

Reimagining Climate Resilience in Rainfed Agricultural Landscapes



NATIONAL ACADEMY OF AGRICULTURAL SCIENCES, NEW DELHI
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Preface

Rainfed agriculture plays a crucial role in India's food and livelihood security, supporting a large proportion of farmers and contributing significantly to national agricultural production. However, increasing climate variability and change, including rising temperatures, erratic rainfall, prolonged dry spells, droughts and extreme weather events are posing serious challenges to the productivity and sustainability of rainfed agricultural systems. As climate risks intensify, strengthening the resilience of rainfed agriculture is becoming increasingly important for ensuring food security, farmer livelihoods and sustainable resource management.

Over the past several years, climate change has emerged as one of the major threats to agricultural production, particularly in rainfed regions that are highly dependent on the availability and distribution of rainfall. Its impacts are reflected through increasing frequency of droughts, heat stress, intense rainfall events, soil and water degradation and emerging pest and disease pressures. In India, several initiatives have generated and demonstrated climate-resilient technologies and approaches for improving the adaptive capacity of farming communities. Despite these efforts, gaps remain in the large-scale adoption, convergence and integration of proven technologies across farm and agricultural landscapes. Furthermore, climate resilience cannot be achieved through isolated farm-level interventions alone; it requires an integrated landscape approach that brings together soil, water, crops, livestock, biodiversity and farming communities.

Recognising the need, the Academy convened a brainstorming session on “*Reimagining Climate Resilience in Rainfed Agricultural Landscapes*”. The resulting policy paper highlights the emerging challenges, identifies critical gaps and presents strategic recommendations for strengthening climate resilience in rainfed agriculture. It emphasises the need to move from fragmented interventions towards integrated, landscape-based approaches that can enhance productivity, sustainability and the adaptive capacity of farming communities.

By providing a holistic framework for strengthening climate resilience, the document seeks to support informed policy formulation, effective technology scaling and coordinated action towards sustainable and resilient rainfed agricultural landscapes in the country. I appreciate the efforts of the Convener, Co-Convener, Reviewers and Editors for bringing the document in the present form.



(M.L. Jat)

President, NAAS

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1.0 INTRODUCTION

Rainfed agriculture constitutes one of the most important yet vulnerable components of India's agricultural economy. Rainfed agriculture should no longer be viewed only as a production system for resource-constrained regions. It represents one of India's most strategic national assets for achieving multiple national priorities. Consequently, strengthening the resilience of rainfed landscapes is not merely an agricultural objective, it is an investment in India's long-term economic, environmental and social security.

The Green Revolution has substantially increased productivity in irrigated regions and still 65 million ha (Mha) is under rainfed area which are yet to achieve the benefits. The recent study by ICAR-CRIDA shows that there are 307 climate vulnerable districts in the country. Rainfed agriculture currently occupies nearly 45% of the country's net sown area and contributes approximately 40% of total food grain production. More importantly, rainfed systems produce nearly 80% of nutri-cereals, 77% of pulses, 69% of oilseeds, a substantial proportion of cotton and support nearly 60% of the national livestock population, making them indispensable for food and nutritional security, income generation and ecological sustainability. India also has the largest area under rainfed rice at the global level.

Rainfed agriculture is distributed across diverse agro-ecological regions ranging from Deccan Plateau, Central India, Bundelkand, Vidarbha, Marathwada, Rayalaseema, Telangana Plateau, Western Rajasthan and Gujarat, dry regions of Karnataka and Tamil Nadu. These landscapes differ considerably in rainfall, soils, topography, vegetation, cropping systems and socio-economic conditions. Nevertheless, they share several common characteristics including dependence on monsoon rainfall, fragmented landholdings, low external input use, degraded natural resources and limited access to irrigation, markets and institutional support.

The significance of rainfed agriculture extends beyond crop production. These landscapes support rich agrobiodiversity, sustain mixed crop-livestock production systems, provide ecosystem services such as carbon sequestration, groundwater recharge and biodiversity conservation and serve as livelihood hubs for millions of small and marginal farmers. Rainfed agriculture also plays a critical role in achieving several Sustainable Development Goals (SDGs), including poverty reduction (SDG 1), zero hunger (SDG 2), climate action (SDG 13) and life on land (SDG 15).

Despite its strategic importance, rainfed agriculture remains highly vulnerable to climatic and environmental stresses. The rainfed agricultural districts (307) in India have less

than 45% net irrigated area, making them highly susceptible to droughts, dry spells, heat stress and rainfall variability. Crop yields in these districts exhibit considerable inter-annual fluctuations, often resulting in unstable farm incomes and increased livelihood vulnerability.

Paradoxically, rainfed regions also represent India's greatest opportunity for sustainable agricultural transformation numerous studies conducted by CRIDA (Central Research Institute for Dryland Agriculture), CAZRI (Central Arid Zone Research Institute) and ICRISAT (International Crops Research Institute for the Semi-Arid Tropics) have demonstrated that integrated watershed management, conservation agriculture, climate-resilient crop varieties, diversified farming systems, agroforestry, precision nutrient management, weather-based advisories and improved mechanization can substantially enhance productivity, resource-use efficiency and resilience under rainfed conditions.

The National Innovations in Climate Resilient Agriculture (NICRA) have further demonstrated that integrated climate-resilient interventions implemented at the village level can significantly reduce production risks and enhance livelihood security under diverse climatic conditions. State-level initiatives such as Maharashtra's Project on Climate Resilient Agriculture (PoCRA) and Odisha Integrated Irrigation Project for Climate Resilient Agriculture (OIIPCRA) have also contributed to strengthening climate resilience through improved natural resource management, diversified farming systems and community-based approaches. However, these successes have largely remained confined to pilot villages and project areas. The principal challenge facing Indian agriculture today is therefore not the lack of technologies but the inability to scale scientifically validated solutions across entire rainfed landscapes through institutional convergence, coordinated investments and participatory governance. The rainfed agricultural systems have many constraints that limits its productivity potential.

