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Soil-plant-atmosphere interactions under climate change: an integrative framework for mechanisms, plant responses, and climate-resilient agricultural strategies: review

Florina Stoica[1], *Mariana Rusu*[1,2], *Irina G. Cara*[1,2], *Denis C. Topa*[1], *Gerard Jitareanu*[1]*

[1]Department of Pedotechnics, Faculty of Agriculture, [2]Research Institute for Agriculture and Environment
"Ion Ionescu de la Brad" Iasi University of Life Sciences, 700490 Iasi, Romania

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Abstract. Climate change affects agriculture through elevated atmospheric CO_2, rising temperatures, altered precipitation, and increasingly frequent extreme events, whose effects are transmitted through interacting soil, plant, microbial, and atmospheric processes. This review advances beyond predominantly stressor- or yield-centred syntheses by proposing an operational field-scale soil-plant-atmosphere-management framework that integrates external climate drivers, site parameters, soil and plant state variables, endogenous responses, greenhouse-gas fluxes, management interventions, feedback mechanisms, and explicit validation routes. A structured narrative synthesis of recent literature was used to evaluate how these components interact under heat, drought, flooding, salinity, nutrient limitation, elevated CO_2, and pest pressure. The framework clarifies causal pathways that are often treated separately; for example, heat and drought increase atmospheric water demand and soil-water depletion, promoting stomatal closure, reduced photosynthesis, biomass loss, and yield decline, whereas flooding reduces root-zone oxygen, enhances denitrification and N_2O emissions, restricts nutrient availability, and impairs root and crop performance. The synthesis further shows that management practices such as residue retention, conservation-oriented tillage, cover cropping, diversification, biological inputs, precision agriculture, and climate-resilient breeding can modify these pathways by improving soil structure, water retention, nutrient synchrony, biological functioning, carbon storage, and stress buffering, although their effectiveness remains strongly context dependent. A distinctive contribution of the review is the integration of controlled experiments, field and long-term trials, multi-location testing, and process-based modelling into a common validation logic for assessing soil, plant, crop-quality, resource-use, and greenhouse-gas responses. The framework can help researchers formulate verifiable multi-stress hypotheses, support agronomists in selecting locally appropriate management strategies, and assist policymakers in comparing adaptation-mitigation options according to productivity, resilience, emissions, cost, feasibility, and implementation risk.

Keywords: climate change, soil-plant-atmosphere-management, climate-smart agriculture, crop resilience, greenhouse gas emissions, carbon sequestration

1. INTRODUCTION

Climate change poses major challenges to modern agriculture, with consequences for crop performance, sustainability, nutritional quality, and global food security. Rising temperatures, shifting precipitation regimes, and more frequent extreme weather events are already disrupting agricultural systems, making climate-response strategies paramount to maintain productivity and resilience (Abebaw, 2025). These climatic pressures coincide with increasing global food demand, intensifying the challenge of maintaining sufficient, safe, and nutritionally adequate agricultural production under increasingly variable environmental conditions (Rivero *et al.,* 2022).

*Corresponding author e-mail: gerard.jitareanu@iuls.ro

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Agricultural systems are increasingly exposed to interacting climatic, edaphic, biotic, and anthropogenic stressors. Heat, drought, flooding, salinity, nutrient imbalance, pollutants, and pest or pathogen pressure can act simultaneously or sequentially, altering crop physiology, resource acquisition, yield stability, and quality (Raza *et al.,* 2024a). Their combined effects therefore require assessment through field-relevant and measurable variables.

Climate change, driven primarily by increasing emissions of CO_2 and other greenhouse gases, is reshaping agricultural systems in interacting and sometimes opposing ways (Zhu *et al.,* 2023). It affects crop quantity as well as crop quality, including nutrient composition and the efficiency of agricultural inputs. At the same time, heavy reliance on fertilizers and pesticides contributes to GHG emissions, creating feedback loops that intensify climate pressure and weaken the long-term sustainability of agricultural production systems (Semba *et al.,* 2022; Ekele *et al.,* 2025). These links show why assessments based only on yield, atmospheric CO_2 concentration, or isolated management practices are incomplete.

Previous research has established the substantial effects of climate change on agricultural productivity, but these effects have often been examined at different organizational levels and within relatively distinct disciplinary perspectives. Broad reviews have synthesized the consequences of rising air temperatures, altered precipitation, drought, and other climate-related pressures for crop productivity and mitigation options (Malhi *et al.,* 2021; Abebaw, 2025), whereas plant-focused syntheses have emphasized physiological and molecular responses to combinations of abiotic stresses and the development of climate-resilient crops (Rivero *et al.,* 2022; Zandalinas *et al.,* 2024). Other approaches have addressed climate adaptation through spatial or crop-modelling frameworks. For example, Vahdati *et al*. (2019) combined climatic, edaphic, and topographic variables with GIS and AOGCM-AR5 projections to assess changes in land suitability for walnut cultivation under future climate conditions. Similarly, Bracho-Mujica *et al*. (2024) evaluated interactions between climate scenarios and agricultural technology packages using crop models across contrasting global locations. Together, these studies demonstrate the importance of considering multiple environmental and management factors, but their principal outcomes remain focused on particular components of the agricultural system, such as crop stress physiology, yield and yield gaps, farmer adaptation, or land suitability.

An important knowledge gap therefore remains between discipline-specific understanding of individual processes and an operational representation of how climate effects are transmitted through the complete field-scale agricultural system. Changes in atmospheric conditions do not affect crops independently of soil conditions: higher air temperature and vapour-pressure deficit modify soil-water availability and plant transpiration; drought restricts nutrient diffusion and root uptake; flooding alters root-zone oxygen status and microbial nitrogen transformations; and elevated CO_2 modifies plant carbon assimilation while interacting with water and nutrient availability. These responses can subsequently influence biomass production, crop quality, soil organic carbon (SOC) dynamics, and CO_2, N_2O, and CH_4 exchange. Management interventions further modify the strength and direction of these pathways. Consequently, integrating atmospheric forcing, soil states, plant and microbial responses, management actions, and greenhouse-gas feedbacks provides mechanistic information that cannot be obtained when climate impacts are assessed only through final yield responses or within individual disciplinary compartments.

The present review addresses this gap through an integrated soil-plant-atmosphere-management framework. Unlike frameworks that principally organize climate hazards, adaptation practices, crop outcomes, or land-suitability factors, the proposed framework is structured as a verifiable causal system. It explicitly distinguishes external drivers, relatively stable site parameters, dynamic soil and plant state variables, endogenous physiological and microbial responses, management interventions, greenhouse-gas and resource-use indicators, and final system outcomes. It further incorporates reinforcing and balancing feedback loops and links each pathway to appropriate validation routes, including controlled experiments, field trials, long-term experiments, multi-location testing, and process-based modelling. Management is therefore treated not simply as an outcome or recommendation, but as a controllable intervention capable of modifying causal relationships among atmospheric exposure, soil condition, plant function, resource use, and greenhouse-gas exchange.

Accordingly, the specific objectives of this review are to: (i) synthesize the major climate drivers and their interconnected effects on soil physical, chemical, and biological processes and plant physiological responses; (ii) identify mechanistic pathways linking climate exposure and site conditions with crop performance, crop quality, resource-use efficiency, and greenhouse-gas outcomes; (iii) determine how agronomic, biological, and climate-smart management strategies modify these pathways and the associated adaptation-mitigation trade-offs; (iv) define measurable variables and validation approaches through which the proposed interactions can be experimentally tested and incorporated into process-based models; and (v) identify research priorities required to translate mechanistic understanding into climate-resilient agricultural strategies across contrasting soils, crops, climates, and management systems.

In this review, the soil-plant-atmosphere-management system is defined at the field and cropping-system scale. The lower boundary is the managed root-zone soil profile, where water storage, aeration, nutrient availability, organic carbon dynamics, microbial activity, salinity, compaction,

and denitrification regulate plant access to resources. The upper boundary is the crop canopy-atmosphere interface, where elevated CO_2, air temperature, vapour-pressure deficit, radiation, rainfall, drought, flooding, and heat events affect photosynthesis, transpiration, stomatal conductance, canopy temperature, and gas exchange. The temporal boundary extends from short-term stress events within a crop season to multi-season and rotation-scale changes in SOC, nutrient cycling, biological functioning, and yield stability. Management practices, including tillage, residue retention, fertilization, irrigation, cover cropping, intercropping, biological inputs, and precision technologies, are treated as controllable interventions within the system. Broader food-system processes, post-harvest losses, markets, policy, renewable energy, and urban infrastructure are outside the primary analytical boundary unless they directly affect field-level soil, crop, or greenhouse-gas responses.

The framework distinguishes external drivers, dynamic state variables, endogenous responses, and relatively stable site parameters. External drivers include atmospheric CO_2, air temperature, precipitation, drought, flooding, vapour-pressure deficit, salinity, radiation, and management inputs. Dynamic soil and plant states encompass water and nutrient availability, soil physical condition, microbial functioning, root development, gas exchange, canopy status, biomass, yield, and crop quality, together with CO_2, N_2O, and CH_4 fluxes. Endogenous responses include physiological acclimation, nutrient uptake, biomass allocation, phenology, microbial nutrient transformations, evapotranspiration, and emission intensity. Site parameters-including soil texture, drainage, baseline SOC and fertility, climate zone, cropping history, crop genotype, and root traits-determine the magnitude and direction of these responses.

Interaction mechanisms describe how climate and management drivers modify soil and plant states to generate agronomic and greenhouse-gas outcomes. For example, heat and drought couple atmospheric water demand with soil-water depletion and reduced carbon assimilation, whereas flooding links root-zone oxygen limitation with altered nitrogen cycling and N_2O emissions. Elevated CO_2 responses are similarly conditioned by water, nutrients, crop type, and concurrent stresses. Management modifies these pathways through effects on soil structure, resource availability, microbial functioning, and emission intensity.

