NATURE-POSITIVE SOLUTIONS FOR ABIOTIC STRESS MANAGEMENT IN INDIAN AGRICULTURE

Soil-Centred Pathways for Climate-Resilient and Sustainable Food Production

ICAR-National Institute of Abiotic Stress Management
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2025

Technical Bulletin No.: ICAR–NIASM/ABSTRESS/NPS/2025/15

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2025

FORWORD

Indian agriculture is increasingly confronted with pronounced climate variability, manifested through more frequent and intense abiotic stresses such as drought, heat waves, salinity, sodicity, flooding, and nutrient imbalances. These stresses directly threaten crop productivity, soil functionality, and farm incomes, particularly in rainfed, dryland, and marginal production systems that constitute a substantial share of the country's agricultural land. Conventional, input-intensive approaches have delivered short-term gains but have often resulted in declining soil health, inefficient water use, and heightened vulnerability to climate extremes.

In this context, nature-positive solutions (NPS), grounded in ecological processes and optimized use of local natural resources, offer a scientifically robust and practically viable pathway for managing abiotic stresses. By emphasizing soil organic matter enhancement, biodiversity-driven regulation, efficient water management, and resilient cropping systems, nature-positive and low-external-input approaches strengthen the inherent buffering capacity of agroecosystems. These strategies not only mitigate abiotic stress impacts but also enhance long-term system resilience, productivity stability, and environmental sustainability.

The approach outlined in this technical bulletin is well aligned with national priorities and ongoing initiatives aimed at building climate-resilient and resource-efficient agriculture. Programmes and missions led by institutions such as Indian Council of Agricultural Research support science-based innovations for sustainable intensification, while flagship initiatives including the National Mission for Sustainable Agriculture and the Pradhan Mantri Krishi Sinchayee Yojana emphasize soil health improvement, water-use efficiency, and climate adaptation. By integrating nature-positive solutions into abiotic stress management, Indian agriculture can progress toward the dual goals of productivity enhancement and ecological sustainability, ensuring food and livelihood security under changing climatic conditions.

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PREFACE

Abiotic stresses arising from climate variability and resource degradation have emerged as critical constraints to sustainable agricultural production in India. Erratic rainfall, rising temperatures, declining soil fertility, salinity, sodicity, and frequent episodes of drought and flooding are increasingly affecting crop growth, yield stability, and farm profitability. These challenges are particularly acute in rainfed, marginal, and resource-poor farming systems, where the scope for high external input use is limited.

This technical bulletin has been prepared to present Nature-Positive Solutions (NPS) as a practical and science-based framework for managing abiotic stresses in agriculture. Nature-positive approaches emphasize working with natural processes such as soil organic matter dynamics, biological regulation, efficient water use, and diversified cropping systems to enhance the resilience of agroecosystems. Rather than focusing solely on stress avoidance, these strategies aim to strengthen the inherent adaptive capacity of soil–plant–water systems, thereby ensuring long-term sustainability and productivity.

The bulletin is intended to serve as a reference for researchers, extension professionals, development practitioners, and policymakers engaged in climate-resilient and sustainable agriculture. It synthesizes current scientific understanding, field-based evidence, and national experiences, with a particular emphasis on Indian agro-ecological conditions. The content is aligned with ongoing national efforts and institutional mandates of organizations such as the Indian Council of Agricultural Research and its allied State Agricultural Universities, and is designed to support informed decision-making, technology dissemination, and capacity building at multiple scales.

By bridging research insights with field-level applicability, this bulletin aims to facilitate the wider adoption of nature-positive solutions for abiotic stress management, contributing to improved soil health, efficient water use, climate resilience, and sustainable food production in India.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the institutional support provided by the Indian Council of Agricultural Research (ICAR) and the ICAR–National Institute of Abiotic Stress Management (NIASM), Baramati**,** for facilitating the preparation of this technical bulletin.

The scientific insights presented in this bulletin draw upon contributions from ICAR institutes, State Agricultural Universities, and national research programmes working on soil health, climate resilience, and sustainable agriculture. The authors also acknowledge the valuable contributions of researchers whose published work has informed the synthesis of nature-positive solutions for abiotic stress management.

Support from national missions and policy frameworks focused on sustainable and climate-resilient agriculture is duly acknowledged. Any remaining errors or interpretations are solely the responsibility of the authors.

EXECUTIVE SUMMARY

Abiotic stresses such as drought, heat, salinity, flooding, and nutrient imbalance pose increasing threats to agricultural productivity and sustainability in India under changing climatic conditions. Conventional, input-intensive approaches have provided short-term yield gains but have often degraded soil health, reduced water-use efficiency, and increased vulnerability to climate extremes.

This technical bulletin presents Nature-Positive Solutions (NPS) as a scientifically grounded, ecosystem-based framework for managing abiotic stresses by strengthening soil–plant–water–climate interactions. NPS emphasize enhancement of soil organic matter, biological regulation, improved soil structure, efficient water management, diversified cropping systems, and agroforestry integration.

The bulletin synthesizes evidence showing that NPS mitigate abiotic stress through four core mechanisms**:**

(i) soil moisture retention and root-zone buffering,
(ii) improved nutrient cycling efficiency under stress,
(iii) enhanced physiological stress tolerance in crops, and
(iv) moderation of field-scale microclimate.

These mechanisms operate synergistically, resulting in improved yield stability, reduced input dependency, enhanced resource-use efficiency, and faster recovery following climatic shocks.

A comprehensive indicator framework is presented to evaluate NPS outcomes, linking soil indicators (SOC, aggregate stability, PAW, enzymes) with plant and system indicators (root traits, yield stability, water productivity). The bulletin also demonstrates strong alignment of NPS with national missions such as NMSA, PMKSY, natural farming initiatives, and the National Agroforestry Policy.

Overall, the bulletin provides a robust scientific basis and practical roadmap for scaling nature-positive agriculture as a cornerstone of climate-resilient, sustainable food systems in India.

CONTENTS

1. INTRODUCTION

Abiotic stresses refer to adverse effects on crop growth, development, and productivity caused by non-living environmental factors. Unlike biotic stresses, which arise from pests and diseases, abiotic stresses originate from climatic, edaphic, and hydrological constraints that directly influence soil–plant–atmosphere interactions. In the Indian agricultural context, the most critical abiotic stresses include drought, heat stress, salinity, sodicity, flooding or waterlogging, and nutrient-related stresses. These stresses rarely occur in isolation; instead, they often interact spatially and temporally, amplifying their negative impacts on crop performance and system sustainability.

Drought and moisture stress result from insufficient or erratic rainfall and inadequate soil moisture availability during critical crop growth stages. Drought stress limits seed germination, root proliferation, nutrient uptake, photosynthesis, and biomass accumulation, ultimately reducing yield and yield stability. In rainfed and dryland regions, drought remains the single most important constraint to agricultural productivity.

Heat stress occurs when temperatures exceed the optimal threshold for physiological processes such as photosynthesis, respiration, pollen viability, and grain filling. Rising maximum temperatures and frequent heat waves during reproductive stages of crops have become increasingly common, leading to yield penalties, poor grain quality, and accelerated crop senescence.

Salinity stress arises from the accumulation of soluble salts in the soil solution, increasing osmotic stress and ion toxicity to plants. High concentrations of sodium (Na^+) and chloride (Cl^-) interfere with water uptake, nutrient balance, and metabolic activities. Salinity is particularly prevalent in arid and semi-arid regions, coastal belts, and irrigated command areas with inadequate drainage.

Sodicity stress, distinct from salinity, is associated with excessive exchangeable sodium in soils, leading to dispersion of clay particles, poor soil structure, reduced infiltration, and surface crusting. Sodic soils severely restrict root growth, water movement, and aeration, thereby limiting crop productivity even when water is available.

Flooding and waterlogging stress occur when soils remain saturated for prolonged periods, resulting in oxygen deficiency in the root zone. Anaerobic conditions impair root respiration, nutrient uptake, and microbial processes, often causing root decay, lodging, and nutrient losses through denitrification and leaching. Flooding stress is increasingly relevant in high-rainfall zones and low-lying landscapes under changing rainfall regimes.

Nutrient stress encompasses both nutrient deficiencies and toxicities arising from poor soil fertility, imbalanced fertilizer use, low organic matter content, and impaired nutrient cycling. Nutrient stress is closely linked with other abiotic stresses, as drought, salinity, and flooding directly affect nutrient availability, mobility, and plant uptake efficiency.

1.1 Increasing Severity of Abiotic Stresses under Climate Change

The frequency, intensity, and spatial extent of abiotic stresses are increasing under changing climate scenarios. Climate change has altered rainfall patterns, increased temperature extremes, and intensified hydrological variability, thereby exacerbating stress conditions across diverse agro-ecological regions. Projections indicate that climate-induced abiotic stresses will pose one of the most significant challenges to global and Indian agriculture in the coming decades.

In India, climate variability is manifested through delayed monsoon onset, prolonged dry spells, short-duration high-intensity rainfall events, and increasing heat waves. These changes have direct implications for soil moisture dynamics, crop phenology, and nutrient cycling. Rainfed agriculture, which accounts for a major share of cultivated land and supports a large proportion of small and marginal farmers, is particularly vulnerable.

Rising temperatures accelerate evapotranspiration losses, reduce soil moisture availability, and shorten crop growth duration, especially in cereals such as wheat and rice. Heat stress during flowering and grain filling stages has been associated with reduced pollen viability, poor grain set, and lower harvest indices. Similarly, increased evaporation under arid and semi-arid conditions promotes secondary salinization in irrigated landscapes.

Climate change also intensifies compound and sequential stresses, such as drought followed by heat stress, or flooding followed by nutrient stress. These stress combinations exert greater pressure on crops and soils than single stress events, often overwhelming conventional management practices. The resilience of agroecosystems, therefore, depends not only on tolerance to individual stresses but also on the capacity to buffer multiple interacting stresses.

At the national and global levels, scientific assessments by organizations such as the Intergovernmental Panel on Climate Change highlight that climate change impacts on agriculture are already evident and will intensify without effective adaptation and mitigation strategies. These assessments emphasize the urgent need for systemic, ecosystem-based approaches that enhance resilience rather than relying solely on technological or input-driven solutions.

1.2 Limitations of Conventional, Input-Intensive Stress Management Approaches

Historically, abiotic stress management in agriculture has relied heavily on input-intensive and engineering-based interventions, such as increased irrigation, higher fertilizer doses, chemical soil amendments, and stress-tolerant crop varieties. While these approaches have contributed to productivity gains in favorable environments, their effectiveness under increasing climatic uncertainty has become limited.

Excessive reliance on irrigation to mitigate drought and heat stress has led to groundwater depletion, declining water tables, and increased energy costs. In many regions, water availability itself has become a limiting factor, making irrigation-based stress management unsustainable in the long term. Similarly, indiscriminate fertilizer use aimed at overcoming nutrient stress has resulted in nutrient imbalances, declining nutrient-use efficiency, soil acidification or alkalization, and environmental pollution.

Chemical amendments such as gypsum or salts may provide short-term relief in saline or sodic soils but often fail to address the underlying causes of soil degradation when not integrated with organic matter management and biological restoration. Moreover, these inputs are often cost-prohibitive for smallholders and require repeated applications to maintain effectiveness.

Conventional approaches also tend to address symptoms rather than processes. For example, drought stress is often managed through supplemental irrigation without improving soil water-holding capacity, while nutrient stress is addressed through fertilizer application without restoring soil organic matter or microbial activity. Such strategies offer limited resilience against climate-induced variability and often degrade ecosystem services over time.

Another major limitation is the fragmented nature of conventional stress management, where soil, water, crop, and nutrient interventions are implemented independently. This reductionist approach overlooks the interconnectedness of soil physical, chemical, and biological processes that govern stress responses at the system level.

1.3 Rationale for Nature-Positive Solutions in Abiotic Stress Management

Nature-Positive Solutions (NPS) offer a transformative framework for addressing abiotic stresses by working with natural processes rather than attempting to control them through external inputs. NPS are based on the principle that healthy, biologically active soils and diversified agroecosystems possess inherent buffering capacity against climatic and edaphic stresses.

