The Resilience–Trait–Function Nexus: Linking Plant Adaptive Responses to Ecosystem Functioning and Agroecosystem Resilience under Climate Change

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ABSTRACT

Climate change is intensifying the frequency, duration and complexity of environmental disturbances affecting plants and agroecosystems. Drought, heat, salinity, flooding, nutrient imbalance and their combinations can disrupt water relations, photosynthesis, nutrient acquisition, growth, reproduction and ecosystem functioning. Although extensive research has examined individual stress responses and plant functional traits, the mechanistic links between plant adaptive responses, resilience and ecosystem functioning remain fragmented. This review proposes a Resilience–Trait–Function (RTF) Nexus as an integrative conceptual framework connecting these dimensions across biological and ecological scales.

The framework conceptualizes plant resilience as a context-dependent, trait-mediated process through which coordinated morphological, physiological, biochemical and phenological responses influence resistance, acclimation and recovery following environmental disturbance. Particular emphasis is placed on root and hydraulic traits, leaf and photosynthetic characteristics, phenological strategies, nutrient-use traits, biochemical defence mechanisms and reproductive traits, while recognizing that resilience emerges primarily from trait combinations, phenotypic plasticity and trade-offs rather than isolated traits. The framework further distinguishes response traits from effect traits and examines how trait-mediated responses scale from individual plants to populations, communities and ecosystems through functional diversity, response diversity, functional complementarity and plant–soil–microbial interactions.

Special attention is given to compound and sequential stresses, where plant responses may be additive, synergistic or antagonistic and where stress history can influence subsequent recovery. The RTF Nexus is subsequently extended to agroecosystems, highlighting applications in crop breeding, crop diversification, intercropping, agroforestry, soil management, microbiome-informed strategies, high-throughput phenotyping and precision agriculture. Key research priorities include standardized resilience metrics, dynamic assessment of recovery, below-ground trait integration, multi-location field validation, predictive modelling and integration of trait, environmental and management datasets. The proposed framework provides a mechanistic basis for shifting climate-resilient agriculture from the selection of isolated stress-tolerance traits toward the design of agroecosystems capable of maintaining essential functions during disturbance and recovering effectively afterwards.

Keywords: Plant resilience; Functional traits; Ecosystem functioning; Agroecosystem resilience; Climate-smart agriculture

INTRODUCTION

Climate change is increasingly expressed not simply as a gradual shift in mean environmental conditions but as a changing disturbance regime. Rising temperatures, altered precipitation, drought, heat waves, salinity, flooding, nutrient imbalance and extreme events can occur singly, repeatedly or in combination. These disturbances influence photosynthesis, plant water relations, nutrient acquisition, biomass allocation,

reproduction and ultimately ecosystem productivity. Resilience therefore needs to be considered as a dynamic property of biological systems rather than as a synonym for survival [7, 31].

Plants respond to environmental stress through coordinated morphological, physiological, biochemical and phenological adjustments. Stomatal regulation, root-system modification, osmotic adjustment, antioxidant defence, changes in carbon allocation and phenological shifts are examples of mechanisms that can reduce damage or facilitate recovery. Functional traits provide a useful language for connecting such responses to ecological processes because traits describe measurable characteristics that influence plant performance and interactions with the environment [10, 30].

At the same time, functional traits should not be treated as universal predictors of resilience. A root trait that is advantageous under one drought regime may be less useful under another; a conservative leaf strategy may improve water retention while limiting rapid carbon gain; and a phenological shift may avoid one stress while increasing exposure to another. Intraspecific functional variation and phenotypic plasticity further modify these relationships [1].

At community level, functional diversity, response diversity and functional complementarity provide possible mechanisms through which species and genotypes can differ in their responses to disturbance. However, recent evidence does not support a universal positive relationship between functional diversity and resilience, and the generality of response-diversity effects remains debated [12, 17, 20, 25]. This context dependence is central to the present framework.

Agroecosystems provide a particularly important test of these ideas because resilience must be expressed through maintained or restored functions such as productivity, water-use efficiency, nutrient cycling, soil health and yield stability. Plant traits can influence these functions, but their effects are mediated by competition, facilitation, soil processes, microbial interactions, management and environmental conditions [2, 14, 16, 19, 33].

Despite extensive research on plant stress physiology, functional traits, biodiversity–ecosystem functioning relationships and climate-resilient agriculture, these fields are often examined separately. The mechanistic pathway from disturbance through plant traits and plasticity to resistance, recovery and ecosystem functioning remains insufficiently integrated, especially for compound and sequential stresses.

The objectives of this review are therefore to: (i) synthesize mechanisms underlying plant resistance, acclimation and recovery; (ii) evaluate functional traits, trait combinations and phenotypic plasticity as components of resilience; (iii) examine the roles of functional diversity, response diversity, complementarity and plant–soil–microbial interactions; (iv) develop the Resilience–Trait–Function Nexus as an integrative conceptual framework; and (v) translate the framework into applications for sustainable and climate-resilient agroecosystem management.

This review synthesizes foundational and recent literature on plant resilience, functional traits, ecosystem functioning, compound abiotic stresses and climate-resilient agriculture, with particular emphasis on studies that provide mechanistic or quantitative evidence linking plant responses with ecological processes.

CONCEPTUAL FOUNDATIONS OF PLANT RESILIENCE

Plant resilience is defined here as the capacity of plants to maintain or restore functional performance following environmental disturbance through coordinated morphological, physiological, biochemical and phenological responses, with outcomes determined by trait combinations, phenotypic plasticity and environmental context.

Resilience should be distinguished from related concepts. Resistance refers to the ability to maintain performance during disturbance; tolerance describes the ability to withstand stress while remaining viable; acclimation refers to reversible adjustment within an individual's lifetime; phenotypic plasticity is the

capacity to alter phenotype in response to environmental conditions; recovery concerns the trajectory toward pre-disturbance or functionally acceptable performance; and adaptation refers to heritable evolutionary change across generations [7, 31]. Survival is not necessarily resilience, and tolerance of stress is not necessarily equivalent to rapid recovery.