Figure 1 presents this field-scale framework by separating external drivers from internal soil, plant, and atmosphere-related state variables and by showing the main pathways through which management can modify system sensitivity. The figure links soil water and nutrient supply, plant physiological responses, greenhouse-gas fluxes, and final outcomes such as productivity, yield stability, nutritional quality, soil resilience, carbon sequestration,

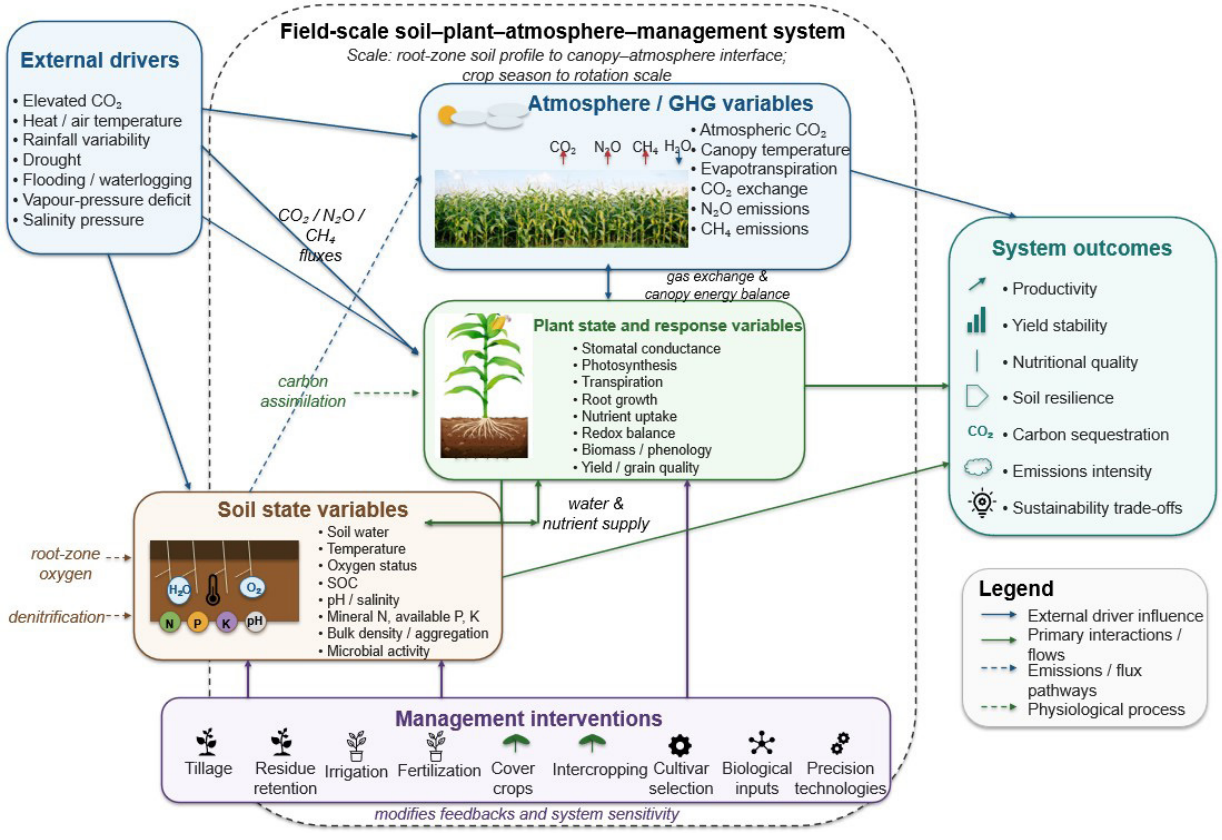


Fig. 1. Mechanistic soil–plant–atmosphere–management framework for analysing crop responses to combined climate stressors.

emission intensity, and sustainability trade-offs. In this way, Fig. 1 provides a mechanistic basis for evaluating climate-response and mitigation strategies through measurable variables rather than through yield responses alone.

Within this structure, sustainable agriculture must balance productivity with ecological stewardship. New technologies and management approaches can improve crop performance under climate variability, but their use is often constrained by cost, access, technical capacity, and the need for region-specific planning (Yimer and Tarnawa, 2025). Projected climatic conditions will alter land-use suitability and require adjustments in cropping systems, input management, and mitigation practices. Sustainable production methods and climate-response technologies can contribute to food security, food quality and safety, biodiversity protection, farmer livelihoods, and rural economic development, especially in vulnerable regions.

Through this structure, the review moves from descriptive synthesis toward an operational interpretation of climate-agriculture interactions. The following sections first examine atmospheric and climatic drivers and their effects on soil and plant processes, then evaluate biological and agronomic strategies that can modify these responses, and finally integrate mitigation, validation, and economic trade-offs. This progression is intended to connect mechanistic understanding with experimentally verifiable indicators and management decisions relevant to climate-resilient agricultural systems.

2. METHODOLOGY

This review was conducted as a structured narrative synthesis of evidence on climate-change effects within the soil-plant-atmosphere-management system. The analysis was organized around defined system boundaries, measurable variables, interaction pathways, feedback loops, and validation needs, using evidence from agronomy, soil science, plant physiology, environmental science, and greenhouse-gas research.

The literature search included peer-reviewed journal articles and selected authoritative institutional reports retrieved through ScienceDirect and publisher platforms including Frontiers, MDPI, and SpringerLink. Publications from 2015 to 2026 were prioritized, while earlier studies were included when they provided foundational concepts, long-term field evidence, or widely used methods relevant to climate–agriculture interactions. Search terms included climate change, elevated CO_2, increased soil temperature, heat stress, drought, flooding, salinity, SOC, nutrient cycling, plant stress physiology, greenhouse-gas emissions, conservation agriculture, cover crops, intercropping, biological inputs, and precision agriculture.

Studies were selected when they addressed at least one field-scale component of the soil-plant-atmosphere-management system and provided evidence on mechanisms, measurable indicators, or management effects. Priority was given to studies on combined climate stressors, field or long-term experiments, soil physical, chemical, or biological responses, plant physiological responses, greenhouse-gas fluxes, yield, crop quality, and management practices relevant to both climate response and mitigation. Opinion-based papers, studies without clear agricultural relevance, and papers focused only on post-harvest or food-chain issues without a field-level link were excluded.

The selected studies were coded according to four categories: external drivers, state variables, endogenous response variables, and relatively stable site parameters. Mechanistic pathways were then extracted to show how drivers such as heat, drought, flooding, salinity, elevated CO_2, and management inputs affect soil condition, plant physiology, microbial processes, greenhouse-gas emissions, yield, and crop quality. The synthesis was also used to identify where mechanisms are supported by field data, long-term trials, multi-location testing, or process-based modelling, and where further validation is needed.

During the synthesis, evidence was not treated as equivalent across study types. Meta-analyses, long-term experiments, and multi-location field studies were used primarily to identify general response patterns and their heterogeneity, whereas individual field or controlled-environment studies were used mainly to clarify mechanisms or illustrate context-specific responses. Divergent findings were interpreted in relation to climate zone, soil type and drainage, baseline fertility and SOC, crop species and genotype, stress intensity and timing, experimental duration, management history, measurement depth, and study scale. Where these factors did not adequately explain disagreement among studies, the inconsistency was retained as an explicit source of uncertainty rather than resolved into a single generalized conclusion. Because pooled meta-analytic estimates integrate heterogeneous climates, soils, crops, management histories, and experimental durations, mean effect sizes should be interpreted as overall tendencies rather than universally expected responses; moderator effects and between-study heterogeneity may be more informative for site-specific management decisions than the pooled mean alone.

3. ATMOSPHERIC CO_2, CLIMATE STRESSORS, AND CROP-SYSTEM RESPONSES

Rising atmospheric CO_2 is a central climate driver with simultaneous effects on radiative forcing, crop physiology, soil processes, and management performance. Its agricultural consequences therefore extend beyond direct CO_2 fertilization and depend on interactions with temperature, water availability, nutrient status, and other environmental stresses (Keeling, 1995; Yang *et al.,* 2024).

Elevated CO_2 can stimulate plant growth by enhancing photosynthesis and improving intrinsic water-use efficiency, but the magnitude and persistence of this CO_2

fertilization effect depend strongly on nutrient availability, water supply, crop type, and the interaction with other climatic stressors (De Kauwe *et al.,* 2021).

CO_2 responses differ between photosynthetic pathways, with C_3 crops generally showing stronger direct stimulation than C_4 crops (Sales *et al.,* 2021; Dingkuhn *et al.,* 2020). FACE evidence indicates yield increases of approximately 17% in wheat and rice under 550-590 μmol mol^{-1} CO_2 under favourable conditions (Hu *et al.,* 2021), but these gains decline when sink strength, nutrient availability, water supply, or concurrent heat stress become limiting (Ainsworth and Long, 2021; Dingkuhn *et al.,* 2020).

Higher air temperature, drought, and excess precipitation interact through both atmospheric and soil-mediated pathways. Heat increases atmospheric water demand and can intensify drought, whereas drought restricts stomatal conductance, photosynthesis, and nutrient acquisition. Conversely, flooding and waterlogging reduce root-zone oxygen, disrupt nutrient cycling, and impair root function (Moore *et al.,* 2021; Cooper and Messina, 2023; Langan *et al.,* 2022; Kaur *et al.,* 2020; Liu K. *et al.,* 2023). Their combined effects therefore depend on the coupling between atmospheric exposure, soil conditions, and plant physiological regulation.

Climate-driven salinization associated with sea-level rise and prolonged drought imposes additional ionic, osmotic, and oxidative stress, causing major economic losses and reducing land productivity (Raza *et al.,* 2023c; Raza *et al.,* 2023b). At the same time, warmer and more variable climates intensify pest and pathogen pressure, while elevated CO_2 can modify host-pathogen interactions in ways that are often difficult to predict (Savary *et al.,* 2019; Deutsch *et al.,* 2018; Khan and Rizvi, 2020; Skendžić *et al.,* 2021). Projections of declining yields in major crops under continued GHG emissions reflect the combined action of these atmospheric, soil, and biological pressures rather than any single stressor alone (Agnolucci *et al.,* 2020; Schleussner *et al.,* 2018; Tran *et al.,* 2025). Consequently, the following sections evaluate climate impacts through measurable soil, plant, and atmospheric response variables rather than through isolated stressor effects.

4. CLIMATE CHANGE IMPACTS ON SOIL PROCESSES AND FUNCTIONS IN AGRICULTURAL SYSTEMS

Climate change affects agricultural soils through interconnected physical, chemical, and biological pathways rather than through isolated processes. Rising temperatures, altered precipitation regimes, droughts, flooding, and extreme weather events modify soil structure, nutrient cycling, organic matter dynamics, microbial activity, and erosion risk, with direct consequences for crop performance and long-term soil resilience. These responses are strongly mediated by soil texture, mineralogy, drainage conditions, baseline organic matter content, and management history, which means that climate effects on soils are often context specific rather than uniform across agricultural systems (Radulov and Berbecea, 2023; Mondal, 2021; Furtak and Wolińska, 2023). A major challenge, therefore, is not only to describe individual soil responses to climate change but also to understand how changes in soil physical condition, chemical fertility, and biological functioning interact to influence plant growth, nutrient availability, GHG emissions, and the sustainability of production systems. The magnitude and direction of these responses differ markedly among agroecological regions because climate exposure interacts with soil mineralogy, texture, drainage, baseline fertility, cropping history, and management intensity. In arid and semi-arid systems, low soil water availability, high evaporative demand, salt accumulation, and poor vegetation cover often make water retention, infiltration, and salinity the dominant constraints. By contrast, humid regions and fine-textured or poorly drained soils are more vulnerable to prolonged saturation, oxygen limitation, compaction, denitrification, and nutrient loss. Highly weathered tropical soils frequently combine low nutrient-retention capacity with acidity, phosphorus fixation, erosion, and rapid organic-matter turnover, whereas cold-region agricultural soils are additionally affected by freeze-thaw cycles, delayed soil warming, snowmelt-driven saturation, and episodic nutrient and N_2O losses. Consequently, identical climatic drivers can generate contrasting soil-plant outcomes among regions, and management responses should be evaluated against local pedoclimatic conditions rather than generalized from individual sites or climate zones.