2.0 CHALLENGES AND EMERGING CLIMATE RISKS

2.1 Changing rainfall patterns, drought and temperature extremes

Rainfed agriculture is inherently vulnerable to climate variability because crop production depends strongly on the amount, distribution and timing of rainfall. Increasing temperatures, erratic rainfall, prolonged dry spells, recurrent droughts and extreme rainfall events are further intensifying production risks. Historical IMD estimates indicate that rainfall of 75% of normal or less occurs approximately once in 2.5 years in West Rajasthan, Tamil Nadu, Jammu and Kashmir and Telangana; once in three years in East Rajasthan, Gujarat and western Uttar Pradesh; once in four years in South Interior Karnataka, eastern Uttar Pradesh and Vidarbha; and once in five years in West Bengal, Madhya Pradesh, Konkan, Bihar and Odisha (Deshpande, 2022). In semiarid regions receiving 500–750 mm annual rainfall, drought occurs in 40-60% of years because of seasonal rainfall deficits or inadequate soil moisture availability between successive rainfall events. Even in dry sub-humid regions receiving 750–1200 mm

annual rainfall, contingent droughts can occur because of breaks in the monsoon. A very high incidence of drought (>20%) has been reported in some districts of Rajasthan and Gujarat, whereas the incidence is relatively low in the Western Ghats, eastern and north-eastern India (Fig. 1; Rama Rao *et al.*, 2019).

Rising temperatures further intensify these risks by accelerating crop development, shortening the grain-filling period and increasing evaporative demand. The concurrence of heat and moisture stress can therefore cause substantially greater reductions in crop productivity than either stress occurring independently. Climate variability is also increasingly expressed through compound, sequential and cascading stresses, rather than as isolated climatic events. Prolonged dry spells may be followed by intense rainfall, while drought and heat stress can coincide with poor soil fertility, pest and disease outbreaks or terminal moisture stress. Such interacting hazards can produce disproportionately large impacts on crop productivity and farm livelihoods.

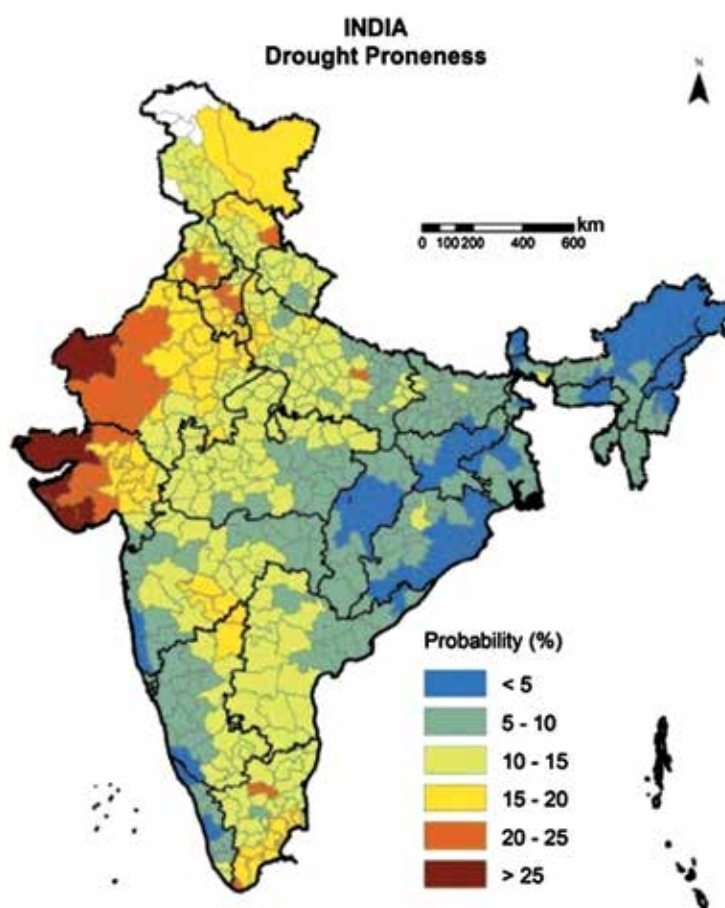


Fig. 1: Drought prone districts in India (Rama Rao *et al.*, 2019)

The changing nature of climate risk is particularly evident in the increasing frequency and intensity of hydro-meteorological extremes. Observational evidence indicates an increase in warm days and warm nights across most agro-climatic regions of India, along with a marked rise in extremely hot days since the 1980s (IMD, 2023). At the same time, rainfall is increasingly characterized by fewer rainy days and greater intensity during individual rainfall events. This creates greater runoff, flash flooding and soil erosion while reducing effective infiltration and groundwater recharge. Consequently, rainfed farmers increasingly face the paradox of “too much water at one time and too little water when crops actually require it.”

Delayed onset of the southwest monsoon can postpone sowing and shorten the effective crop-growing period, increasing the likelihood of terminal drought. Conversely, intense rainfall over short periods may result in substantial runoff losses, particularly where soils are degraded and have poor infiltration and water-holding capacity. These changes have fundamentally altered the hydrological behaviour of rainfed landscapes and demonstrate that vulnerability is increasingly associated not simply with rainfall deficits but with greater uncertainty in the timing, distribution and intensity of rainfall.