Four dimensions are especially useful for the RTF framework: resistance, recovery, adaptation and reorganization. Resistance determines how much function is lost during disturbance. Recovery determines how quickly and completely function is restored. Adaptation concerns longer-term evolutionary adjustment, while reorganization describes changes in composition or system configuration that allow essential functions to persist under altered conditions [31].

These dimensions operate across scales from molecular and cellular responses to organs, individuals, populations, communities, ecosystems and agroecosystems. A physiological adjustment in an individual plant can affect competitive performance; population-level variation can influence demographic stability; community-level response diversity can buffer functional loss; and plant–soil–microbial interactions can alter ecosystem processes.

The RTF Nexus therefore uses a simple but important analytical chain: Disturbance → Plant response → Functional trait → Resilience dimension → Ecological consequence. This avoids conflating the environmental event, the biological response, the trait through which the response is expressed, and the resulting ecosystem effect.

An operational statement of the framework is: Plant resilience is a context-dependent, trait-mediated process in which coordinated functional traits and phenotypic plasticity regulate resistance, acclimation and recovery from environmental disturbance. Through population- and community-level processes—including intraspecific variation, response diversity and functional complementarity—these trait-mediated responses can propagate to ecosystem functioning and ultimately influence agroecosystem resilience.

The central question consequently shifts from “Which trait makes a plant resilient?” to “Under which environmental and disturbance conditions do particular combinations of traits and plastic responses improve resistance, recovery and ecosystem functioning?”

Plant Adaptive Responses to Climate-Related Disturbances

Climate-related disturbances vary in intensity, duration, frequency, timing and sequence. Their effects therefore depend not only on stress type but also on exposure history and interactions among stresses. The following synthesis emphasizes mechanisms that connect adaptive responses with functional traits and resilience dimensions.

Drought

Drought directly constrains plant water status and indirectly affects photosynthesis, nutrient transport, carbon allocation and reproduction. Plants may respond through stomatal regulation, osmotic adjustment, antioxidant defence, changes in root allocation and altered phenology. Root depth, root length density, diameter, specific root length, tissue density, branching, root:shoot allocation and hydraulic traits can influence access to water and the balance between acquisition and conservation. A 2024 meta-analysis showed that drought effects on root morphology vary with drought intensity, duration, trait identity and plant functional group [28]. Recovery after rewatering is equally important because plants can differ markedly in the speed and completeness with which physiological functions return after stress [32]. Repeated drought may also generate acclimation or stress-memory effects.

Heat

Heat stress can impair membranes, photosystem II, stomatal function, carbon assimilation and reproductive processes. Plants may adjust canopy temperature, stomatal conductance, leaf morphology, antioxidant

systems, membrane protection and phenology. Heat and drought frequently interact because evaporative cooling depends on water availability. Recent work emphasizes heat acclimation as a dynamic process integrating cellular protection with whole-plant responses [4]. High-throughput phenotyping can help identify traits associated with heat resilience and selection under warming conditions [18].

Salinity

Salinity imposes both osmotic and ionic constraints. Adaptive responses include osmotic adjustment, ion exclusion or compartmentalization, maintenance of K+/Na+ homeostasis, antioxidant defence, hormonal regulation and modification of root growth. Roots are a primary interface with saline soil and can alter rhizosphere processes. Cross-resistance between drought and salinity has been documented at physiological, biochemical and growth levels, but the degree of cross-protection depends on the trait and stress context [3].

Flooding and waterlogging

Flooding reduces oxygen availability and can impair respiration, nutrient uptake and root function. Plants may develop aerenchyma, adventitious roots, altered root porosity, anaerobic metabolic pathways and carbohydrate-conservation strategies. Reoxygenation during drainage creates an additional oxidative challenge. Flooding responses therefore need to include both resistance during oxygen deficiency and recovery after water recedes [24].

Nutrient imbalance

Climate variability can modify nutrient mineralization, leaching, mobility and root–microbe interactions. Plants may adjust root architecture, nutrient uptake, nutrient-use efficiency, tissue stoichiometry and nutrient resorption. These traits influence both individual performance and ecosystem nutrient cycling. Nutrient-use strategies therefore need to be evaluated alongside water availability, soil structure and microbial activity.

Multiple and interacting stresses

Combined stresses such as heat × drought, drought × salinity, salinity × flooding and drought followed by flooding can produce additive, synergistic or antagonistic effects. The response to a combination cannot necessarily be predicted from the responses to each stress separately [8, 22, 29]. Stress order and history may modify acclimation, resource depletion and recovery. This makes sequential disturbance an important dimension of resilience.

Repeated and sequential disturbances

Repeated exposure can lead to stress memory, priming, cumulative damage or altered recovery. The same disturbance may therefore have different consequences depending on previous exposure. Resilience assessment should consequently include pre-disturbance condition, disturbance response, recovery trajectory and post-recovery performance rather than a single measurement taken during stress.

Synthesis: Climate-related disturbances select for coordinated combinations of functional traits and plastic responses rather than isolated “resilience traits.”