At the core of NPS is the enhancement of soil organic matter and soil carbon stocks, which improve aggregate stability, infiltration, water-holding capacity, and nutrient retention. Improved soil structure and biological activity enable crops to access water and nutrients more efficiently under stress conditions, thereby reducing vulnerability to drought, heat, and nutrient stress.

Nature-positive approaches emphasize biological regulation, including microbial-mediated nutrient cycling, root–microbe interactions, and biodiversity-driven ecosystem services. These processes enhance nutrient availability, suppress stress-induced toxicity, and improve plant physiological resilience. For instance, mycorrhizal associations improve phosphorus and water uptake under drought and salinity stress, while diverse microbial communities contribute to soil structural stability.

NPS also promote cropping system diversification, such as intercropping, crop rotations, cover cropping, and agroforestry. Diversified systems distribute risk, improve resource-use efficiency, and create favourable microclimates that reduce thermal and moisture stress. Perennial components in agroforestry systems, for example, enhance deep water extraction, moderate soil temperature, and contribute to long-term carbon sequestration.

Importantly, NPS align with national priorities related to climate resilience, soil health restoration, and sustainable intensification. Research and extension efforts under the Indian Council of Agricultural Research increasingly emphasize integrated, ecosystem-based approaches to stress management that deliver co-benefits for productivity, environmental quality, and livelihoods.

In contrast to input-intensive models, NPS are knowledge-intensive rather than resource-intensive, making them particularly suitable for smallholder-dominated agricultural systems.

By strengthening the functional capacity of agroecosystems, NPS provide a robust and scalable pathway for managing abiotic stresses under current and future climate scenarios.

2. CONCEPTUAL FRAMEWORK: NATURE-POSITIVE SOLUTIONS IN ABIOTIC STRESS MANAGEMENT

NPS in agriculture refer to management practices and system designs that enhance agricultural productivity and resilience while simultaneously restoring, conserving, and regenerating natural resources. In the context of abiotic stress management, NPS emphasize working with natural processes rather than relying predominantly on external inputs or engineered interventions.

Abiotic stresses, such as drought, heat, salinity, sodicity, flooding, and nutrient imbalance, are fundamentally expressions of ecosystem dysfunction, particularly in soil–water–plant interactions. NPS seek to address the root causes of stress by improving ecosystem functioning, rather than merely mitigating symptoms at the crop level.

The core principles of NPS in agriculture include:

1. **Enhancement of Natural Capital**
   NPS aim to improve soil organic matter, biodiversity, water-holding capacity, and nutrient cycling. By strengthening these natural assets, agricultural systems gain inherent resilience against climatic and edaphic stresses.

2. **Process-Based Management**
   Instead of focusing solely on inputs (fertilizers, irrigation, chemicals), NPS emphasize biological and physical processes such as carbon sequestration, microbial turnover, aggregation, infiltration, and evapotranspiration regulation.

3. **System-Level Resilience over Short-Term Maximization**
   Productivity is viewed in conjunction with yield stability, risk reduction, and long-term sustainability. Under NPS, moderate but stable yields under stress are often prioritized over high but volatile yields.

4. **Context-Specific and Adaptive Design**
   NPS are tailored to agro-ecological zones, soil types, rainfall regimes, and cropping systems. This contextualization is particularly critical in India, where spatial variability in climate and soils is high.

5. **Co-benefits across Multiple Outcomes**
   Abiotic stress mitigation under NPS simultaneously delivers co-benefits such as

carbon sequestration, reduced greenhouse gas emissions, improved water-use efficiency, enhanced soil fertility, and biodiversity conservation.

In essence, NPS reposition abiotic stress management from a reactive, input-intensive strategy to a preventive, ecosystem-based strategy.

2.1 Linkages among Soil–Plant–Water–Climate Systems

Abiotic stresses emerge from disruptions in the tightly coupled soil–plant–water–climate continuum. Understanding these linkages is central to the conceptual framework of NPS.

2.1.1 Soil as the Central Regulator

Soil functions as the primary interface between climate variability and plant response. Its physical, chemical, and biological properties regulate how climatic stressors are transmitted to crops.

- Soil physical properties (texture, structure, aggregation, bulk density) govern water infiltration, storage, and aeration.
- Soil chemical properties (pH, salinity, sodicity, nutrient balance) influence nutrient availability and root functioning.
- Soil biological properties (microbial biomass, enzyme activity, rhizosphere interactions) regulate nutrient cycling and stress signaling pathways.

Degraded soils amplify climatic stress by reducing plant-available water, increasing osmotic stress, and limiting nutrient uptake. NPS interventions, such as organic matter addition, residue retention, and reduced disturbance, restore soil buffering capacity against extreme weather events.

2.1.2 Plant Responses and Root–Soil Feedbacks

Plants do not passively experience abiotic stress; they actively modify their soil environment through root architecture, exudation, and symbiotic associations.

- Deeper and more extensive root systems enhance access to subsoil moisture during drought.
- Root exudates stimulate microbial activity, improving nutrient solubilization under nutrient stress.

- Mycorrhizal associations enhance water and phosphorus uptake under both drought and salinity.

NPS strengthen these root–soil feedbacks by creating favorable soil conditions that allow crops to express their inherent adaptive traits.

2.1.3 Water Dynamics and Climate Variability

Climate change alters rainfall intensity, distribution, and evaporative demand. The impact of these changes on crops is largely mediated by soil water dynamics.

- In drought-prone systems, soils with higher organic carbon content retain more water and release it gradually to crops.
- Under high rainfall or flooding, well-structured soils with stable aggregates improve drainage and oxygen diffusion.
- Mulched and covered soils moderate soil temperature, reducing heat stress during extreme events.

Thus, NPS-based soil and water management act as climate buffers, decoupling crop performance from short-term climatic extremes.

2.1.4 Integrated System Perspective

The conceptual framework of NPS recognizes that abiotic stress is not a single-factor problem. Instead, it arises from interacting soil, plant, water, and climate processes. Effective stress management therefore requires integrated, system-level interventions, rather than isolated input-based solutions.

2.2 Ecosystem Services Underpinning Abiotic Stress Resilience

NPS derive their effectiveness from the enhancement of ecosystem services—the benefits that agricultural landscapes obtain from natural processes.

2.2.1 Regulating Services

Regulating ecosystem services are central to abiotic stress mitigation:

- Soil moisture regulation through improved infiltration and water retention.
- Temperature moderation via surface cover and improved soil structure.

- Salinity regulation through enhanced leaching, ion exchange, and biological buffering.
- Nutrient regulation through synchronized mineralization and plant uptake.

By strengthening these services, NPS reduce the intensity and frequency of stress experienced by crops.

2.2.2 Supporting Services

Supporting services provide the foundational capacity for resilience:

- Soil formation and aggregation, driven by organic matter and biological activity.
- Nutrient cycling, mediated by microorganisms and enzymes.
- Root–microbe symbioses, enhancing nutrient and water uptake.

These services operate continuously and are often invisible, yet they determine long-term system performance under stress.

2.2.3 Provisioning and Stability Benefits

While provisioning services (yield, biomass, fodder) are the most visible outcomes, NPS place particular emphasis on yield stability rather than maximum yield. Under abiotic stress conditions, systems with strong ecosystem services typically show:

- Lower inter-annual yield variability
- Reduced crop failure risk
- Improved recovery after extreme events

This stability is especially critical for rainfed and marginal farming systems.

2.2.4 Linking Ecosystem Services to Measurable Indicators

An important conceptual advancement in NPS is the translation of ecosystem services into measurable soil and plant indicators (e.g., soil organic carbon, aggregate stability, available water capacity, enzyme activity). This linkage enables monitoring, evaluation, and policy integration of NPS-based stress management.

2.5 Distinction between Adaptive, Regenerative, and Restorative Approaches

NPS encompass a continuum of management approaches that differ in objectives, time horizons, and system conditions.

2.5.1 Adaptive Approaches

Adaptive approaches focus on short- to medium-term adjustments that allow crops and farming systems to cope with existing abiotic stresses.

Examples include:

- Adjusting sowing dates to avoid heat or terminal drought
- Mulching to reduce evaporation
- Selecting stress-tolerant crop varieties

While adaptive strategies reduce immediate vulnerability, they may not fundamentally improve ecosystem condition unless integrated with regenerative measures.

2.5.2 Regenerative Approaches

Regenerative approaches aim to enhance ecosystem functions over time, thereby reducing stress sensitivity in the long term.

Key features include:

- Building soil organic carbon (SOC)
- Enhancing biological activity
- Improving soil structure and rooting depth
- Increasing system diversity (crop rotations, intercropping, agroforestry)

Regenerative NPS shift systems from stress-prone to stress-resilient by strengthening natural buffering mechanisms.

2.5.3 Restorative Approaches

Restorative approaches are applied where soils and landscapes are severely degraded, such as saline–sodic soils, eroded lands, or shallow and gravelly barren lands.

Objectives include:

- Re-establishing basic soil functions

- Rebuilding soil depth and structure
- Reintroducing vegetation and biological activity

Restorative NPS often require higher initial investment and longer time frames but provide substantial long-term benefits in terms of stress mitigation and land productivity.

2.5.4 Integrating the Three Approaches

The conceptual framework of NPS emphasizes that adaptive, regenerative, and restorative approaches are complementary rather than mutually exclusive. Effective abiotic stress management often involves:

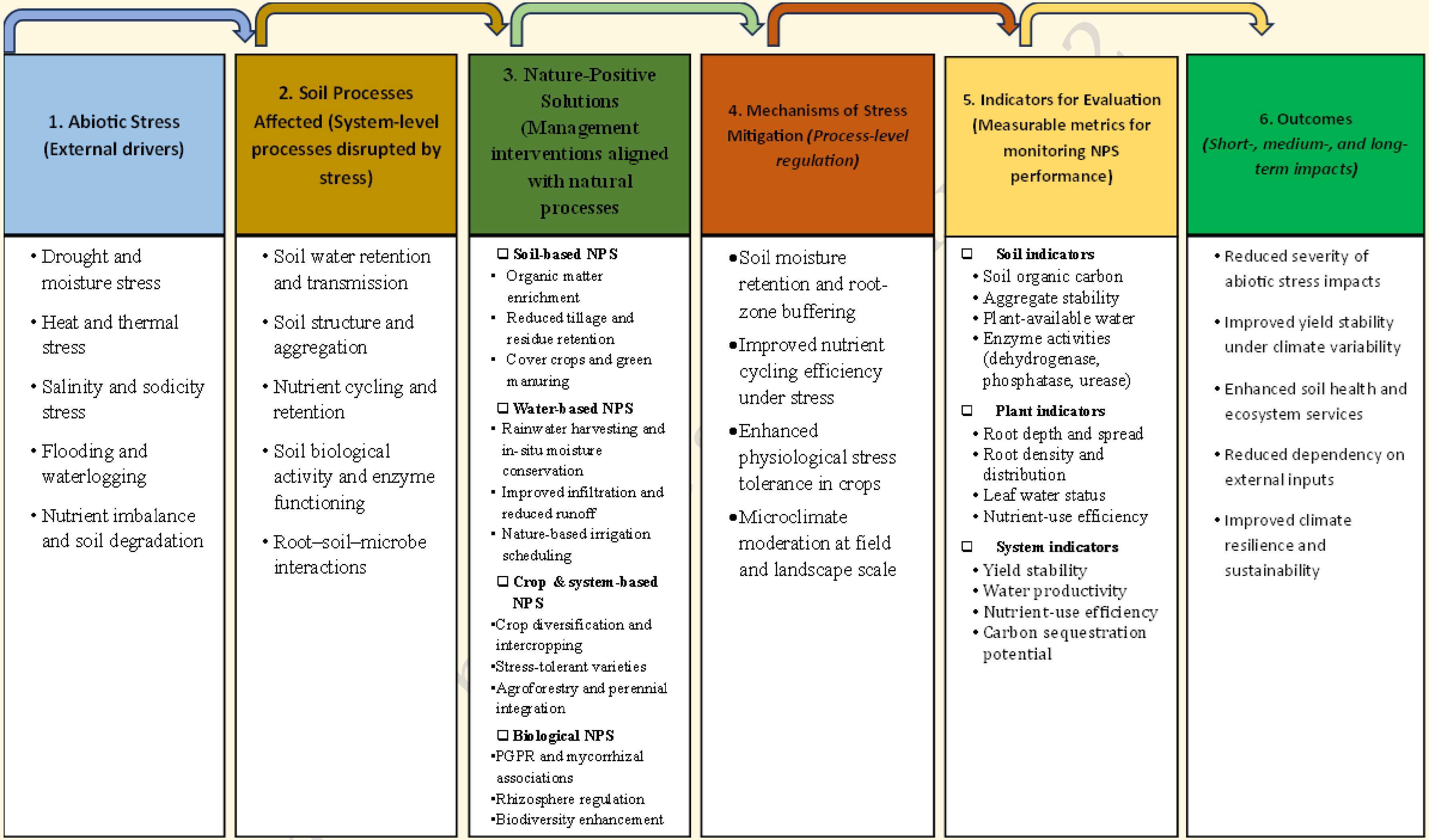
- Adaptive measures for immediate risk reduction
- Regenerative practices for medium-term resilience
- Restorative interventions for long-term sustainability in degraded systems

Selecting the appropriate combination depends on baseline soil condition, climatic risk, and socio-economic context.