2.2 Biological stresses and degradation of natural resources

Climate variability and change also influence pest, disease and weed dynamics. Rising temperatures, altered humidity and changing rainfall regimes can modify pest and pathogen population dynamics and expand the geographical distribution of several pests and diseases. New pest complexes may emerge in regions where they were previously less important, increasing uncertainty in crop protection. Changes in weed flora under warmer and more variable climatic conditions can further complicate weed management in dryland ecosystems. The interaction of climatic stresses with biological stresses therefore adds another dimension to production risk.

Climate risks are further amplified by degradation of soil and water resources. Nearly 97.85 Mha in India are affected by land degradation, with water erosion accounting for about 61% of the degraded area. Declining soil organic carbon, soil erosion and nutrient depletion reduce soil structure, infiltration and water-holding capacity, thereby increasing crop vulnerability during dry periods. At the same time, increasing dependence on groundwater for supplemental irrigation is placing additional pressure on already stressed water resources. According to CGWB (2025), 730 of 6,762 groundwater assessment units are classified as over-exploited and another 201 as critical. In rainfed landscapes, inadequate rainwater harvesting, degraded watersheds and reduced opportunities for groundwater recharge can further intensify water insecurity. Increasing temperature, drought and groundwater stress may also contribute to salinity and sodicity problems in vulnerable regions.

2.3 Livestock, farm operations and productivity constraints

The impacts of climate variability extend beyond crop production to livestock and the timeliness of farm operations. Livestock production in rainfed regions is particularly vulnerable to heat stress, seasonal shortages of water and fodder and limited availability of quality feed. Dry matter availability in rainfed regions is estimated at 5.45 kg LU⁻¹ day⁻¹, compared with 7.47 kg LU⁻¹ day⁻¹ in irrigated regions, contributing to comparatively lower livestock productivity. Average milk production is also lower in rainfed areas, at approximately 1.2 litres cow⁻¹, compared with 1.78 litres cow⁻¹ in irrigated regions. Rainfed livestock systems are further characterized by acute seasonal water and feed shortages and greater dependence on draft animal power, whereas irrigated regions generally have more stable year-round feed and water availability and higher levels of mechanization (Omprakash *et al.*, 2023). These constraints can further increase livelihood vulnerability during periods of climatic stress. Similarly, limited access to appropriate-scale farm mechanization can constrain the timely completion of sowing, weeding, plant protection and harvesting operations, particularly as favourable weather windows become increasingly narrow and unpredictable. Mechanization levels remain relatively low for several critical farm operations, especially weeding, plant protection and harvesting (Gol, 2022). Thus, climatic uncertainty can generate cascading effects across crop and livestock production, labour requirements, machinery use, farm operations and household income.

These interacting climatic, environmental and socio-economic constraints contribute to substantial yield instability and persistent yield gaps in rainfed agriculture. Yield gaps have been estimated at 30-60% in pearl millet, 40-70% in sorghum, 50-100% in pulses, 40-80% in oilseeds, 40-90% in rainfed rice and 30-80% in rainfed maize. Consequently, improving rainfed productivity requires not only closing existing yield gaps but also strengthening the capacity of production systems and farming communities to withstand, recover from and adapt to climatic shocks.

2.4 From climate adaptation to resilience-based approaches

The evolving nature of climate risks necessitates a corresponding evolution in adaptation strategies. Earlier approaches to climate adaptation in agriculture primarily focused on reducing vulnerability to individual stresses through interventions such as drought-tolerant varieties, supplemental irrigation, weather forecasting, crop insurance, conservation tillage and soil-moisture conservation. These interventions remain important; however, increasing climatic uncertainty and the emergence of compound and cascading stresses have demonstrated the limitations of addressing individual hazards through isolated technologies.

Consequently, the focus is increasingly shifting from hazard specific adaptation towards integrated, system-based resilience building. Climate adaptation aims to reduce vulnerability and adjust agricultural systems to actual or expected climatic changes,

whereas mitigation focuses on reducing greenhouse gas emissions or enhancing carbon sequestration. Resilience extends beyond both concepts by emphasizing the capacity of farming households, production systems and landscapes to anticipate, absorb, recover from and adapt to climatic disturbances while sustaining productivity, livelihoods and ecosystem services (FAO, 2023).

This resilience perspective is closely aligned with the principles of Climate-Smart Agriculture (CSA), which seeks to simultaneously increase agricultural productivity and incomes sustainably, strengthen adaptation and resilience to climate change and reduce greenhouse gas emissions wherever feasible. However, implementation of CSA has often emphasized individual technologies or practices. Given the increasingly interconnected nature of climate, soil, water, ecological and socio-economic risks, resilience building requires a broader systems perspective.

2.5 Landscape resilience as an emerging framework

The increasing recognition of interconnected risks has led to a shift from farm-level adaptation towards landscape-scale resilience. Agricultural fields are embedded within larger ecological, hydrological and socio-economic systems and the effectiveness of farm-level interventions is often influenced by processes occurring beyond individual farm boundaries. Soil erosion and runoff generated in upper catchments, for example, can affect downstream water availability; groundwater extraction in one location can influence resource availability elsewhere; and pest, disease and biodiversity dynamics can extend across farm boundaries.

Landscape resilience therefore recognizes that the capacity of rainfed agriculture to cope with climate change emerges from interactions among soils, water resources, vegetation, biodiversity, cropping and livestock systems, infrastructure, institutions, communities and policy frameworks. Building resilience consequently requires coordinated interventions across farm, watershed and landscape scales rather than isolated responses to individual climatic hazards.

Such an approach integrates soil and water conservation, rainwater harvesting and groundwater recharge with climate-resilient crops and cropping systems, diversified farming and livestock enterprises, resource-use-efficient technologies, climate-informed farm planning, mechanization, weather and climate services, risk management and institutional support. The objective is not merely to maintain production during favourable years but to reduce year-to-year variability, enhance recovery after climatic shocks and sustain livelihoods and ecosystem services over the long term.