Table 1. Climate-related disturbances, plant adaptive responses, functional traits and resilience consequences

Disturbance	Major adaptive responses	Representative traits	Resilience dimension	Potential consequence
Drought	Stomatal regulation; osmotic adjustment; root allocation; antioxidants	Root depth; SRL; tissue density; hydraulic traits;	Resistance + recovery	Water acquisition, productivity

		stomatal traits		stability
Heat	Thermal protection; stomatal adjustment; antioxidant defence; phenological shifts	Leaf thickness; canopy temperature; stomatal traits; fluorescence; phenology	Resistance + acclimation	Photosynthesis and reproductive stability
Salinity	Ion exclusion/compartmentalization; osmotic adjustment	Root traits; K+/Na+ regulation; osmolytes; antioxidants	Resistance + recovery	Growth and nutrient balance
Flooding	Aerenchyma; adventitious roots; anaerobic metabolism	Root porosity; aerenchyma; carbohydrate reserves	Resistance + recovery	Root function and survival
Nutrient imbalance	Root foraging; nutrient-use adjustment; resorption	Root architecture; tissue N/P; NUE; resorption	Acclimation + recovery	Nutrient cycling and productivity
Compound stress	Integrated responses; cross-acclimation or trade-offs	Trait syndromes; plasticity; stress-history responses	Resistance + recovery	Yield and ecosystem-function stability
Sequential stress	Priming; memory; altered resource allocation	Dynamic physiological and phenological traits	Recovery + acclimation	Recovery trajectory and future tolerance

Plant Functional Traits as the Resilience Interface

Functional traits constitute the interface between environmental disturbance and biological performance, but resilience emerges primarily from coordinated trait combinations, phenotypic plasticity and their interaction with environmental context [10, 30]. A functional trait is a measurable characteristic of an organism that influences its performance, interactions or effects on ecosystem processes [30].

Response traits describe characteristics associated with how organisms respond to environmental variation, whereas effect traits describe characteristics through which organisms influence ecosystem processes. Some traits can function in both roles. Root traits are a strong example because they respond to soil moisture and nutrient conditions while simultaneously affecting soil structure, carbon inputs and nutrient cycling [2, 19].

Root and hydraulic traits include depth, length density, diameter, specific root length, tissue density, branching, root:shoot allocation, root hairs, hydraulic conductivity, xylem characteristics, aerenchyma, suberization and exudation. Root depth should not be treated as universally beneficial: deeper roots can improve access to water, but root construction and exploration impose carbon costs, and the advantage depends on soil profile and disturbance regime [2, 16, 28].

Leaf and photosynthetic traits include specific leaf area, leaf dry-matter content, thickness, area, chlorophyll concentration, photosynthetic capacity, stomatal density and conductance, leaf water potential, chlorophyll fluorescence and leaf temperature. These traits are connected to the global leaf economics spectrum and to the broader fast–slow spectrum of plant strategies [6, 23, 34].

Stomatal traits illustrate trade-offs especially clearly. Greater stomatal control can conserve water but may restrict carbon gain and evaporative cooling. Under heat, maintaining sufficient transpiration may protect

leaf temperature, whereas under severe drought water conservation becomes more important. Thus the same trait can have contrasting consequences under different combinations of environmental conditions.

Phenological traits include germination, emergence, flowering, fruiting, senescence and maturity. Earlier flowering or accelerated development can represent stress escape, but may also reduce resource acquisition or reproductive duration. Phenology therefore provides a temporal component of resilience.

Nutrient and resource-use traits include tissue N and P, nutrient-use efficiency, nutrient resorption, root uptake characteristics and associations with mycorrhizal fungi. These traits connect plant resource acquisition with nutrient cycling and soil processes.

Biochemical and defence traits include antioxidant capacity, osmolyte accumulation, secondary metabolites, hormone signalling, reactive-oxygen regulation, stress proteins and membrane stability. Such traits can protect cellular function, but protection requires energy and metabolites that could otherwise support growth or reproduction.

Reproductive traits—flowering timing, pollen performance, seed and fruit set, reproductive duration and yield stability—are essential when resilience is considered from an agricultural perspective. Physiological resilience does not automatically translate into agricultural resilience if reproductive performance remains unstable.

Trait syndromes are therefore more informative than isolated traits. Drought resilience may involve coordinated root, hydraulic, stomatal, osmotic and phenological characteristics; salinity resilience may involve ion regulation, root adjustment, antioxidants and osmotic control. These combinations are not universal packages but context-dependent strategies.

Trade-offs are central to interpretation: carbon gain versus water conservation; acquisition versus persistence; growth versus defence; root exploration versus carbon cost; and resistance versus rapid recovery. Intraspecific variation and plasticity can alter these trade-offs and create additional resilience options [1, 26].

Table 2. Major plant functional traits and their links with ecosystem processes

Trait category	Representative traits	Potential ecological linkage
Root architecture	Depth, branching, length density, SRL	Water/nutrient acquisition; soil exploration
Root structure	Diameter, tissue density, root hairs	Persistence, resource economics, soil interaction
Hydraulic	Conductivity, xylem traits, water potential	Water transport and drought response
Root interface	Exudation, suberization, mycorrhizal association	Rhizosphere processes and nutrient cycling
Leaf economics	SLA, LDMC, thickness	Carbon gain, tissue persistence, decomposition
Stomatal	Density, conductance, sensitivity	Water use, cooling, carbon exchange
Photosynthetic	Chlorophyll, fluorescence, capacity	Primary productivity and recovery
Phenological	Flowering, maturity, senescence	Stress escape and temporal resource use
Nutrient	Tissue N/P, NUE, resorption	Nutrient cycling and resource efficiency
Biochemical	Osmolytes, antioxidants, defence	Cell protection and stress tolerance

	metabolites	
Reproductive	Pollen, seed/fruit set, reproductive duration	Yield stability and population persistence
Plasticity	Trait adjustment across environments	Acclimation and environmental matching
Trait combinations	Syndromes and coordinated strategies	Integrated resistance, recovery and function

From Plant Traits to Ecosystem Functioning

The significance of traits extends beyond individual plant performance. The RTF pathway is best represented as Trait expression → plant performance → population response → community processes → plant–soil–microbial interactions → ecosystem processes → ecosystem functioning.

At population level, intraspecific trait variation can determine whether some individuals maintain function under disturbance and contribute to demographic stability [1]. Selection can alter trait distributions over time, while plasticity can generate short-term adjustment without genetic change.

At community level, three concepts should be distinguished. Functional diversity describes the distribution of functional characteristics; response diversity concerns variation in responses among organisms performing related functions; and functional complementarity concerns differences that allow more complete use of resources or reduce direct competition. These mechanisms can support stability, but none should be assumed to increase resilience under every disturbance [12, 17, 20, 25].