2.5 Synthesis of the Conceptual Framework

In summary, the NPS framework for abiotic stress management views agricultural resilience as an emergent property of well-functioning ecosystems. By strengthening soil–plant–water–climate linkages and ecosystem services, NPS transform abiotic stress from an unavoidable constraint into a manageable risk.

This framework provides the scientific and operational foundation for subsequent sections of the bulletin, which translate these concepts into stress-specific strategies, indicators, and field-level practices.



1. Abiotic Stress (External drivers)

- Drought and moisture stress
- Heat and thermal stress
- Salinity and sodicity stress
- Flooding and waterlogging
- Nutrient imbalance and soil degradation

2. Soil Processes Affected (System-level processes disrupted by stress)

- Soil water retention and transmission
- Soil structure and aggregation
- Nutrient cycling and retention
- Soil biological activity and enzyme functioning
- Root–soil–microbe interactions

3. Nature-Positive Solutions (Management interventions aligned with natural processes)

☐ **Soil-based NPS**
- Organic matter enrichment
- Reduced tillage and residue retention
- Cover crops and green manuring

☐ **Water-based NPS**
- Rainwater harvesting and in-situ moisture conservation
- Improved infiltration and reduced runoff
- Nature-based irrigation scheduling

☐ **Crop & system-based NPS**
- Crop diversification and intercropping
- Stress-tolerant varieties
- Agroforestry and perennial integration

☐ **Biological NPS**
- PGPR and mycorrhizal associations
- Rhizosphere regulation
- Biodiversity enhancement

4. Mechanisms of Stress Mitigation *(Process-level regulation)*

- Soil moisture retention and root-zone buffering
- Improved nutrient cycling efficiency under stress
- Enhanced physiological stress tolerance in crops
- Microclimate moderation at field and landscape scale

5. Indicators for Evaluation (Measurable metrics for monitoring NPS performance)

☐ **Soil indicators**
- Soil organic carbon
- Aggregate stability
- Plant-available water
- Enzyme activities (dehydrogenase, phosphatase, urease)

☐ **Plant indicators**
- Root depth and spread
- Root density and distribution
- Leaf water status
- Nutrient-use efficiency

☐ **System indicators**
- Yield stability
- Water productivity
- Nutrient-use efficiency
- Carbon sequestration potential

6. Outcomes *(Short-, medium-, and long-term impacts)*

- Reduced severity of abiotic stress impacts
- Improved yield stability under climate variability
- Enhanced soil health and ecosystem services
- Reduced dependency on external inputs
- Improved climate resilience and sustainability

Figure 1. Conceptual framework linking abiotic stresses, soil processes, Nature-Positive Solutions (NPS), mechanisms of stress mitigation, indicators, and outcomes in Indian agriculture.

3. MAJOR ABIOTIC STRESSES IN INDIAN AGRICULTURE

Indian agriculture is increasingly challenged by a complex interplay of abiotic stresses, including drought and moisture deficit, heat stress, salinity and sodicity, flooding and waterlogging, and nutrient-related stresses, all of which vary widely across agro-ecological regions and cropping systems. Drought and erratic rainfall remain the most widespread constraints, particularly in rainfed and semi-arid areas, where limited soil water storage and high evaporative demand severely restrict crop growth and yield stability (NDMA, 2010; Pathak et al., 2022). Rising temperatures and frequent heat waves exacerbate these effects by accelerating evapotranspiration, disrupting crop phenology, and impairing reproductive processes (IMD, 2023; Asseng et al., 2015).

In irrigated and coastal regions, salinity and sodicity pose serious challenges by degrading soil structure, reducing nutrient availability, and impairing root function, while periodic flooding and waterlogging in low-lying and high-rainfall zones create oxygen-deficient conditions that inhibit root respiration and nutrient uptake (Sharma et al., 2015; CSSRI, 2022). Nutrient-related stresses, including both deficiencies and imbalances, often interact with these physical stresses, further constraining crop performance by limiting physiological resilience under adverse conditions (Ladha et al., 2016). Collectively, these abiotic stresses not only reduce mean productivity but also increase inter-annual yield variability, underscoring the need for integrated, ecosystem-based management strategies that enhance soil function, water regulation, and system-level resilience rather than addressing individual stresses in isolation.

3.1 Drought and moisture stress

Drought defined as moisture deficit relative to crop water demand, reduces crop growth by restricting root water uptake, inducing stomatal closure (thereby reducing photosynthesis), limiting cell expansion, accelerating phenological development (shortened grain-filling period), and increasing susceptibility to pests and post-harvest losses (Farooq et al., 2009). Drought also amplifies nutrient uptake limitations by reducing mass flow and diffusion of nutrients to the root surface (Lambers et al., 2008).

India has a long history of episodic and spatially heterogeneous drought. National assessments classify nearly two-thirds of the country as drought-prone, with increasing frequency and intensity observed in several regions due to changing monsoon patterns and warming trends (NDMA, 2010; Mishra et al., 2020). Recent high-resolution drought reconstructions and atlases indicate that large multi-district drought events have become more frequent since the early 2000s, particularly in central and peninsular India (Chuphal et al., 2024). For operational drought monitoring and planning, NDMA guidelines and IMD-based drought indices remain the primary government references.

3.2 Heat stress

Heat stress, exposure to excessively high day or night temperatures, affects crops by reducing pollen viability, impairing fertilisation, accelerating crop development, increasing respiration relative to photosynthesis, and intensifying water stress through higher evapotranspiration demand (Hatfield & Prueger, 2015). Heat-sensitive crops such as wheat, rice, maize, and grain legumes show sharp yield declines when critical temperature thresholds are exceeded during flowering and grain-filling stages (Asseng et al., 2015).

India has experienced a marked increase in the frequency, duration, and spatial extent of extreme heat events over the last three decades, particularly across the Indo-Gangetic Plains and peninsular regions (IMD, 2023). Climate projections indicate that terminal heat stress risks for wheat and other rabi crops will intensify under future warming scenarios, threatening yield stability and food security (CRIDA, 2020; Asseng et al., 2015). Heat stress risk mapping based on degree-day accumulation and extreme temperature indices is increasingly used to guide adaptation planning at district and regional scales.

3.3 Salinity and sodicity stress

Salinity and sodicity stress impose osmotic constraints, ion toxicity (Na^+ and Cl^-), nutrient imbalance (reduced uptake of K^+, Ca^{2+}, and Mg^{2+}), and structural deterioration of soils through clay dispersion under sodicity, collectively impairing germination, root growth, and crop productivity (Sharma et al., 2015). Crop tolerance varies widely, and without reclamation measures, salt-affected soils often shift from productive agriculture to low-yielding or fallow systems.

National surveys estimate that approximately 6.7 million hectares of land in India are affected by salinity and sodicity, with significant concentrations in irrigated arid and semi-arid regions and coastal belts (CSSRI, 2022). Improper irrigation practices, inadequate drainage, and seawater intrusion continue to drive secondary salinisation in several states.

The Central Soil Salinity Research Institute (CSSRI) and NBSS&LUP provide state-wise mapping, diagnostic criteria, and reclamation guidelines that inform national and state-level land management programmes.

3.4 Flooding and waterlogging stress

Flooding and waterlogging stress deprive plant roots of oxygen, induce hypoxic or anoxic conditions, alter soil redox chemistry, reduce nutrient uptake (particularly nitrogen and sulfur), and increase susceptibility to root diseases; severe or prolonged events can cause complete crop failure (Setter & Waters, 2003). Recurrent waterlogging also restricts crop choice and reduces land productivity in affected landscapes.

India has one of the largest flood-prone areas globally. Classical estimates place the flood-liable area at around 40 million hectares, while annual satellite-based assessments by the Central Water Commission document substantial inter-annual variability in the area actually affected (CWC, 2022). Flood Management Statistical Reports provide state- and district-wise data on flood-affected area, crop loss, and population exposure, which are critical for agricultural disaster planning and drainage interventions.

3.5 Nutrient imbalance and soil degradation stress

Nutrient imbalance and broader soil degradation—including erosion, organic carbon depletion, compaction, and chemical degradation—represent chronic stresses that progressively reduce soil productive capacity. These processes limit plant-available nutrients, reduce water-holding capacity, weaken aggregate stability, and lower the buffering capacity of soils against climatic extremes (Lal, 2015).

National land degradation assessments report that 97.8 million hectares of India's land area are degraded, with water erosion constituting the dominant process (ISRO-SAC, 2019). Reconciled estimates that include chemical degradation and nutrient depletion place the affected area closer to 115–120 million hectares (NAAS, 2019). Declining SOC and widespread nutrient deficiencies—documented through the Soil Health Card programme—indicate that a large proportion of cultivated soils are low in nitrogen and deficient in one or more macro- or micronutrients (DAC&FW, 2023).

Because nutrient imbalance and soil degradation accumulate gradually, they act as persistent background stresses that reduce yield stability, increase dependence on external inputs, and interact synergistically with acute stresses such as drought, heat, salinity, and flooding.

4. NATURE-POSITIVE SOLUTIONS FOR ABIOTIC STRESS MANAGEMENT

Soil is the primary buffering medium through which abiotic stresses—such as drought, heat, salinity, nutrient imbalance, and moisture extremes—are either amplified or moderated. NPS for abiotic stress management place soil at the center of intervention, recognizing it as a living system rather than an inert growth medium. Soil-based NPS enhance the soil's inherent capacity to regulate water, nutrients, temperature, and biological processes, thereby improving crop resilience under climate variability (Lal, 2004; Six et al., 2002).

4.1 Soil-Based Nature-Positive Solutions

4.1.1 Organic Matter Enrichment and Carbon Sequestration

Organic matter enrichment is the foundational pillar of soil-based NPS. Soil organic matter, particularly SOC, governs multiple soil functions that directly influence abiotic stress tolerance, including water-holding capacity, nutrient retention, cation exchange capacity, and microbial habitat quality (Six et al., 2002; Lal, 2004).

Under drought and heat stress conditions, soils with higher SOC exhibit greater moisture buffering, reduced evaporative losses, and moderated soil temperature fluctuations. Hudson (1994) demonstrated that even small increases in SOC substantially improve plant-available water, particularly in coarse-textured and structurally weak soils. In semi-arid, shallow, and gravelly soils common in India, modest SOC increases of approximately 0.2–0.4% have been shown to significantly improve drought resilience and yield stability (Bhattacharyya et al., 2009; Lal, 2015).

In saline and sodic environments, organic matter improves electrolyte balance, enhances calcium availability through organic acid production, and mitigates sodium-induced clay dispersion, thereby restoring soil structure and permeability (Sharma et al., 2015; Choudhury et al., 2014). Carbon sequestration through organic inputs not only enhances abiotic stress buffering but also contributes to climate change mitigation, positioning soil-based NPS as a dual-benefit strategy for adaptation and mitigation (Lal, 2004; Smith et al., 2014).