Thus, the central challenge for rainfed agriculture is no longer simply the occurrence of drought, heat, flood or other individual hazards. Rather, it is the interaction of multiple climatic stresses with degraded natural resources, biological pressures and socio-economic vulnerabilities. Addressing these challenges requires a transition from fragmented, hazard-specific adaptation towards integrated resilience-building at farm

and landscape scales. This provides the foundation for reorienting rainfed agricultural development towards sustainable intensification, efficient resource use, diversified livelihoods and climate-resilient landscapes.

3.0 REIMAGINING OF CURRENT APPROACHES

3.1 Policy and institutional progress in climate-resilient agriculture

India has made remarkable progress in developing technologies and policy interventions to address climate risks in agriculture. Since the early 1990s, several national programmes including the National Watershed Development Programme for Rainfed Areas (NWDPA), Drought Prone Area Program (DPAP), Integrated Watershed Management Programme (IWMP), National Mission for Sustainable Agriculture (NMSA), National Innovations in Climate Resilient Agriculture (NICRA), *Pradhan Mantri Krishi Sinchayee Yojana* (PMKSY), Soil Health Card Scheme, Rainfed Area Development (RAD) and *Pradhan Mantri Fasal Bima Yojana* (PMFBY) have significantly strengthened the country's adaptive capacity. These initiatives have generated a wealth of scientific knowledge, institutional experience and technological innovations that have improved water conservation, soil health, crop productivity and farmers' preparedness against climate variability. At the state level, programmes such as PoCRA in Maharashtra and OIIPCRA in Odisha have further strengthened efforts towards climate-resilient agriculture through integrated natural resource management, sustainable farming practices and community participation.

3.2 Evidence of technology driven climate resilience

Research has generated considerable scientific evidence supporting climate-resilient agriculture. Programmes such as NICRA have demonstrated the effectiveness of integrated interventions, including climate-resilient crop varieties, *in situ* and *ex situ* water conservation, farm ponds, custom hiring centres, weather-based agro-advisories, livestock shelters and integrated farming systems, in reducing climate-induced production risks across diverse agro-ecological regions. Similarly, state-level initiatives such as PoCRA in Maharashtra and OIIPCRA in Odisha provide additional examples of approaches to climate-resilient agriculture, particularly through soil and water management, crop diversification, sustainable production practices and farmer participation. NICRA's analysis of national-level secondary data from the Department of Agriculture and Farmers Welfare indicates improved resilience in coarse cereals, particularly pearl millet, after 2011-12 (Fig. 2). Despite the occurrence of droughts during 2009-10, 2015-16 and 2018-19, rainfed regions demonstrated increasing resilience in food grain production compared with irrigated areas, reflecting the positive impacts of technological interventions and improved agricultural management practices (Fig. 3). These improvements reflect the combined contribution of improved crop varieties, better agronomic practices and drought management technologies,

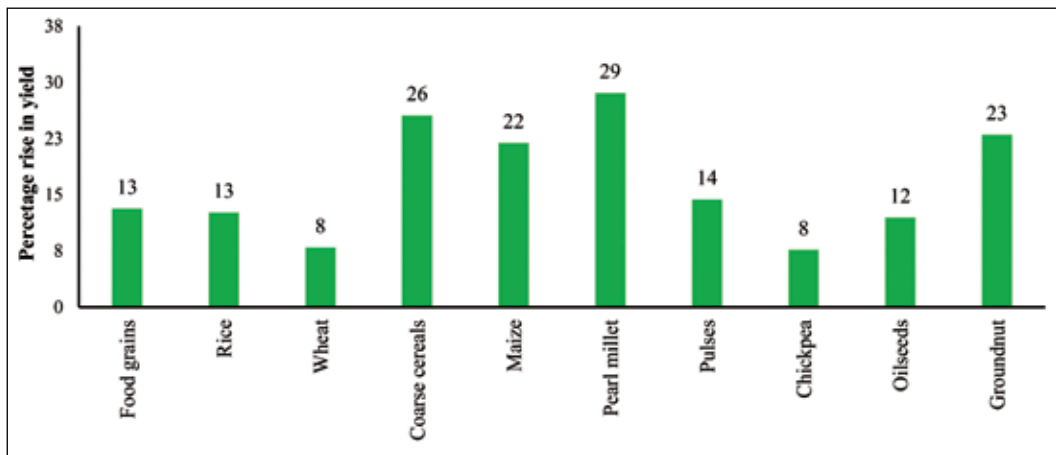


Fig. 2: Change in resilience in different crops and crop groups (Singh *et al.*, 2026)

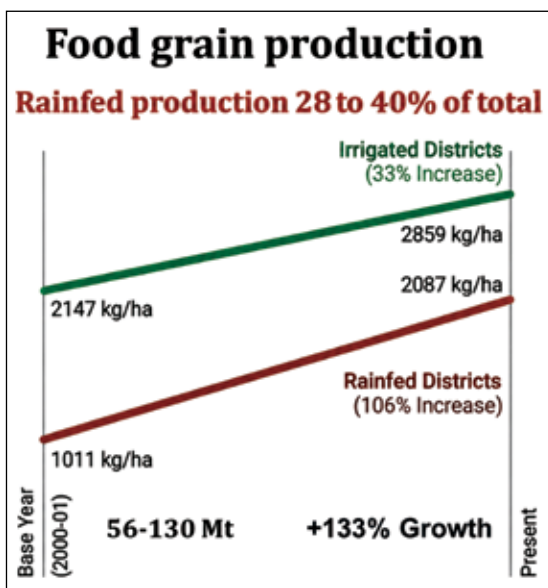


Fig. 3: Changes in food grain productivity in rainfed and irrigated districts of India (Singh *et al.*, 2026)

which have played a particularly important role in rainfed agriculture. However, the benefits of many location-specific interventions have not yet been adequately scaled across larger rainfed landscapes due to institutional and implementation constraints.

