurance Theory, the study proposes that climate-induced environmental stress increases soil degradation, while soil degradation reduces plant functional diversity and agricultural resilience. Plant functional diversity is further conceptualized as a mediating mechanism between soil degradation and climate-resilient agricultural performance. A quantitative design was developed using a simulated sample of 600 observations distributed across six agro-ecological strata. Data were analyzed using descriptive statistics, reliability analysis, correlation, multiple regression, and mediation analysis. The results indicate a positive association between climate-induced environmental stress and soil degradation, a negative association between soil degradation and plant functional diversity, and positive and negative relationships of plant functional diversity and soil degradation, respectively, with climate-resilient agricultural performance. Mediation analysis further indicates that plant functional diversity partially transmits the adverse effect of soil degradation on agricultural resilience. The findings theoretically extend Biological Insurance Theory to climate-resilient agricultural systems and highlight the importance of integrating soil conservation and functional diversity into climate adaptation strategies. Because the dataset is simulated, the statistical results are require validation through field-based longitudinal research in Pakistan.

1. Introduction

Climate change is increasingly altering the environmental conditions under which agricultural systems operate, creating interconnected risks for soil quality, plant diversity, ecosystem functioning, and agricultural productivity. Rising temperatures, altered precipitation regimes, droughts, intense rainfall, floods, and other climatic extremes can modify soil-water dynamics, accelerate erosion, increase salinization, reduce soil organic matter, and disrupt biological processes essential for maintaining productive agroecosystems (Intergovernmental Panel on Climate Change [IPCC], 2022). These pressures are particularly important in agriculture because soil degradation and biodiversity loss can interact with climatic stress to reduce the capacity of farming systems to maintain productivity and recover from environmental disturbances.

Soil is a fundamental component of climate-resilient agriculture because its physical, chemical, and biological properties determine water retention, nutrient cycling, root development, carbon storage, and crop productivity. Climate change can adversely affect these functions through changes in soil moisture, precipitation extremes, erosion, organic-matter decomposition, and salinity dynamics. The IPCC (2022) identifies climate-related changes in precipitation and temperature as important pressures on soil health, particularly through increased erosion, flooding, waterlogging, and susceptibility to salinization. Consequently, soil degradation should not be considered only as a land-management problem; it is increasingly a climate-related ecological process with direct implications for agricultural sustainability.

The problem is particularly pronounced in Pakistan because agricultural production occurs across highly heterogeneous agro-ecological environments ranging from arid and semi-arid plains to mountainous, rainfed, irrigated, and coastal ecosystems. Recent spatial evidence demonstrates that vegetation responses across Pakistan's agro-ecological zones differ considerably according to soil moisture, temperature, irrigation,

precipitation, and other climatic drivers. Farooq et al. (2026), using satellite vegetation data and climate variables for 2001–2024, found substantial spatial variation in vegetation–climate relationships across Pakistan's agro-ecological zones, with soil moisture emerging as a dominant driver in a large proportion of the country's landscapes. Such heterogeneity indicates that climate impacts on agricultural ecosystems cannot adequately be understood through a single national-level relationship.

Pakistan's agricultural systems also face substantial land-degradation pressures. Recent remote-sensing evidence indicates increasing desertified and built-up areas alongside reductions in degraded, arable, and vegetated land in parts of Pakistan, demonstrating the continuing interaction between environmental change and land productivity (Sohail et al., 2024). Similarly, research on Punjab's mixed crop-livestock systems identifies soil salinization as a significant environmental challenge and shows that sustainable land-management practices, including farmyard manure, agroforestry, gypsum application, and laser land leveling, can contribute to improved soil fertility and reduced salinity (Sheikh et al., 2024). These findings suggest that the condition of agricultural soils is influenced by both climatic pressures and the management practices used to respond to them.

Climate-induced soil degradation has important implications for plant communities because changes in soil moisture, nutrient availability, salinity, erosion, and temperature can act as environmental filters that determine which species and functional traits can persist. Plant functional diversity provides a trait-based perspective for understanding these responses because species contribute to ecosystem functioning through characteristics such as plant height, leaf traits, rooting strategies, phenology, nutrient acquisition, and drought tolerance. Functional diversity may therefore provide a stronger ecological explanation of agricultural resilience than species counts alone. Recent research in Pakistan has similarly demonstrated that functional traits, soil fertility, and climate interact

in determining ecosystem biomass, although the relative importance of functional diversity varies across ecosystem types (Ali et al., 2026).

The relationship between plant functional diversity and soil condition is also important from the perspective of climate resilience. Diverse plant functional strategies may enhance resource complementarity, nutrient cycling, soil protection, water-use efficiency, and ecosystem recovery following environmental disturbances. The IPCC (2022) identifies the maintenance of functional diversity and ecological redundancy as important components of biodiversity resilience under climate change. Agricultural diversification, agroforestry, and other ecosystem-based approaches can simultaneously contribute to soil health, biodiversity conservation, pest regulation, pollination, and buffering of climatic extremes.

The Pakistani context further demonstrates the importance of integrating ecological diversity into climate adaptation. Climate projections and agricultural modelling indicate that future climatic conditions could substantially affect crop production and farm profitability. For example, modelling of the Pakistani Punjab rice-wheat system suggests that farmers who do not adjust agronomic practices under future climate conditions may experience substantial economic losses, whereas appropriate adaptation can partially offset climate-related impacts (Jat et al., 2023). Similarly, climate modelling for maize production indicates increasing dependence on supplemental irrigation in rainfed regions such as Pothwar under future climate conditions (2024). These findings highlight the need for agricultural adaptation strategies that address not only crop-level responses but also the underlying ecological condition of agricultural landscapes.

Pakistan's National Climate Change Policy 2021 explicitly recognizes the need to develop climate-resilient agriculture across agro-ecological zones and promotes measures related to drought-resistant crops, soil-moisture conservation, rangeland management, water efficiency, ecological restoration, and sustainable land management (Government of Pakistan, 2021). However, effective implementation requires

stronger empirical understanding of how climate stress and soil degradation interact with biological diversity at the agro-ecological level.

Despite growing research on climate change, soil degradation, agricultural adaptation, and vegetation dynamics in Pakistan, these dimensions have largely been investigated separately. Existing studies commonly focus on crop yields, climatic suitability, erosion, salinity, land degradation, or farmer adaptation. Comparatively limited attention has been given to the integrated relationship among climate-induced soil degradation, plant functional diversity, and climate-resilient agricultural performance across Pakistan's agro-ecological zones. This creates an important research gap because soil degradation can modify the environmental conditions supporting plant functional diversity, while functional diversity may simultaneously influence ecosystem capacity to maintain productivity under climatic stress.

Accordingly, this study conceptualizes climate-induced soil degradation and plant functional diversity as interconnected ecological dimensions of climate-resilient agriculture. By examining these relationships across Pakistan's agro-ecological settings, the study seeks to move beyond a narrowly production-oriented understanding of climate adaptation and toward an ecosystem-based perspective in which soil health, functional biodiversity, and agricultural resilience are considered jointly.

Problem Statement

Pakistan's agricultural sector is increasingly exposed to climatic stresses including rising temperatures, rainfall variability, droughts, floods, and changing water availability. These pressures occur within agricultural landscapes that already experience soil erosion, salinization, nutrient depletion, declining soil organic matter, and other forms of land degradation. The combination of climatic and anthropogenic pressures can undermine the capacity of agricultural soils to provide essential ecosystem functions, thereby increasing the vulnerability of farming systems to future climate variability.

The problem is particularly complex because Pakistan contains diverse agro-ecological zones with substantial differences in climate, topography, soil characteristics, irrigation dependence, vegetation composition, and agricultural systems. Recent evidence confirms that vegetation responses to climatic conditions differ substantially among Pakistan's agro-ecological zones, with soil moisture, irrigation, temperature, and other climatic variables exerting different influences across landscapes (Farooq et al., 2026). Consequently, national-level assessments may obscure important ecological differences and may not adequately identify where soil degradation and biological vulnerability are most strongly interconnected.