Nature-positive pathways for organic matter enrichment include:

- Application of farmyard manure (FYM), compost, and enriched organic amendments
- Recycling of crop residues rather than burning
- Inclusion of green manures and leguminous crops
- Integration of agroforestry, cover crops, and perennial vegetation

4.1.2 Aggregate Stability and Soil Structure Improvement

Soil structure determines the physical framework within which water, air, roots, and microorganisms interact. Aggregate stability—the resistance of soil aggregates to disintegration—is a key regulator of infiltration, aeration, drainage, and root penetration under stress conditions (Bronick & Lal, 2005).

Abiotic stresses such as drought, intense rainfall, and salinity are amplified in structurally degraded soils characterized by surface crusting, compaction, and poor pore continuity. Nature-positive soil management improves aggregation through organic binding agents (microbial polysaccharides), fungal hyphae, root exudates, and glomalin produced by arbuscular mycorrhizal fungi (Six et al., 2002).

Empirical studies from Indian rainfed systems demonstrate that residue retention, organic amendments, and reduced tillage significantly enhance macro-aggregate stability, resulting in higher infiltration rates and reduced runoff losses (Bhattacharyya et al., 2009; Choudhury et al., 2014). Improved aggregate stability leads to:

Enhanced infiltration during high-intensity rainfall

Increased soil water retention under drought

Improved root proliferation and anchorage

Reduced erosion and surface sealing

Structurally improved soils thus function as “soil water reservoirs,” a property that is particularly critical for dryland and rainfed agro-ecosystems exposed to increasing rainfall variability.

4.1.3 Soil Biological Regulation (Microbial Activity and Enzymes)

Soil biology forms the regulatory core of nature-positive abiotic stress management. Soil microorganisms govern nutrient cycling, organic matter turnover, aggregate formation, and plant stress signaling through complex biochemical interactions (Burns et al., 2013).

Biologically active soils exhibit greater resilience and faster recovery under moisture and temperature stress. Enhanced microbial biomass improves synchronization of nitrogen mineralization with crop demand, increases phosphorus solubilization in calcareous soils, and promotes the production of osmolytes and phytohormones that protect plants under drought and salinity stress (Balota et al., 2004; Philippot et al., 2013).

Soil enzymes such as dehydrogenase, urease, phosphatase, and β-glucosidase are sensitive indicators of biological functioning. Higher enzyme activities reflect efficient nutrient cycling even under sub-optimal moisture regimes (Burns et al., 2013). Long-term experiments show that organic amendments and reduced chemical disturbance maintain enzyme activity under drought stress more effectively than conventionally managed systems (Balota et al., 2004).

Through these processes, nature-positive practices shift soils from chemically regulated systems to biologically regulated systems, which are inherently more resilient to abiotic shocks.

4.1.4 Mulching, Residue Retention, and Cover Cropping

Surface soil protection through mulching, residue retention, and cover crops is among the most effective nature-positive strategies for mitigating drought and heat stress. Residue cover reduces soil temperature fluctuations, minimizes evaporative water loss, and protects soil aggregates from raindrop impact (Blanco-Canqui & Lal, 2007).

In rainfed Indian systems, residue retention has been shown to improve water-use efficiency by 10–25%, while simultaneously enhancing SOC accumulation and soil aggregation (Ghosh et al., 2010). Cover crops extend these benefits by providing continuous root activity, improving infiltration, and stimulating microbial processes. Leguminous cover crops further contribute biologically fixed nitrogen, improving nutrient availability under stress conditions (Lithourgidis et al., 2011).

Over time, these practices create a positive feedback loop of improved SOC, aggregation, and biological activity, strengthening system-level resilience to drought and heat stress.

To conclude, soil-based NPS operate through synergistic physical, chemical, and biological pathways. Organic matter improves water and nutrient buffering; stable aggregates regulate hydrology; biological activity sustains nutrient cycling and stress signaling; and surface protection moderates microclimate extremes. Collectively, these processes transform soils from stress-sensitive systems into stress-buffering systems.

4.2 Water-Based Nature-Positive Solutions for Abiotic Stress Management

Water scarcity, erratic rainfall, and declining water-use efficiency are among the most critical abiotic constraints affecting agriculture. Water-based NPS emphasize rainfall capture, infiltration enhancement, soil–water–biological interactions, and demand-side management rather than supply-side expansion (Rockström et al., 2007; Wani et al., 2009).

4.2.1 Rainwater Harvesting and In-situ Moisture Conservation

Rainwater harvesting aims to slow, spread, and store rainfall within the landscape. Practices such as contour bunding, broad-bed and furrow systems, and compartmental bunding increase effective rainfall by extending soil moisture availability (Wani et al., 2009).

Farm ponds, percolation tanks, and recharge structures reduce runoff losses and enhance groundwater recharge while stabilizing yields under delayed monsoon or mid-season droughts (Rockström et al., 2007).

4.2.2 Improved Infiltration and Reduced Runoff

Soil infiltration capacity is a critical determinant of water availability under rainfed conditions. Many degraded agricultural soils suffer from surface sealing, compaction, and poor aggregation, leading to rapid runoff and low infiltration. Nature-positive water management emphasizes soil physical and biological restoration to improve infiltration rather than relying solely on structural measures.

Practices such as residue retention, cover cropping, reduced tillage, and organic amendments enhance soil aggregation and pore continuity. Improved macro-porosity allows rainfall to infiltrate rapidly, while stable micro-aggregates facilitate longer-term water storage. Enhanced infiltration reduces runoff losses, mitigates soil erosion, and improves groundwater recharge.

Vegetative barriers, grassed waterways, and agroforestry strips further slow runoff velocity, allowing water to percolate into the soil profile. The cumulative effect of these practices is a shift from runoff-dominated to infiltration-dominated hydrology at the field scale.

Reduced runoff also minimizes nutrient losses, thereby linking water-based NPS with nutrient-use efficiency and soil fertility improvement. This integrated regulation of water and nutrients is a defining feature of nature-positive systems.

4.2.3 Nature-Positive Irrigation Scheduling and Deficit Irrigation

In irrigated and supplemental irrigation systems, nature-positive water management prioritizes precision, timing, and crop physiological demand rather than maximizing water application. Nature-Positive irrigation scheduling relies on soil moisture status, crop growth stage, and climatic demand to optimize water use.

Deficit irrigation, strategically applying less than full crop water requirement during non-critical growth stages, is increasingly recognized as a viable NPS for abiotic stress management. When combined with improved soil moisture retention and root development, controlled water stress can enhance water productivity without proportionate yield penalties.

Micro-irrigation systems (drip and sprinkler), when integrated with organic mulches and biologically active soils, amplify the benefits of deficit irrigation by reducing evaporative losses and improving root-zone efficiency. Nature-positive scheduling thus transforms irrigation from a compensatory input into a regulatory tool that enhances crop resilience.

By aligning irrigation practices with natural soil-water buffering processes, NPS-based irrigation management reduces groundwater over-extraction, energy consumption, and irrigation-induced salinity risks.

4.2.4 Soil Moisture Buffering through Organic Inputs

Soil organic matter is the most critical biological regulator of soil moisture dynamics. Organic inputs such as farmyard manure, compost, crop residues, green manures, and bio-based amendments increase the water-holding capacity and moisture buffering ability of soils.

Organic matter improves soil structure, enhances aggregate stability, and increases the proportion of plant-available water. Even small increases in SOC can significantly improve moisture retention in coarse-textured and degraded soils. This buffering effect reduces the intensity of moisture stress during dry spells and prolongs water availability between rainfall or irrigation events.

In biologically active soils, organic inputs stimulate microbial activity and the production of extracellular polysaccharides, which further enhance soil aggregation and water retention. Root–microbe interactions promoted under organic-rich conditions also improve root proliferation and access to deeper soil moisture.

Unlike synthetic water-retaining polymers, organic-based moisture buffering is self-reinforcing, regenerative, and climate-adaptive, making it a core component of water-based NPS.

4.2.5 Integrated Role of Water-Based NPS in Abiotic Stress Resilience

Water-based NPS operate synergistically across soil, crop, and landscape scales. Rainwater harvesting increases water availability, improved infiltration ensures efficient entry into the soil profile, nature-positive irrigation optimizes water use, and organic inputs stabilize moisture availability over time. Together, these processes reduce the frequency and severity of drought stress, enhance yield stability, and improve water productivity.

Beyond stress mitigation, water-based NPS generate co-benefits including soil carbon sequestration, nutrient retention, biodiversity enhancement, and reduced dependence on external irrigation inputs. These multiple ecosystem services position water-based NPS as a foundational strategy for climate-resilient and sustainable agriculture.

4.3 Crop and Cropping System-Based Solutions

Crop and cropping system management represents a central pillar of nature-positive abiotic stress management, as it directly influences resource capture, risk distribution, and system resilience. Unlike input-centric approaches that attempt to correct stress effects post-occurrence, crop-based NPS strategies work proactively by aligning plant traits, spatial arrangements, and temporal patterns with prevailing soil–climate constraints. These approaches enhance system stability while maintaining productivity under drought, heat, salinity, nutrient stress, and rainfall variability.

4.3.1 Crop Diversification and Stress-Tolerant Varieties

Crop diversification is one of the most effective nature-positive strategies for buffering abiotic stress at the field and farm scale. Diversified systems reduce the probability of total crop failure by distributing risk across species with contrasting stress tolerance mechanisms. Cereals, pulses, oilseeds, and millets differ markedly in rooting depth, water-use efficiency, nutrient demand, and thermal tolerance, allowing better utilization of available resources under stress-prone conditions.

The use of stress-tolerant and climate-resilient varieties further strengthens diversification benefits. Varieties with traits such as deeper or proliferative root systems, early vigour, shorter duration, osmotic adjustment, and improved canopy temperature regulation are better adapted to drought and heat stress. Salt-tolerant and nutrient-efficient varieties contribute to productivity stability in degraded soils without increasing external inputs. Importantly, nature-positive varietal selection emphasizes resilience and yield stability rather than maximum yield potential under ideal conditions.

At the system level, diversification enhances biological interactions, supports soil microbial diversity, and improves nutrient cycling efficiency. Over time, diversified cropping systems demonstrate lower inter-annual yield variability, making them particularly suitable for rainfed and semi-arid regions.

4.3.2 Intercropping and Relay Cropping for Risk Buffering

Intercropping and relay cropping are core nature-positive strategies for managing abiotic stress through complementary resource use. By growing two or more crops simultaneously or sequentially in the same field, these systems optimize light interception, root zone exploitation, and soil moisture use, while reducing exposure to climatic extremes.

Cereal–legume intercropping systems are particularly effective in stress-prone environments. Legumes contribute biological nitrogen fixation, improve rhizosphere activity, and enhance soil organic inputs, which indirectly improve soil moisture retention and nutrient availability. Differences in rooting depth between component crops reduce direct competition and improve water extraction from multiple soil layers during dry spells.

Relay cropping extends these benefits by ensuring continuous ground cover and resource utilization, especially under erratic rainfall patterns. The presence of a standing crop during transition periods reduces evaporative losses, moderates soil temperature, and maintains biological activity in the soil. From a risk perspective, intercropping and relay systems stabilize income and biomass production, even when one component crop is adversely affected by stress.

Nature-positive intercropping designs prioritize functional complementarity rather than yield maximization of a single crop, thereby enhancing resilience at the system level.

4.3.3 Agroforestry and Perennial Integration

Integration of trees and perennial components into cropping systems is a highly effective long-term nature-positive solution for abiotic stress management. Agroforestry systems enhance vertical and temporal resource use, improve microclimate regulation, and strengthen soil structure and carbon stocks.

Trees contribute deep rooting systems that access subsoil moisture and nutrients beyond the reach of annual crops, thereby improving overall system water use efficiency. Leaf litter and root turnover add organic matter to the soil, enhancing aggregation, infiltration, and moisture-holding capacity. Canopy cover moderates extreme temperatures, reduces wind speed, and lowers evapotranspiration demand for understorey crops.

Perennial crops and fruit-based systems provide sustained ground cover and continuous root activity, which are critical for maintaining soil biological functions under climatic stress. In drought- and heat-prone regions, agroforestry systems often demonstrate higher yield stability and recovery capacity following extreme events compared to monocropping systems.

