Climate-Resilient Cropping Systems for Managing Extreme Weather Events

Neelam Bisen Pawar[1] and Shweta Masram[2]

[1]State Technical Coordinator Green Ag (GEF 6), Directorate of Farmers Welfare and Agriculture Development, Bhopal Madhya Pradesh.

[2]Senior Technical Assistant (Agronomy), Krishi Vigyan Kendra, Dindori, Madhya Pradesh.

Abstract

Global agriculture is confronting unprecedented disruptions from the intensifying frequency and severity of extreme weather events, including droughts, heatwaves, floods, and unseasonal frosts. Resilient cropping systems comprising diversified crop varieties, agroforestry, intercropping, conservation tillage, and climate-smart agronomic practices have emerged as evidence-based responses to sustain food production under such volatile conditions. This article reviews the scientific basis of resilient cropping strategies, the physiological and ecological mechanisms underpinning plant stress tolerance, and the technological advances enabling the deployment of climate-resilient cultivars. Drawing on peer-reviewed literature, the article argues that no single intervention is sufficient; instead, a bundled adoption of complementary practices offers the most robust pathway to food security in an era of climatic uncertainty.

Introduction

The global climate is undergoing structural change at a pace that outstrips the adaptive capacity of conventional agricultural systems. The Intergovernmental Panel on Climate Change (IPCC) has documented a global surface temperature increase of approximately 1.07 °C between the periods 1850–1900 and 2010–2019, with cascading effects on precipitation variability, phenological timing, and the frequency of extreme events such as heatwaves, flash floods, and persistent droughts (Kopeć, 2024). Agriculture, which directly depends on climate stability, bears the brunt of these shifts. It is estimated that extreme weather events now account for significant yield losses across major staple crops globally, threatening the food security of billions particularly in rain-fed farming regions of South Asia, Sub-Saharan Africa, and Latin America.

The concept of a resilient cropping system refers to the capacity of an agricultural production unit to absorb disturbance from weather extremes, reorganize under stress, and maintain essential functions while continuing to produce food (Zampieri et al., 2020). Resilience is not a static property of a single crop variety; it is an emergent quality of the entire agro-ecosystem encompassing genetic diversity, soil health, water management, landscape structure, and farmer decision-making. Scientists and policymakers increasingly advocate for transitioning from high-input monocultures, which are inherently fragile, toward diversified, climate-adaptive systems. This article synthesizes the current scientific understanding of resilient cropping systems, examines the physiological mechanisms that underlie stress tolerance, and evaluates the suite of strategies that farmers and institutions can deploy against extreme weather.

The Threat Landscape: Extreme Weather and Crop Systems

Extreme weather events interact with crop systems through multiple pathways — thermal stress on reproductive processes, soil moisture depletion, waterlogging of root zones, and physical crop damage. A global analysis published found that the simultaneous occurrence of hot and dry weather extremes during the growing season significantly increases the probability of concurrent yield failures across major production regions, a phenomenon described as a "compound weather risk" that poses disproportionate threats to global food systems (Heino et al., 2023). Heat stress during anthesis, for instance, causes irreversible damage to pollen viability in wheat and rice, reducing grain set even when vegetative tissues appear unaffected. Similarly, waterlogging during the seedling stage triggers anaerobic respiration, root hypoxia, and premature senescence, with documented losses of 20–50% in susceptible cultivars (Liu et al., 2023).

Droughts present a particularly complex challenge because they interact synergistically with high temperatures to create compound stress conditions that exceed the sum of individual stressor effects. Kopeć (2024) describes how simultaneous drought and heat stress triggers "differential transpiration" in plants stomata in leaves close to conserve moisture while floral stomata remain open to prevent reproductive overheating a sophisticated but energetically costly acclimation strategy that still leaves yields vulnerable when stress duration is prolonged. The recognition that plants in field conditions face multifactorial stresses simultaneously, rather than single stressors in isolation as studied in controlled experiments, has fundamentally reoriented plant stress physiology research.

Resilient Cropping Strategies: A Scientific Overview

Crop Diversification and Intercropping

Monoculture systems, which currently dominate global production with rice, wheat, and maize collectively supplying approximately 60% of human caloric intake concentrate biological and economic risk. Diversified cropping systems, including intercropping and mixed-species cultivation, buffer farms against total failure by distributing risk across multiple crops with different stress response profiles (Kopeć, 2024). Research reviewing agroforestry practices in the context of climate resilience found that tree–crop integrations contribute to microclimatic regulation, reducing canopy temperatures and buffering crops against heat extremes, while simultaneously improving soil moisture retention through enhanced organic matter accumulation (Systematic Review in *Climate Research*, 2025).