Plant–plant interactions provide another pathway. Differences in root depth, phenology, canopy architecture and nutrient acquisition can generate competition, facilitation or resource partitioning. Whether complementarity improves resilience depends on resource availability, species combinations and disturbance intensity.

Plant–soil interactions are equally important. Root inputs, exudates and litter affect soil aggregation, carbon storage, nutrient availability and water retention. Soil conditions then feed back to plant performance. Plant traits therefore participate in reciprocal feedback loops rather than one-way effects.

Plant–microbial interactions add another layer. Rhizosphere organisms influence nutrient acquisition, hormone signalling, pathogen suppression and stress responses, while root traits modify microbial habitats and substrates [19]. These interactions can influence both resistance and recovery.

Trait effects on ecosystem processes include productivity, carbon cycling, nitrogen cycling, water regulation and soil functioning. The same trait may influence several functions, and multiple traits may jointly control one function. This explains why ecosystem responses are often emergent rather than reducible to a single plant characteristic [5, 13].

Temporal dynamics are essential. Before disturbance, traits influence exposure and resource status; during disturbance they influence resistance; after disturbance they influence recovery. Different traits may dominate at different stages. A resilience assessment that measures only performance during stress may therefore miss the ecological importance of recovery.

The scaling principle is consequently: Plant functional traits influence ecosystem resilience through ecological pathways rather than through direct one-to-one relationships.

The Resilience–Trait–Function Nexus

The Resilience–Trait–Function Nexus integrates three dimensions that are often studied separately: resilience describes the capacity to maintain or restore function; traits describe measurable characteristics

through which plants respond to and influence their environment; and ecosystem functions describe processes such as productivity, carbon and nutrient cycling and water regulation.

The framework is not a simple linear trait-to-resilience model. It recognizes response traits, effect traits, trait syndromes, plasticity, trade-offs, disturbance history and ecological interactions. A trait may influence resistance but not recovery, or improve resource acquisition while increasing sensitivity to another stress.

Resistance and recovery are explicitly separated. A plant can show high resistance but slow recovery, or substantial damage but rapid recovery. These trajectories can lead to similar final outcomes while representing different resilience strategies.

Phenotypic plasticity is incorporated as a potential mechanism linking environmental variation with trait expression. Plasticity can improve environmental matching, but it may also involve costs or produce maladaptive responses when environmental cues are unreliable [26].

At community level, functional diversity, response diversity and complementarity are treated as mechanisms that may translate individual variation into functional buffering. Recent evidence indicates that their effects are conditional rather than universal [12, 20, 25].

Compound and sequential stresses are central to the Nexus. Non-additive interactions mean that the ecological outcome of combined stress can differ substantially from predictions based on single-stress experiments [3, 8, 22, 24, 29].

Scaling occurs through intervening ecological processes: intraspecific variation and selection at the population level; response diversity and complementarity at the community level; and plant–soil–microbial interactions at the ecosystem level. Management then modifies exposure, resource availability and the expression of these processes.

The central proposition is therefore: The Resilience–Trait–Function Nexus conceptualizes plant resilience as a context-dependent, trait-mediated process in which coordinated functional traits and phenotypic plasticity regulate resistance, acclimation and recovery from environmental disturbance. Through population and community-level processes—including response diversity, functional complementarity and plant–soil–microbial interactions—these trait-mediated responses can propagate to ecosystem functioning and ultimately influence agroecosystem resilience.

Traits do not directly become ecosystem resilience—ecological processes provide the intervening pathway.

Figure 1. The Resilience–Trait–Function Nexus. Climate change alters the disturbance regime; coordinated plant responses modify functional traits and plasticity; trait combinations influence resistance, acclimation and recovery; ecological scaling through diversity, complementarity and plant–soil–microbial interactions affects ecosystem functioning and agroecosystem resilience. Environment × Disturbance × Biodiversity × Management act as context modifiers.

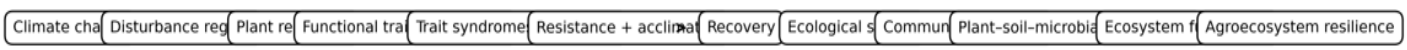

Fig 1. The Resilience Trait Function Nexus

Figure 2. Scaling of Trait-Mediated Resilience from molecular and cellular processes to organ, individual, population, community, ecosystem and agroecosystem levels.

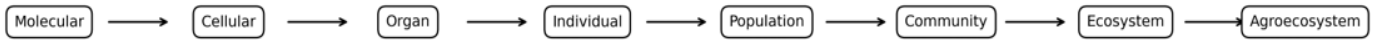

Fig.2 Scaling of Trait Mediated Resilience

Scaling the Nexus to Agroecosystems

Agroecosystems translate ecological resilience into practical outcomes such as yield stability, resource-use efficiency, soil health and livelihood security. Crop functional traits relevant to the RTF framework include root and hydraulic traits, canopy and stomatal characteristics, phenology, nutrient-use efficiency, water-use efficiency, reproductive stability and biochemical stress responses [14, 33].

Crop diversity can broaden trait ranges and create opportunities for resource partitioning, response diversity and complementarity. However, diversity should not be equated automatically with resilience. The value of diversity depends on whether component crops differ in relevant responses while maintaining useful ecological functions.

Intercropping provides a practical example. Deep- and shallow-rooted crops, early- and late-season crops, or cereals and legumes can occupy different resource niches. Indian evidence from mango-based systems illustrates how intercropping can affect productivity, resource-use efficiency and environmental sustainability [9]. Yet complementarity must be balanced against competition for water, nutrients and light.

Agroforestry can create vertical and temporal complementarity through differences in canopy structure, rooting depth and phenology. The same structural diversity can, however, increase competition for water or radiation under stressful conditions. Management must therefore match trait combinations to local resource constraints.

Cover crops and soil-protective systems influence resilience through root inputs, residues, soil organic matter, water retention, nutrient cycling and microbial processes. Roots are particularly important because they connect plant traits with below-ground ecosystem processes [2, 16, 19].