4.1. Physical changes in soil under climate stress

Climate stress alters soil structure, water storage, aeration, and erosion risk. Increases in soil temperature and repeated drying-rewetting may increase mechanical resistance and reduce aggregation and soil-water retention, drought enhances hard-setting and water limitation, whereas flooding reduces aeration and structural stability (Ma *et al.,* 2024; Shah *et al.,* 2017; Topali *et al.,* 2024). These responses can increase runoff, SOC loss, and subsequent vulnerability to erosion.

However, these physical responses vary substantially across soil types and management systems. Fine-textured and poorly drained soils are generally more prone to compaction and waterlogging, while coarse-textured soils tend to be more vulnerable to rapid drying and reduced water-holding capacity. Likewise, the effects of tillage are not uniform. Conventional tillage often disrupts aggregates, accelerates SOC decomposition, and increases exposure to erosion and moisture loss, whereas conservation systems such as minimum tillage (MT) and no-tillage (NT) frequently improve aggregation, pore continuity, capillary water storage, and resistance to climatic stress (Lal, 2015; Blanco-Canqui and Ruis, 2018; Kassam *et al.,* 2019). Yet, the reported outcomes remain variable. For example, NT has been associated with yield reductions in humid

or poorly drained soils due to compaction and delayed soil warming, while yield benefits are more consistently observed in water-limited environments where residue retention improves moisture conservation (Blanco-Canqui and Ruis, 2018; Pittelkow *et al.,* 2015). Long-term experiments from Romania, Mexico, and other temperate systems further indicate that reduced tillage combined with straw retention or residue mulching can improve SOC, porosity, aggregate stability, and nutrient stratification, but the magnitude and agronomic significance of these effects depend on climate, soil depth, crop stage, and the duration of management (Topa *et al.,* 2021; Calistru *et al.,* 2024; Cakpo *et al.,* 2026; González-Breijo *et al.,* 2025). These findings suggest that soil physical resilience under climate change is shaped by the interaction between climatic stress and management context, rather than by tillage intensity alone. Apparent contradictions among tillage studies often reflect differences in experimental context rather than fundamentally incompatible mechanisms. Yield penalties under no-tillage are more likely where poor drainage, surface compaction, low early-season soil temperature, or inadequate residue and rotation management constrain crop establishment, whereas benefits are more frequently reported in water-limited environments where residue retention improves soil-water conservation. Differences in trial duration, sampling depth, baseline SOC, residue management, crop rotation, and rainfall regime can also explain contrasting conclusions regarding carbon storage and productivity. Thus, management effects should be interpreted through the moderators that determine the direction and magnitude of response rather than through the nominal tillage category alone.

Recent quantitative syntheses reinforce this context dependence. A global meta-analysis by Sun *et al*. (2024) concluded that conservation-tillage effects on crop yield are strongly region dependent, supporting the adaptation of tillage intensity to local climate and production conditions rather than the universal adoption of no-tillage. More recently, Huang *et al*. (2025) synthesized 527 observations from 140 publications conducted in the black-soil region of Northeast China and reported that conservation tillage increased SOC by an average of 4.17% and crop yield by 2.69% relative to conventional tillage. No-tillage produced a larger increase in SOC (+5.92%) than reduced tillage (+0.97%), whereas yield responses showed the opposite pattern, illustrating a potential trade-off between maximizing carbon accumulation and optimizing short-term crop productivity. These findings support evaluating conservation tillage through simultaneous measurements of SOC distribution through the soil profile, water availability, compaction, nutrient dynamics, greenhouse-gas fluxes, and yield rather than through a single soil-health indicator.

4.2. Chemical changes and nutrient dynamics

Climate change modifies soil pH, salinity, and nutrient availability through interacting hydrological and biogeochemical processes. Intense rainfall can accelerate base-cation and nutrient losses, whereas drought and inefficient irrigation favour salt accumulation; these responses are particularly important in acidic tropical soils and saline or coastal agricultural systems (Ferdush *et al.,* 2023; Miah *et al.,* 2020; Zhu *et al.,* 2024).

Nitrogen cycling is similarly moisture dependent. Drought restricts nutrient mobility and microbial activity, whereas prolonged saturation promotes denitrification and N_2O losses when nitrate and labile carbon are available (Mehra *et al.,* 2018; Plett *et al.,* 2020; Hui *et al.,* 2024). Consequently, climate effects on nutrient availability must be interpreted in relation to soil moisture, aeration, fertility, and microbial activity.

In tropical agriculture, many soils are strongly weathered and acidic, with low nutrient-retention capacity and high phosphorus sorption or fixation; climate stress in these systems often interacts with phosphorus limitation, aluminium toxicity, erosion, runoff, leaching, monsoon flooding, salinity, and high pest pressure in crops such as rice, maize, pulses, root crops, and perennial systems (Agegnehu *et al.,* 2021; Johan *et al.,* 2021). Validation in tropical systems should therefore include soil pH, cation-exchange capacity, available phosphorus, infiltration, runoff, nitrate leaching, root-zone oxygen, CH_4 and N_2O fluxes, crop quality, and yield stability.

In cold-region agriculture, short growing seasons, delayed spring soil warming, frost risk, snowmelt timing, wet spring soils, freeze-thaw cycles, and permafrost-affected active layers where present can regulate phenology, root growth, nitrogen release, nutrient leaching, N_2O pulses, and crop establishment (Green *et al.,* 2022; Krogstad *et al.,* 2022). Validation in cold-region systems should therefore include soil temperature, freeze-thaw frequency, snow-cover duration, snowmelt timing, duration of soil saturation after thaw, active-layer depth where applicable, mineral nitrogen, root growth, phenology, biomass production, yield stability, and CO_2, N_2O, and CH_4 fluxes. These regional contrasts show that the same chemical or nutrient pathway should not be generalized across agricultural regions without site-specific measurements of soil, crops, climate, and management.

Elevated CO_2 may increase SOC inputs through enhanced biomass production and greater carbon allocation belowground, but reported effects are mixed across carbon fractions and nutrient pools. Particulate organic carbon (POC) appears more responsive to CO_2 enrichment and nitrogen inputs than mineral-associated organic carbon (MAOC), while increases in total nitrogen or available potassium may coexist with reductions in ammonium, available nitrogen, and phosphorus because of intensified

plant uptake or altered microbial processing (Rocci *et al.,* 2021; Yue *et al.,* 2017; Shen *et al.,* 2022). This means that greater carbon input does not automatically translate into improved soil fertility, and the trade-offs between carbon sequestration, nutrient balance, and crop nutrition must be evaluated cautiously. Elevated CO_2 also modifies soil fertility through coupled C-N-P interactions rather than through carbon inputs alone. Greater photosynthetic carbon fixation and belowground allocation can stimulate rhizodeposition, root growth, and microbial activity, thereby increasing biological demand for N and P. At the cropland scale, Cui *et al*. (2023) estimated that elevated CO_2 could increase nitrogen-use efficiency by approximately 19% and biological nitrogen fixation by 55%, indicating substantial reorganization of crop nitrogen cycling rather than a simple increase in N demand. However, these responses depend on nutrient availability. Increased plant growth can intensify N and P demand, while additional rhizosphere carbon can stimulate microbial biomass and temporarily immobilize nutrients, increasing competition between roots and microorganisms. Crop-specific evidence further indicates that elevated CO_2 interacts with higher soil temperature, drought, and N fertilization to alter the wheat rhizomicrobiome, demonstrating that microbial responses cannot be separated from nutrient and climate interactions (Krause *et al.,* 2023). Phosphorus limitation may become particularly important where increased carbon supply stimulates microbial P demand. Experimental evidence from a phosphorus-limited ecosystem showed that microbial competition for P substantially constrained the biomass response to elevated CO_2, although this result derives from a mature woodland and should not be transferred directly to croplands without field validation (Jiang *et al.,* 2024). Thus, elevated CO_2 should be evaluated through coupled measurements of mineral N, available and fractionated P, microbial biomass C:N:P, extracellular enzyme activity, root nutrient acquisition, rhizodeposition, tissue nutrient concentration, and crop yield. An important unresolved question is whether enhanced nutrient acquisition under elevated CO_2 can compensate for progressively stronger microbial immobilization and plant nutrient demand under realistic combinations of higher soil temperature and water stress.

4.3. Biological changes and soil ecological functioning

Soil microbial communities mediate organic-matter turnover, nutrient transformations, aggregate stabilization, and greenhouse-gas production, making biological responses central to climate effects on soil fertility. Higher soil temperature may initially stimulate microbial activity, but responses weaken or reverse under moisture limitation, substrate depletion, or disrupted microbial networks; extracellular enzyme responses are similarly context dependent (Zhao *et al.,* 2016; Tiedje *et al.,* 2022; Liu G. *et al.,* 2023; Li *et al.,* 2018).

Microbial community composition also changes under climate stress. Drought and higher soil temperature tend to favour heat- and drought-tolerant taxa, while altered precipitation can shift dominant bacterial groups and reshape the balance between bacteria, fungi, and soil fauna (Jin *et al.,* 2022; Ibáñez *et al.,* 2023; Zadrapova *et al.,* 2024). Floods and droughts may reduce nematode and microarthropod populations, thereby slowing recovery of soil food webs and reducing ecological resilience (Barreto and Lindo, 2022).

These changes matter because biological communities influence both chemical fertility and physical stability: microbial byproducts contribute to aggregate formation, enzyme-mediated nutrient release influences plant uptake, and anaerobic microbial pathways under saturation conditions enhance denitrification and GHG emissions. For this reason, microbial, chemical, and physical changes should not be interpreted separately. Climate-driven shifts in moisture, temperature, and carbon inputs alter microbial function, which then feeds back on SOC stability, aggregate formation, nutrient availability, and crop performance across the soil-plant-atmosphere system.

Recent research has moved beyond describing taxonomic shifts toward evaluating microbial functional diversity, resistance, resilience, and ecological memory under climate extremes. In a multi-region experiment using soils from 30 European grasslands exposed to drought, flooding, freezing, or heat, Knight *et al*. (2024) combined community profiling with shotgun metagenomics and showed that 46% of annotated genes changed in relative abundance following climatic disturbance. Microbiome resistance and resilience also depended on the climate of origin: communities from warmer and drier environments were generally more resistant or resilient to heat and, to a lesser extent, drought, whereas communities from colder and wetter environments were more sensitive. Initial soil and climatic properties explained 58 ± 4% of the variance in microbiome responses across perturbations. These findings emphasize that microbial resilience reflects functional traits and climatic legacy rather than taxonomic diversity alone.