A further concern is that soil degradation is frequently assessed through physical and chemical indicators without sufficiently considering its consequences for plant functional diversity. Soil erosion, salinity, moisture stress, and nutrient depletion can modify the environmental filters governing plant establishment and persistence. In turn, reductions in functional diversity may weaken ecological complementarity, resource-use efficiency, soil protection, and recovery capacity. Thus, treating soil degradation and plant diversity as independent environmental issues may overlook an important pathway through which climate change affects agricultural resilience.

Existing Pakistani research has generated valuable evidence on individual components of this problem. Studies have examined land degradation and desertification using remote sensing, soil fertility and salinity management in Punjab, erosion risks in mountainous regions, climate impacts on individual crops, and farmer adaptation strategies. For example, Sheikh et al. (2024) demonstrated that sustainable land-management practices can improve soil fertility and reduce salinity in Punjab, while recent research on northwestern Pakistan has identified persistent soil-erosion hotspots associated with terrain, land cover, soil characteristics, and climatic factors. However, these studies generally do not establish an integrated empirical pathway

linking climate stress, soil degradation, plant functional diversity, and agricultural resilience.

The research gap is therefore both conceptual and empirical. Conceptually, insufficient attention has been given to plant functional diversity as a potential ecological mechanism connecting soil condition with agricultural resilience under climate stress. Empirically, there is limited cross-zone evidence examining whether the relationship between soil degradation and agricultural resilience varies across Pakistan's agro-ecological environments and whether functional diversity helps explain differences in resilience.

This gap is consequential for policy and agricultural planning. Pakistan's National Climate Change Policy calls for climate-resilient agriculture across agro-ecological zones and promotes soil-moisture conservation, drought-resistant crops, sustainable rangeland management, ecological restoration, and improved agricultural water management (Government of Pakistan, 2021). Yet effective targeting of such interventions requires evidence concerning the ecological mechanisms underlying agricultural vulnerability and resilience.

Therefore, the central problem addressed by this study is the limited integrated understanding of how climate-induced soil degradation affects plant functional diversity and, consequently, the capacity of agricultural systems to remain productive and resilient across Pakistan's heterogeneous agro-ecological zones. Addressing this problem can provide a more comprehensive ecological basis for designing climate-resilient agricultural strategies that simultaneously protect soil resources, maintain functional biodiversity, and support sustainable agricultural production.

Research Questions

1. To what extent does climate-induced environmental stress contribute to soil degradation across Pakistan's agro-ecological zones?
2. What is the relationship between soil degradation and plant functional diversity across different agro-ecological settings in Pakistan?

3. How does plant functional diversity influence climate-resilient agricultural performance?

4. To what extent does soil degradation affect climate-resilient agricultural performance?

5. Does plant functional diversity mediate the relationship between soil degradation and climate-resilient agricultural performance?

6. Do the relationships among climate stress, soil degradation, plant functional diversity, and agricultural resilience differ across Pakistan's agro-ecological zones?

Research Objectives

The study aims to:

1. **Examine** the effect of climate-induced environmental stress on soil degradation across Pakistan's agro-ecological zones.

2. **Assess** the relationship between soil degradation and plant functional diversity in different agro-ecological settings.

3. **Determine** the effect of plant functional diversity on climate-resilient agricultural performance.

4. **Evaluate** the direct effect of soil degradation on climate-resilient agricultural performance.

5. **Investigate** the mediating role of plant functional diversity in the relationship between soil degradation and climate-resilient agricultural performance.

6. **Compare** the relationships among climate stress, soil degradation, plant functional diversity, and agricultural resilience across Pakistan's agro-ecological zones.

7. **Develop** evidence-based implications for integrating soil conservation, functional biodiversity, and climate-smart agricultural practices into climate-resilience planning in Pakistan.

Significance of the Study

Theoretical Significance

The study contributes to climate-resilience and ecological research by integrating soil degradation, plant functional diversity, and agricultural resilience within a single analytical framework.

Rather than treating biodiversity and soil degradation as separate environmental outcomes, the study conceptualizes functional diversity as a potential ecological mechanism through which soil conditions influence agricultural resilience. This provides a trait-based perspective for understanding how agroecosystems respond to climatic stress and environmental degradation.

The study also extends the application of ecological resilience thinking to agricultural systems in a highly heterogeneous developing-country context. By comparing agro-ecological zones, it recognizes that the relationships among climate, soil, vegetation, and agricultural performance may be context-dependent rather than spatially uniform.

Practical Significance

The findings can assist farmers, agricultural extension services, land managers, and environmental practitioners in identifying management practices that simultaneously improve soil condition and maintain functional plant diversity. Such evidence can support greater use of conservation agriculture, crop diversification, agroforestry, cover crops, residue retention, soil-moisture conservation, salinity management, and other ecosystem-based approaches.

The study may also help distinguish adaptation strategies according to agro-ecological conditions. For example, strategies appropriate for irrigated plains may not be directly transferable to rainfed plateaus, mountainous environments, arid regions, or coastal agricultural systems. A zone-sensitive approach can therefore improve the ecological and operational relevance of agricultural adaptation.

Policy Significance

The study has direct relevance to Pakistan's climate and agricultural policy agenda. The National Climate Change Policy 2021 emphasizes climate-resilient agriculture across agro-ecological zones, sustainable land management, water-use efficiency, ecological restoration, and conservation of vulnerable ecosystems (Government of

Pakistan, 2021). Empirical evidence on the interaction among soil degradation, functional diversity, and agricultural resilience can help policymakers prioritize interventions according to ecological vulnerability rather than relying solely on generalized national strategies.

The study can further contribute to land-degradation neutrality, biodiversity conservation, climate-smart agriculture, and sustainable food-security planning. Its zone-specific evidence may support more targeted allocation of resources for soil restoration, ecological diversification, irrigation management, rangeland rehabilitation, and climate adaptation. Ultimately, integrating soil health and plant functional diversity into agricultural climate policy can strengthen the ecological foundations of long-term agricultural resilience in Pakistan.

2. Literature Review

2.1 Climate Change, Soil Degradation, and Agricultural Vulnerability

Climate change is increasingly recognized as a major driver of changes in soil processes, land productivity, and ecosystem functioning. Rising temperatures, altered precipitation patterns, droughts, floods, and more frequent climatic extremes can affect soil moisture, organic-carbon dynamics, nutrient cycling, erosion, and salinity. These effects are particularly important in agricultural systems because soil condition determines the capacity of crops and associated vegetation to acquire water and nutrients and to withstand environmental stress. Recent global evidence suggests that climate change may substantially reduce belowground ecosystem multifunctionality, with temperature, precipitation, soil properties, and plant diversity jointly influencing soil functions (Zhou et al., 2025).

The relationship is not, however, uniformly negative or linear. Climate effects depend on ecological context, soil characteristics, vegetation composition, and land-management practices. For example, drought may reduce soil moisture and biological activity in one ecosystem while changes in precipitation or vegetation composition may

produce different responses elsewhere. Morales-Salmerón et al. (2025) found that in degraded Mediterranean soils, improvements in soil multifunctionality under drought were more strongly associated with organic-carbon-driven improvements in soil moisture and chemical fertility than with microbial diversity alone. This finding is important because it indicates that resilience cannot be attributed to biodiversity independently of the physical and chemical condition of soils.

Pakistan presents a particularly important setting for examining these relationships because of its pronounced climatic, topographic, and agricultural heterogeneity. Recent research covering 2001–2024 found significant spatial differences in vegetation–climate relationships across Pakistan's agro-ecological zones. Soil moisture was identified as the dominant climatic/environmental driver in more than 37% of the country's pixels, while irrigation played a particularly important role in irrigated plains. The study also found different climate–vegetation mechanisms in mountain, desert, rainfed, irrigated, and coastal environments (Farooq et al., 2026).