Trait-based breeding can move beyond selection for a single stress-tolerance trait toward multi-trait strategies that include dynamic recovery. High-throughput phenotyping and genome-wide association approaches can help identify trait combinations associated with resilience under combined stresses [18, 27].

The G×E×M perspective is essential. Genotype or cultivar performance depends on environment and management, and a trait combination that is advantageous under controlled conditions may behave differently under field conditions. Trait-based selection should therefore be validated across locations, seasons and management regimes.

The practical objective of climate-resilient agriculture should not simply be to produce stress-tolerant plants. It should design agroecosystems in which complementary plant traits, biological diversity, soil processes, and management interact to maintain essential functions during disturbance and facilitate recovery afterwards [11, 15, 21].

Figure 3. Trait-based pathways for climate-resilient agriculture. The framework connects climate-risk assessment and target functions with trait selection, complementarity, breeding/diversification, soil–rhizosphere management, resistance and recovery, and maintenance of production and ecosystem functions.



Fig 3. Trait Based Pathways for Climate Resilient Agriculture

Applications for Sustainable Agroecosystem Management

Trait-based selection of crops and cultivars

Selection can target coordinated trait syndromes rather than isolated stress-tolerance markers. Root architecture, hydraulic regulation, phenology, nutrient-use efficiency and reproductive stability can be considered jointly.

A practical example of trait-based selection is provided by drought-resilient rice. Root-system architecture, particularly rooting depth and root growth angle, can influence access to soil moisture under water-limited conditions. The DEEPER ROOTING 1 (DRO1) locus provides a well-established example in which modification of root growth angle promoted deeper rooting and improved rice performance under drought conditions. Such evidence illustrates how a specific root trait can contribute to drought avoidance while also demonstrating the importance of integrating below-ground traits with yield and reproductive performance during cultivar selection [35].

Salinity tolerance in rice provides another example of coordinated trait expression. Tolerant genotypes can maintain cellular ion homeostasis through mechanisms including restricted Na^+ accumulation in shoots and maintenance of a favourable Na^+/K^+ balance, together with osmotic adjustment and continued growth under saline conditions. Traditional donors such as Pokkali and Nona Bokra, and breeding materials derived from them, have contributed valuable traits for understanding and improving salinity tolerance. These responses demonstrate that selection for climate resilience may require integration of ionic, physiological and growth-related traits rather than reliance on a single tolerance indicator [36].

Breeding for resistance and recovery

Breeding programmes should distinguish traits that reduce damage during stress from traits that accelerate recovery. Dynamic measurements after stress removal can complement conventional performance screening [18, 27, 32].

Rice also illustrates the value of breeding for both resistance and recovery under flooding. The SUB1 locus, particularly SUB1A, confers enhanced tolerance to complete submergence by restricting excessive shoot elongation during flooding and conserving carbohydrate reserves. Submergence-tolerant cultivars carrying SUB1 subsequently show improved survival and recovery after floodwater recedes. This example demonstrates how breeding can incorporate a defined physiological strategy that limits damage during disturbance while improving the capacity of plants to resume growth following stress [37].

High-throughput phenotyping and remote sensing

Canopy temperature, spectral signals, growth trajectories and fluorescence can provide repeated measures of plant response. Combining phenotyping with genetic information can improve identification of resilience-associated traits [18, 27].

Maize provides an example of how high-throughput phenotyping can be used to characterize resilience under heat and combined drought–heat stress. Traits such as canopy temperature, spectral characteristics, chlorophyll-related signals, growth dynamics and stay-green expression can provide repeated, non-destructive indicators of plant performance under stress. When these phenotypic measurements are integrated with genomic or genome-wide association approaches, they can assist in identifying trait combinations associated with resilience. Recent maize research demonstrates the potential of this integrated approach for characterizing genotypic variation under combined drought and high-temperature environments [27].

Trait-based crop diversification

Diversification can be designed around complementary root systems, phenologies, canopy structures and

resource-use strategies. The objective is functional complementarity and response diversity rather than diversity for its own sake [11].

Intercropping and agroforestry

Intercropping and agroforestry can distribute resource acquisition across space and time. Their success depends on matching complementary traits with local water, nutrient and radiation regimes [9, 21].

Soil and rhizosphere management

Maintaining soil organic matter, aggregation, moisture and microbial activity strengthens the below-ground component of resilience. Root traits and rhizosphere processes should therefore be included in management design [2, 16, 19].

Microbiome-informed resilience

Beneficial microbial associations can influence nutrient acquisition, pathogen suppression and stress responses. Future management may increasingly combine plant trait selection with microbiome management.

Precision agriculture and decision support

Trait-informed monitoring can be combined with soil, weather and crop data to identify emerging stress and adjust irrigation, nutrient application or crop management. The long-term objective is adaptive rather than purely reactive management.

Managing for ecosystem functions

Yield should remain important, but resilience assessment should also consider soil health, water regulation, nutrient cycling, carbon storage and recovery capacity. Multifunctional crop concepts support this broader perspective [15].

Monitoring and adaptive management

Resilience should be evaluated through repeated measurements before, during and after disturbance. Monitoring should feed into management decisions, creating a cycle of observe → evaluate → adapt → recover → redesign.

Table 3. Trait-based strategies for enhancing agroecosystem resilience under climate stresses

Management strategy	Trait focus	Expected resilience pathway
Cultivar selection	Root, hydraulic, phenological, reproductive traits	Improved resistance and recovery
Crop diversification	Functional and response diversity	Risk buffering and compensation
Intercropping	Root depth, phenology, canopy architecture	Resource partitioning and productivity stability
Agroforestry	Vertical structure, rooting, phenology	Microclimate moderation and complementarity
Cover crops	Root traits, biomass, residue quality	Soil protection, moisture and carbon
Rhizosphere management	Root–microbe interactions	Nutrient acquisition and stress buffering

Precision agriculture	Dynamic physiological and environmental indicators	Timely stress response and resource efficiency
Multifunctional cropping	Traits linked to multiple ecosystem services	Production plus ecological function
Adaptive monitoring	Resistance + recovery metrics	Learning and management redesign

RESEARCH GAPS AND FUTURE DIRECTIONS

Integrated trait–resilience datasets

Trait databases often contain static measurements, whereas resilience requires repeated observations through disturbance and recovery. Integrated datasets should combine trait values, environmental exposure, management and recovery trajectories.