Agricultural studies provide similar evidence for ecological memory. Schmidt *et al*. (2024) used shotgun metagenomics in wheat soils with almost four decades of contrasting water-stress histories and found that intermittent water stress selected for microbial functions associated with indole-acetic acid and osmolyte production and was associated with greater wheat biomass during subsequent drought. Likewise, Bandopadhyay *et al.* (2024) combined RNA-based characterization of active rhizosphere bacteria with metabolomics in common bean and switchgrass and demonstrated that short-term drought responses were strongly plant dependent, helping distinguish direct environmental effects from plant-mediated microbiome changes. These advances suggest that future soil-plant-atmosphere studies should complement amplicon-based community profiling

with shotgun metagenomics, metatranscriptomics, metabolomics, functional-gene analysis, and measurements of enzyme activity, nutrient transformations, greenhouse-gas fluxes, and crop responses. Such integration is needed to determine whether apparent changes in microbial diversity correspond to functional redundancy, functional loss, ecological memory, or true changes in soil resilience.

4.4. Regenerative and climate-resilient soil management

Regenerative and conservation-oriented practices can strengthen soil buffering capacity by improving SOC, aggregation, infiltration, water retention, nutrient cycling, and biological activity (Adimassu *et al.,* 2018; Lal, 2016). However, their benefits are context dependent: no-tillage may increase surface compaction or delay soil warming in some environments, while residue retention may improve water conservation but alter nutrient distribution or pest pressure. Moreover, SOC and structural benefits often develop more slowly than short-term yield responses (Pittelkow *et al.,* 2015; Blanco-Canqui and Ruis, 2018; Țopa *et al.,* 2021; Cakpo *et al.,* 2026). Regenerative management should therefore be evaluated as a context-specific combination of mechanisms rather than a universally superior production strategy.

Table 1 integrates these mechanisms by linking major climate drivers with soil responses, crop consequences, management options, measurable indicators, and validation approaches.

5. INTEGRATED PLANT RESPONSES AND ADAPTATION UNDER COMBINED CLIMATE STRESSES

Plants respond to climate-related stress through coordinated adjustments in signalling, metabolism, physiology, and development. These responses vary with species, genotype, developmental stage, stress intensity, duration, and stress combination. As a result, plant adaptation to climate change cannot be understood as a single trait or pathway; rather, it emerges from the integration of stress perception, resource allocation, photoprotection, redox control, and root-shoot coordination under fluctuating environmental conditions (Deutsch *et al.,* 2018; Zandalinas *et al.,* 2021; Rivero *et al.,* 2022; Mittler *et al.,* 2022). Within this framework, the central challenge for plants is to maintain growth and reproductive success while limiting cellular injury under conditions such as drought, heat, salinity, flooding, and elevated atmospheric CO_2. Many of the mechanisms discussed below therefore involve trade-offs, particularly between stress protection and carbon gain, water conservation and nutrient uptake, or survival and yield formation.

5.1. Stress perception and signalling

Stress adaptation requires the integration of environmental signals across hormonal, metabolic, and root-shoot regulatory networks, particularly under simultaneous or sequential stresses (Zandalinas *et al.,* 2021; Mittler *et al.,* 2022). ABA is a central regulator of drought and osmotic stress, coordinating stomatal closure and water conservation, but this response can restrict CO_2 assimilation and therefore involves a trade-off between water saving and carbon gain (Munemasa *et al.,* 2015; Wang and Chang, 2024). Under combined stresses, however, acclimation depends on broader hormonal and long-distance signalling interactions rather than ABA alone.

Recent evidence supports viewing climate-stress signalling as an interconnected regulatory network rather than an ABA-dominated linear cascade. Auxin, brassinosteroids, strigolactones, and peptide signals interact with ABA and redox pathways to regulate growth allocation, root-system development, vascular function, and water use. In wheat, the root-derived peptide TaCLE24b interacts with the TaCLV1 receptor pathway to regulate lateral-root development and contributes to drought tolerance, providing direct evidence that peptide signalling can connect root architecture with whole-plant stress adaptation (Yang *et al.,* 2025). Strigolactone-ABA cross-talk has also been resolved mechanistically in apple, where strigolactones enhance drought resistance through an MsABI5-MsSMXL1-MsNAC022 regulatory cascade associated with proline accumulation (Zhang *et al.,* 2025). Brassinosteroid signalling further intersects with hormonal and redox regulation; for example, exogenous 24-epibrassinolide altered ABA and auxin status together with antioxidant responses under high-temperature stress in fenugreek, although such exogenous-treatment studies require validation under field conditions and combined stresses (Sheikhi *et al.,* 2023). Recent work further shows that soil-drying signals, including sulphate and CLE25, and the high-light-derived oxylipin OPDA converge on a plastid cysteine synthase complex that promotes ABA biosynthesis and stomatal closure (Sun *et al.,* 2025). These findings indicate that climate adaptation is governed by spatially and temporally coordinated hormonal, peptide, metabolic, and organelle-derived signals. However, direct mechanistic evidence resolving auxin-brassinosteroid-strigolactone-peptide interactions under simultaneous field stresses remains limited. Future studies should therefore combine time-resolved hormone profiling with signalling-gene expression, receptor and kinase activity, root and stomatal traits, and crop-performance measurements under defined stress combinations.

Table 1. Climate change effects on soil processes, crop response, measurable variables, and validation approaches

Physical soil response	Chemical soil response	Biological soil response	Likely crop consequence	Management response	Measurable variables	Suggested validation approach
			Increase in soil temperature			
Aggregate breakdown, higher compaction risk, faster soil moisture loss	Faster SOM turnover, altered nitrogen cycling, possible nutrient imbalance	Higher microbial activity under moderate warming, reduced microbial stability under severe or prolonged stress	Reduced root growth, lower water and nutrient access, shorter crop duration, possible yield loss	Residue retention, reduced or strategic tillage, SOM-building practices, heat-tolerant cultivars	Soil temperature, heat-stress duration, heat-wave timing relative to crop growth stage, soil moisture, bulk density, aggregate stability, SOC, mineral N, microbial biomass, enzyme activity, root biomass, canopy temperature, photosynthetic rate, phenology, grain filling duration, and yield	Field warming or heat-stress plots combined with monitoring of heat-stress duration and timing, soil moisture, root measurements, soil C and N testing, crop physiology measurements, phenology, grain filling, and yield assessment across seasons
			Drought			
Reduced infiltration, crusting, hard setting, lower plant-available water	Salt accumulation, reduced nutrient mobility, lower nutrient diffusion to roots	Lower microbial activity, altered enzyme activity, slower nutrient mineralization	Reduced nutrient uptake, stomatal closure, lower photosynthesis, reduced biomass and yield, greater stress injury	Mulching, cover crops, residue retention, water-conserving tillage, deficit or scheduled irrigation, drought-tolerant cultivars	Soil water content, soil matric potential, infiltration rate, electrical conductivity, mineral N, available P and K, rooting depth, root length density, stomatal conductance, transpiration, photosynthetic rate, canopy temperature, biomass, and yield	Rainfed and irrigated field trials with drought treatments, soil-water sensors, tensiometers or matric-potential sensors, rooting-depth assessment, nutrient monitoring, canopy temperature sensing, gas-exchange measurements, and yield-quality assessment
			Intense rainfall / flooding			
Waterlogging, reduced aeration, erosion, surface sealing, structural breakdown	Leaching, denitrification, nitrogen loss, possible pH and redox shifts	Shift toward anaerobic microbial processes, lower soil-fauna recovery, higher denitrifier activity	Root stress, lower nutrient uptake, reduced root respiration, impaired growth, higher N_2O risk	Drainage management, residue cover, contour practices, raised beds, controlled traffic, flood-tolerant cultivars	Root-zone oxygen, soil redox potential, soil redox threshold, duration of soil saturation, soil moisture, mineral N, nitrate leaching, N_2O flux, CH_4 flux, root activity, stomatal conductance, biomass, and yield	Controlled drainage or waterlogging field plots with recorded duration of saturation, soil redox threshold monitoring, root-zone oxygen probes, mineral N sampling, runoff or leaching measurements, static chamber GHG monitoring, root assessment, and yield measurement
Indirect effects through residue inputs, root growth, soil moisture relations, and canopy water use	Altered C:N:P balance, possible nutrient dilution, changes in mineral N and available P	Shifts in decomposition, microbial activity, rhizosphere processes, and carbon stabilization	Variable effects on biomass, yield, water-use efficiency, and crop quality depending on crop type, nutrient supply, and water status	Balanced nutrient management, cultivar selection, residue management, irrigation scheduling, combined CO_2–heat–water testing	Atmospheric CO_2, crop type, C_3/C_4 photosynthetic pathway, sink strength, stomatal conductance, transpiration, photosynthetic rate, leaf area index, biomass, harvest index, grain protein, tissue N and P, SOC fractions, mineral N, CO_2 and N_2O fluxes	Free-Air CO_2 Enrichment or controlled-chamber experiments combined with nutrient and water treatments, using crop type, C_3/C_4 photosynthetic pathway, sink strength, genotype, and growth stage as crop parameters, and measuring plant gas exchange, tissue nutrient status, soil carbon fractions, greenhouse-gas fluxes, yield, and crop quality

5.2. Photosynthetic adjustment: photoprotection versus carbon gain

Under climate stress, photosynthetic performance reflects a trade-off between maintaining photoprotection and sustaining carbon assimilation. Protective adjustments that stabilize photosystem function and dissipate excess excitation energy can limit irreversible damage, but they may also reduce carbon fixation and growth. Consequently, photosynthetic resilience should be evaluated not only using conventional indicators such as Fv/Fm but also by determining whether photoprotection can maintain biomass accumulation, grain filling, crop quality, and yield under fluctuating and combined stresses (Cui *et al.,* 2014; Moustaka *et al.,* 2020; Malhi *et al.,* 2021). Within the framework, photosynthetic adjustment should be evaluated by linking soil water status, salinity, or root-zone oxygen limitation → stomatal conductance, chlorophyll fluorescence, photosynthetic rate, and transpiration → biomass accumulation, grain filling, and crop quality → water-use efficiency, nutrient-use efficiency, or emission intensity per unit yield.