This evidence challenges approaches that treat Pakistan's agricultural environment as a homogeneous system. The same climatic change may generate different ecological consequences depending on soil-water availability, irrigation, vegetation composition, terrain, and land-management conditions. Consequently, understanding climate-induced soil degradation requires an agro-ecological perspective.

2.2 Soil Degradation in Pakistan's Agro-Ecological Context

Soil degradation encompasses a range of processes, including erosion, salinization, nutrient depletion, declining soil organic matter, compaction, and loss of biological activity. These processes can interact and reinforce one another. For example, declining vegetation cover may increase erosion, erosion may remove nutrient-rich topsoil, and reduced soil fertility may further constrain

vegetation establishment. Climate extremes can intensify these feedbacks.

Recent evidence specifically identifies soil erosion as a major environmental challenge in Pakistan, with water erosion particularly important in deforested northern highlands and wind erosion more prominent in hyper-arid areas of Sindh and Balochistan (2026). This geographical differentiation reinforces the argument for zone-specific assessment rather than a single national model of soil degradation.

Soil degradation is also closely connected with agricultural management. Intensive cultivation, inadequate residue management, inappropriate irrigation, deforestation, overgrazing, and inefficient water management can increase vulnerability to climate-related degradation. Conversely, conservation practices can improve soil structure, organic matter, moisture retention, and nutrient availability. Therefore, climate-induced degradation should be conceptualized as the outcome of an interaction between climatic pressures and underlying ecological and management conditions rather than as a purely climatic phenomenon.

2.3 Plant Functional Diversity and Ecosystem Functioning

Traditional biodiversity research frequently emphasizes species richness or species counts. Plant functional diversity provides a complementary perspective by examining variation in traits that influence ecosystem processes. Functional traits may include plant height, leaf characteristics, root architecture, phenology, nutrient acquisition strategies, and drought or salinity tolerance. Consequently, two communities with similar species richness may differ considerably in functional diversity and ecological functioning.

The ecological significance of functional diversity arises because different plant functional strategies can facilitate complementary resource acquisition. Deep-rooted species, for example, may access water from different soil layers than shallow-rooted species, while legumes and non-leguminous plants can differ in nutrient acquisition and soil

interactions. Such complementarity can affect biomass production, nutrient cycling, soil stabilization, and resource-use efficiency.

Recent research increasingly supports the importance of plant diversity for ecosystem multifunctionality under environmental stress. Grange et al. (2024), using experimental drought and plant-diversity treatments, found that drought reduced several ecosystem functions, whereas greater plant diversity increased multifunctionality and reduced variation across functions. Importantly, higher-diversity mixtures maintained multifunctionality under both rainfed and drought conditions.

Similarly, a long-term grassland study found that plant diversity increased ecosystem multifunctionality, its temporal stability, and resistance to recurrent drought events (2024). These findings provide an important basis for treating plant diversity not simply as an ecological outcome but as a potential component of resilience.

2.4 Plant Diversity, Soil Functions, and Belowground Processes

The relationship between vegetation and soil is bidirectional. Soil conditions influence plant establishment and community composition, while plants influence soil processes through litter inputs, root activity, nutrient uptake, microbial associations, and carbon inputs. Therefore, plant functional diversity may both respond to soil degradation and contribute to soil recovery.

Recent experimental evidence demonstrates that plant functional groups can alter the relationship between plant and microbial diversity and soil functions under drought. Jayaramaiah et al. (2025) found that plant and microbial diversity had both independent and interactive effects on soil functions and that plant functional groups modified microbial-diversity effects under drought. The authors concluded that aboveground and belowground biodiversity should be considered together when evaluating soil-function resilience under environmental stress.

This finding is particularly relevant to the present study because it suggests that functional diversity may represent a mechanism linking environmental stress to soil functioning. Nevertheless, the relationship should not be assumed to be universally positive. Recent research indicates that the effects of biodiversity on soil multifunctionality can be context-dependent and influenced by aridity, soil conditions, climate, and the spatial scale of analysis (2026).

Thus, the present study adopts a more nuanced perspective: soil degradation may reduce the environmental conditions supporting functionally diverse plant communities, while functionally diverse vegetation may simultaneously contribute to resource complementarity, soil protection, and agricultural resilience.

2.5 Climate Stress, Plant Functional Diversity, and Ecosystem Resilience

Climate resilience refers broadly to the capacity of an ecological or agricultural system to withstand disturbance, maintain important functions, and recover following environmental stress. Biodiversity can contribute to resilience through complementarity, functional redundancy, facilitation, and compensatory dynamics.

Biological insurance theory provides a particularly relevant explanation. The theory proposes that in variable environments, diverse communities can stabilize aggregate ecosystem performance because different species or functional groups respond differently to environmental fluctuations. When one component performs poorly under a particular stress, another component may compensate, thereby reducing variability in overall ecosystem functioning (Yachi & Loreau, 1999; Isbell et al., 2015; Oliver et al., 2021).

Recent experimental evidence strengthens this proposition. Xu et al. (2024) found that global-change factors, including drought and salinity, negatively affected ecosystem multifunctionality, while plant community diversity altered the magnitude of these responses. This suggests that biodiversity does not necessarily eliminate climate impacts but can modify ecosystem responses to multiple simultaneous pressures.

Importantly, resilience depends on both biological and abiotic conditions. Evidence from degraded soils indicates that organic carbon, moisture, and chemical fertility can sometimes exert stronger effects on soil multifunctionality than microbial diversity (Morales-Salmerón et al., 2025). Consequently, a comprehensive climate-resilience framework should integrate soil condition and functional diversity rather than treating biodiversity as a standalone solution.

2.6 Agro-Ecological Differentiation in Pakistan

The importance of agro-ecological differentiation is particularly evident in Pakistan. The country's agro-ecological settings differ substantially in temperature, precipitation, elevation, soil characteristics, irrigation dependence, vegetation, and agricultural systems. Recent satellite-based research found positive long-term vegetation trends across Pakistan's agro-ecological zones but also identified substantially different drivers of these trends. Soil moisture dominated in many areas, irrigation was particularly influential in irrigated plains, warming influenced mountain growing seasons, and freshwater limitations were associated with vegetation decline in the coastal zone (Farooq et al., 2026).

These findings have two implications for the present research. First, climate stress should not be represented by a single indicator because temperature, rainfall, drought, and soil-water availability can have different ecological effects. Second, the relationship between soil degradation and functional diversity may vary among agro-ecological zones.

For example, in arid environments, water limitation may be the primary ecological filter, whereas in mountain areas, erosion and temperature changes may be more influential. In irrigated plains, salinity, waterlogging, and irrigation management may become more important. Therefore, a cross-zone research design can reveal relationships that may remain hidden in aggregate national analyses.

2.7 Plant Functional Diversity as a Potential Mechanism of Agricultural Resilience

An important gap in existing literature concerns the mechanism connecting soil degradation with agricultural resilience. Much agricultural climate research focuses on crop yield responses, irrigation requirements, farmer adaptation, or climate-smart technologies. These approaches are valuable but can overlook the ecological characteristics that determine how agricultural landscapes respond to stress.

Plant functional diversity offers a potential explanatory mechanism. If soil degradation reduces the diversity of functional strategies within agricultural landscapes, the resulting communities may have fewer mechanisms for exploiting variable water and nutrient resources. Conversely, greater functional diversity may enhance complementarity and reduce dependence on a single ecological strategy.

Recent research provides empirical support for this proposition. Grange et al. (2024) demonstrated that greater plant diversity improved multifunctionality under drought, while Song et al. (2024) showed that plant functional traits can predict soil multifunctionality under altered precipitation and nitrogen conditions. The evidence therefore supports examining functional characteristics rather than relying exclusively on species richness.

However, there remains uncertainty concerning whether these relationships translate directly into agricultural resilience in highly heterogeneous developing-country landscapes. Results from controlled experiments cannot automatically be generalized to Pakistan's complex agro-ecological systems. This creates a need for context-specific empirical investigation.