From a nature-positive perspective, agroforestry also delivers multiple co-benefits, including carbon sequestration, biodiversity enhancement, and diversified farm income, making it a cornerstone of climate-resilient agricultural landscapes.

4.3.4 Adjusted Sowing Windows and Crop Geometry

Temporal and spatial adjustments in cropping practices play a critical role in mitigating abiotic stress impacts. Adjusting sowing windows to synchronize sensitive crop growth stages with favourable climatic periods reduces exposure to drought, heat, and terminal stress. Early or staggered sowing strategies are particularly effective in rainfed systems where rainfall onset and distribution are uncertain.

Crop geometry, defined by plant spacing, row orientation, and population density, directly influences canopy microclimate, root competition, and soil moisture dynamics. Optimized geometry reduces excessive competition for water and nutrients under stress conditions, while ensuring adequate ground cover to limit evaporation. Wider row spacing combined with appropriate plant population allows deeper root penetration and improved access to soil moisture during dry spells.

Nature-positive crop geometry emphasizes efficient resource use rather than maximum plant density. These adjustments often require no additional inputs, making them cost-effective and easily adoptable by farmers.

4.3.5 Soil Moisture Buffering through Organic Inputs (Cropping System Perspective)

While soil management practices are addressed separately, cropping systems strongly influence soil moisture buffering through organic inputs derived from crop residues, root biomass, and intercrop vegetation. Residue-retaining cropping systems improve surface cover, reduce soil temperature fluctuations, and minimize evaporation losses.

Organic inputs from diversified and legume-based systems enhance SOC pools, which directly increase soil water-holding capacity and improve soil structure. Improved aggregation and porosity facilitate greater infiltration during rainfall events, reducing runoff and increasing effective rainfall use.

From a nature-positive standpoint, cropping systems that generate and recycle biomass internally reduce dependence on external amendments while strengthening intrinsic soil resilience mechanisms. Over time, such systems develop higher resistance to drought and quicker recovery following stress events.

Overall Significance of Crop and Cropping System-Based NPS

Crop and cropping system-based NPS represent low-cost, scalable, and ecologically sound approaches to abiotic stress management. By integrating diversification, functional crop combinations, perennial components, and adaptive agronomic practices, these systems enhance resilience through biological regulation rather than chemical or mechanical intervention. Their cumulative effects on yield stability, soil health, and climate adaptation make them essential components of sustainable and climate-resilient agriculture.

4.4 Biological and Ecological Solutions for Abiotic Stress Management

Biological and ecological solutions constitute a core pillar of NPS for abiotic stress management. Unlike chemical or engineering interventions, these approaches work by strengthening natural soil–plant–microbe interactions, enhancing self-regulation, resilience, and buffering capacity of agroecosystems. Under increasing drought, heat, salinity, and nutrient stress conditions, biological pathways play a decisive role in sustaining crop productivity with reduced external inputs.

4.4.1 Plant–Microbe Interactions under Abiotic Stress

Plant roots coexist with diverse beneficial microorganisms that directly and indirectly improve plant tolerance to abiotic stresses. Among these, Plant Growth-Promoting Rhizobacteria (PGPR) and arbuscular mycorrhizal fungi (AMF) are the most extensively studied and field-relevant biological agents.

4.4.1.1 Role of PGPR in Stress Alleviation

PGPR enhance plant performance under stress through multiple mechanisms:

- Improved nutrient acquisition, particularly nitrogen, phosphorus, iron, and zinc, under moisture-limited or alkaline soil conditions.
- Production of phytohormones (auxins, cytokinins, gibberellins) that stimulate root elongation and branching, improving soil exploration under drought.
- ACC deaminase activity, which reduces stress-induced ethylene levels in plants, thereby sustaining root growth under salinity and heat stress.
- Induced systemic tolerance, where microbial signals prime plant defense and stress-response pathways.

In rainfed and degraded soils, PGPR help stabilize yields by improving root vigor and early crop establishment, particularly under erratic rainfall and temperature extremes.

4.4.1.2 Role of Mycorrhizal Associations

Mycorrhizal fungi form symbiotic associations with plant roots, extending the effective root system through extraradical hyphae. Their contribution to abiotic stress tolerance includes:

- Enhanced phosphorus and micronutrient uptake from low-availability soil pools.
- Improved soil moisture extraction from micro-pores inaccessible to roots.
- Regulation of ionic balance, especially under salinity stress, by restricting sodium uptake and maintaining favorable K^+:Na^+ ratios.
- Improvement in soil aggregation through glomalin production, which enhances soil structure and water retention.

Mycorrhizal dependency is particularly high in dryland crops, horticultural orchards, and agroforestry systems established on shallow or gravelly soils.

4.4.2 Rhizosphere Regulation under Abiotic Stress

The rhizosphere—the narrow soil zone influenced by root exudates and microbial activity—is a critical interface for stress adaptation. Under abiotic stress, plants actively modify rhizosphere chemistry and biology to maintain functional stability.

4.4.2.1 Root Exudation and Microbial Recruitment

Under drought, salinity, or nutrient stress, plants alter the quantity and composition of root exudates (sugars, organic acids, amino acids, phenolics), which:

- Selectively stimulate beneficial microbial populations.
- Enhance microbial production of osmolytes and stress-protective metabolites.
- Promote nutrient solubilization and localized nutrient availability (Philippot et al., 2013).

This dynamic feedback mechanism allows plants to engineer their rhizosphere for survival under unfavorable conditions.

4.4.2.2 Rhizosphere Processes Improving Stress Tolerance

Key rhizosphere-mediated processes include:

- Enhanced nutrient mineralization under low moisture availability through microbial enzymatic activity.
- Improved soil redox regulation under waterlogging and flooding stress.
- Biological buffering of soil pH and salinity, reducing ionic toxicity near the root surface.

Nature-positive management practices such as organic amendments, residue retention, reduced tillage, and diversified cropping systems strengthen these rhizosphere functions over time.

4.4.3 Biodiversity-Driven Resilience Mechanisms

Agroecosystem resilience to abiotic stress is strongly linked to biological diversity at multiple levels—soil organisms, crops, and landscape components.

4.4.3.1 Soil Biodiversity and Functional Redundancy

High soil biodiversity ensures functional redundancy, meaning that:

- Multiple microbial groups can perform similar ecological functions (nutrient cycling, decomposition, stress mitigation).
- Failure of one functional group under extreme stress does not collapse the entire system.

Diverse microbial communities stabilize carbon and nitrogen cycling, regulate soil moisture dynamics, and sustain biological activity during prolonged stress periods.

4.4.3.2 Crop and System Diversity

Biological resilience is further enhanced through:

- Crop diversification, which reduces system-level vulnerability to specific stresses.
- Intercropping and cover crops, which improve below-ground biodiversity and soil cover.
- Agroforestry systems, where perennial roots, litter inputs, and shade moderate microclimate and improve soil biological activity.

Such systems demonstrate lower yield variability and higher recovery capacity following droughts, heat waves, or salinity episodes (Isbell et al., 2015; Altieri et al., 2015).

4.4.4 Integration with Nature-Positive Management Practices

Biological and ecological solutions are most effective when embedded within broader nature-positive management frameworks:

- Organic matter addition supports microbial habitat and energy supply.
- Reduced chemical disturbance preserves beneficial microbial populations.
- Continuous soil cover sustains biological activity across seasons.
- Landscape-level biodiversity enhances ecological connectivity and stability.

Rather than acting as standalone inputs, biological solutions function as process-based regulators that improve system efficiency and resilience.

4.4.5 Significance for Sustainable Abiotic Stress Management

Biological and ecological solutions offer multiple co-benefits:

- Reduced dependence on synthetic fertilizers and stress-mitigation chemicals.
- Improved yield stability rather than only yield maximization.
- Enhanced soil carbon sequestration and climate mitigation.
- Long-term restoration of degraded and stress-prone agroecosystems (Altieri et al., 2015).

From a nature-positive perspective, these solutions shift abiotic stress management from reactive correction to preventive system strengthening, aligning productivity goals with ecological sustainability.

5. MECHANISMS OF STRESS MITIGATION THROUGH NATURE-POSITIVE SOLUTIONS

NPS mitigate abiotic stresses not through isolated interventions, but by activating and strengthening inherent soil–plant–atmosphere processes that govern resilience in agroecosystems. Unlike conventional stress management strategies that rely on external inputs or short-term corrective measures, NPS operate through process-level regulation, enhancing the capacity of agricultural systems to buffer, adapt, and recover from stress (Lal, 2015; Altieri et al., 2015). The mechanisms underlying stress mitigation are therefore integrative, interdependent, and cumulative over time.

Four core mechanisms—soil moisture retention and root-zone buffering, nutrient cycling efficiency under stress, physiological stress tolerance pathways, and microclimate moderation—collectively define how nature-positive systems function under adverse environmental conditions (Rockström et al., 2007; Six et al., 2002).

5.1 Soil Moisture Retention and Root Zone Buffering

Soil moisture availability is the most fundamental determinant of crop performance under abiotic stress, particularly in rainfed and semi-arid regions (Farooq et al., 2009). NPS enhance soil moisture retention primarily by improving soil organic matter content, aggregation, and pore continuity, thereby increasing the soil's capacity to store and gradually release water (Hudson, 1994; Lal, 2004).

Organic amendments, residue retention, cover cropping, and reduced tillage increase the proportion of stable macro- and micro-aggregates, which protect soil pores from collapse and reduce evaporative losses (Six et al., 2002; Bronick & Lal, 2005). As a result, rainfall is more effectively captured, infiltration rates improve, and runoff losses decline (Bhattacharyya et al., 2009).

Beyond water storage alone, NPS improve root-zone buffering, defined as the soil's ability to maintain relatively stable moisture conditions around active roots despite fluctuations in rainfall or atmospheric demand. Improved aggregation and higher organic carbon content increase the proportion of plant-available water, allowing crops to sustain transpiration for longer periods during dry spells (Hudson, 1994; Lal, 2015). This buffering capacity is particularly critical under erratic rainfall regimes, where short dry intervals between rain events can otherwise induce acute moisture stress (Rockström et al., 2007).

Root systems respond dynamically to these improved soil physical conditions. In nature-positive systems, enhanced soil structure and biological activity promote deeper and more proliferative root growth, increasing the effective soil volume explored by plants (Lynch, 2013). Deeper root penetration allows access to subsoil moisture reserves, while greater lateral spread improves water capture from heterogeneous soil profiles. Importantly, these effects are cumulative; as organic matter and biological activity build over time, the resilience of the root zone increases, reducing inter-annual yield variability (Lal, 2015).

Thus, soil moisture retention under NPS is not merely a function of higher water content, but of temporal and spatial redistribution of water within the soil profile, ensuring sustained root access during stress periods.

5.2 Nutrient Cycling Efficiency under Stress Conditions

Abiotic stresses such as drought, heat, salinity, and flooding profoundly disrupt nutrient availability and uptake by altering soil chemical equilibria, microbial activity, and root physiology (Lambers et al., 2008). NPS mitigate these disruptions by improving nutrient cycling efficiency, defined as the capacity of the soil–plant system to mobilize, retain, and utilize nutrients under sub-optimal environmental conditions (Ladha et al., 2016).

A central mechanism is the enhancement of soil biological activity through organic inputs and diversified cropping systems. Soil microorganisms play a pivotal role in nutrient mineralization, immobilization, and transformation processes (Burns et al., 2013). Under stress conditions, biologically active soils maintain higher enzymatic activity, allowing continued nutrient release even when moisture or temperature constraints limit purely chemical processes (Balota et al., 2004).

Nature-positive practices also improve nutrient retention within the root zone. Increased organic matter raises cation exchange capacity and nutrient sorption sites, reducing leaching losses of nitrogen, potassium, calcium, and magnesium during high rainfall or irrigation events (Six et al., 2002; Lal, 2004). Simultaneously, biological immobilization temporarily stores nutrients in microbial biomass, preventing losses during stress periods and releasing them when conditions become favourable (Philippot et al., 2013).

Under salinity and sodicity stress, improved nutrient cycling helps maintain ionic balance by enhancing calcium availability and regulating sodium uptake (Sharma et al., 2015). Under drought stress, enhanced phosphorus solubilization and mycorrhizal associations improve nutrient uptake efficiency per unit of water consumed (Smith & Read, 2008). As a result, crops under NPS exhibit higher nutrient-use efficiency and reduced dependence on external fertilizer inputs (Ladha et al., 2016).