Recent evidence indicates that photosynthetic stress responses should be interpreted as dynamic acclimation processes rather than as static changes in photosynthetic capacity. Under fluctuating irradiance, photoprotection depends on coordinated regulation of non-photochemical quenching, photosystem I and II activities, cyclic electron transport, and the balance between energy dissipation and carbon assimilation. Niu *et al*. (2024) demonstrated that the relative importance of these regulatory processes changes with the amplitude of light fluctuations: PGR5/PGRL1-dependent cyclic electron transport contributed strongly to photosystem regulation across oscillating-light treatments, whereas the NDH-dependent pathway became particularly relevant under large fluctuations, functioning as an additional protective mechanism. Dynamic acclimation can also create resource-use trade-offs. Durand *et al*. (2024) showed that *Arabidopsis* plants acclimated to fluctuating irradiance could maintain substantial photosynthetic capacity despite altered leaf structure, but transpiration under fluctuating high irradiance was markedly greater than under the corresponding steady-light regime. Thus, photoprotection that maintains carbon assimilation may increase water demand, an important consideration when fluctuating radiation coincides with drought and high vapour-pressure deficit. Future climate-response studies should therefore move beyond Fv/Fm alone and combine time-resolved NPQ, PSI and PSII quantum yields, P700 redox state, electron transport, stomatal kinetics, mesophyll conductance, leaf or canopy temperature, transpiration, and carbon assimilation. Such measurements would allow dynamic acclimation to be evaluated against yield, water-use efficiency, and stress-recovery capacity rather than simply against maintenance of the photosynthetic apparatus.

5.3. Redox balance and biochemical regulation

Plant adaptation to climate stress relies strongly on redox regulation. Stress-induced ROS can cause cellular damage but also act as signalling molecules; therefore, successful acclimation depends on tightly controlled ROS production and antioxidant regulation rather than complete ROS suppression (Fichman and Mittler, 2020; Mittler *et al.,* 2022). A further level of complexity arises because ROS signalling is highly dependent on ROS species, subcellular origin, concentration, and duration. Chloroplast-generated singlet oxygen, for example, activates signalling pathways that differ from those associated with more diffusible hydrogen peroxide. Genetic analysis in *Arabidopsis* has identified life-stage-dependent chloroplast singlet-oxygen signalling networks controlling retrograde signalling, chloroplast degradation, and programmed cell death, demonstrating that oxidative responses cannot be inferred solely from total ROS accumulation (Lemke and Woodson, 2024). Recent evidence also reveals direct communication among organelles during light stress. Under high light, chloroplast-derived H_2O_2 has been shown to initiate Ca^{2+}-dependent responses associated with remodelling of mitochondria and the endoplasmic reticulum, providing evidence that chloroplast redox status can reorganize cellular functions beyond the plastid itself (Angelos *et al.,* 2026).

Redox regulation should therefore be interpreted as an inter-organelle network involving ROS production, antioxidant buffering, retrograde signalling, Ca^{2+} dynamics, metabolic status, and nuclear responses. Methodologically, measurements of bulk H_2O_2, lipid peroxidation, or total antioxidant enzyme activity alone are insufficient to resolve these pathways. Where feasible, future studies should integrate compartment-sensitive redox indicators with chloroplast and mitochondrial function, glutathione and thioredoxin redox states, Ca^{2+} signalling, transcriptomic or proteomic responses, photosynthetic performance, biomass, and yield under field-relevant stress combinations.

Plants employ enzymatic antioxidant systems, osmolytes, and secondary metabolites to regulate redox balance, osmotic adjustment, and cellular protection under climate stress (Mittler *et al.,* 2022; Raza *et al.,* 2022; Yadav *et al.,* 2021). However, accumulation of protective metabolites is not necessarily a direct indicator of agronomic tolerance, because their effectiveness depends on species, tissue, developmental stage, stress intensity, and the metabolic cost of their synthesis. Therefore, biochemical protection should be interpreted according to its capacity to preserve photosynthetic function, biomass production, crop quality, and yield stability rather than solely from changes in individual metabolite concentrations. Within the framework, redox and biochemical regulation should be evaluated by

linking soil moisture, salinity, heat exposure, or flooding duration → ROS accumulation, antioxidant enzyme activity, proline concentration, membrane injury, and chlorophyll fluorescence → biomass production, grain filling, and yield stability → resource-use efficiency or greenhouse-gas intensity per unit output.

5.4. Root plasticity and whole-plant adaptation

Root and whole-plant plasticity can enhance survival under drought, flooding, salinity, and other climate-related stresses, but these responses frequently involve allocation and performance trade-offs. Greater investment in root growth or stress-protective structures may improve resource acquisition or stress avoidance while reducing carbon allocation to aboveground growth and reproduction. Their adaptive value therefore depends on the genotype, developmental stage, soil conditions, and stress combination, as well as on whether the response ultimately sustains crop productivity under field conditions (Pedersen *et al.,* 2021; Rankenberg *et al.,* 2021).

Root plasticity should be quantified using complementary field and imaging approaches, including coring, minirhizotrons, root scanning, and three-dimensional imaging. These measurements should be linked to soil water and nutrient status, root-zone oxygen, plant resource acquisition, yield, and resource-use efficiency.

Root adaptation should increasingly be evaluated as an integrated root-system-architecture-rhizosphere phenotype rather than through rooting depth or total root biomass alone. Three-dimensional imaging illustrates the importance of spatial root distribution. Using X-ray computed tomography in rice, Numajiri *et al*. (2024) demonstrated that drought avoidance during early growth was associated with the distribution of roots within specific soil-depth intervals, showing that adaptive performance cannot always be reduced to a simple "deeper rooting is better" relationship. Emerging field-to-model approaches further combine three-dimensional root digitization, architectural reconstruction, hydraulic measurements, and functional–structural modelling to quantify genotype-specific resource-acquisition strategies, as demonstrated for grapevine rootstocks (Fichtl *et al.,* 2024). These approaches complement conventional coring and minirhizotron measurements by linking root topology and spatial distribution with water and nutrient fluxes. Root architecture is also functionally coupled with microbiome assembly and therefore with rhizosphere-mediated climate adaptation. Wang *et al.* (2024) showed that genetic changes in root hair development altered drought-induced microbiome assembly and the recruitment of beneficial Rhizobiaceae. By integrating plant and microbial genetics with metagenomics, root transcriptomics, and metabolomics, the study identified mechanisms through which root traits influence microbiome-mediated drought responses. Such findings support the emerging concept of rhizosphere engineering, in which root traits, exudation, microbial recruitment, and designed microbial communities are considered jointly. However, the performance of engineered or selected microbiomes remains highly dependent on soil type, native microbial communities, host genotype, and environmental conditions, and controlled-environment benefits should not be assumed to persist under field conditions. Future validation should therefore integrate root architecture, exudation, microbial establishment and function, soil resource gradients, plant physiology, and final yield or resource-use outcomes.

6. INNOVATIVE AND BIOLOGICAL APPROACHES FOR CLIMATE-RESILIENT AGRICULTURE

Climate-resilient management seeks to increase the capacity of soil–crop systems to withstand and recover from climatic disturbances while maintaining productivity and resource-use efficiency. Soil-health management, diversification, biological inputs, precision technologies, and climate-smart breeding act through overlapping effects on soil structure, nutrient cycling, rhizosphere function, plant stress regulation, and input efficiency (Teng *et al.,* 2024; Rusu *et al.,* 2025; Țopa *et al.,* 2025). Table 2 compares these approaches according to mechanisms, constraints, evidence, context of use, measurable indicators, and validation requirements.

Table 2 also highlights the temporal nature of these responses: short-term yield effects may be variable even when longer-term improvements in soil structure, water retention, nutrient cycling, and resilience emerge.

The strength of evidence supporting climate-resilient practices remains uneven. Conservation agriculture, crop diversification, and soil-health management are supported by substantial field and long-term evidence, although outcomes vary with soil type, rainfall regime, drainage, crop system, and duration of implementation. By contrast, microbial inoculants, biostimulants, and nano-enabled products frequently show stronger effects under controlled conditions than in heterogeneous field environments, where efficacy may be constrained by native microbiomes, formulation stability, environmental variability, and management interactions. Accordingly, recommendations should distinguish between practices with replicated multi-season field support and technologies whose agronomic effectiveness still requires broader validation.

Practical adoption is also determined by economic and institutional conditions rather than biological efficacy alone. Capital requirements, labour demand, access to credit and advisory services, technical skills, perceived risk, farm size, and compatibility with existing production systems can substantially influence adoption. Regional evidence illustrates this variability: among 270 smallholders surveyed in Koumpentum, Senegal, 56.3% had adopted at least one climate-smart practice, but the adoption ranged from 70.4% for crop rotation to 14.5% for conservation

Table 2. Climate-smart agricultural practices grouped by thematic category: mechanisms, constraints, measurable variables, and validation approaches within the soil-plant-atmosphere-management system

Main mechanism in the soil-plant-atmosphere system	Short-term constraints / costs	Long-term benefits	Quantitative outcomes reported in cited literature	Context where effective	Measurable variables	Suggested validation approach	References
			Soil management				
			Soil health management				
Improves soil organic matter, nutrient retention, water-holding capacity, microbial activity, and carbon storage	Benefits may be gradual; requires monitoring, knowledge transfer, labour, and initial input costs	Greater soil fertility, better drought and rainfall buffering, stronger long-term productivity	Effects vary by amendment type and baseline soil condition; benefits are often greater in degraded soils than in fertile systems	Degraded or low-organic-matter soils under climate-smart planning	SOC, particulate organic carbon, mineral-associated organic carbon, aggregate stability, infiltration, soil moisture, mineral N, available P and K, microbial biomass, enzyme activity, biomass, yield	Long-term field trials comparing amendment types, application rates, and baseline soil conditions, with repeated soil C, nutrient, microbial, water, yield, and GHG measurements	McGuire *et al.* (2022)
			Conservation agriculture				
Reduces soil disturbance, improves aggregation, limits erosion, maintains residue cover, and supports SOC retention and water conservation	Transition costs, higher management demand, possible early yield penalties, variable GHG outcomes	Improved soil structure, carbon storage, moisture retention, and better performance under water-limited conditions	Global meta-analysis reported 5.7% lower yield under no-till than conventional tillage; yield losses were largely removed when no-till was combined with residue retention and crop rotation; in arid and semi-arid systems, no-till increased yields by 7-10%	Erosion-prone and water-limited systems, especially when used as a full conservation package rather than no-till alone	Bulk density, penetration resistance, aggregate stability, infiltration, soil moisture, SOC, residue cover, soil temperature, N_2O and CO_2 fluxes, root growth, yield	Multi-year tillage × residue × rotation trials across contrasting soils and rainfall zones, with soil physical measurements, residue monitoring, GHG chambers, and yield assessment	Teng *t al.* (2024); Pittelkow *et al.* (2015)
			Cover crops and catch crops				
Increase carbon inputs, reduce runoff and erosion, improve aggregation, retain nutrients, and provide off-season soil cover	Seed and labour costs; possible water competition in dry areas; short-term cash-crop yield effects may be neutral or negative	Better soil structure, higher SOC, improved nutrient cycling, and stronger long-term resilience	Outcomes vary with species mix, rainfall, and termination timing; benefits are generally greater after several seasons than in the first year	Systems with suitable seasonal windows, erosion risk, or nutrient-loss risk	Cover biomass, residue cover, SOC, aggregate stability, infiltration, soil moisture, mineral N, nitrate leaching, weed pressure, cash-crop yield, N_2O flux	Multi-season cover-crop trials comparing species mixtures, sowing dates, and termination dates, with soil water, nutrient loss, SOC, weed, GHG, and yield measurements	Deis *et al.* (2025)
			Cropping-system diversification				
			Agroforestry / silvopasture				
Adds perennial biomass, improves microclimate, stabilizes soil, increases carbon storage, and diversifies system functions	Long establishment period; delayed financial return; possible land-use competition and higher management demand	Greater biodiversity, erosion control, carbon storage, microclimate buffering, and livelihood diversification	Yield effects are system-specific, short-term trade-offs may occur before longer-term environmental and productivity gains	Mixed and diversified farming systems	Tree biomass, crop yield, pasture yield, soil moisture, soil temperature, wind speed, erosion rate, SOC, biodiversity indicators, carbon stock, farm income	Long-term paired-site or plot trials comparing tree-crop, tree-pasture, and open-field systems, with microclimate, soil, carbon, production, and economic measurements	Feliciano *et al.* (2018)