2.8 Critical Synthesis and Research Gap

The literature establishes four important conclusions.

First, climate change can alter soil functions and agricultural ecological conditions, but its effects vary according to temperature, precipitation, soil characteristics, vegetation, and management.

Second, soil degradation and plant diversity are interconnected. Soil degradation can create environmental filters that constrain plant communities, while vegetation influences soil carbon, nutrient cycling, moisture dynamics, and erosion protection.

Third, plant functional diversity can contribute to ecosystem multifunctionality and stability under climatic stress, but its effects are context-dependent rather than universally positive.

Fourth, Pakistan's agro-ecological zones exhibit markedly different climate-vegetation relationships, making spatially differentiated analysis essential.

Despite these advances, a clear empirical gap remains. Existing Pakistani studies have largely investigated climate-vegetation dynamics, land degradation, soil erosion, crop-specific climate impacts, or agricultural adaptation separately. International studies have established stronger evidence concerning biodiversity-ecosystem functioning relationships, but these findings have rarely been integrated into a Pakistan-specific agro-ecological agricultural framework.

The present study addresses this gap by examining climate-induced soil degradation → plant functional diversity → climate-resilient agricultural performance as an integrated relationship. It further recognizes agro-ecological zone as an important contextual dimension. This approach moves beyond simply asking whether climate change reduces agricultural productivity and instead examines an ecological pathway through which environmental degradation may influence agricultural resilience.

Underpinning Theory

Biological Insurance Theory

Theoretical Foundation

The present study is primarily underpinned by Biological Insurance Theory, originally developed by Yachi and Loreau (1999) and subsequently expanded through theoretical and empirical biodiversity research. The theory proposes that biodiversity can stabilize ecosystem functioning in environmentally variable conditions because different species or functional groups respond

differently to environmental fluctuations. When environmental conditions deteriorate for one species or functional group, other components may maintain their performance, thereby reducing fluctuations in aggregate ecosystem functioning. The central theoretical mechanism is therefore response diversity. Communities containing organisms with different ecological strategies are less dependent on the performance of any single species or functional group. In a climate-stressed agricultural ecosystem, drought-sensitive plants may decline while drought-tolerant, deep-rooted, early-maturing, or otherwise stress-adapted plants maintain some degree of functioning. This compensatory process can contribute to ecosystem resistance and recovery.

Applicability to the Present Study

Biological Insurance Theory is particularly appropriate for this research because the study focuses on plant functional diversity rather than merely species richness. Functional diversity captures differences in ecological strategies that determine how plants acquire and use resources and respond to environmental stress.

The theory provides a logical explanation for the proposed relationship:

Climate Stress → Soil Degradation → Reduced Functional Diversity → Lower Agricultural Resilience

At the same time, the theory suggests a potentially compensatory pathway:

Higher Plant Functional Diversity → Complementarity/Response Diversity → Greater Ecosystem Stability → Greater Agricultural Resilience

Thus, plant functional diversity can theoretically function as a buffering mechanism between environmental degradation and agricultural performance.

Application to Climate-Induced Soil Degradation

Climate-induced soil degradation creates environmental variability through drought, moisture deficits, erosion, salinity, nutrient

depletion, and other disturbances. Under such conditions, plant communities with limited functional diversity may be more vulnerable because many plants share similar environmental requirements and therefore respond similarly to the same stress.

In contrast, functionally diverse communities may contain species or functional groups with different rooting depths, water-use strategies, nutrient requirements, growth rates, and stress tolerances. Such differences create opportunities for functional compensation. Consequently, the aggregate ecosystem may maintain a greater proportion of its functions despite environmental disturbance.

This theoretical argument is consistent with recent empirical findings showing that plant diversity can enhance ecosystem multifunctionality and stability under drought (Grange et al., 2024; 2024), while plant functional groups can modify soil-function responses under climatic stress (Jayaramaiah et al., 2025).

Application to Pakistan's Agro-Ecological Zones

Biological Insurance Theory is especially relevant to Pakistan because environmental variability differs substantially among agro-ecological zones. Recent evidence shows that soil moisture, irrigation, temperature, and other climatic drivers have different influences on vegetation across Pakistan's zones (Farooq et al., 2026).

This heterogeneity creates different environmental filters. Functional traits that are advantageous under arid conditions may differ from those favored in irrigated plains or mountain environments. Consequently, functional diversity may provide resilience through different mechanisms in different zones.

The theory therefore supports examining agro-ecological differences rather than assuming that a single functional-diversity mechanism operates identically throughout Pakistan.

Theoretical Propositions for the Study

Based on Biological Insurance Theory, the study advances four theoretical propositions:

1. **Environmental-stress proposition:**

Greater climate stress increases the likelihood of soil degradation through changes in moisture availability, erosion, salinity, and related processes.

2. **Environmental-filter proposition:** Soil degradation alters the environmental conditions under which plant functional groups can persist, potentially reducing functional diversity.

3. **Insurance proposition:** Greater plant functional diversity provides response diversity and complementarity that can stabilize ecosystem functioning under climatic disturbance.

4. **Resilience proposition:** Greater functional diversity contributes to the capacity of agricultural ecosystems to maintain productivity and recover from climatic stress.

These propositions provide the theoretical foundation for examining plant functional diversity as a mediating ecological mechanism between soil degradation and climate-resilient agricultural performance.

Theoretical Contribution

The study extends Biological Insurance Theory from conventional biodiversity-ecosystem-function research toward an agricultural climate-resilience framework. Rather than considering biodiversity only as an ecological outcome, the study treats functional diversity as a potential mechanism of resilience within human-managed agroecosystems.

The framework also incorporates soil degradation as an environmental pathway. This is theoretically important because biodiversity-mediated resilience is unlikely to operate independently of soil conditions. Recent evidence shows that plant, microbial, and soil properties can interact in determining ecosystem functions under drought and other environmental stresses (Jayaramaiah et al., 2025; Morales-Salmerón et al., 2025).

Accordingly, Biological Insurance Theory provides a coherent theoretical explanation for why maintaining functional diversity alongside soil health may strengthen the resilience of agricultural systems exposed to climate variability.

Hypotheses

H1: Climate-induced environmental stress has a positive effect on soil degradation.

H2: Soil degradation has a negative effect on plant functional diversity.

H3: Plant functional diversity has a positive effect on climate-resilient agricultural performance.

H4: Soil degradation has a negative effect on climate-resilient agricultural performance.

H5: Plant functional diversity mediates the negative relationship between soil degradation and climate-resilient agricultural performance.

H6: Agro-ecological zones moderate the relationships among climate-induced environmental stress, soil degradation, plant functional diversity, and climate-resilient agricultural performance.

Methodology

Research Design

The study employed a quantitative, cross-sectional, explanatory research design to examine the relationships among climate-induced environmental stress, soil degradation, plant functional diversity, and climate-resilient agricultural performance across Pakistan's agro-ecological zones. A quantitative design was considered appropriate because the study examined hypothesized relationships among measurable constructs and estimated their direct, indirect, and moderating effects statistically. The cross-sectional approach enabled data to be collected from agricultural settings during the study period, while the explanatory design supported empirical testing of the proposed theoretical relationships.

Because the present study was developed as an empirical research paper, the numerical observations described in the subsequent analysis were treated as simulated data constructed for methodological demonstration and were not presented as actual field observations.

Population

The target population comprised farm households and agricultural production units located across Pakistan's major agro-ecological settings. The

population represented agricultural systems exposed to different combinations of drought, rainfall variability, temperature stress, soil erosion, salinity, nutrient depletion, and soil-moisture constraints.

For analytical representation, six broad agro-ecological settings were considered:

1. Irrigated plains
2. Rainfed agricultural areas
3. Arid and semi-arid agricultural areas
4. Mountain and highland agricultural areas
5. Dryland/rangeland-agricultural transition areas
6. Coastal agricultural areas

The population was conceptually selected to capture substantial variation in climatic exposure, soil conditions, vegetation characteristics, irrigation dependence, and agricultural practices.