Standardization of resilience metrics

Studies use different definitions and metrics of resistance, recovery, stability and resilience. Harmonized metrics would improve comparison across experiments and ecosystems.

Greater attention to recovery

Recovery remains less studied than stress response. Experiments should measure the complete trajectory from baseline through disturbance to post-disturbance restoration [32].

Compound and sequential stresses

Research should move beyond single-stress experiments toward realistic combinations and sequences, including stress order, duration and intensity [3, 8, 22, 24, 29].

Below-ground traits and rhizosphere

Roots and rhizosphere interactions are central to water and nutrient acquisition but remain comparatively difficult to measure. Improved root imaging, isotopic methods and microbial profiling are needed [2, 16, 19].

Intraspecific variation and G×E×M

Cultivar and genotype differences should be integrated with environmental and management variation rather than treating species-level averages as fixed responses [1].

Scaling from individuals to ecosystems

Mechanistic links between individual traits and ecosystem functions need field validation. Trait effects should be traced through population and community processes rather than inferred directly.

Functional diversity, response diversity and complementarity

Future studies should measure these concepts separately and test the conditions under which they actually generate compensation or stability [12, 20, 25].

Remote sensing, high-throughput phenotyping and AI

Repeated non-destructive measurements can capture dynamic stress and recovery signatures. Integration with genomic and environmental data offers opportunities for predictive selection [18, 27].

Mechanistic modelling

Models should incorporate trait distributions, disturbance regimes, plasticity, recovery and management rather than relying only on static yield predictions.

Long-term and multi-location field experiments

Controlled experiments reveal mechanisms, but field experiments are needed to test whether trait syndromes remain advantageous under variable climate and management.

Data integration and reproducibility

Open trait databases, transparent protocols, standardized metadata and reproducible analytical workflows will improve synthesis and predictive modelling.

Proposed research roadmap

The research trajectory should progress from single stress to multiple stress; single traits to trait syndromes; resistance to resistance plus recovery; individual plants to ecosystems; controlled experiments to field validation; descriptive studies to prediction; and stress management to resilience design.

Future research hypothesis: Agroecosystems possessing complementary combinations of plant functional traits, greater response diversity and stronger plant–soil–microbial coordination will show greater capacity to maintain and recover essential ecosystem functions under variable and interacting climate disturbances than systems dominated by functionally similar components.

Table 4. Research gaps, methodological challenges and future priorities

Research gap	Why it matters	Recommended approach	Expected advance
Integrated datasets	Resilience is dynamic	Repeated trait + environment + recovery measurements	Mechanistic comparison
Metric standardization	Definitions vary	Common resistance/recovery indices	Cross-study synthesis
Recovery	Often overlooked	Post-stress time series	Better resilience estimates
Compound stress	Single stresses are unrealistic	Factorial/sequential field experiments	Realistic prediction
Below-ground processes	Roots and microbes are difficult to measure	Imaging, isotopes, microbiome profiling	Trait–soil mechanisms
G×E×M	Traits are context dependent	Multi-location genotype trials	Robust cultivar recommendations
Scaling	Individual evidence may not scale	Population-to-ecosystem experiments	Ecological validation
HTP + AI	Dynamic responses are information rich	Remote sensing + modelling	Predictive phenotyping
Long-term field testing	Short experiments miss legacy effects	Multi-year experiments	Operational resilience design

CONCLUSION

Climate change is creating disturbance regimes in which drought, heat, salinity, flooding, nutrient imbalance and their combinations challenge plant performance and ecosystem functioning. Understanding resilience therefore requires more than identifying isolated stress-tolerance traits.

The Resilience–Trait–Function Nexus developed in this review provides an integrative framework in which plant resilience is treated as a context-dependent, trait-mediated process. Coordinated functional traits and phenotypic plasticity influence resistance, acclimation and recovery, while trait trade-offs and stress history shape the resulting performance.

The framework further emphasizes that trait effects do not translate directly into ecosystem resilience. Intraspecific variation, response diversity, functional complementarity and plant–soil–microbial interactions provide the ecological pathways through which individual responses can influence ecosystem processes. Functional diversity may contribute to resilience under some circumstances, but recent evidence demonstrates that its effects are not universal [12, 20, 25].

For agroecosystems, this perspective shifts the goal from producing plants that merely survive stress toward designing systems capable of maintaining essential functions and recovering after disturbance. Crop breeding, diversification, intercropping, agroforestry, soil management, microbiome-informed strategies, high-throughput phenotyping and precision agriculture can all contribute when they are organized around functional complementarity and recovery.

Future research should integrate dynamic trait measurements with disturbance history, environmental context, management and ecosystem functions. Particular attention should be given to compound and sequential stresses, below-ground processes, intraspecific variation, recovery trajectories and multi-location field validation.

The central message of the RTF Nexus is therefore simple but powerful: resilient agriculture is not created by a single resilient plant; it is created when complementary plant traits, biological interactions, soil processes and management collectively sustain function through disturbance and facilitate recovery afterwards.

Resilience should consequently be understood as an emergent property of interacting biological, ecological and management processes. This perspective provides a mechanistic foundation for climate-smart agriculture that is not only stress-tolerant, but functionally resilient.

DECLARATIONS

Ethical Approval: Not applicable. This review is based exclusively on previously published literature and involved no human participants, animals or experimental subjects.

Conflict of Interest: The author declares no conflict of interest.

Data Availability: No new datasets were generated or analysed for this review. The information synthesized in this article was derived from previously published literature cited in the reference list.