Conservation Tillage and Soil Health Management

Healthy soils act as a primary buffer against both drought and flood extremes. Conservation tillage including no-till and reduced-till approaches preserves soil structure, improves water infiltration during rainfall events, and enhances moisture retention during dry spells. A panel data study from Ethiopia examining plot-level data across multiple crop cycles found that the adoption of climate-smart agricultural (CSA) practices, including conservation tillage, improved crop varieties, and crop rotation, showed a significant positive association with crop yields; critically, the study found that "the biggest yield gains are observed when these practices are jointly adopted as a bundle," with climate-resilient variety adoption standing out as the primary driver (SRUC, 2025).

Climate-Resilient Crop Varieties

Plant breeding has produced remarkable stress-tolerant cultivars adapted to specific climate threats. Drought-tolerant maize varieties, submergence-tolerant rice (notably the Sub1A QTL-carrying Swarna Sub1), and heat-tolerant wheat germplasm have demonstrated yield advantages of 10–30% over conventional local varieties under stressful conditions. The strengthening crop resilience to heat, drought, salinity, cold stress, and pathogen pressure requires integrated approaches combining conventional breeding, genomic selection, and targeted gene editing (Mittler et al., 2025). Pearl millet (*Pennisetum glaucum*), sorghum (*Sorghum bicolor*), quinoa (*Chenopodium quinoa*), and amaranth (*Amaranthus* spp.) represent underutilized but genetically robust crops that show particular promise for marginal and drought-prone environments (Kopeć, 2024).

Agroforestry Integration

Integrating trees into cropping landscapes provides multi-dimensional climate buffering. Agroforestry systems offer shade that alleviates heat stress on ground crops, root architecture that reduces soil erosion during flood events, windbreaks that mitigate physical storm damage, and diversified income streams that reduce farmer vulnerability when individual crops fail. Prajapati et al. (2024) demonstrated that agroforestry systems improve soil fertility, enhance water retention, and support biodiversity, all of which cumulatively strengthen the adaptive capacity of farm systems under climate variability.

Water-Smart Farming Practices

Water scarcity and water excess are twin faces of extreme weather. Drip irrigation, rainwater harvesting, contour bunding, and subsurface drainage engineering each address different aspects of water stress. Precision soil moisture monitoring, combined with weather-indexed advisory systems, enables farmers to optimize irrigation scheduling in ways that reduce both water waste and stress-related yield loss. These technologies are increasingly being integrated with digital agriculture platforms, allowing smallholder farmers to receive localized advisories based on satellite-derived weather data and crop models.

Mechanisms of Stress Tolerance

Understanding the physiological basis of stress tolerance is essential for designing resilient systems. At the cellular level, plants respond to extreme heat by upregulating heat shock proteins (HSPs), which prevent protein denaturation and maintain cellular homeostasis. Under drought, abscisic acid (ABA) signalling triggers stomatal closure, reduces transpirational water loss, and activates osmotic adjustment through accumulation of compatible solutes such as proline and glycine betaine. Flood-tolerant genotypes such as Swarna Sub1 rice employ an energy conservation strategy called "quiescence" suppressing metabolic activity to survive submergence for 14–17 days, compared with two to three days for non-tolerant varieties (Liu et al., 2023).

At the genomic level, the identification of quantitative trait loci (QTLs) and candidate genes controlling drought tolerance, submergence tolerance, and heat stability has enabled marker-assisted selection (MAS) in major breeding programs. However, Kopeć (2024) cautions that most QTL studies are conducted under controlled single-stress conditions, which do not accurately represent the multifactorial stress combinations of actual field environments, necessitating greater investment in high-throughput field phenotyping platforms.

Smallholder Vulnerability and Systemic Risks

The impacts of extreme weather events are not uniformly distributed. Smallholder farmers who produce an estimated 70% of food consumed in developing countries are disproportionately exposed due to their dependence on rain-fed agriculture, limited access to improved inputs, and constrained financial reserves for post-disaster recovery. Research published in a global study of smallholders in food value chains revealed an "all-or-nothing" pattern of weather damage, where crop losses of 75% or more were recorded in the wake of severe events, largely due to geographic concentration of production and lack of diversification. This systemic fragility underscores the urgency of not only developing resilient varieties but also strengthening the broader agricultural ecosystem including insurance mechanisms, credit access, and extension services that enables farmers to adopt and maintain resilient practices.