Crucially, nutrient cycling under NPS is adaptive rather than static, responding dynamically to changes in soil moisture and temperature through biologically mediated feedback mechanisms.

5.3 Physiological Stress Tolerance Pathways in Crops

While soil processes form the foundation of stress mitigation, their benefits ultimately manifest through plant physiological responses. NPS enhance crop stress tolerance by indirectly modulating physiological pathways related to water relations, nutrient metabolism, and oxidative stress regulation (Farooq et al., 2009).

Improved soil moisture availability and balanced nutrient supply support sustained stomatal function, enabling plants to optimize transpiration and carbon assimilation under moderate stress. This improves water-use efficiency and delays stress symptoms such as wilting and premature senescence (Hatfield & Prueger, 2015). Biologically active rhizospheres further stimulate the production of plant growth regulators and signalling compounds that enhance root growth and stress responsiveness (Vessey, 2003).

Under heat and drought stress, crops in nature-positive systems often exhibit higher relative water content, improved membrane stability, and reduced accumulation of stress-induced ethylene (Farooq et al., 2009). These responses help maintain photosynthetic efficiency and reproductive development during critical growth stages. Similarly, under salinity stress, improved soil structure and nutrient balance reduce ionic toxicity, supporting physiological mechanisms such as selective ion uptake and osmotic adjustment (Munns & Tester, 2008).

An important feature of nature-positive systems is stress priming, whereby exposure to mild or intermittent stress enhances tolerance to subsequent stress events. This priming effect is mediated through root–microbe interactions, balanced nutrition, and gradual metabolic adjustment (Philippot et al., 2013). Consequently, crops gain not only short-term protection but also season-long resilience.

Thus, physiological stress tolerance under NPS emerges from the integration of soil, biological, and plant regulatory processes, rather than from genetic or chemical interventions alone.

5.4 Microclimate Moderation at the Field Scale

Abiotic stress intensity is strongly influenced by field-level microclimatic conditions, including soil temperature, air temperature, humidity, and wind speed (Hatfield & Prueger, 2015). NPS modify these variables through vegetation cover, residue management, and landscape integration, thereby reducing crop exposure to extreme conditions (Altieri et al., 2015).

Surface residue retention and mulching insulate the soil surface, reducing temperature fluctuations, lowering peak soil temperatures during heat waves, and minimizing evaporative losses (Blanco-Canqui & Lal, 2007). This protects root systems from thermal stress and sustains microbial activity during hot periods. Residue cover also reduces near-surface wind velocity, further limiting moisture loss.

Crop diversification, intercropping, and agroforestry systems create vertical and horizontal heterogeneity in canopy structure, moderating air temperature and improving humidity within the crop canopy (Jose, 2009). Shading reduces heat stress during sensitive growth stages, while improved air circulation prevents stagnation and heat build-up. In perennial systems, continuous litter inputs and deep rooting stabilize microclimate conditions across seasons (Altieri et al., 2015).

At the landscape scale, increased vegetation cover improves evapotranspiration balance, moderates surface albedo, and enhances rainfall infiltration, collectively reducing drought and heat stress intensity at farm and village scales (Rockström et al., 2007).

Microclimate moderation therefore acts as a preventive mechanism, lowering baseline stress exposure rather than responding after damage has occurred.

5.5 Integrated Functioning of Stress Mitigation Mechanisms

Although soil moisture buffering, nutrient cycling efficiency, physiological tolerance, and microclimate moderation can be described separately, their effectiveness lies in their synergistic interaction. Improved soil moisture enhances nutrient uptake; improved nutrition supports physiological resilience; moderated microclimates allow soil and biological processes to function more efficiently (Six et al., 2002; Lal, 2015).

Nature-positive systems thus function as self-reinforcing resilience loops, where incremental improvements in one component amplify benefits across the system. Over time, this integration leads to higher yield stability, reduced input dependency, and improved recovery following extreme climatic events (Isbell et al., 2015).

5.6 Implications for Long-Term Abiotic Stress Management

The mechanistic pathways described above represent a fundamental shift from stress avoidance through inputs to stress buffering through ecosystem processes. NPS do not eliminate abiotic stresses but substantially reduce their impacts by enhancing the adaptive capacity of agroecosystems (Altieri et al., 2015).

From a sustainability perspective, these mechanisms deliver co-benefits including improved soil health, enhanced carbon sequestration, biodiversity conservation, and climate change mitigation (Lal, 2015). Importantly, they provide a strong scientific basis for indicator-based monitoring frameworks, incentive mechanisms, and policy support aimed at scaling nature-positive agriculture.

6. INDICATORS AND METRICS FOR EVALUATING NATURE-POSITIVE ABIOTIC STRESS MANAGEMENT

Effective adoption of NPS for abiotic stress management requires measurable, well-defined indicators that link field practice to soil function, plant performance and system-level outcomes. Indicators must be sensitive to management change, mechanistically meaningful, and scalable from plot to landscape to inform monitoring, incentive schemes and carbon accounting (FAO, 2020; IPCC, 2019). Soil, plant and system indicators form a hierarchic suite: soil indicators capture the medium that determines water and nutrient buffering; plant indicators reveal functional responses and resilience; system indicators evaluate resource use efficiency and socio-economic returns. Using a combination of these indicators reduces ambiguity, increases confidence in attribution of outcomes to NPS, and supports payments for ecosystem services such as carbon credits (Verra, VM0042; FAO, 2020).

6.1 Soil indicators: SOC, aggregate stability, available water and enzyme activity

Soil organic carbon is the foundational indicator for NPS because it is mechanistically linked to multiple soil functions—nutrient supply, aggregate formation, water retention and microbial habitat—and is measurable with established protocols for stocks and changes (Six et al., 2000; FAO, 2020). In addition to total SOC, considerations of depth distribution and aggregate-protected carbon fractions strengthen inference about resilience to disturbance and permanence (Six et al., 2000; Rocci et al., 2024). For monitoring tied to carbon incentives, SOC metrics must follow standardised guidance (IPCC, 2019; FAO, 2020) and the methodological requirements of registries (e.g., Verra VM0042), including minimum sampling depths, baseline definition and uncertainty quantification (Verra, 2021; IPCC, 2019).

Aggregate stability is a second critical soil indicator because stable aggregates improve infiltration, reduce erodibility, protect microbially associated carbon, and facilitate root penetration under drying conditions (Bronick & Lal, 2005; Six et al., 2000). Aggregate-associated carbon fractions provide mechanistic explanation for observed SOC changes and are especially informative when practices—such as residue retention, reduced tillage and organic amendments—are intended to enhance soil structure (Six et al., 2000; Bronick & Lal, 2005).

Plant-available water holding capacity (PAW or AWC) is the next essential indicator for abiotic-stress buffering. Increasing SOC and improving soil structure typically raise available water per unit soil volume, which in turn moderates crop water stress and improves yield stability under variable rainfall (Pereira et al., 2012; Ali et al., 2008). Measuring PAW (or estimating it using pedotransfer functions linked to texture, bulk density and organic matter) is therefore a direct link between soil management and plant drought resilience. In practice, PAW should be reported alongside SOC and bulk density to separate the physical from the biochemical components of water buffering (FAO, 2020).

Soil enzyme activities (e.g., β-glucosidase, phosphatase, urease, dehydrogenase) provide sensitive, process-level indicators of microbial functional capacity and nutrient cycling potential and often respond rapidly to management changes (Adetunji et al., 2017; Daunoras et al., 2024). Enzyme assays measure potential activities and therefore need careful interpretation with environmental covariates, but they are highly useful as early-warning signals of soil biological recovery following NPS interventions (Wang et al., 2023; Genova et al., 2024). Combining enzyme activity indices with microbial biomass and SOC offers a robust biological sub-index for soil health monitoring.

6.2 Plant indicators: root traits, yield stability and stress indices

Plant indicators must translate soil improvements into crop performance and resilience. Root system traits—root length density, rooting depth, root angle, and specific root length—are mechanistically central to drought and nutrient stress tolerance because roots determine soil exploration and resource capture (Bengough, 2011; Lynch, 2018). Phenotyping root traits in situ or using proxy metrics (e.g., canopy response under controlled drought, stable isotope signatures) allows linking NPS practices that improve soil structure and moisture to increases in effective rooting volume and water uptake (Wasaya et al., 2018; Bengough, 2011).

Yield stability is a practical, end-user oriented plant indicator. Rather than single-season yields, interannual metrics such as the coefficient of variation (CV) or resilience indices reveal whether NPS reduce the amplitude of yield losses under episodic stress (Anwaar et al., 2019). Stability metrics should be reported together with baseline yield levels because improved stability with low absolute yields has different implications than stability with high yields. Complementary indices—such as relative yield (yield under stress divided by yield under non-stress) and the Stress Susceptibility Index (SSI) proposed by Fischer and Maurer

(1978)—provide standardized ways to compare genotypes or management packages across environments (Fischer & Maurer, 1978; Anwaar et al., 2019).

Physiological stress indicators (leaf water potential, stomatal conductance, canopy temperature, chlorophyll fluorescence) are useful short-term metrics to detect improved stress buffering from NPS before harvest. When combined with yield and root measurements, they strengthen causal attribution: for example, a practice that raises PAW and SOC should also reduce canopy stress signals during dry spells and thereby maintain photosynthesis and yield (Pereira et al., 2012).

6.3 System indicators: water productivity, input-use efficiency and economic resilience

System indicators assess the efficiency and sustainability of resource use across the farm or landscape. Water productivity—often expressed as crop yield or biomass per unit water consumed ("crop per drop")—is central to evaluating NPS that aim to increase moisture capture, infiltration and crop water use efficiency (FAO, 2017; Pereira et al., 2012). Water productivity can be calculated at multiple scales (field, farm, irrigation system), and its interpretation must be explicit about whether the denominator is blue water, green water, or total evapotranspiration (Giordano et al., 2021). Improvements in soil PAW and rooting often translate into higher water productivity because crops convert limited water more effectively to biomass (Ali et al., 2008).

Input-use efficiency indicators (e.g., agronomic N use efficiency, partial factor productivity of fertilizer, energy-use per unit output) capture how NPS alter the ratio of inputs to outputs and therefore their climate and economic footprint. For example, integrated NPS that enhance nutrient cycling (cover crops, organic amendments, microbial inoculants) can increase agronomic efficiency of applied fertilizers and reduce GHG emissions per unit product—metrics that are material for both policy and carbon accounting (Verra, 2021; FAO, 2020).

Economic resilience and livelihood indicators (variable cost per unit yield, income stability across years, diversification index) are also necessary to assess whether NPS are adoptable at scale by smallholders. Combining biophysical and socio-economic indicators enables a full appraisal of trade-offs (e.g., short-term labour for residue retention versus long-term soil improvement).

6.4 Relevance for monitoring, incentives and carbon credits

Indicator selection must be fit-for-purpose: monitoring for local extension and adaptive management requires different frequency, cost and precision from monitoring intended to support carbon credits or national greenhouse gas inventories. For carbon crediting, SOC must be measured and reported against rigorous baselines and uncertainty thresholds (IPCC, 2019; FAO, 2020), and methodologies such as Verra's VM0042 provide operational rules—including eligibility of practices, permanence requirements, leakage checks and depth conventions (Verra, 2021). Soil enzyme or root trait measurements, while highly informative for research and demonstration, are rarely acceptable as stand-alone evidence for tradable carbon units; instead, they function well as complementary indicators that increase confidence in the biophysical plausibility of SOC changes (Wang et al., 2023; Genova et al., 2024).

For incentive programs and extension, pragmatic indicator bundles work best: SOC (baseline and periodic reassessment), simple aggregate stability tests, PAW estimates, one or two enzyme assays as biological signals, and crop performance metrics (yield and CV, SSI) provide a balanced portfolio of evidence. System indicators such as water productivity and input-use efficiency should be included to demonstrate co-benefits for water and nutrient conservation, which are often required by integrated public incentive schemes (FAO, 2020; Pereira et al., 2012).