REFERENCES

1. Albert, C. H., Thuiller, W., Yoccoz, N. G., Soudant, A., Boucher, F., Saccone, P., & Lavorel, S. (2010). Intraspecific functional variability: Extent, structure and sources of variation. Journal of Ecology, 98(3), 604–613. https://doi.org/10.1111/j.1365-2745.2010.01651.x
2. Bardgett, R. D., Mommer, L., & de Vries, F. T. (2014). Going underground: Root traits as drivers of ecosystem processes. Trends in Ecology & Evolution, 29(12), 692–699. https://doi.org/10.1016/j.tree.2014.10.006

3. Cao, H., Ding, R., Du, T., Kang, S., Tong, L., Chen, J., & Gao, J. (2024). A meta-analysis highlights the cross-resistance of plants to drought and salt stresses from physiological, biochemical, and growth levels. Physiologia Plantarum, 176(2), e14282. https://doi.org/10.1111/ppl.14282
4. Crawford, T., Pratx, L., & Bäurle, I. (2026). Principles and mechanisms of plant acclimation to heat stress. Nature Reviews Molecular Cell Biology, 27, 668–683. https://doi.org/10.1038/s41580-026-00977-x
5. de Bello, F., Lavorel, S., Hallett, L. M., Valencia, E., Garnier, E., Roscher, C., et al. (2021). Functional trait effects on ecosystem stability: Assembling the jigsaw puzzle. Trends in Ecology & Evolution, 36(9), 822–836. https://doi.org/10.1016/j.tree.2021.05.001
6. Díaz, S., Kattge, J., Cornelissen, J. H. C., Wright, I. J., Lavorel, S., Dray, S., Reu, B., Kleyer, M., Wirth, C., Prentice, I. C., Garnier, E., Bönisch, G., Westoby, M., Poorter, H., Reich, P. B., Moles, A. T., Dickie, J., Gillison, A. N., Zanne, A. E., Chave, J., et al. (2016). The global spectrum of plant form and function. Nature, 529(7585), 167–171. https://doi.org/10.1038/nature16489
7. Holling, C. S. (1973). Resilience and stability of ecological systems. Annual Review of Ecology and Systematics, 4, 1–23. https://doi.org/10.1146/annurev.es.04.110173.000245
8. Jiang, Z., van Zanten, M., & Sasidharan, R. (2025). Mechanisms of plant acclimation to multiple abiotic stresses. Communications Biology, 8, 655. https://doi.org/10.1038/s42003-025-08077-w
9. Kishore, K., Sangeetha, G., Rupa, T. R., Ganeshmurthy, A. N., Samant, D., Acharya, G. C., & Srinivas, P. (2025). Assessment of mango-based intercropping systems for productivity, resource use efficiency and environmental sustainability in tropical region of India. Next Sustainability, 5, 100121. https://doi.org/10.1016/j.nxsust.2025.100121
10. Lavorel, S., & Garnier, E. (2002). Predicting changes in community composition and ecosystem functioning from plant traits: Revisiting the Holy Grail. Functional Ecology, 16(5), 545–556. https://doi.org/10.1046/j.1365-2435.2002.00664.x
11. Lin, B. B. (2011). Resilience in agriculture through crop diversification: Adaptive management for environmental change. BioScience, 61(3), 183–193. https://doi.org/10.1525/bio.2011.61.3.4
12. Lipoma, L., Kambach, S., Díaz, S., Sabatini, F. M., Damasceno, G., Kattge, J., et al. (2024). No general support for functional diversity enhancing resilience across terrestrial plant communities. Global Ecology and Biogeography, 33(10), e13895. https://doi.org/10.1111/geb.13895
13. Liu, C., Li, Y., Yan, P., & He, N. (2021). How to improve the predictions of plant functional traits on ecosystem functioning? Frontiers in Plant Science, 12, 622260. https://doi.org/10.3389/fpls.2021.622260
14. Martin, A. R., & Isaac, M. E. (2015). Plant functional traits in agroecosystems: A blueprint for research. Journal of Applied Ecology, 52(6), 1425–1435. https://doi.org/10.1111/1365-2664.12526
15. Mastronardi, M. G., Arcieri, F., Crudele, M., Didonna, A., Laterza, I., Somma, A., Guerriero, M., Pavan, S., Santamaria, P., De Miccolis Angelini, R. M., & Tamburini, G. (2026). Reframing crops as multifunctional: A trait-based approach for sustainable agriculture. npj Sustainable Agriculture, 4, 63. https://doi.org/10.1038/s44264-026-00176-3
16. Meister, R., Rajani, M. S., Ruzicka, D., & Schachtman, D. P. (2014). Challenges of modifying root traits in crops for agriculture. Trends in Plant Science, 19(12), 779–788. https://doi.org/10.1016/j.tplants.2014.08.005
17. Mori, A. S., Furukawa, T., & Sasaki, T. (2013). Response diversity determines the resilience of ecosystems to environmental change. Biological Reviews, 88(2), 349–364. https://doi.org/10.1111/brv.12004
18. Palermo, N., Resentini, F., Moscatelli, S., Mendes, M. A., Costa, A., & Janni, M. (2025). Heat stress phenotyping: A key for plant selection in a warming climate. Plant Science, 359, 112675. https://doi.org/10.1016/j.plantsci.2025.112675
19. Philippot, L., Raaijmakers, J. M., Lemanceau, P., & van der Putten, W. H. (2013). Going back to the roots: The microbial ecology of the rhizosphere. Nature Reviews Microbiology, 11(11), 789–799. https://doi.org/10.1038/nrmicro3109
20. Polazzo, F., Limberger, R., Pennekamp, F., Ross, S. R. P.-J., Simpson, G., & Petchey, O. L. (2024). Measuring the response diversity of ecological communities experiencing multifarious environmental change. Global Change Biology, 30(11), e17594. https://doi.org/10.1111/gcb.17594