3.3 Convergence and scaling deficit

The principal challenge is no longer technology generation but integrating these innovations into coherent production systems and scaling them across rainfed

landscapes through institutional convergence, coordinated investments and effective implementation mechanisms. This shows that, India does not face a technology deficit; rather, it faces a convergence and scaling deficit. Scientifically validated technologies exist, but they remain dispersed across projects, institutions and schemes operating largely in isolation. One of the major constraints is the sectoral nature of planning. Soil conservation, watershed development, irrigation, agriculture, horticulture, livestock, forestry, rural development and climate adaptation programmes are generally implemented by different departments operating under separate mandates, budgets and monitoring frameworks. Such institutional silos hinder convergence and reduce the cumulative impact of public investments. Another limitation concerns the scale of intervention. Most climate-resilient technologies are implemented at the individual farm level, whereas climate processes operate at watershed and landscape scales. International experience increasingly demonstrates that climate resilience requires coordinated governance across sectors rather than isolated interventions.

3.4 Strengthening extension and climate information systems

Furthermore, extension systems responsible for technology dissemination require significant strengthening. Public agricultural extension has played a pivotal role in transforming Indian agriculture; however, declining investments and limited technical capacity have reduced its effectiveness in many rainfed regions. Climate resilience requires continuous advisory support rather than periodic technology transfer. Digital agriculture, artificial intelligence, remote sensing, Internet of Things (IoT)-based monitoring and mobile-based agro-advisories offer unprecedented opportunities for strengthening climate information services, yet their integration within public extension systems remains limited. Emerging challenges such as carbon markets, ecosystem service payments, regenerative agriculture, biodiversity conservation and nature-based solutions are also inadequately reflected in existing agricultural policies.

3.5 Need for landscape scale transformational adaptation

The evidence clearly indicates that future climate policies must move beyond incremental improvements toward transformational adaptation. Accordingly, the next generation of climate-resilient agricultural policy must move beyond the dissemination of individual technologies toward the design of integrated, landscape-based resilience systems. Such systems should combine scientific innovation with institutional convergence, digital technologies, participatory governance, climate information services, natural resource restoration and diversified livelihood strategies. This paradigm shift from farm-level adaptation to landscape-scale resilience forms the conceptual foundation of the present policy paper and provides the basis for developing a comprehensive One Nation Climate Resilience Framework for India's rainfed agricultural landscapes.

3.6 Land resource inventory and integrated decision support systems

Effective climate adaptation in rainfed agriculture requires a clear understanding of the land resources, their potential and limitations across different agro-ecological regions. Land resource inventories, integrating information on soil characteristics, land use, terrain, rainfall, water availability and existing cropping systems, can provide a scientific basis for identifying suitable agricultural interventions. Advances in remote sensing, Geographic Information Systems (GIS), digital soil mapping and spatial modelling have made it possible to generate location-specific information on land suitability, soil and water conservation needs, crop diversification opportunities and climate-related risks. However, such information is often scattered across institutions and is not adequately integrated into agricultural planning and implementation.

There is a need to develop integrated decision support systems that bring together land resource information, climate projections, crop suitability, water availability, socio-economic conditions and available adaptation technologies on a common platform. Such systems can help identify appropriate crops, cropping systems, soil and water management practices and other climate-resilient interventions for different locations. Linking these decision support systems with existing programmes, agricultural extension networks and district-level planning processes can support evidence-based prioritization of interventions and investments. This would enable a shift from generalized technology recommendations to location-specific, resource-based planning at farm, village, watershed and landscape scales. Strengthening the use of land resource inventories and integrated decision support systems is therefore essential for improving the effectiveness, coordination and scalability of climate-resilient agriculture in India.

4.0 STRATEGIC FRAMEWORK FOR RAINFED AGRICULTURE

Building an *Atmanirbhar* rainfed agricultural sector requires a paradigm shift from fragmented, technology-centric interventions towards an integrated, inclusive and landscape-based resilience framework. Such a framework should simultaneously enhance productivity, resource-use efficiency, environmental sustainability, livelihood security and adaptive capacity. As climate change intensifies production risks through increasing temperatures, erratic rainfall, prolonged dry spells, droughts and extreme rainfall events, India's rainfed regions need a transition from vulnerable production systems towards resilient and economically viable landscapes capable of sustaining agricultural growth and rural livelihoods.

The strategic framework for resilient rainfed agriculture is organized around seven interconnected pillars: (i) climate intelligence (ii) water security (iii) soil health restoration, (iv) diversified farming systems (v) water security and governance (vi) risk protection and (vii) inclusive institutions and markets (Fig. 4). These pillars provide a basis for integrating technological, ecological, institutional and economic dimensions of resilience



Fig. 4: Pillars for resilience, strengthening capacity and sustainability in rainfed areas

and translating them into location-specific approaches at farm, village, watershed and landscape scales.

4.1 Climate intelligence

Climate intelligence forms the basis for shifting rainfed agriculture from reactive responses to anticipatory climate-risk management. Increasing availability of weather observations, seasonal forecasts, remote-sensing information, soil-moisture data, crop information and hydrological datasets provides opportunities for more informed and timely decision-making. Weather forecasts, seasonal advisories, drought monitoring and dynamic contingency planning can support decisions related to sowing, crop and variety selection, irrigation, nutrient management, pest and disease management and harvesting. Remote sensing and soil-moisture information can further strengthen early identification of crop stress and emerging climatic risks. The emphasis should therefore move from information dissemination alone towards actionable, location-specific advisories that enable farmers to respond to changing weather conditions.