6.5 Practical recommendations for implementation and reporting

Operationalising the indicator suite requires standardised sampling protocols (depth, timing, replication), transparent metadata, and explicit uncertainty estimates. For SOC and carbon accounting, follow IPCC (2019) and FAO GSOC-MRV guidance for depth, bulk density correction and Tier selection (FAO, 2020; IPCC, 2019). For rapid monitoring and extension use, pair laboratory SOC with simple field measurements (slake test for aggregate stability, simple PAW estimation using texture-based charts) and targeted enzyme assays to detect biological response (Adetunji et al., 2017; Meena et al., 2021). Plant measurements—root cores, shovelomics or proxy canopy/physiological metrics—should be collected at critical growth stages. Finally, present indicators as coherent dashboards that show short-term biological responses, medium-term soil structural and carbon changes, and long-term yield and system performance, thereby providing a credible evidence base for scaling NPS both agronomically and through payment or credit mechanisms (Verra, 2021; FAO, 2020).

7. SYNERGY WITH NATIONAL MISSIONS AND POLICIES

NPS for abiotic stress management align strongly with India’s evolving agricultural policy architecture, which increasingly emphasizes sustainability, resilience, and resource-use efficiency. National missions and programmes provide an enabling institutional framework through which NPS can be mainstreamed, scaled, and operationalized at farm, watershed, and landscape levels. This section examines how major national initiatives synergize with NPS-based abiotic stress management and how these linkages can be strategically leveraged to enhance climate resilience in Indian agriculture.

7.1 Integration of Nature-Positive Solutions with the National Mission for Sustainable Agriculture (NMSA)

The National Mission for Sustainable Agriculture (NMSA), a key component of India’s National Action Plan on Climate Change, explicitly recognizes climate variability and abiotic stresses as major threats to agricultural productivity. Its core objectives—enhancing adaptive capacity, improving soil and water conservation, and promoting climate-resilient technologies, are fundamentally congruent with the principles of Nature-Positive Solutions.

NPS-based interventions such as organic matter enhancement, residue retention, diversified cropping systems, and soil biological management directly contribute to the adaptive goals of NMSA by strengthening soil structure, improving moisture retention, and stabilizing nutrient cycling under stress conditions. These interventions address drought, heat stress, and nutrient imbalance not through external inputs, but by restoring ecosystem functions within the soil–plant–water continuum.

Furthermore, NMSA’s emphasis on integrated farming systems and location-specific resource management provides a practical platform for embedding NPS approaches. By prioritizing soil carbon sequestration, water-use efficiency, and biodiversity enhancement, NPS transforms NMSA from a climate-adaptation programme into a regenerative framework that simultaneously supports mitigation, resilience, and long-term productivity. Thus, NPS operationalizes the mission’s vision by translating policy intent into field-level ecological processes.

7.2 Synergizing Nature-Positive Solutions with the Pradhan Mantri Krishi Sinchayee Yojana (PMKSY)

Water stress remains the most pervasive abiotic constraint in Indian agriculture, particularly in rainfed and semi-arid regions. PMKSY focuses on improving irrigation coverage, enhancing water-use efficiency, and promoting micro-irrigation technologies. While infrastructure and irrigation efficiency are central to PMKSY, NPS complement these efforts by improving the soil's inherent capacity to store, transmit, and regulate water.

Practices such as mulching, cover cropping, organic amendments, and improved aggregation significantly increase soil infiltration rates and plant-available water, thereby enhancing the effectiveness of every unit of irrigation or rainfall. In this context, NPS reduces dependency on frequent irrigation and buffers crops against intermittent dry spells, even under limited water availability.

Importantly, NPS shifts the emphasis from "more water application" to "better water retention and use," aligning seamlessly with PMKSY's goal of "per drop, more crop." When soil health-centered NPS practices are integrated with micro-irrigation systems, the combined effect results in higher water productivity, reduced evaporation losses, and improved crop resilience to moisture stress. This synergy highlights the necessity of integrating soil-based ecological solutions into water-centric policy frameworks.

7.3 Nature-Positive Solutions within Natural Farming and Organic Farming Initiatives

India's Natural Farming and Organic Farming initiatives represent a paradigm shift away from input-intensive agriculture toward ecological self-regulation. These initiatives emphasize minimal external inputs, on-farm resource recycling, and enhancement of soil biological processes—all of which are foundational to Nature-Positive Solutions.

Under abiotic stress conditions, particularly nutrient stress, drought, and salinity, NPS-based natural farming practices such as microbial inoculants, fermented organic formulations, and residue-based mulching enhance root–soil interactions and nutrient availability. By strengthening rhizosphere processes, these practices enable crops to tolerate stress through improved nutrient uptake efficiency and physiological resilience.

Organic and natural farming systems also promote crop diversification and mixed cropping, which reduce risk exposure under climatic uncertainty. From a policy perspective, NPS provides a scientific and mechanistic underpinning to these initiatives by explaining how soil carbon dynamics, microbial turnover, and water buffering translate into stress resilience.

This strengthens the credibility of natural farming approaches and supports evidence-based scaling through mission-mode programmes.

7.4 Alignment of Nature-Positive Solutions with the National Agroforestry Policy

Agroforestry systems are widely recognized as one of the most effective NPS for managing multiple abiotic stresses simultaneously. The National Agroforestry Policy aims to integrate trees into agricultural landscapes to enhance productivity, environmental sustainability, and farmer livelihoods.

Tree-based systems improve microclimatic moderation, reduce heat stress, enhance SOC stocks, and improve deep soil moisture access through extensive root systems. These ecological benefits directly mitigate drought, temperature extremes, and soil degradation—key abiotic stresses threatening Indian agriculture.

NPS provides the conceptual framework to understand agroforestry not merely as a land-use option, but as an ecosystem-based stress management strategy. By improving soil structure, reducing evapotranspiration, and enhancing nutrient recycling, agroforestry systems function as long-term buffers against climate variability. When aligned with the National Agroforestry Policy, NPS strengthens the case for incentivizing tree-based systems as a core climate-resilience intervention rather than a peripheral land-use practice.

7.5 Nature-Positive Solutions and Climate-Resilient Agriculture Programmes

Climate-resilient agriculture programmes implemented through ICAR, State Agricultural Universities, and Krishi Vigyan Kendras focus on enhancing adaptive capacity at the regional and farm levels. These programmes increasingly recognize that resilience cannot be achieved solely through stress-tolerant varieties or contingency planning, but requires systemic improvements in soil and ecosystem functioning.

NPS offer a unifying framework that integrates soil health restoration, biodiversity enhancement, and water regulation into climate-resilient strategies. By emphasizing yield stability, rather than yield maximization, NPS aligns with resilience metrics such as reduced inter-annual variability, improved resource-use efficiency, and sustained productivity under stress.

Moreover, NPS enables climate-resilient programmes to adopt measurable indicators—such as SOC, aggregate stability, and water productivity—that can be monitored over time. This supports outcome-based evaluation and strengthens the linkage between field interventions and policy goals related to adaptation, mitigation, and sustainability.

7.6 Policy Convergence and Strategic Implications

The convergence of NPS with national missions creates an opportunity to move from fragmented scheme-based interventions toward integrated landscape-level resilience planning. NPS serves as a common ecological language linking soil health, water management, cropping systems, and climate adaptation across policy domains.

By embedding NPS indicators into mission guidelines, incentive structures, and monitoring frameworks, policymakers can ensure that abiotic stress management delivers long-term ecological and economic benefits. This convergence also facilitates alignment with emerging mechanisms such as ecosystem service payments and carbon credit markets, thereby enhancing farmer incentives to adopt NPS-based practices.

7.7 Embedding Nature-Positive Indicators into Incentive and Outcome-Based Policy Instruments

NPS become scalable and durable only when their benefits are translated into measurable outcomes that can be linked to incentives and policy support. Indicator-based evaluation provides the bridge between field-level practices and outcome-oriented schemes. Core soil indicators such as SOC, aggregate stability, and plant-available water can serve as proxy metrics for climate resilience, drought buffering, and carbon sequestration, while supporting indicators such as soil enzyme activity, root depth, and yield stability (coefficient of variation) capture functional improvements in nutrient cycling and system performance. These indicators are scientifically robust, relatively stable over time, and amenable to periodic monitoring, making them suitable for integration into performance-linked incentive frameworks.

At the policy level, such indicators can be embedded into existing schemes through a shift from input-based subsidies to outcome-based rewards. For example, incremental increases in SOC or demonstrable improvements in soil moisture retention can be used as eligibility criteria or performance benchmarks under programmes promoting climate-resilient agriculture, natural farming, or watershed development. Similarly, verified improvements in SOC stocks and biomass carbon under agroforestry and perennial systems can be aligned with soil and land-based carbon credit mechanisms, enabling farmers to access emerging voluntary carbon markets. When combined with geotagged sampling, standardized protocols, and digital soil health platforms, NPS indicators offer a transparent and credible basis for payments for ecosystem services (PES), resilience incentives, and climate finance, thereby directly rewarding farmers for delivering public environmental goods.

7.8 From Pilots to Policy: Scaling Nature-Positive Solutions

While pilot-scale projects and localized success stories have clearly demonstrated the agronomic and ecological benefits of Nature-Positive Solutions, their broader impact depends on mainstreaming NPS into policy, planning, and institutional frameworks. Moving from pilots to policy requires harmonizing scientific indicators with administrative simplicity, ensuring that monitoring requirements remain farmer-friendly while retaining scientific credibility. Standardized indicator sets, tiered monitoring approaches, and convergence across national missions can enable scalable adoption without overburdening implementing agencies or farmers. By embedding NPS indicators into incentive structures, carbon finance, and outcome-based schemes, policy can shift from compensating inputs to rewarding resilience, ecosystem services, and long-term sustainability. Such a transition positions Nature-Positive Solutions not as niche or alternative practices, but as core strategies for climate-resilient agricultural development in India.

8. CONSTRAINTS AND CHALLENGES IN SCALING NATURE-POSITIVE SOLUTIONS

Despite strong scientific evidence and policy relevance, the large-scale adoption of NPS for abiotic stress management in Indian agriculture remains limited. The constraints are not solely technological; rather, they arise from interconnected challenges related to knowledge dissemination, farmer perceptions, monitoring complexities, and institutional arrangements. Understanding these barriers is essential for designing effective strategies to mainstream NPS from pilot initiatives to widespread practice.

8.1 Knowledge and Capacity Gaps

One of the most significant challenges in scaling NPS is the persistent knowledge gap across multiple stakeholder groups, including farmers, extension personnel, and local implementing agencies. NPS practices are inherently process-based, relying on improvements in soil biological activity, organic matter dynamics, and ecosystem interactions. These processes are often invisible, slow-acting, and difficult to communicate compared to input-driven technologies that deliver immediate and observable outcomes.

At the farmer level, limited awareness of soil ecological functions constrains adoption. Practices such as residue retention, cover cropping, or microbial enhancement are frequently perceived as optional or secondary, rather than as core strategies for abiotic stress mitigation. In many regions, advisory services continue to emphasize crop nutrition and pest management while giving insufficient attention to soil structure, water buffering capacity, and biological resilience.

Capacity gaps are also evident within extension systems. Many frontline extension workers are trained in conventional agronomy and input recommendations, with limited exposure to systems-based or regenerative approaches. As a result, NPS interventions are often communicated in fragmented or prescriptive ways, without explaining the underlying mechanisms that justify their adoption under drought, heat, or salinity stress. This weakens farmer confidence and limits sustained uptake.

8.2 Short-Term Yield Perceptions and Risk Aversion

A major behavioural constraint to scaling NPS is the dominance of short-term yield as the primary decision-making criterion for farmers. NPS typically deliver their full benefits over medium to long time horizons through gradual improvements in SOC, aggregation, and water-holding capacity. In contrast, many farmers operate under economic pressures that necessitate immediate returns, making them hesitant to adopt practices perceived as slow or uncertain.

In the initial years of transition, some NPS practices may result in yield neutrality or modest yield fluctuations, particularly when chemical input use is reduced without adequate system redesign. These early responses, although temporary, reinforce the perception that NPS compromises productivity. Such perceptions are especially strong in rainfed and marginal areas, where farmers face high climatic risk and limited financial buffers.