Table 2. Contination

Main mechanism in the soil-plant-atmosphere system	Short-term constraints / costs	Long-term benefits	Quantitative outcomes reported in cited literature	Context where effective	Measurable variables	Suggested validation approach	References
Intercropping / crop diversification / polyculture							
Increases crop diversity, improves resource partitioning, supports nutrient cycling, buffers climatic risk, and may reduce pest pressure	More demanding planning and management; possible crop competition; higher labour needs	Greater yield stability, biodiversity, and lower dependence on external inputs	Yield responses vary by crop combination and environment; pearl millet-cowpea intercropping under water-limited conditions is one example, but no universal percentage applies	Diversified and smallholder systems exposed to climate variability	Root distribution, canopy structure, light interception, soil water extraction, N uptake, biological N fixation, pest pressure, microbial activity, land-equivalent ratio, biomass, yield stability, GHG emissions per unit output	Field trials comparing monocultures and crop mixtures under rainfed and stressed conditions, with root, canopy, nutrient, pest, yield, and emissions measurements	Brooker *et al*. (2015); Nelson *et al*. (2022)
Biological approaches							
Plant growth-promoting microbes and microbiome engineering							
Improves rhizosphere function, nutrient uptake, stress signalling, plant defence, and soil biological activity	Field performance is variable; formulation, shelf life, host specificity, and adoption remain challenges	Better nutrient-use efficiency, stress buffering, and stronger soil biological functioning	Effects are often positive in controlled studies, but field consistency remains limited; reduced metal uptake in ryegrass and reduced red rot severity in sugarcane are examples of targeted benefits	Soils where microbial limits reduce plant performance and where inoculants are combined with broader soil-health management	Microbial survival, colonization, microbial biomass, enzyme activity, root growth, nutrient uptake, plant stress markers, disease severity, biomass, yield, soil moisture, N_2O and CO_2 fluxes	Controlled-to-field validation pipeline: greenhouse screening, replicated field trials across soil types, native microbiome assessment, inoculant persistence testing, yield monitoring, and economic assessment	Trivedi *et al*. (2020); Ke *et al*. (2021); Amna *et al*. (2020)
Digital and precision approaches							
Precision agriculture							
Improves timing and spatial targeting of water and nutrients, increases input-use efficiency, and reduces avoidable losses and emissions	High upfront cost, data needs, technical skills, and limited access for resource-poor farmers	Better input efficiency, lower input-related emissions, and possible yield stability gains	Benefits depend on technology level and farm scale; reported gains often include lower excess fertilizer or water use while maintaining or improving yield	Mechanized and digitally supported systems; simpler versions may fit smaller farms	Soil moisture, crop water status, NDVI or canopy indices, fertilizer rate, irrigation amount, mineral N, nitrate leaching, N_2O flux, water-use efficiency, nutrient-use efficiency, yield, cost	On-farm strip trials comparing variable-rate and uniform management, linked with sensor data, remote sensing, input records, yield maps, emissions monitoring, and cost-benefit analysis	Awais *et al*. (2026)
Genetic and phenotyping approaches							
Climate-smart crop breeding and phenotyping							
Improves tolerance to drought, heat, flooding, or nutrient stress and may reduce GHG intensity per unit yield	Long breeding cycles, investment needs, and multi-environment validation	Better performance under recurring climate stress, improved yield stability, and possible reduction in emissions intensity	Impacts depend on crop, trait, and target environment; benefits are strongest when improved genotypes are combined with suitable agronomic practices	Major crops where climate stress is recurrent and breeding targets are clearly defined	Phenology, canopy temperature, chlorophyll fluorescence, stomatal conductance, photosynthetic rate, root traits, biomass, harvest index, grain quality, yield stability, water-use efficiency, emissions intensity	Multi-location genotype × environment × management trials, using field phenotyping, remote sensing, soil monitoring, yield-quality analysis, and model-assisted trait evaluation	Begna (2021)

tillage and only 1.97% for agroforestry, demonstrating that technically promising practices may differ greatly in local feasibility (Ewulo *et al.,* 2025). Economic assessment should therefore accompany biophysical evaluation through indicators such as establishment and operating costs, labour requirements, payback period, yield variability, access to finance and extension services, and persistence of adoption over time.

Diversified cropping systems can improve functional diversity, biological nitrogen inputs, resource partitioning, and yield stability, particularly where complementary rooting patterns and crop combinations reduce competition for water and nutrients (Chamkhi *et al.,* 2022; Nelson *et al.,* 2022). However, benefits vary with crop combination, fertility, climate, labour availability, and management capacity. Diversification should therefore be evaluated through the land-equivalent ratio, resource capture, yield stability, pest pressure, and emission intensity rather than assumed to be universally advantageous.

Arbuscular mycorrhizal fungi (AMF) and plant growth-promoting bacteria, including rhizobacteria (PGPB/PGPR), can enhance nutrient acquisition, rhizosphere functioning, and stress tolerance, but field performance remains inconsistent (Verzeaux *et al.,* 2017; Li, Wang *et al.,* 2022). Variability in soil properties, native microbiomes, host genotype, formulation stability, and climatic conditions often limits translation from controlled experiments to commercial production. Microbial inputs should therefore be evaluated as components of integrated soil management rather than stand-alone solutions.

Biostimulants, osmoprotectants, microbial products, and nano-enabled formulations can improve stress regulation and resource-use efficiency, but most evidence still derives from controlled or short-term experiments (Sabagh *et al.,* 2021; Campos *et al.,* 2023; Raza *et al.,* 2023b; Raza *et al.,* 2024b, c). Their practical value requires multi-season field validation linking physiological responses with yield stability, crop quality, input demand, and economic return. Nano-enabled products additionally require assessment of environmental persistence, soil and plant transport, microbial effects, accumulation in edible tissues, greenhouse-gas responses, worker exposure, and food-chain safety before broader agricultural deployment. These technologies should therefore be treated as targeted, site-specific tools rather than universally applicable climate-resilience solutions.

6.1. Digital and AI-enabled approaches for climate adaptation

Digital agriculture provides an emerging pathway for operationalizing soil-plant-atmosphere interactions through the integration of field sensors, remote sensing, crop models, artificial intelligence (AI), and machine-learning algorithms. These tools can combine weather, soil-water, crop-canopy, management, and yield data to support early stress detection, irrigation and nutrient scheduling, yield forecasting, and spatially targeted interventions. For example, ensemble machine-learning approaches have been applied to climate-sensitive crop-yield prediction across Canada (Gharakhanlou and Perez, 2024), while integration of satellite remote sensing with the DSSAT crop model has improved estimation of crop phenology, leaf-area index, and biomass (Amin *et al.,* 2025). AI-supported water-management models using remote-sensing and reanalysis datasets have also demonstrated strong predictive performance, indicating potential for more responsive irrigation management (Ye *et al.,* 2024).

However, predictive accuracy alone does not by itself demonstrate value for climate adaptation. Model transferability across regions, crops, soil types, management systems, and unprecedented climate extremes remains a major limitation, particularly when droughts or other rare events are poorly represented in training datasets. Recent work evaluating machine-learning yield prediction across European and Asian drought environments illustrates the need to explicitly test spatial and climatic transferability rather than assuming that models calibrated in one region will remain reliable elsewhere (Sahu *et al.,* 2026). Digital approaches also depend on data quality, ground-truth measurements, connectivity, technical skills, computational infrastructure, and economic accessibility. Evidence from 723 farm households in Punjab, Pakistan, showed that digital training was associated with a 25.4% improvement in adoption of energy-smart agricultural practices and an estimated increase in net farm returns of PKR 14,365 per acre, illustrating that digital capacity and farmer training can be as important as the technology itself (Sher *et al.,* 2025). Future applications should therefore combine AI and remote sensing with process-based crop models, field measurements, economic assessment, and independent multi-location validation to ensure that digital recommendations remain interpretable, locally relevant, and robust under climate extremes.

Taken together, biological, agronomic, and digital innovations require coordinated field and model validation. Figure 2 therefore links climate and management drivers with measurable soil, plant, and greenhouse-gas indicators, feedback loops, and validation routes. The figure shows how hypotheses on climate response can be tested through coordinated field experiments, long-term trials, multi-location studies, and process-based modelling.