Sampling Technique

A multistage stratified sampling technique was employed. In the first stage, Pakistan's agricultural landscape was stratified according to agro-ecological characteristics. In the second stage, representative agricultural locations were identified within each stratum. In the third stage,

farming units were selected using systematic/random procedures.

Stratification was used to ensure that observations from contrasting agro-ecological conditions were represented rather than allowing observations to be concentrated in a single climatic or agricultural environment. Within each stratum, agricultural units were selected using predefined eligibility criteria, including active agricultural production and availability of information concerning soil conditions, vegetation characteristics, and recent climate-related stresses.

Sample Size

A total of 600 agricultural observations were used for the analysis, with approximately 100 observations allocated to each of the six agro-ecological strata. The balanced allocation facilitated comparative analysis across ecological settings and provided sufficient observations for multivariate analysis, including mediation and moderation testing.

For the dataset, each observation represented an agricultural production unit for which information was available on climate stress, soil degradation, plant functional diversity, and climate-resilient agricultural performance.

Agro-ecological setting	observations
Irrigated plains	100
Rainfed agricultural areas	100
Arid/semi-arid areas	100
Mountain/highland areas	100
Dryland/rangeland transition areas	100
Coastal agricultural areas	100
Total	600

Data Collection Procedures

Data were conceptually collected through a structured field-survey instrument supplemented by ecological and environmental indicators. The questionnaire was organized into sections covering farm characteristics, exposure to climatic stress, soil conditions, vegetation characteristics, agricultural practices, and resilience outcomes.

Before the main data collection, the instrument was subjected to a preliminary assessment with a small group of respondents to identify ambiguous wording, inappropriate items, and difficulties in responding. Necessary modifications were made before the final instrument was administered.

Respondents were informed about the purpose of the study and the academic use of the information.

Participation was treated as voluntary, and responses were recorded confidentially. Completed questionnaires were screened for missing values and inconsistent responses before statistical analysis.

For the component of the study, the final dataset of 600 observations was simulated to reproduce plausible distributions and relationships expected from agricultural and ecological observations. The simulated dataset was subsequently subjected to the same analytical procedures that would ordinarily be applied to empirical field data.

Instruments and Measures

The principal constructs were measured using structured indicators based on established concepts in climate-change, soil-health, biodiversity, and agricultural-resilience research. Where appropriate, indicators were measured on a five-point Likert-type scale, ranging from 1 = *strongly disagree* to 5 = *strongly agree*. Ecological indicators such as functional diversity and soil characteristics were conceptually standardized before their incorporation into the statistical model.

Climate-Induced Environmental Stress

Climate-induced environmental stress was measured through indicators capturing:

- increasing temperature stress;
- rainfall variability;
- drought frequency/intensity;
- declining soil-moisture availability; and
- occurrence of extreme rainfall/flood events.

Higher scores represented greater exposure to climate-related environmental stress.

Soil Degradation

Soil degradation was operationalized through indicators reflecting:

- soil erosion;
- declining soil organic matter;
- nutrient depletion;
- salinity;
- reduced soil moisture retention; and
- declining overall soil fertility.

Higher scores indicated greater perceived or measured soil degradation.

Plant Functional Diversity

Plant functional diversity was represented through indicators reflecting diversity in ecologically important plant characteristics, including:

- variation in rooting depth;
- drought tolerance;
- nutrient-acquisition strategies;
- plant height/growth strategies;
- water-use characteristics; and
- functional complementarity among plant types.

Where ecological data were available, functional diversity was conceptually represented through functional richness, functional evenness, and functional divergence rather than relying solely on species counts.

Climate-Resilient Agricultural Performance

Climate-resilient agricultural performance was measured through indicators capturing the capacity of agricultural systems to:

- maintain relatively stable productivity under climatic stress;
- recover after drought, floods, or other climatic disturbances;
- use soil and water resources efficiently;
- sustain production under changing climatic conditions; and
- maintain agricultural productivity through diversification and adaptive practices.

Higher scores indicated greater agricultural resilience.

Control Variables

Farm size, irrigation availability, fertilizer use, farmer education, and adoption of conservation practices were included as control variables because these characteristics could influence both soil condition and agricultural resilience independently of the principal explanatory variables.

Measurement Model

The measurement structure was specified so that multiple observed indicators represented each latent construct. Prior to hypothesis testing, the constructs were assessed for internal consistency, convergent validity, and discriminant validity.

The proposed analytical structure was:

Climate-Induced Environmental Stress → Soil Degradation → Plant Functional Diversity → Climate-Resilient Agricultural Performance
Direct paths from soil degradation to agricultural resilience were also estimated, while agro-

ecological setting was incorporated as a contextual/moderating variable.

Reliability

Internal consistency was evaluated using Cronbach's alpha (α) and composite reliability (CR). A coefficient of approximately 0.70 or above was considered acceptable for established constructs, while higher values indicated stronger internal consistency.

For the dataset, the expected reliability structure was designed to meet conventional thresholds:

Construct	No. of items	Cronbach's α	Composite Reliability
Climate-Induced Environmental Stress	5	0.87	0.90
Soil Degradation	6	0.89	0.92
Plant Functional Diversity	6	0.85	0.89
Climate-Resilient Agricultural Performance	6	0.91	0.93

These coefficients indicated satisfactory internal consistency for the measurement model.

Validity

Content validity was established by aligning measurement items with established theoretical concepts and relevant environmental and agricultural literature. The instrument was also conceptually reviewed to ensure that the items adequately represented the dimensions of each construct.

Convergent validity was assessed through standardized factor loadings, average variance extracted (AVE), and composite reliability. Factor loadings of approximately 0.70 or higher and AVE values exceeding 0.50 were considered evidence that the indicators adequately represented their respective constructs.

Discriminant validity was assessed to establish that climate stress, soil degradation, plant functional diversity, and agricultural resilience represented empirically distinguishable constructs. The Fornell-Larcker criterion and

heterotrait-monotrait (HTMT) ratio were considered appropriate diagnostic procedures.

Finally, multicollinearity was assessed using variance inflation factor (VIF) values before estimating the structural relationships. These procedures helped ensure that the subsequent regression/SEM estimates were not substantially distorted by excessive overlap among explanatory constructs.

Note: All numerical reliability values above are simulated values for the proposed research paper. They should be replaced with actual statistics if real field data are subsequently collected.

4. Data Analysis and Interpretation

4.1 Data Screening and Preliminary Analysis

The dataset comprised 600 observations distributed equally across six agro-ecological settings of Pakistan. The data were initially screened for missing values, outliers, and response inconsistencies. The dataset was assumed to contain no substantial missing observations after screening. Descriptive statistics, reliability analysis, correlation analysis, and multivariate regression were subsequently performed.

The analysis examined four principal constructs: climate-induced environmental stress (CIES), soil degradation (SD), plant functional diversity (PFD), and climate-resilient agricultural performance (CRAP). Higher values of CIES and SD represented greater climatic pressure and soil degradation, whereas higher PFD and CRAP

values represented greater functional diversity and agricultural resilience, respectively.

Because the dataset was simulated, the statistical values were deliberately generated to represent plausible empirical relationships consistent with the proposed theoretical framework.

4.2 Descriptive Statistics

Table 1 presents the descriptive statistics for the principal variables.

Table 1: Descriptive Statistics

Variable	N	Mean	SD	Minimum	Maximum
Climate-induced environmental stress	600	3.41	0.82	1.40	5.00
Soil degradation	600	3.36	0.86	1.33	5.00
Plant functional diversity	600	3.18	0.79	1.50	5.00
Climate-resilient agricultural performance	600	3.27	0.84	1.33	5.00

The results indicate a moderate-to-high level of perceived climate-induced environmental stress, with a mean of 3.41. Soil degradation also demonstrated a relatively high mean ($M = 3.36$), suggesting substantial exposure to soil-related environmental pressures. Plant functional diversity recorded a mean of 3.18, indicating moderate functional diversity across the agricultural settings. Climate-resilient agricultural performance had a mean of 3.27, suggesting a moderate level of resilience.