Climate intelligence also requires effective interaction between digital technologies and established extension systems. Krishi Vigyan Kendras (KVKs), Farmer Producer Organizations (FPOs), Panchayati Raj Institutions and other farmer organizations can play an important role in translating climate information into locally relevant farm decisions. Digital services are therefore best viewed as complementary to, rather than substitutes for, public extension and community-based advisory systems.

4.2 Water security

Water security is fundamental to resilient rainfed agriculture because production depends not only on the total amount of rainfall received but also on its timing, distribution

and effective utilization. Increasing rainfall variability, prolonged dry spells and intense rainfall events require an integrated approach to managing soil moisture, surface runoff, harvested water and groundwater. At the field level, *in-situ* moisture-conservation practices such as conservation furrows, contour farming, mulching, residue retention and conservation tillage can improve infiltration, reduce runoff and enhance soil-moisture availability. These measures can be complemented by *ex-situ* rainwater-harvesting interventions such as farm ponds, check dams, percolation tanks and other watershed structures.

At the watershed and landscape scales, water management needs to integrate rainwater harvesting, groundwater recharge, water budgeting, demand management and efficient supplemental irrigation. Such an approach can improve the productive use of rainfall while reducing erosion, runoff losses and pressure on groundwater resources. Water security therefore represents both a farm-level production strategy and a broader landscape-management objective.

4.3 Soil health restoration

Healthy soils are the ecological foundation of productive and climate-resilient rainfed systems. Soil degradation, declining organic carbon, nutrient depletion and erosion reduce infiltration, water-holding capacity and biological activity, thereby increasing the susceptibility of crops to climatic stresses. Soil health restoration requires integrated nutrient management, balanced fertilization, residue recycling, organic amendments, bio-inputs, reduced tillage and erosion-control measures. These practices can improve soil structure, enhance soil organic carbon, increase infiltration and moisture retention and strengthen biological functioning.

Regular assessment of soil health is also important for guiding location-specific management. Indicators such as soil organic carbon, nutrient status, soil moisture and water productivity provide a basis for assessing whether interventions are improving the capacity of soils to support production under variable climatic conditions.

4.4 Diversified and climate-resilient farming systems

Diversification is central to reducing the dependence of rainfed households on individual crops or enterprises. Climate-resilient production systems should therefore incorporate suitable combinations and rotations of millets, pulses, oilseeds, cereals, horticultural crops and fodder crops according to local rainfall, soils, water availability and market conditions. Stress-tolerant and short-duration varieties can further reduce exposure to drought, delayed rainfall and terminal moisture stress. Diversified farming systems can also include livestock, horticulture, agroforestry and silvi-pastoral components wherever appropriate. Such integration distributes climatic and market risks across enterprises while improving nutrient and biomass recycling, household nutrition, income stability and employment opportunities.

Livestock remains particularly important in rainfed livelihood systems. Improved fodder systems, climate-resilient livestock breeds and better management of livestock water requirements can strengthen the contribution of livestock to household resilience. Diversified production systems therefore provide an important bridge between agricultural productivity, nutritional security and livelihood stability.

4.5 Water security and governance

Water governance is essential for ensuring the sustainable and equitable use of limited water resources in rainfed regions. While rainwater harvesting and soil-moisture conservation can improve water availability, their long-term benefits depend on how effectively water resources are managed and shared among different users. Community participation in water budgeting, groundwater monitoring, maintenance of water-harvesting structures and decisions on water allocation can help improve water-use efficiency and reduce conflicts. Local institutions such as Panchayati Raj Institutions, Water User Associations and watershed committees have an important role in promoting collective responsibility and ensuring equitable access to water, particularly for small and marginal farmers.

Water management also needs to consider the linkages between surface water, groundwater, cropping patterns and local water demand. Encouraging crops and irrigation practices suited to available water resources can help reduce pressure on groundwater and improve preparedness for prolonged dry spells. Greater coordination among watershed development programmes, irrigation schemes, agricultural departments and local institutions is needed to avoid fragmented interventions and ensure efficient use of available resources. Strengthening community participation and local institutional capacity can therefore contribute to more sustainable water management and long-term resilience of rainfed farming systems.

4.6 Risk protection

Rainfed agriculture is highly vulnerable to climatic and economic uncertainties, including droughts, floods, extreme temperatures, crop failures and fluctuations in market prices. These risks can affect farm income, household food security and the ability of farmers to invest in the following cropping season. While climate-resilient technologies can reduce production losses, farmers also need financial and institutional support to cope with adverse events. Crop and livestock insurance, access to institutional credit, emergency assistance and social protection measures can help reduce the economic burden of climatic shocks. Particular attention is needed to ensure that these mechanisms are affordable and accessible to small and marginal farmers, tenant farmers, women farmers and other vulnerable groups.

Risk protection should also be linked with early-warning systems, weather advisories, contingency crop planning and livelihood diversification so that farmers can take timely

action before and during extreme weather events. Improving insurance coverage, simplifying claim procedures and ensuring timely compensation can help farmers recover more quickly from crop losses. Community-based risk-sharing mechanisms and better coordination among government agencies, financial institutions, insurance providers and farmer organizations can further strengthen support at the local level. An effective risk-protection system should therefore focus not only on providing relief after climatic shocks but also on reducing vulnerability, protecting farm assets and helping farmers maintain their livelihoods under increasingly uncertain climatic conditions.

4.7 Inclusive institutions and markets

Technological resilience can be sustained only when supported by appropriate institutions, financial mechanisms and markets. Production choices in rainfed areas are influenced not only by agro-climatic suitability but also by relative profitability, procurement arrangements, prices, access to credit, insurance and market opportunities.