7. CLIMATE CHANGE MITIGATION STRATEGIES FOR AGRICULTURE

Agricultural mitigation requires simultaneous reduction of greenhouse gas (GHG) emissions and enhancement of carbon storage while maintaining productivity and resilience (Clark *et al.,* 2020; Crippa *et al.,* 2021; IPCC, 2023). Within the present framework, the key pathways involve

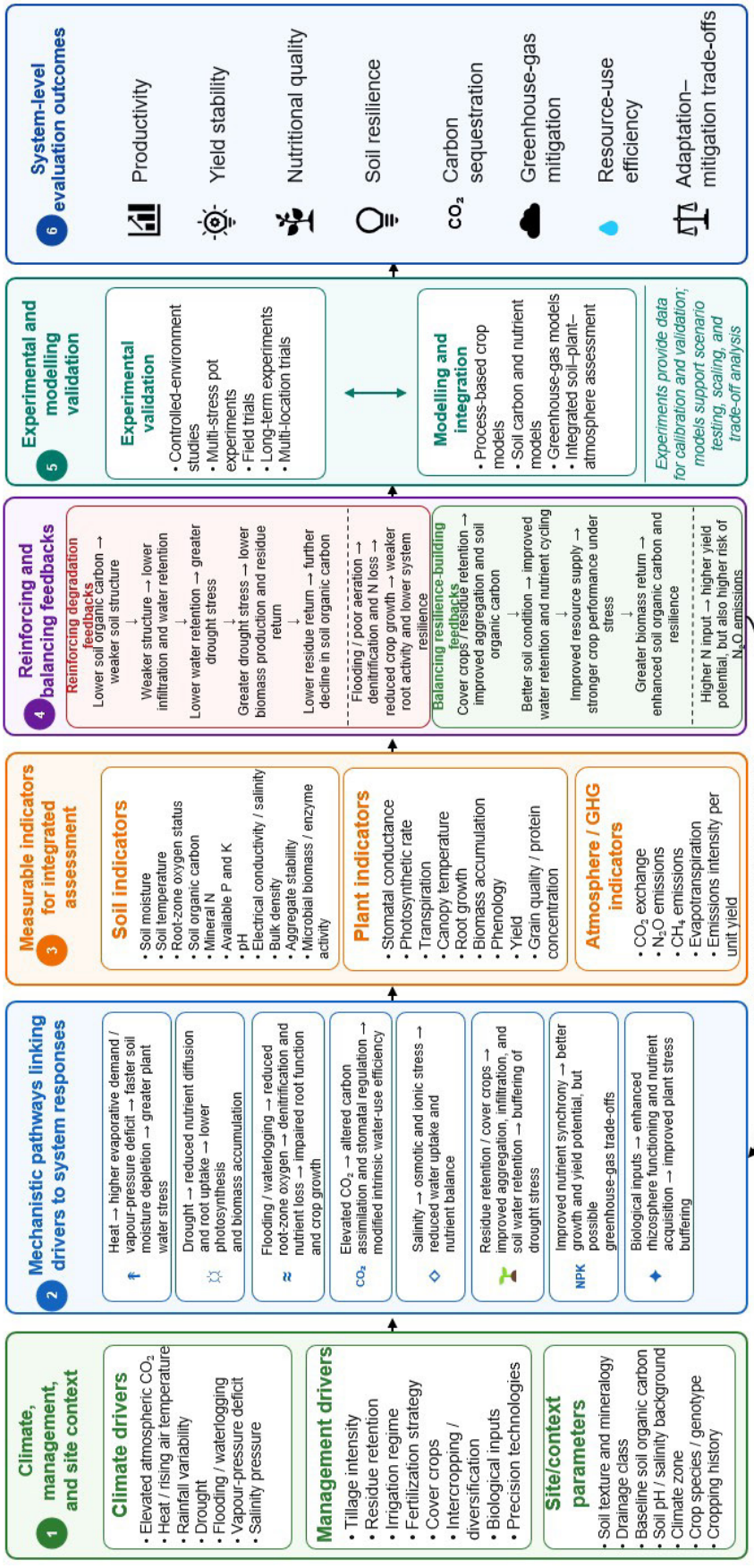


Fig. 2. Operational framework for testing and validating soil-plant-atmosphere interactions under combined climate stressors.

SOC management, nitrogen-use efficiency, resource targeting, and emission intensity, all of which are strongly context dependent.

Improved soil and land management is a central agricultural mitigation pathway to protect and increase SOC. Practices such as cover cropping, residue retention, organic amendments, agroforestry, reduced tillage, and broader soil restoration strategies can strengthen the land–atmosphere carbon sink while also improving soil fertility, water retention, and crop productivity (Lal, 2004; 2021). Recent field evidence further supports the importance of management-driven changes in soil structure, nutrient retention, and carbon storage within climate-stressed agricultural systems (Cakpo *et al.,* 2026). Nevertheless, SOC sequestration is not a uniform or unlimited mitigation option. Reported gains vary with climate, soil type, sampling depth, baseline SOC levels, and the duration of management, and some practices promoted as mitigation solutions may deliver smaller net benefits than sometimes assumed. For example, no-till is often associated with carbon sequestration potential, but its mitigation value remains debatable because SOC gains may be modest, concentrated near the surface, or partly offset when carbon redistribution through the soil profile is considered (Powlson *et al.,* 2014; Haddaway *et al.,* 2017). These uncertainties indicate that soil-carbon strategies should be interpreted cautiously and assessed over appropriate temporal and spatial scales.

Nitrogen management is a major mitigation leverage point because excess fertilizer use increases both upstream emissions and field N_2O losses. Integrated nutrient management, legumes, soil testing, and precision fertilization can improve nitrogen-use efficiency, but excessive input reduction may constrain productivity in low-fertility systems, while cover-crop and legume benefits depend on synchronization between nutrient release and crop demand (Ladha *et al.,* 2016; Stagnari *et al.,* 2017; Lal *et al.,* 2020; Paramesh *et al.,* 2023).

Conservation and precision approaches can jointly improve resource targeting, reduce erosion and nutrient losses, and support adaptation-mitigation synergies. However, their net mitigation effects depend on soil, climate, farm scale, technology access, and indirect input requirements; productivity gains should therefore not automatically be interpreted as net GHG reductions (Pittelkow *et al.,* 2015; Brown *et al.,* 2018; Jat *et al.,* 2024).

Crop diversification and genetic improvement can reduce emission intensity when they stabilize productivity or reduce resource losses. Direct-seeded rice, for example, has shown substantially lower global warming potential than transplanted systems in specific contexts (Tao *et al.,* 2016). Climate-resilient breeding and phenotyping may further improve resource-use efficiency, but mitigation benefits require validation under realistic genotype × environment × management conditions and should be quantified as actual GHG reductions per unit land or product (Langridge *et al.,* 2021).

Overall, agricultural mitigation strategies are most effective when evaluated as integrated systems rather than as isolated practices. Soil-carbon management, nitrogen-use efficiency, conservation-oriented farming, precision input management, diversification, and breeding all operate through linked effects on carbon storage, nutrient cycling, water relations, and crop performance. Their mitigation value depends not only on theoretical sequestration or emission-reduction potential but also on feasibility, duration, local biophysical conditions, and possible trade-offs with productivity and adaptation. For this reason, mitigation in agriculture should be assessed through integrated frameworks that jointly consider emission outcomes, agronomic performance, and resilience, ensuring that practices promoted as climate solutions contribute meaningfully to long-term agricultural sustainability.

8. FRAMEWORK APPLICATION AND VALIDATION LOGIC

This framework is intended not only to describe relationships among soil, plant, atmosphere, and management components but also to guide their experimental testing. It can be applied through five linked steps. First, research hypotheses should be written as causal pathways linking external drivers, site parameters, state variables, and outcomes. For example, heat and drought can be tested as a pathway from higher vapour-pressure deficit to soil water depletion, stomatal closure, lower photosynthetic rate, biomass loss, and yield decline. Flooding can be tested as a pathway from lower root-zone oxygen to denitrification, nitrogen loss, N_2O emissions, impaired root function, and reduced crop growth. Second, each pathway should be linked to measurable variables, including soil water, soil temperature, root-zone oxygen, mineral nitrogen, SOC, microbial activity, stomatal conductance, photosynthetic rate, canopy temperature, biomass, yield, crop quality, and CO_2, N_2O, and CH_4 fluxes. Third, these variables should be assessed through controlled multi-stress experiments, field trials, long-term experiments, and multi-location testing. Fourth, measured data should be used to calibrate and validate crop, soil carbon, nutrient, and greenhouse-gas models. Finally, field and model outputs should be compared through trade-off assessment among productivity, yield stability, soil resilience, carbon storage, emission intensity, resource-use efficiency, cost, and feasibility.

Each pathway should include, at minimum, one climate or management driver, one soil state variable, one plant response, one greenhouse-gas or resource-use indicator, one site parameter, and one management factor. Validation should match the mechanism: controlled experiments for isolating processes, field trials for management and soil-crop interactions, long-term experiments for slowly

Table 3. Examples of verifiable mechanisms, measurable indicators, validation routes, and trade-offs within the soil-plant-atmosphere-management framework

Mechanism	Measurable variables	Field testing	Model use	Trade-off assessed
Heat + drought → soil water loss → stomatal closure → yield decline	Soil water, VPD, stomatal conductance, canopy temperature, photosynthesis, yield	Multi-stress field plots	Crop-water	Yield stability *vs* irrigation demand
Flooding → low oxygen → denitrification → N_2O + N loss	Root-zone oxygen, mineral N, N_2O flux, root activity, yield	Drainage/ waterlogging plots	Soil N/GHG	Yield *vs* emissions
Residue retention → aggregation → water retention → drought buffering	SOC, aggregate stability, infiltration, soil moisture, biomass	Long-term tillage/ residue trial	Soil carbon-water	Carbon storage *vs* yield response
Intercropping → resource partitioning → yield stability	Root distribution, light interception, N uptake, biomass, LER, yield	Multi-species field trial	Crop mixture	Yield stability *vs* management cost

changing soil properties, multi-location studies for context dependence, and calibrated process-based models for scenario and trade-off analysis. Table 3 translates this structure into representative research units.

The framework also provides a way to test feedback structure. Reinforcing feedbacks are pathways that intensify degradation after stress begins. For example, climate-driven reductions in biomass and ground cover can increase erosion and SOC loss, which then weakens soil structure, nutrient retention, and water-holding capacity. These changes increase crop exposure to later drought and heat stress, further reducing growth and residue return. Similar feedbacks may occur when nutrient depletion, reduced microbial function, or higher greenhouse-gas losses weaken the soil-plant system. In contrast, balancing feedbacks are pathways that buffer stress and stabilize performance. Practices that build SOC, improve aggregation, increase plant-available water, support nutrient cycling, and maintain functional biodiversity can reduce crop sensitivity to climate variability, improve yield stability, and lower greenhouse-gas emission intensity per unit output (Lal, 2016). This feedback logic can be expressed as a verifiable pathway. For example, a reinforcing degradation loop can be written as: drought or heat stress → lower biomass production and ground cover → lower residue return → lower SOC → weaker aggregate stability and water-holding capacity → higher crop water stress → further biomass reduction. A balancing resilience-building loop can be written as: residue retention or cover cropping → higher SOC and aggregation → better infiltration and plant-available water → lower drought sensitivity → higher biomass return → further support for SOC and yield stability. These loops should be tested using measured SOC, aggregate stability, infiltration, soil water content, biomass return, canopy temperature, yield stability, and greenhouse-gas fluxes.

This structure also helps explain why the same climate driver or management practice can produce different outcomes across sites. Soil texture, drainage, baseline SOC, fertility status, crop genotype, rooting depth, management history, and climate zone determine the strength and direction of system responses. For this reason, management practices should not be judged as universal solutions. Their value should be tested against local soil and climate conditions, measured crop responses, greenhouse-gas outcomes, and practical feasibility.