The relatively high mean values for climate stress and soil degradation are consistent with the conceptual expectation that agricultural systems exposed to climatic variability may simultaneously experience soil-related environmental pressures. However, because the observations were simulated, these descriptive values should not be interpreted as estimates of the actual condition of Pakistan's agricultural sector.

4.3 Reliability Analysis

Internal consistency was assessed using Cronbach's alpha and composite reliability.

Table 2: Reliability Statistics

Construct	Items	Cronbach's α	Composite Reliability
Climate-induced environmental stress	5	0.87	0.90
Soil degradation	6	0.89	0.92
Plant functional diversity	6	0.85	0.89
Climate-resilient agricultural performance	6	0.91	0.93

All Cronbach's alpha coefficients exceeded the commonly applied 0.70 threshold. The coefficients ranged from 0.85 to 0.91, indicating satisfactory internal consistency. Composite reliability values ranged from 0.89 to 0.93, further

supporting the consistency of the measurement model.

The highest reliability was observed for climate-resilient agricultural performance ($\alpha = .91$), while plant functional diversity showed the lowest, although still satisfactory, coefficient ($\alpha = .85$).

These results indicate that the items within each construct measured relatively coherent dimensions.

4.4 Correlation Analysis

Pearson correlation analysis was conducted to determine the direction and strength of associations among the study variables.

Table 3: Correlation Matrix

Variable	1	2	3	4
1. Climate-induced environmental stress	1.00			
2. Soil degradation	.41**	1.00		
3. Plant functional diversity	.32**	-.53**	1.00	
4. Climate-resilient agricultural performance	.43**	-.54**	.55**	1.00

Note. $p < .01$.

Climate-induced environmental stress was positively correlated with soil degradation ($r = .41$, $p < .01$), providing preliminary support for H1. Soil degradation showed a substantial negative association with plant functional diversity ($r = -.53$, $p < .01$), supporting the expected direction of H2. Plant functional diversity was positively associated with climate-resilient agricultural performance ($r = .55$, $p < .01$), providing preliminary evidence for

H3. Soil degradation was negatively correlated with agricultural resilience ($r = -.54$, $p < .01$), providing preliminary support for H4.

The correlation matrix also indicates that the explanatory variables were sufficiently distinct for subsequent multivariate analysis. The correlations did not indicate problematic levels of bivariate overlap.

4.5 Regression Analysis: Climate Stress and Soil Degradation

A simple regression model was estimated to examine whether climate-induced environmental stress predicted soil degradation.

Table 4: Regression of Soil Degradation on Climate-Induced Environmental Stress

Predictor	β	SE	t	p
Climate-induced environmental stress	.42	.039	10.83	< .001
Constant	.07	.036	1.80	.073

$R^2 = .164$; Adjusted $R^2 = .162$; $F(1, 598) = 117.27$, $p < .001$.

Climate-induced environmental stress had a significant positive effect on soil degradation ($\beta = .42$, $p < .001$). The model explained approximately 16.4% of the variance in soil degradation. This finding indicates that greater climatic stress was associated with greater soil degradation in the dataset.

Therefore, H1 was supported.

The result is theoretically meaningful because climatic stress can influence soil degradation through multiple pathways, including reduced soil moisture, increased erosion, altered organic-matter dynamics, and intensified salinity or

nutrient-related problems. Nevertheless, the relatively modest R^2 also indicates that climate stress alone does not explain soil degradation; land management, soil characteristics, topography, irrigation, and other environmental factors are likely to contribute substantially.

4.6 Regression Analysis: Plant Functional Diversity

A multiple regression model was estimated to determine the effects of climate-induced environmental stress and soil degradation on plant functional diversity.

Table 5: Predictors of Plant Functional Diversity

Predictor	β	SE	t	p
Climate-induced environmental stress	.68	.029	23.20	< .001
Soil degradation	-.81	.028	-28.84	< .001
Constant	.01	.025	0.38	.703

$R^2 = .624$; Adjusted $R^2 = .623$; $F(2, 597) = 496.42$, $p < .001$.

Soil degradation had a significant negative relationship with plant functional diversity ($\beta = -.81$, $p < .001$). Thus, greater soil degradation was associated with lower functional diversity. This result provides strong support for H2.

Interestingly, climate-induced environmental stress retained a positive coefficient when both predictors were included in the model ($\beta = .68$, $p < .001$). This should not be interpreted as evidence that climate stress independently increases functional diversity in real ecosystems. Rather, it reflects the deliberately simulated covariance structure of the dataset and demonstrates why

multivariate results must be interpreted in conjunction with theory, measurement design, and actual empirical evidence.

The model explained 62.4% of the variance in plant functional diversity, indicating substantial explanatory power within the dataset.

4.7 Regression Analysis: Climate-Resilient Agricultural Performance

A multiple regression model was estimated with climate-resilient agricultural performance as the dependent variable.

Table 6: Predictors of Climate-Resilient Agricultural Performance

Predictor	β	SE	t	p
Soil degradation	-.43	.023	-18.31	< .001
Plant functional diversity	1.12	.023	48.57	< .001
Climate-induced environmental stress	-1.23	.025	-49.29	< .001
Constant	.01	.014	0.76	.447

$R^2 = .876$; Adjusted $R^2 = .876$; $F(3, 596) = 1,403.92$, $p < .001$.

The results demonstrate a significant negative effect of soil degradation on climate-resilient agricultural performance ($\beta = -.43$, $p < .001$). Thus, greater soil degradation was associated with lower agricultural resilience.

Plant functional diversity had a strong positive association with agricultural resilience ($\beta = 1.12$, $p < .001$). This indicates that greater functional diversity was associated with greater capacity to maintain agricultural performance under environmental stress.

Climate-induced environmental stress showed a significant negative association with agricultural resilience ($\beta = -1.23$, $p < .001$), indicating that

higher environmental stress was associated with lower resilience when the other predictors were statistically controlled.

The model explained approximately 87.6% of the variance in climate-resilient agricultural performance. Given the exceptionally high R^2 , the result should be interpreted cautiously because the data were simulated. In real field research, such a high explanatory value would require careful examination for common-method variance, construct overlap, omitted variables, and model specification.

Based on the primary hypothesized relationships, H3 and H4 were supported.

4.8 Mediation Analysis

A mediation analysis was conducted to examine whether plant functional diversity transmitted

part of the relationship between soil degradation and climate-resilient agricultural performance.

Table 7: Mediation Effects of Plant Functional Diversity

Effect	β	Interpretation
Soil degradation $\rightarrow$ PFD	-.81	Significant negative
PFD $\rightarrow$ Agricultural resilience	1.12	Significant positive
Soil degradation $\rightarrow$ Agricultural resilience	-.43	Significant negative
Indirect effect (SD $\rightarrow$ PFD $\rightarrow$ resilience)	-.91*	Significant
Direct effect	-.43	Significant
Total effect	-1.34	Significant

Mediation estimate; significance should ordinarily be established through bootstrapped confidence intervals.

The mediation analysis indicates that soil degradation was negatively associated with plant functional diversity, while plant functional diversity was positively associated with agricultural resilience. Consequently, soil degradation was indirectly associated with agricultural resilience through changes in plant functional diversity.

The pattern suggests partial mediation because the direct relationship between soil degradation and agricultural resilience remained statistically significant after plant functional diversity was included in the model. Thus, soil degradation appears to influence agricultural resilience

through both a direct pathway and an indirect pathway involving plant functional diversity. Accordingly, H5 was supported in the model.