21. Pretty, J., Benton, T. G., Bharucha, Z. P., Dicks, L. V., Butler, A., Godfray, H. C. J., Goulson, D., Hartley, S., Lampkin, N., Morris, C., Pierzynski, G., Prasad, P. V. V., Reganold, J., Rockström, J., Smith, P., Thorne, P., & Wratten, S. (2018). Global assessment of agricultural system redesign for sustainable intensification. Nature Sustainability, 1, 441–446.
22. Qiu, S., Zhang, Y., Dai, J., & Dong, H. (2026). Ecological divergence governs plant resilience to compound salinity–waterlogging stress under global change. Global Change Biology, 32(4), e70875. https://doi.org/10.1111/gcb.70875
23. Reich, P. B. (2014). The world-wide 'fast–slow' plant economics spectrum: A traits manifesto. Journal of Ecology, 102(2), 275–301. https://doi.org/10.1111/1365-2745.12211
24. Renziehausen, T., Frings, S., & Schmidt-Schippers, R. (2024). 'Against all floods': Plant adaptation to flooding stress and combined abiotic stresses. The Plant Journal, 117(6), 1836–1855. https://doi.org/10.1111/tpj.16614
25. Ross, S. R. P.-J., & Sasaki, T. (2024). Limited theoretical and empirical evidence that response diversity determines the resilience of ecosystems to environmental change. Ecological Research, 39(2), 115–130. https://doi.org/10.1111/1440-1703.12434
26. Schneider, R., Bäurle, I., Nikoloski, Z., & Lenhard, M. (2026). Plant phenotypic plasticity: From molecular mechanisms to breeding and climate change adaptation. Annual Review of Plant Biology, 77, 707–731. https://doi.org/10.1146/annurev-arplant-063025-111942
27. Shi, R., López-Malvar, A., Knoch, D., Tschiersch, H., Heuermann, M. C., Shaaf, S., Madur, D., Santiago, R., Balconi, C., Frascaroli, E., Erdal, S., Palaffre, C., Charcosset, A., Revilla, P., & Altmann, T. (2025). Integrating high-throughput phenotyping and genome-wide association analyses to unravel Mediterranean maize resilience to combined drought and high temperatures. Plant Stress, 17, 100954. https://doi.org/10.1016/j.stress.2025.100954
28. Sun, Y., Robert, C. A. M., & Thakur, M. P. (2024). Drought intensity and duration effects on morphological root traits vary across trait type and plant functional groups: A meta-analysis. BMC Ecology and Evolution, 24, 92. https://doi.org/10.1186/s12862-024-02275-6
29. Tahjib-Ul-Arif, M., Hasan, M. T., Rahman, M. A., Nuruzzaman, M., Rahman, A. M. S., Hasanuzzaman, M., Haque, M. R., Hossain, M. A., Abdel Latef, A. A. H., Murata, Y., & Brestic, M. (2023). Plant response to combined salinity and waterlogging stress: Current research progress and future prospects. Plant Stress, 7, 100137. https://doi.org/10.1016/j.stress.2023.100137
30. Violle, C., Navas, M.-L., Vile, D., Kazakou, E., Fortunel, C., Hummel, I., & Garnier, E. (2007). Let the concept of trait be functional! Oikos, 116(5), 882–892. https://doi.org/10.1111/j.0030-1299.2007.15559.x
31. Walker, B., Holling, C. S., Carpenter, S. R., & Kinzig, A. (2004). Resilience, adaptability and transformability in social–ecological systems. Ecology and Society, 9(2), 5.
32. Wang, J., & Xu, Z. (2026). Plant response to and recovery from drought. Current Biology, 36(8), R343–R362. https://doi.org/10.1016/j.cub.2026.02.025
33. Wood, S. A., Karp, D. S., DeClerck, F., Kremen, C., Naeem, S., & Palm, C. A. (2015). Functional traits in agriculture: Agrobiodiversity and ecosystem services. Trends in Ecology & Evolution, 30(9), 531–539. https://doi.org/10.1016/j.tree.2015.06.013
34. Wright, I. J., Reich, P. B., Westoby, M., Ackerly, D. D., Baruch, Z., Bongers, F., Cavender-Bares, J., Chapin, T., Cornelissen, J. H. C., Diemer, M., Flexas, J., Garnier, E., Groom, P. K., Gulias, J., Hikosaka, K., Lamont, B. B., Lee, T., Lee, W., Lusk, C., Midgley, J. J., Navas, M.-L., Niinemets, Ü., Oleksyn, J., Osada, N., Poorter, H., Poot, P., Prior, L., Pyankov, V. I., Roumet, C., Thomas, S. C., Tjoelker, M. G., Veneklaas, E. J., & Villar, R. (2004). The worldwide leaf economics spectrum. Nature, 428(6985), 821–827. https://doi.org/10.1038/nature02403
35. Uga, Y., Sugimoto, K., Ogawa, S., Rane, J., Ishitani, M., Hara, N., Kitomi, Y., Inukai, Y., Ono, K., Kanno, N., Inoue, H., Takehisa, H., Motoyama, R., Nagamura, Y., Wu, J., Matsumoto, T., Takai, T., Okuno, K., & Yano, M. (2013). Control of root system architecture by DEEPER ROOTING 1 increases rice yield under drought conditions. Nature Genetics, 45(9), 1097–1102. https://doi.org/10.1038/ng.2725

36. Platten, J. D., Egdane, J. A., & Ismail, A. M. (2013). Salinity tolerance, Na^+ exclusion and allele mining of HKT1;5 in Oryza sativa and O. glaberrima: Many sources, many genes, one mechanism? BMC Plant Biology, 13, 32. https://doi.org/10.1186/1471-2229-13-32
37. Xu, K., Xu, X., Fukao, T., Canlas, P., Maghirang-Rodriguez, R., Heuer, S., Ismail, A. M., Bailey-Serres, J., Ronald, P. C., & Mackill, D. J. (2006). Sub1A is an ethylene-response-factor-like gene that confers submergence tolerance to rice. Nature, 442(7103), 705–708. https://doi.org/10.1038/nature04920