At the farm scale, the framework links management decisions with long-term performance. Strategies aimed at yield gain should also be assessed for their effects on soil function, nutrient and water use, greenhouse-gas fluxes, crop quality, and yield stability. This makes the framework suitable for comparing management options under combined climate stressors and for identifying where productivity, resilience, and mitigation goals align or conflict.

9. ECONOMIC IMPLICATIONS AND COST TRADE-OFFS

Economic impacts arise not only from yield losses but also from climate-induced changes in water, nutrient, pest-management, and input requirements. Integrating economic indicators with soil, plant, atmospheric, and management variables allows costs and returns to be interpreted as system-level outcomes.

9.1. Direct yield losses

One major economic pathway is the direct loss of revenue caused by lower yields under drought, heat, flooding, salinity, and related climatic extremes. Climate-induced drought has imposed a particularly large burden on agriculture, with disaster-related agricultural losses averaging approximately USD 170 billion per year globally and more than USD 37 billion in drought-related losses in low- and middle-income countries between 2008 and 2018 (FAO, 2021b). Likewise, droughts and heatwaves reduced European cereal yields by approximately 9.0 and 7.3%, respectively, over 1961-2018 (Brás *et al.,* 2021). These losses reflect the underlying physiological effects of heat and water stress, including reduced photosynthesis, increased respiration, stomatal closure, and lower soil moisture availability. Economically, such yield

shocks reduce gross returns while often increasing per-unit production costs, since many fixed and semi-fixed expenditures remain unchanged even when output declines. These losses should therefore be linked to the underlying climate and crop-response variables rather than interpreted solely as changes in final yield.

9.2. Increased input and operating costs

Climate stress also raises production costs by changing the biophysical variables that determine input demand. Under drought, lower soil water content, higher vapour-pressure deficit, and higher canopy temperature increase irrigation demand and energy use for water pumping. These costs should therefore be assessed together with crop water status, transpiration, water-use efficiency, biomass, and yield. Fertilizer costs should be interpreted through mineral nitrogen, available phosphorus and potassium, nutrient diffusion to roots, root length density, nutrient uptake, N_2O loss, and yield response. Under flooding or waterlogging, lower root-zone oxygen and higher denitrification can increase nitrogen losses and reduce fertilizer recovery, making N_2O flux and mineral nitrogen key variables for both economic and environmental assessment. Crop-protection costs should be linked to pest and disease pressure, stress-weakened crop condition, treatment frequency, crop damage, and yield loss. This variable-based structure allows input costs to be tested as outcomes of defined soil, plant, and atmosphere processes. In this way, climate change not only reduces output but also increases the cost of maintaining each unit of output. Similar cost pressures arise under heat and rainfall variability, where greater management intensity may be required to stabilize crop growth and limit stress damage. These input-cost pathways are especially important in regions where farmers already face high energy prices, limited irrigation infrastructure, or restricted access to credit.

9.3. Pest, disease, and soil degradation costs

A further cost pathway arises from the combined burden of pest pressure and soil degradation. Warmer temperatures and shifting humidity patterns often intensify pest and pathogen risks, increasing both direct crop losses and the costs of surveillance, pesticides, and disease management. Global annual economic losses due to plant diseases and pests have been estimated at approximately USD 220 billion, with major yield losses documented across key crops such as wheat, rice, maize, potato, and soybean (Savary *et al.,* 2019). Soil degradation represents another major but often underappreciated economic burden. For example, soil salinization causes global losses of about USD 27.3 billion per year in irrigated agriculture (FAO, 2021a). These losses reflect the need for additional drainage, gypsum or other soil amendments, improved irrigation management, and salt-tolerant varieties, often without full recovery of productivity. More broadly, degradation of soil structure, nutrient retention, and water-holding capacity increases production risk and reduces the economic efficiency of inputs over time.

9.4. Economic benefits of climate-smart practices

Although climate change raises costs through multiple channels, some climate-smart and soil health–oriented practices can reduce long-term expenditure and improve economic stability. Practices such as reduced tillage, diversification, improved nutrient management, and more efficient water use may lower fuel, labour, machinery, fertilizer, or irrigation costs while strengthening resilience through improved soil structure, moisture retention, and resource-use efficiency. A useful example comes from Central Europe, where long-term evidence showed that conservation tillage systems reduced operating costs by about 9.8% relative to conventional tillage over a 20-year period, while increasing gross income by 2.3% and overall profit by approximately 13.0% (Madarász *et al.,* 2025). These gains were associated with lower fuel and labour requirements and with improvements in soil condition that supported production. However, such outcomes should be interpreted carefully. The results are region-specific, depend on long-term implementation, and may not capture transitional risks, early adoption costs, or possible short-term yield variability. Reduced tillage and related practices can produce uneven economic results depending on soil type, drainage, climate regime, equipment availability, and farmer experience.

9.5. Short-term versus long-term trade-offs

Adoption depends on the balance between short-term investment and longer-term gains in productivity, soil function, input efficiency, and risk reduction. Economic feasibility should therefore consider establishment and operating costs, labour and technical requirements, payback period, yield variability, access to finance and extension services, and persistence of adoption. Linking these indicators with soil, crop, resource-use, and GHG outcomes allows climate-smart practices to be evaluated according to both biophysical effectiveness and practical feasibility.

10. UNRESOLVED SCIENTIFIC QUESTIONS AND PRIORITIES FOR INTEGRATED CLIMATE-RESILIENT AGRICULTURE

Despite substantial progress in understanding climate-agriculture interactions, several major uncertainties limit the translation of mechanistic knowledge into reliable adaptation strategies. A first unresolved question concerns how simultaneous and sequential stresses modify responses established under single-stressor conditions. Heat, drought, flooding, salinity, nutrient limitation, and biotic pressure may interact synergistically or antagonistically, while their effects also depend on stress sequence,

and their effects depend strongly on the developmental stage, stress duration, recovery periods, and previous exposure. Future experiments should therefore move beyond factorial combinations of individual stresses toward realistic stress sequences and thresholds representative of field environments.

A second uncertainty concerns the transferability of mechanisms across spatial and temporal scales. Responses demonstrated in growth chambers or pot experiments may not persist under heterogeneous field soils, fluctuating weather, crop competition, native microbiomes, and management operations. Likewise, short-term improvements in plant physiology or soil properties do not necessarily predict long-term changes in yield stability, SOC, nutrient cycling, or greenhouse-gas emissions. Coordinated controlled experiments, long-term field trials, and multi-location studies are therefore required to determine which mechanisms remain robust across scales.

A third priority is to understand genotype × environment × management interactions. Soil texture, drainage, baseline organic carbon, fertility, rooting depth, climatic history, crop genotype, and management legacy can alter both the direction and magnitude of climate responses. Future research should therefore identify response thresholds and moderator variables rather than rely primarily on global average effects. Meta-analyses are particularly valuable for identifying general tendencies, but their heterogeneity should be examined explicitly to determine where management recommendations are transferable and where region-specific strategies are required.

Important uncertainty also remains regarding soil and rhizosphere biological processes. Taxonomic shifts in microbial communities do not necessarily indicate changes in ecosystem function because functional redundancy, microbial adaptation, ecological memory, and plant-mediated recruitment can alter soil responses independently of community composition. The integration of metagenomics, metatranscriptomics, metabolomics, functional assays, nutrient transformations, and greenhouse-gas measurements with root and crop phenotyping is needed to determine whether microbiome changes causally improve climate resilience.

Emerging digital technologies introduce an additional research frontier. Artificial intelligence, machine learning, remote sensing, high-throughput phenotyping, and process-based models can integrate large volumes of soil, plant, weather, and management information, but their reliability under novel climate extremes and outside the regions used for model calibration remains uncertain. Independent validation, uncertainty quantification, model interpretability, and comparison with measured field data should therefore accompany predictive performance.

Finally, climate-resilient management should be evaluated through adaptation-mitigation-economic trade-offs rather than through isolated productivity gains. Practices that increase yield or water-use efficiency may not reduce greenhouse-gas emissions, while practices that increase soil carbon may involve short-term yield, labour, or financial costs. Future research should jointly quantify productivity, yield stability, crop quality, soil resilience, resource-use efficiency, greenhouse-gas intensity, economic return, adoption barriers, and implementation risk. The central research challenge is therefore not to identify universally superior practices, but to determine which interventions work, through which mechanisms, under which combinations of soil, climate, crop, and management conditions, and with what trade-offs.

11. CONCLUSIONS AND FUTURE DIRECTIONS

This review advances climate-agriculture research from a largely component-based interpretation toward an integrated soil-plant-atmosphere-management perspective in which climate drivers, soil processes, plant physiology, microbial functioning, management interventions, and greenhouse-gas feedbacks are evaluated as interacting components of a common system. The principal conceptual contribution is therefore not the identification of individual climate effects, but the organization of these effects into measurable causal pathways, feedback structures, and validation routes. This approach helps explain why apparently similar climatic pressures or management practices can generate contrasting outcomes across soils, crops, regions, and production systems.

Future research should prioritize realistic multi-stress combinations, genotype × environment × management interactions, long-term soil and crop responses, and coordinated assessment of productivity, crop quality, resource-use efficiency, soil resilience, and greenhouse-gas emissions. Greater integration of systems biology, root and rhizosphere phenotyping, microbiome and multi-omics approaches, remote sensing, artificial intelligence, machine learning, and process-based crop and soil models will be particularly important for identifying mechanisms that remain robust across scales. These approaches should be supported by interdisciplinary collaboration among soil scientists, plant physiologists, microbiologists, agronomists, modellers, data scientists, economists, and social scientists, because biological effectiveness alone does not ensure technological feasibility, farmer adoption, or regional suitability.

The proposed framework can also guide experimental design by requiring each hypothesis to link a defined climate or management driver with measurable soil and plant responses, site parameters, resource-use or greenhouse-gas indicators, and an appropriate validation pathway. Such experiments can generate the field data needed to calibrate and independently validate predictive models under future climate scenarios. In turn, model outputs can be used to compare alternative management strategies across regions and quantify trade-offs among yield stability, carbon storage,

emission intensity, water and nutrient use, economic cost, and implementation risk. This creates a direct connection between mechanistic research and decision support.

At the policy level, the framework provides a basis for moving away from universally prescribed climate-smart practices toward context-specific recommendations supported by measurable evidence. Policies promoting conservation agriculture, biological inputs, irrigation technologies, digital decision-support tools, or climate-resilient cultivars should therefore consider soil type, climate exposure, crop system, infrastructure, economic feasibility, and locally demonstrated effectiveness. Future climate adaptation will depend less on identifying a single optimal practice than on determining which combinations of interventions are effective, where they are effective, through which mechanisms, and under which environmental and socioeconomic constraints. The soil-plant-atmosphere-management framework proposed here provides a structured basis for addressing these questions through integrated experimentation, predictive modelling, and evidence-based agricultural policy.

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