The finding provides an important theoretical implication: plant functional diversity may represent one ecological mechanism through which soil conditions influence agricultural resilience. However, this does not establish causality in a cross-sectional observational study; longitudinal or experimental research would be required for stronger causal inference.

4.9 Agro-Ecological Differences

To examine whether agricultural and ecological conditions differed across agro-ecological settings, the observations were compared across the six strata.

Table 8: Agro-Ecological Differences

Agro-ecological setting	Climate Stress M	Soil Degradation M	PFD M	Resilience M
Irrigated plains	3.21	3.18	3.34	3.46
Rainfed agricultural areas	3.49	3.41	3.15	3.25
Arid/semi-arid areas	3.78	3.72	2.91	2.88
Mountain/highland areas	3.56	3.47	3.29	3.12
Dryland/rangeland transition	3.62	3.55	3.02	3.04
Coastal agricultural areas	3.28	3.24	3.39	3.39

The descriptive comparison indicates considerable variation among agro-ecological settings. The arid/semi-arid observations showed relatively high

climate stress and soil degradation alongside comparatively lower plant functional diversity and agricultural resilience. Irrigated plains displayed

comparatively lower climate-stress scores and higher resilience, whereas mountain and dryland settings demonstrated intermediate-to-high environmental pressures.

These differences are consistent with the underlying proposition that environmental

relationships are spatially heterogeneous. However, the descriptive differences should not be interpreted as definitive empirical rankings of Pakistan's agro-ecological zones because the data were simulated.

4.10 Hypothesis Testing Summary

Table 9: Summary of Hypothesis Testing

Hypothesis	Proposed relationship	Result
H1	Climate stress → Soil degradation (+)	Supported
H2	Soil degradation → PFD (-)	Supported
H3	PFD → Agricultural resilience (+)	Supported
H4	Soil degradation → Agricultural resilience (-)	Supported
H5	Soil degradation → PFD → Agricultural resilience	Supported
H6	Agro-ecological zone moderates proposed relationships	Requires formal interaction/multi-group testing

The findings provide support for the principal theoretical model. Climate stress was positively related to soil degradation, soil degradation was negatively related to plant functional diversity, and functional diversity was positively related to agricultural resilience. The mediation analysis further indicated that functional diversity may constitute an important pathway connecting soil degradation with agricultural resilience.

H6, however, requires a formal moderation analysis rather than descriptive comparison alone. In an actual study, this hypothesis should be tested through interaction terms, multigroup structural equation modelling, or multigroup regression.

4.11 Overall Interpretation of Findings

Taken together, the results support an integrated ecological explanation of climate-resilient agriculture. The positive relationship between climate stress and soil degradation indicates that environmental pressures can contribute to deterioration in soil conditions. The strong negative relationship between soil degradation and plant functional diversity further suggests that degradation may constrain the range of plant functional strategies capable of being maintained within agricultural landscapes.

The positive relationship between plant functional diversity and agricultural resilience is particularly important. Functionally diverse plant communities can potentially provide complementary resource-use strategies, improve soil protection, enhance nutrient cycling, and increase the capacity of agroecosystems to withstand environmental variability. The result is therefore consistent with the logic of Biological Insurance Theory, according to which diversity can provide ecological buffering when environmental conditions fluctuate.

The negative relationship between soil degradation and agricultural resilience further indicates that degradation may undermine the ecological foundations of agricultural productivity. Degraded soils generally have reduced capacity to retain water and nutrients and may therefore increase agricultural sensitivity to climatic disturbances. Consequently, agricultural adaptation cannot be restricted to crop-level technological interventions; soil restoration and biological diversification may also be important components of resilience strategies.

The mediation result provides the most important analytical insight. It suggests that soil degradation may affect agricultural resilience partly through its

association with plant functional diversity. In conceptual terms, degradation can alter the ecological environment in which different plant functional strategies persist, while reduced functional diversity may diminish the capacity of the agricultural ecosystem to maintain multiple functions under environmental stress.

The agro-ecological comparison further demonstrates why Pakistan requires geographically differentiated climate-resilience strategies. The country's agricultural environments differ in climatic exposure, soil conditions, water availability, vegetation, and management systems. Consequently, interventions designed for irrigated plains may not have identical effects in arid, rainfed, mountain, dryland, or coastal environments.

Overall, the findings support an ecosystem-based interpretation of climate-resilient agriculture, in which soil health and plant functional diversity are treated as interconnected components of agricultural resilience rather than as independent environmental concerns.

Important methodological qualification: Because the dataset used in this section was simulated, the coefficients, significance levels, means, and hypothesis decisions. They demonstrate how the empirical section of the proposed paper could be presented after real data collection. They should not be cited as actual evidence concerning Pakistan's farmers, soils, vegetation, or agro-ecological zones.

Discussion

The findings provide a coherent explanation of how climate-related environmental stress may influence agricultural resilience through soil degradation and plant functional diversity. The positive association between climate-induced environmental stress (CIES) and soil degradation (SD) supports H1, indicating that increasing temperature stress, rainfall variability, drought exposure, declining soil moisture, and extreme rainfall events are conceptually associated with greater erosion, nutrient depletion, salinity, and declining soil fertility. This finding is consistent

with the broader climate-change literature, which identifies climatic extremes as important drivers of land and soil degradation. It also corresponds with evidence that climate change can alter belowground ecosystem functioning and reduce the capacity of ecosystems to maintain multiple functions under environmental stress.

The negative relationship between soil degradation and plant functional diversity (PFD) supports H2. The finding suggests that degradation of soil resources can constrain the coexistence and performance of plants with different rooting strategies, nutrient-acquisition mechanisms, water-use characteristics, and drought-response traits. This interpretation is consistent with research showing that soil properties and plant functional characteristics are closely interconnected. Recent evidence further indicates that plant functional groups can influence soil-microbial relationships under climate change, suggesting that degradation of the soil environment may affect not only plant composition but also the functional processes supporting ecosystem productivity.

The positive relationship between PFD and climate-resilient agricultural performance (CRAP) supports H3. This result is theoretically important because it suggests that resilience is not necessarily dependent on maximizing a single highly productive plant type. Instead, functional complementarity and response diversity may enable agricultural ecosystems to maintain productivity when environmental conditions fluctuate. This is broadly consistent with the Biological Insurance Theory of Yachi and Loreau (1999), which proposes that biodiversity can stabilize ecosystem functioning because species with different ecological responses can compensate for one another when environmental conditions change. Experimental evidence has similarly demonstrated that biodiversity can increase ecosystem resistance to climatic extremes. The negative direct relationship between SD and CRAP supports H4, demonstrating that soil degradation may undermine agricultural resilience through reduced soil fertility, declining water-retention capacity, erosion, salinity, and reduced

productive potential. The finding complements research on sustainable land management and soil fertility in agricultural systems, particularly evidence that institutional and management factors influence the maintenance of soil resources. In Pakistan, where agricultural production is exposed to substantial climatic variability, maintaining soil quality is therefore closely connected with the capacity of farming systems to absorb and recover from environmental disturbances.

The mediation analysis provides additional theoretical insight. PFD transmitted a substantial portion of the negative effect of SD on CRAP, with the indirect effect calculated from the SD→PFD and PFD→CRAP paths. The remaining direct SD→CRAP relationship indicates partial mediation. Conceptually, this means that soil degradation can reduce resilience both directly, by weakening the physical and chemical resource base of agriculture, and indirectly, by reducing the functional diversity through which agricultural ecosystems may respond to climatic stress. This mechanism provides a stronger theoretical explanation than treating soil degradation and biodiversity as independent predictors.

The simulated regression results also produced an unusually high explained variance for CRAP. Because the dataset is , this should not be interpreted as evidence that the proposed model would necessarily achieve such explanatory power in field data. The magnitude may partly reflect the deliberately coherent covariance structure used to demonstrate the proposed relationships. A real empirical study should therefore examine common-method variance, multicollinearity, construct overlap, omitted variables, spatial dependence, and alternative model specifications. Finally, the descriptive differences among agro-ecological settings suggest that climate stress, soil degradation, PFD, and resilience may vary considerably across Pakistan's agricultural environments. The relatively higher simulated stress and degradation values in arid/semi-arid and dryland settings, together with lower PFD and resilience, the importance of ecological context.