KVKs, research institutions, State Agricultural Universities, line departments, FPOs, Panchayati Raj Institutions and farmer organizations have complementary roles in technology validation, extension, capacity strengthening and implementation. Institutional arrangements also need to address the specific constraints faced by small and marginal farmers, tenant farmers, women farmers, tribal communities and other vulnerable groups. Markets and financial services constitute an equally important component of resilience. Procurement, value addition, institutional credit, agricultural insurance, value-chain development and improved market access can strengthen the economic viability of climate-resilient production systems. Public and private institutions therefore need to function in a complementary manner, with private-sector participation supporting technology delivery, processing, value addition, financial inclusion and market linkages while public institutions retain critical roles in research, extension, regulation and protection of vulnerable farming communities.

5.0 PATHWAYS FOR IMPLEMENTATION AND SCALING

The transition from individual climate-resilient technologies to resilient rainfed landscapes requires implementation mechanisms that integrate technologies, institutions, infrastructure and financial support. India has already developed a substantial portfolio of climate-resilient practices through NICRA, watershed programmes, ICAR research, state-level initiatives such as PoCRA, OIIPCRA and other development initiatives. The principal challenge is therefore to move beyond isolated technologies and localized demonstrations towards coordinated implementation and scaling across larger rainfed landscapes.

5.1 Integrated climate-resilient technology packages

Climate-resilient interventions should increasingly be delivered as Integrated Climate-Resilient Technology Packages rather than as isolated technologies. Such

packages can combine climate-resilient varieties, improved agronomy, soil-health management, rainwater management, precision resource management, appropriate mechanization, integrated crop–livestock systems, climate advisories, risk-management instruments and market linkages.

The composition of these packages should reflect local climatic risks, soil and water resources, farming systems and socio-economic conditions. For example, drought-prone watersheds may require a combination of climate advisories and contingency planning, *in-situ* soil-moisture conservation, rainwater harvesting, resilient crops and varieties, livestock and fodder management, appropriate mechanization and market support. Integrating these components can generate greater resilience than implementing individual technologies independently.

5.2 Landscape-scale implementation and adaptive learning

Scaling should progressively move from individual farms and village-level demonstrations towards watersheds and larger rainfed landscapes. Landscape-level planning allows soil, water, vegetation, crop and livestock resources to be managed together while accounting for the ecological linkages among upstream and downstream areas. Climate-resilience technology parks or living field laboratories can provide platforms for testing, refining and demonstrating integrated technology packages across major rainfed agro-ecologies. Such platforms can facilitate farmer participation, adaptive learning and continuous refinement of interventions under real farming conditions. They can also strengthen the link between research, extension and implementation by allowing technologies to be evaluated under varying climatic and socio-economic conditions before wider scaling.

5.3 Institutional convergence and coordinated implementation

Effective implementation of rainfed resilience strategies requires convergence among existing programmes rather than the creation of fragmented standalone initiatives. Programmes such as the National Mission for Sustainable Agriculture (NMSA), Pradhan Mantri Krishi Sinchayee Yojana (PMKSY), Viksit Bharat Gramin Rainfed Area Mission (VB-G-RAM-G), Rashtriya Krishi Vikas Yojana (RKVY), watershed development programmes, soil-health initiatives and digital agriculture programmes provide opportunities for coordinated investment in rainfed landscapes. Convergence needs to be operationalized through clearly defined institutional responsibilities, coordinated financing, shared outcome indicators and joint monitoring at district and block levels. ICAR institutions, State Agricultural Universities, KVKs, line departments, Panchayati Raj Institutions, FPOs, civil society organizations and private-sector partners can participate in common planning and implementation processes.

Such convergence can reduce duplication, overcome administrative silos and improve the efficiency of public investment. Common landscape resilience plans can provide an

operational mechanism for aligning programmes around shared objectives related to water security, soil health, production resilience, livelihood diversification and market development.

5.4 Climate-smart mechanization and service delivery

Mechanization assumes particular importance in rainfed agriculture because uncertain rainfall often creates narrow operational windows for sowing, weeding, plant protection and harvesting. Delays during these critical periods can substantially reduce the benefits of other climate-resilient interventions. Mechanization pathways should therefore emphasize affordable, energy-efficient and smallholder-friendly machinery, including precision seeders, conservation-agriculture implements, sensor-based equipment and renewable-energy-powered machinery. Site-specific and variable-rate technologies can further improve the efficiency of seed, nutrient, water and crop-protection inputs.

Custom Hiring Centres, machinery-sharing platforms and farmer collectives provide mechanisms for expanding access to machinery without requiring individual ownership. Such service-delivery models are especially important for small and marginal farmers. Mechanization strategies should also contribute to reducing labour drudgery, particularly for women and enable timely completion of critical operations under increasingly uncertain weather conditions.

5.5 Digital platforms, monitoring and resilience assessment

Implementation should be supported by an integrated climate–agriculture data ecosystem combining weather observations, seasonal forecasts, soil-health information, groundwater and hydrological data, crop performance, remote-sensing information and relevant socio-economic indicators. These datasets can support landscape-specific decision systems for crop planning, drought monitoring, water allocation, pest and disease surveillance and contingency management. Monitoring and evaluation should also move beyond physical outputs such as numbers of structures constructed, farmers trained or technologies distributed. Greater emphasis is required on measurable resilience outcomes, including yield stability, soil organic carbon, soil moisture, groundwater status, water productivity, ecosystem restoration, farm income, livelihood diversification and the capacity of households to recover from climate-induced losses.

A National Climate Resilience Digital Dashboard could integrate climate forecasts, drought alerts, crop and livestock advisories, natural-resource indicators, market information and programme implementation data. Such a platform could support evidence-based decision-making, real-time monitoring and coordinated action across rainfed landscapes.