Moreover, abiotic stress management through NPS focuses on yield stability and resilience rather than yield maximization. While reduced inter-annual variability and improved crop survival under stress are significant benefits, they are less tangible than absolute yield gains. The absence of explicit resilience-based performance metrics in extension advisories further limits farmer appreciation of NPS advantages. Consequently, risk aversion and short-term performance expectations continue to act as major barriers to adoption.

8.3 Monitoring and Quantification Challenges

Scaling NPS also faces substantial challenges related to monitoring, measurement, and verification of outcomes. Unlike conventional technologies, where input–output relationships are relatively direct, NPS outcomes are mediated through complex ecological processes operating across soil depths and time scales. Quantifying improvements in soil moisture buffering, biological activity, or nutrient cycling efficiency requires specialized indicators, consistent sampling protocols, and long-term datasets.

At present, routine monitoring systems largely focus on crop yield and input use, with limited inclusion of soil biological or functional indicators such as aggregate stability, enzyme activity, or plant-available water. This creates a disconnect between NPS implementation and formal evaluation frameworks, making it difficult to demonstrate impact in a manner acceptable to policymakers and funding agencies.

The lack of standardized, field-friendly indicators further complicates scaling efforts. While advanced laboratory methods exist, they are often impractical for large-scale monitoring. Without simple, robust, and cost-effective indicators, NPS remains difficult to integrate into performance-based incentive schemes, carbon credit mechanisms, or ecosystem service payments. As a result, the benefits of NPS are under-recognized in formal accounting systems, limiting institutional support for scaling.

8.4 Policy and Institutional Bottlenecks

Although national missions and programmes increasingly emphasize sustainability and resilience, institutional frameworks remain largely structured around input delivery and short-term output targets. This creates a policy environment where NPS are acknowledged conceptually but inadequately supported operationally.

One key bottleneck is the fragmentation of responsibilities across soil, water, crop, and forestry sectors. NPS requires integrated, landscape-level planning, yet implementation often occurs through isolated schemes with limited coordination. This reduces synergy among soil health, water management, and cropping system interventions, diluting the cumulative benefits of NPS.

In addition, incentive structures are not fully aligned with regenerative outcomes. Subsidies and support mechanisms continue to prioritize fertilizers, irrigation infrastructure, and varietal replacement, while investments in soil carbon building, residue management, and biodiversity enhancement receive comparatively limited financial backing. The absence of outcome-based incentives tied to resilience indicators further constrains adoption.

Institutional time horizons also pose challenges. Many programmes operate within short project cycles, whereas NPS benefits accrue gradually. This mismatch discourages long-term investment in practices whose full impacts extend beyond typical planning periods. Furthermore, limited convergence among research institutions, extension agencies, and policy bodies restricts the feedback loops necessary for adaptive scaling of NPS.

8.5 Synthesis of Constraints

The constraints to scaling NPS are interconnected rather than isolated. Knowledge gaps reinforce short-term yield perceptions; monitoring limitations weaken policy justification; and institutional fragmentation constrains coordinated action. Addressing any single constraint in isolation is unlikely to yield sustained impact. Instead, a systems approach is required, integrating capacity building, behavioural change, indicator development, and policy reform.

8.6 Way Forward: Enabling Conditions for Scaling

Overcoming these challenges requires targeted investments in knowledge systems, including training of extension personnel in soil and ecosystem processes, development of farmer-friendly resilience indicators, and demonstration of long-term benefits through field-based evidence. Equally important is the need to realign policy incentives toward outcome-based metrics that reward yield stability, soil health improvement, and water productivity rather than short-term input responses.

By addressing knowledge, perception, monitoring, and institutional barriers in a coordinated manner, NPS can move from niche adoption to mainstream practice. This transition is critical for managing abiotic stresses sustainably and ensuring long-term resilience of Indian agriculture under increasing climatic uncertainty.

9. SUMMARY AND CONCLUSIONS

Abiotic stresses such as drought, heat, salinity, waterlogging, and nutrient imbalance are increasingly constraining agricultural productivity and stability across India. These stresses are intensifying due to climate variability, land degradation, declining soil health, and growing pressure on natural resources. Conventional, input-intensive approaches to stress management, while offering short-term relief, have shown limited capacity to sustain productivity or enhance resilience under recurring climatic extremes. In this context, NPS provide a scientifically grounded and ecologically sustainable pathway for managing abiotic stresses while simultaneously restoring ecosystem functions.

This technical bulletin has synthesized current knowledge, field evidence, and policy perspectives on NPS-based abiotic stress management, with particular emphasis on soil-centered interventions, water regulation, crop and system diversification, and biological processes. A central message emerging from the bulletin is that abiotic stress resilience is fundamentally a function of ecosystem health. Healthy soils with improved organic carbon content, stable aggregates, active biological communities, and enhanced water-holding capacity form the foundation for crop tolerance to moisture, thermal, and nutrient stresses. NPS approaches strengthen these foundational processes rather than addressing stress symptoms alone.

The bulletin highlights that soil-based Nature-Positive Solutions—such as organic matter enrichment, residue retention, cover cropping, and reduced soil disturbance—play a pivotal role in buffering crops against drought and heat stress by improving soil moisture retention and nutrient availability. Similarly, water-focused NPS interventions enhance the efficiency of rainfall and irrigation by improving infiltration, reducing runoff, and minimizing evaporative losses. Crop diversification, intercropping, agroforestry, and integration of perennials further stabilize production systems by moderating microclimates, expanding rooting zones, and spreading risk across species and seasons. Together, these interventions shift stress management from reactive, input-dependent strategies to proactive, ecosystem-driven resilience building.

A key contribution of this bulletin is its emphasis on mechanisms rather than practices alone. NPS mitigate abiotic stress through well-defined pathways, including improved soil–water relations, enhanced nutrient cycling efficiency, strengthened root–soil interactions, and moderated microclimatic extremes. By elucidating these mechanisms, the bulletin provides a scientific rationale for NPS adoption and supports evidence-based decision-making at both farm and policy levels. This mechanistic understanding is essential for moving beyond generic recommendations toward location-specific, stress-targeted interventions.

The bulletin also underscores the strong alignment between NPS and national agricultural missions and policies. Programmes focused on sustainable agriculture, water-use efficiency, natural and organic farming, agroforestry, and climate-resilient agriculture provide institutional platforms for mainstreaming NPS at scale. When integrated effectively, NPS can operationalize policy objectives related to climate adaptation, resource conservation, and long-term productivity. However, the bulletin clearly identifies that such integration requires deliberate convergence across schemes, harmonized indicators, and outcome-oriented implementation frameworks.

Despite their potential, the scaling of NPS faces significant constraints. Knowledge and capacity gaps among farmers and extension personnel, strong emphasis on short-term yield outcomes, challenges in monitoring and quantifying ecosystem benefits, and institutional fragmentation collectively limit widespread adoption. These constraints are systemic and interlinked, highlighting the need for coordinated strategies rather than isolated interventions. The bulletin emphasizes that without appropriate indicators, incentives, and long-term commitment, the transformative potential of NPS will remain underutilized.

From a monitoring and evaluation perspective, the bulletin highlights the importance of shifting from yield-centric assessments to resilience-oriented metrics. Indicators such as SOC, aggregate stability, PAW, yield stability, and water productivity are better suited to capture the benefits of NPS under abiotic stress conditions. Incorporating such indicators into routine monitoring frameworks can strengthen accountability, support adaptive management, and enable linkage with emerging incentive mechanisms, including ecosystem service payments and carbon markets.

In conclusion, NPS represent a strategic and sustainable approach to abiotic stress management in Indian agriculture. By restoring and harnessing natural processes, NPS enhances the capacity of agricultural systems to withstand climatic shocks while delivering co-benefits for soil health, water security, biodiversity, and climate mitigation. The transition toward NPS-based stress management requires a paradigm shift—from input substitution to ecosystem regeneration, from short-term productivity to long-term resilience, and from fragmented interventions to integrated landscape approaches.

For researchers, the bulletin emphasizes the need for long-term, process-oriented studies that quantify resilience outcomes across agro-ecological regions. For extension systems, it calls for capacity building focused on soil and ecosystem literacy and for communication strategies that make invisible processes visible to farmers. For policymakers, it highlights the urgency of aligning incentives, indicators, and institutional structures with regenerative outcomes. Collectively, these actions can enable NPS to move from pilot initiatives to mainstream agricultural practice.

Ultimately, strengthening abiotic stress resilience through NPS is not only a technical necessity but also a strategic investment in the sustainability of Indian agriculture. As climatic uncertainty intensifies, the adoption of NPS offers a pathway to safeguard food security, enhance farmer livelihoods, and restore the ecological foundations upon which agriculture depends.

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Annexure –I

Table 1. Nature-Positive Solutions for Drought and Moisture Stress Management

Nature-positive practice	Stress predominantly addressed	Mechanism of stress alleviation	Crop-level outcomes
Mulching (crop residues, organic mulch)	Drought, heat	Reduces evaporation; moderates soil temperature; enhances infiltration	Improved soil moisture availability; stable yields
Cover crops / intercrops	Drought, nutrient stress	Improves soil aggregation; increases organic carbon; enhances rooting depth	Greater drought tolerance; yield stability
Conservation tillage	Drought	Preserves soil structure; increases water retention and infiltration	Reduced moisture stress during dry spells
Agroforestry systems	Drought, heat	Deep root water lifting; microclimate moderation	Improved crop resilience and long-term productivity

Table 2. Nature-Positive Solutions for Drought and Moisture Stress Management

Nature-positive practice	Stress predominantly addressed	Mechanism of stress alleviation	Crop-level outcomes
Agroforestry / tree-based systems	Heat	Canopy shading; reduced radiation load; evapotranspirative cooling	Reduced heat injury; improved flowering and grain set
Soil organic matter enhancement	Heat	Higher soil heat buffering capacity; improved moisture retention	Reduced thermal stress on roots
Diverse cropping systems	Heat	Spreads risk; improves canopy architecture	Greater system-level resilience
Residue retention	Heat	Insulates soil surface; reduces temperature extremes	Sustained root activity and nutrient uptake

Table 3. Nature-Positive Solutions for Salinity and Sodicity Stress Management

Nature-positive practice	Stress predominantly addressed	Mechanism of stress alleviation	Crop-level outcomes
Organic amendments (FYM, compost, biochar)	Salinity, sodicity	Improves soil structure; enhances Ca^{2+} availability; reduces Na^{+} activity	Improved root growth and nutrient uptake

Salt-tolerant intercrops / halophytes	Salinity	Phyto-remediation; salt sequestration	Gradual soil quality restoration
Green manuring	Salinity	Improves microbial activity; increases soil porosity	Enhanced crop establishment
Integrated nutrient management (INM)	Salinity, nutrient imbalance	Balanced nutrient supply reduces salt injury	Higher nutrient use efficiency

Table 4. Nature-Positive Solutions for Flooding and Water logging Stress Management

Nature-positive practice	**Stress predominantly addressed**	**Mechanism of stress alleviation**	**Crop-level outcomes**
Raised bed and ridge–furrow systems	Waterlogging	Improves surface drainage; aerated root zone	Reduced root hypoxia
Soil organic carbon enhancement	Waterlogging	Improves soil aggregation and macroporosity	Faster drainage and recovery
Crop diversification (deep-rooted crops)	Waterlogging	Enhances vertical water movement	Reduced crop failure risk
Agroforestry in flood-prone areas	Flooding	Stabilizes soil; moderates runoff	Improved system resilience

Table 5. Nature-Positive Solutions for Management of Nutrient Imbalance and Soil Degradation

Nature-positive practice	**Stress predominantly addressed**	**Mechanism of stress alleviation**	**Crop-level outcomes**
Legume-based intercropping	Nutrient stress	Biological N fixation; residue C:N balancing	Improved soil fertility
Residue recycling	Nutrient stress	Nutrient return; microbial stimulation	Enhanced nutrient availability
Reduced chemical input dependency	Soil degradation	Restores biological processes	Improved soil health indicators
Microbial inoculants (biofertilizers)	Nutrient stress	Enhances nutrient solubilization and uptake	Higher nutrient use efficiency