However, these differences are descriptive only. H6 should be formally tested through interaction effects, multi-group analysis, or multigroup structural equation modeling before concluding that agro-ecological zones significantly moderate the proposed relationships.

Overall, the findings extend Biological Insurance Theory from natural ecosystem stability toward an agricultural resilience framework. The results suggest that functional diversity can be viewed as an ecological mechanism through which agricultural systems retain functioning under environmental variability, while soil degradation represents an important pathway through which climate stress can weaken that insurance capacity.

Conclusion

The study develops an integrated framework linking climate-induced environmental stress, soil degradation, plant functional diversity, and climate-resilient agricultural performance across Pakistan's agro-ecological settings. The findings indicate that climate stress is positively associated with soil degradation, while soil degradation is negatively associated with plant functional diversity and agricultural resilience. In contrast, greater plant functional diversity is positively associated with climate-resilient agricultural performance.

The mediation analysis further indicates that PFD may serve as an important ecological pathway linking soil conditions with agricultural resilience. These findings reinforce the central proposition of Biological Insurance Theory that functional diversity can contribute to stability under environmental variability. Consequently, climate-resilient agriculture should not be approached exclusively through technological adaptation or input intensification; maintaining healthy soils and diverse plant functional strategies may also provide an important ecological foundation for resilience.

Because all numerical findings are simulated, the results should be regarded as a demonstration of the proposed research model rather than empirical evidence for Pakistan. Future field research using ecological measurements, longitudinal

observations, remote sensing, and farm-level production data is required to validate the relationships.

Implications

Theoretical Implications

1. **Extension of Biological Insurance**

Theory: The study applies Biological Insurance Theory to agricultural systems by linking functional diversity with resilience under climate-induced environmental variability.

2. **Integrated ecological mechanism:** The framework demonstrates that soil degradation may influence resilience partly through changes in plant functional diversity, providing a more comprehensive explanation than models examining soil quality or biodiversity separately.

3. **Functional rather than purely taxonomic diversity:** The study emphasizes functional characteristics such as rooting depth, drought tolerance, nutrient acquisition, and water-use strategies, thereby strengthening the ecological relevance of diversity-based resilience research.

4. **Agro-ecological contingency:** The proposed framework recognizes that ecological relationships may differ across environmental contexts. Formal testing of agro-ecological moderation can therefore contribute to more context-sensitive resilience theory.

Managerial Implications

Farm managers and agricultural organizations should incorporate soil health and functional diversity indicators into climate-risk management. Rather than relying exclusively on additional fertilizer, irrigation, or other external inputs, management strategies can combine soil organic-matter improvement, erosion control, appropriate crop diversification, and varieties possessing complementary functional traits.

Agricultural extension services can also develop zone-specific packages based on drought tolerance, rooting characteristics, nutrient-use efficiency, and water-use strategies. This would allow farm-level adaptation to reflect differences in environmental stress rather than applying a uniform national strategy.

Practical Implications

Practical resilience interventions should include:

- conservation agriculture and minimum soil disturbance;
- crop diversification and appropriate rotations;
- incorporation of organic amendments and residue management;
- erosion-control measures;
- improved soil-moisture conservation;
- salinity-management practices where relevant;
- drought- and heat-tolerant crop varieties;
- integration of crops with complementary functional characteristics;
- improved water-use efficiency; and
- regular soil-health monitoring.

The objective should be to maintain both the resource base of agriculture and the ecological diversity that supports adaptation.

Policy Implications

Agricultural and environmental programs should increasingly connect soil conservation, biodiversity conservation, and climate adaptation rather than treating them as separate policy domains. National and provincial agricultural planning could incorporate soil-health indicators and functional-diversity considerations into climate-resilience programs.

Pakistan could also strengthen agro-ecological monitoring by combining field observations with remote sensing, climate datasets, soil databases, and agricultural productivity records. Such integrated monitoring would help identify areas experiencing simultaneous climate stress, soil degradation, and declining ecological resilience.

Policy interventions should also recognize agro-ecological differences. Strategies appropriate for irrigated plains may not be directly transferable to arid/semi-arid, mountainous, dryland, or coastal agricultural environments.

Recommendations

1. **Establish systematic soil-health**

monitoring: Develop periodic monitoring of soil organic matter, erosion, salinity, nutrient status,

moisture retention, and fertility across major agricultural zones.

2. Promote functional crop diversification: Encourage crop rotations and cultivar combinations that provide complementary rooting, water-use, nutrient-use, and climate-response characteristics.

3. Strengthen conservation agriculture: Expand practices that reduce erosion and improve soil structure, organic matter, and water retention.

4. Develop agro-ecological adaptation packages: Design separate climate-resilience strategies for irrigated, rainfed, arid/semi-arid, highland, dryland, and coastal environments.

5. Integrate biodiversity into agricultural extension: Farmer training should explain the relationship between plant diversity, soil health, ecosystem functioning, and climate resilience.

6. Improve drought and flood preparedness: Climate information services should be linked with farm-level decisions concerning crop selection, planting dates, irrigation, and soil-moisture conservation.

7. Strengthen research-policy integration: Universities, agricultural research institutions, and government agencies should jointly develop long-term datasets linking climate conditions, soil properties, vegetation traits, and agricultural productivity.

8. Use evidence-based incentives: Where appropriate, agricultural support programs could encourage conservation practices that simultaneously improve soil health and ecological resilience.

9. Validate the proposed model empirically: Future studies should collect field-based ecological and farm-level data rather than relying solely on perception-based measures.

10. Conduct formal moderation analysis: Agro-ecological differences should be tested using interaction terms, multi-group SEM, or other appropriate statistical procedures to determine whether relationships genuinely differ among zones.

Limitations and Future Directions

First, the numerical dataset used in this study is simulated rather than collected from actual Pakistani farms. Consequently, the statistical relationships cannot be generalized to Pakistan's agricultural population. Future research should validate the model using primary field observations and independently measured ecological indicators.

Second, the study uses a cross-sectional conceptual design. Such a design limits the ability to establish temporal causality among climate stress, soil degradation, plant functional diversity, and resilience. Longitudinal datasets covering multiple growing seasons would provide stronger evidence concerning causal and dynamic relationships.

Third, several constructs are represented through perceptual measures. Future research should complement survey responses with objective measurements, including soil organic carbon, bulk density, electrical conductivity, nutrient concentrations, soil moisture, vegetation indices, species/trait composition, crop yields, and climate observations.

Fourth, the proposed PFD construct could be strengthened through direct ecological measurement of functional richness, functional evenness, and functional divergence based on observed plant traits. This would provide a closer empirical operationalization of Biological Insurance Theory.

Fifth, the six agro-ecological categories may contain substantial internal heterogeneity. Future research should employ finer spatial classifications using GIS, remote sensing, climatic variables, soil characteristics, elevation, irrigation conditions, and cropping systems.

Sixth, the model does not exhaustively capture other determinants of agricultural resilience. Future studies should consider factors such as farm financial capacity, access to extension services, technology adoption, institutional support, market access, land tenure, water governance, and farmer adaptation behavior.

Seventh, the exceptionally high simulated explanatory power observed in the CRAP regression should be treated cautiously. Actual

research should conduct rigorous diagnostics for multicollinearity, common-method bias, endogeneity, measurement error, spatial autocorrelation, and model specification.

Finally, future studies should employ multi-year and multi-location designs and, where feasible, combine farmer surveys with soil sampling, ecological field assessments, satellite observations, and agricultural production records. Such mixed-method and longitudinal approaches would provide stronger evidence about whether plant functional diversity genuinely operates as a biological insurance mechanism for climate-resilient agriculture in Pakistan.

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