5.6 Phased implementation roadmap

The transformation towards *Atmanirbhar* rainfed agriculture needs to follow a phased approach, reflecting the different time horizons required to reduce immediate risks, strengthen adaptive capacity and restore landscape resilience.

- ◆ Short-term priorities should focus on reducing immediate climate risks through improved weather and climate advisories, dynamic contingency planning, drought monitoring, moisture conservation, climate-resilient varieties and timely access to seed and other critical inputs.
- ◆ Medium-term priorities should strengthen adaptive capacity through watershed development, soil-health restoration, diversified production systems, integrated farming systems, climate-smart mechanization, digital decision-support systems and institutional convergence.
- ◆ Long-term priorities should focus on landscape restoration, groundwater sustainability, ecosystem-based adaptation, resilient value chains, climate finance, carbon and ecosystem-service markets and durable institutional mechanisms for landscape governance.

6.0 RECOMMENDATIONS

Based on the climate risks, constraints and strategic pathways identified for rainfed agriculture, the following recommendations are proposed:

- ◆ **Promote location-specific climate-resilient and diversified farming systems :** Diversification towards suitable combinations of millets, pulses, oilseeds, cereals, horticultural crops and fodder crops should be encouraged together with stress-tolerant and short-duration varieties. Integrated crop–livestock, horticulture, agroforestry and silvi-pastoral systems should be promoted according to local agro-ecological and socio-economic conditions.
- ◆ **Strengthen rainwater management and sustainable water security :** *In-situ* moisture conservation, *ex-situ* rainwater harvesting, groundwater recharge, community-level water budgeting and efficient supplemental irrigation should be integrated at watershed and landscape scales to improve productive use of rainfall and reduce vulnerability to dry spells and drought.
- ◆ **Restore soil health and strengthen the soil–water continuum :** Integrated nutrient management, balanced fertilization, residue recycling, organic amendments, bio-inputs, reduced tillage and erosion-control measures should be promoted to enhance soil organic carbon, infiltration, water-holding capacity and nutrient-use efficiency.
- ◆ **Strengthen climate early-warning systems and climate information services :** Strengthen dedicated infrastructure and institutional mechanisms

for climate monitoring, early-warning systems and delivering location-specific climate information services. Integration of weather forecasts, remote sensing, soil-moisture monitoring and digital technologies, supported by stronger linkages among research, meteorological and extension agencies, should enable timely and actionable advisories for rainfed farmers.

- ◆ **Break disciplinary silos and promote integrated, problem-solving research for climate-resilient agriculture :** Agricultural research should move beyond disciplinary and institutional silos towards a holistic, system-based and problem-solving approach to address the interconnected challenges of climate change, natural resource degradation, agricultural productivity and livelihood security. Research priorities should shift from isolated, discipline-specific technologies towards integrated, location-specific solutions that address real-world challenges of rainfed farming systems, with greater emphasis on participatory research, systems-level evaluation and scaling across rainfed landscapes.
- ◆ **Institutionalize climate intelligence and dynamic contingency planning :** Weather forecasts, seasonal advisories, drought monitoring, remote sensing and soil-moisture information should be translated into location-specific, actionable advisories. Dynamic contingency plans should support timely adjustment of crops, varieties and agronomic practices in response to delayed monsoon onset, prolonged dry spells and excessive rainfall.
- ◆ **Expand climate-smart mechanization for timely farm operations :** Smallholder-friendly precision seeders, conservation-agriculture implements, sensor-based equipment and other appropriate machinery should be made accessible through Custom Hiring Centres, machinery-sharing platforms and farmer collectives. Mechanization should particularly address narrow operational windows and reduce labour drudgery.
- ◆ **Strengthen livestock resilience and livelihood diversification :** Improved fodder systems, climate-resilient livestock breeds, livestock water management and integration of crops with livestock, horticulture, agroforestry and other complementary enterprises should be strengthened to diversify household income and reduce dependence on single crops.
- ◆ **Scale integrated climate-resilient technology packages across rainfed landscapes :** The focus should shift from isolated technologies and village-level demonstrations towards integrated packages combining resilient varieties, agronomy, soil and water management, mechanization, crop–livestock integration, climate advisories, risk management and market support. Technology parks and living field laboratories can facilitate their validation and scaling under farmers' conditions.

- ◆ **Strengthen institutional convergence and coordinated financing** : Existing programmes related to sustainable agriculture, irrigation, watershed development, soil health, rural development and digital agriculture should be aligned through common landscape resilience plans. Clearly defined institutional responsibilities, coordinated financing, common outcome indicators and joint monitoring should support implementation at district and block levels.
- ◆ **Improve access to markets, finance, insurance and resilient value chains** : Climate-resilient technologies should be supported by appropriate procurement and price mechanisms, institutional credit, agricultural insurance, value addition and market access. Public–private partnerships can contribute to technology delivery, machinery services, digital agriculture, financial inclusion, processing and development of climate-resilient value chains while ensuring equitable access for vulnerable farming communities.
- ◆ **Establish measurable resilience indicators and long-term monitoring mechanisms** : Programme assessment should increasingly focus on outcomes such as yield stability, soil organic carbon, soil moisture, groundwater status, water productivity, ecosystem restoration, farm income, livelihood diversification and recovery from climatic shocks. An integrated digital monitoring platform can support evidence-based planning, accountability and long-term assessment of resilience across rainfed landscapes.
- ◆ **Assess and incentivize ecosystem services from rainfed agricultural systems** : Rainfed farming systems should be evaluated not only for productivity and income but also for ecosystem services such as carbon sequestration, soil health, groundwater recharge, biodiversity conservation and erosion control. Standardized assessment frameworks and appropriate mechanisms, including Payments for Ecosystem Services (PES), carbon credits and outcome-based incentives should be developed to recognize and reward farmers for sustainable land management practices.

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