Table 1: Resilient cropping strategies, the primary extreme weather threats they address and their documented yield benefits

Strategy	Primary Weather Threat Addressed	Documented Yield Benefit
Climate-resilient cultivars (drought-tolerant maize, Sub1 rice)	Drought, flooding	10–30% higher yield than local varieties under stress
Conservation tillage (no-till/reduced till)	Drought, erratic rainfall	Significant positive yield association under stress
Intercropping and crop diversification	Multiple stresses (drought, pest, flood)	Reduced total crop failure risk; improved income stability
Agroforestry integration	Heat stress, soil erosion, wind damage	Improved soil moisture retention and microclimate buffering
Water-smart irrigation (drip, rainwater harvesting)	Drought, water scarcity	Significant reduction in crop water stress mortality
Bundled CSA practice adoption	All weather extremes	Greatest yield gains observed under bundled adoption

Conclusion

Resilient cropping systems represent one of the most scientifically grounded and practically actionable responses to the mounting threat of extreme weather events on global food security. The evidence consistently demonstrates that resilience is not the product of any single technology or variety, but emerges from the strategic integration of genetic diversity, soil health management, diversified cropping architectures, and water-smart practices deployed in context-specific combinations. Studies across multiple continents confirm that bundled adoption of climate-smart practices — particularly when climate-resilient varieties are incorporated alongside conservation tillage and crop diversification — delivers the greatest mitigation of weather-induced yield losses. The path forward requires intensified investment in high-throughput field phenotyping, accelerated breeding of multi-stress-tolerant cultivars, scaling of agroforestry models, and the development of inclusive agricultural support systems that enable smallholder farmers to access and sustain resilient practices. As the climate crisis deepens, the transformation of cropping systems from productive but fragile monocultures toward biodiverse, ecologically grounded, and scientifically informed agro-ecosystems is no longer an option — it is an agricultural imperative.

References

Heino, M., Kinnunen, P., Anderson, W., Ray, D. K., Puma, M. J., Varis, O., Siebert, S., & Kummu, M. (2023). Increased probability of hot and dry weather extremes during the growing season threatens global crop yields. *Scientific Reports*, *13*, 3583. https://doi.org/10.1038/s41598-023-29378-2

Kopeć, P. (2024). Climate change—The rise of climate-resilient crops. *Plants*, *13*(4), 490. https://doi.org/10.3390/plants13040490

Liu, K., Harrison, M. T., Yan, H., Liu, D. L., Meinke, H., Hoogenboom, G., ... & Wang, B. (2023). Silver lining to a climate crisis in multiple prospects for alleviating crop waterlogging under future climates. *Nature Communications*, *14*, 765. https://doi.org/10.1038/s41467-023-36129-4

Mittler, R., Karlova, R., Bassham, D. C., & Lawson, T. (2025). Crops under stress: Can we mitigate the impacts of climate change on agriculture and launch the "resilience revolution"? *Philosophical Transactions of the Royal Society B: Biological Sciences*, *380*(1927), 20240228. https://doi.org/10.1098/rstb.2024.0228

Prajapati, R., Singh, S., Anand, A., Mallesh, Y., & Gulaiya, S. (2024). Green solutions: The impact of agroforestry on climate change resilience—A review. *International Journal of Environment and Climate Change*, *14*(11), 1–13. https://doi.org/10.9734/ijecc/2024/v14i114522

Rivero, R. M., Mittler, R., Blumwald, E., & Zandalinas, S. I. (2022). Developing climate-resilient crops: Improving plant tolerance to stress combination. *The*

Plant Journal, *109*(2), 373–389. https://doi.org/10.1111/tpj.15483

Zampieri M., Weissteiner C. J. and Grizzetti B. (2020). Estimating resilience of crop production systems. *Science of The Total Environment*, *735*, 139378. https://doi.org/10.1016/j.scitotenv.2020.139378.

Zandalinas, S. I., Fritschi, F. B., & Mittler, R. (2021). Global warming, climate change, and environmental pollution: Recipe for a multifactorial stress combination disaster. *Trends in Plant Science*, *26*(6), 588–599. https://doi.org/10.1016/j.tplants.2021.02.011

* * * * * * * * *