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Review Article

Adaptation and Mitigation Strategies for Climate-Resilient Agriculture: A Review

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ABSTRACT

Climate change poses significant challenges to agricultural productivity, food security, and rural livelihoods through rising temperatures, altered precipitation patterns, extreme weather events, droughts, floods, and emerging pest pressures. This review examines key adaptation and mitigation strategies for developing climate-resilient agricultural systems. Adaptation approaches include climate-smart crop varieties, diversified cropping systems, conservation agriculture, efficient irrigation, integrated pest and nutrient management, agroforestry, and precision farming technologies. Mitigation strategies emphasize carbon sequestration, improved soil health, renewable energy, reduced greenhouse gas emissions, and efficient resource utilization. The review highlights the importance of integrating indigenous knowledge, digital technologies, policy support, and farmer-centered approaches to enhance resilience, sustainability, productivity, and long-term food security under changing climatic conditions.

Keywords: *Climate-resilient agriculture, Adaptation, Mitigation, Conservation agriculture, Food security.*

INTRODUCTION

Agriculture is the economic activity most intimately coupled to climate. Every phenological stage of a crop, every reproductive cycle of a farm animal and every microbial transformation in the soil is regulated by temperature, moisture and radiation, which makes the sector uniquely exposed to a warming planet. The annually averaged global mean near-surface temperature in 2024 reached 1.55 °C above the 1850–1900 baseline, the warmest year in the 175-year observational record, and the ten years from 2015 to 2024 were the ten warmest on record (WMO, 2025).

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Beyond the shift in mean temperature, the more damaging agricultural signal lies in the rising frequency of compound extremes, that is, heat waves coinciding with terminal drought, erratic monsoon onset followed by high-intensity rainfall, and unseasonal warm spells during grain filling.

The consequences are already measurable rather than merely projected. Anthropogenic warming over 1961–2017 is assessed to have reduced the combined global yields of maize, wheat and rice by 5.3 per cent, with individual losses of 5.9 per cent for maize, 4.9 per cent for wheat and 4.2 per cent for rice (IPCC, 2022a). Climate change has additionally suppressed global agricultural total factor productivity growth by approximately 21 per cent since 1961, a penalty equivalent to forfeiting seven years of productivity gains, and the reduction reaches 30 to 33 per cent in Africa and in Latin America and the Caribbean (Ortiz-Bobea et al., 2021; & IPCC, 2022a). Under a high-emission pathway, about 10 per cent of the area currently suitable for crop and livestock production is projected to become climatically unsuitable by 2050 and over 30 per cent by 2100 (IPCC, 2022a). These losses land on an already fragile food system in which around 733 million people, one in eleven globally and one in five in Africa, faced hunger in 2023 (FAO, IFAD, UNICEF, & WFP & WHO, 2024).

Agriculture is not only a casualty of climate change but also a substantial contributor to it. Global agrifood-system emissions totalled 16.2 Gt CO2eq in 2022, equal to 29.7 per cent of total anthropogenic emissions, comprising 7.8 Gt CO2eq from within the farm gate, 5.3 Gt CO2eq from pre- and post-production supply-chain activities and 3.1 Gt CO2eq from land-use change (FAO, 2024). Farm-gate emissions rose 15 per cent and supply-chain emissions 52 per cent between 2000 and 2022, whereas land-use-change emissions fell 30 per cent, indicating a structural shift in where agricultural emissions originate (Figure 1). Methane from enteric fermentation and flooded rice, and nitrous oxide from nitrogen fertiliser, dominate the farm-gate share, and both gases have far higher radiative efficiency than carbon dioxide.

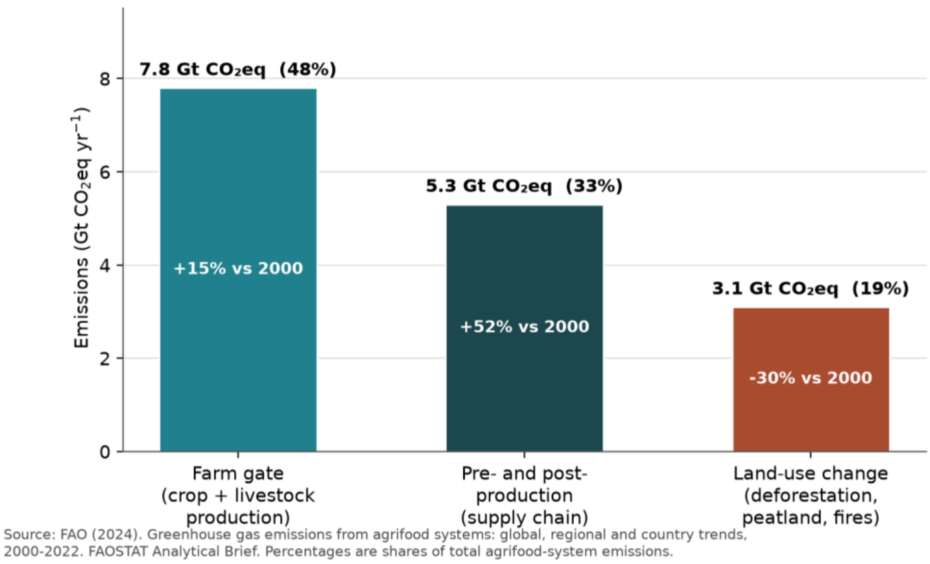

Fig. 1. Global agrifood-system greenhouse gas emissions by component in 2022. Constructed from data reported by FAO (2024); percentages denote shares of total agrifood-system emissions and arrows indicate change relative to 2000

This dual identity defines the policy problem. Adaptation, understood as adjustment in agricultural systems to moderate harm from actual or expected climatic stimuli, and mitigation, understood as reduction of greenhouse gas sources or enhancement of sinks, were long pursued as separate agendas. The climate-smart agriculture framework introduced at the 2010 Hague Conference reframed them as inseparable, pursuing three objectives concurrently: sustainably increasing productivity and incomes, building resilience to climate variability, and reducing or removing greenhouse gases wherever possible (FAO, 2013; & Lipper et al., 2014). Climate-resilient agriculture is the operational expression of that framework at farm and landscape scale.

2. CLIMATE CHANGE IMPACTS ON AGRICULTURAL SYSTEMS

2.1 Crop production and physiology

Elevated temperature shortens crop duration, curtails the grain-filling period and reduces radiation interception, while heat stress above species-specific thresholds impairs pollen viability and spikelet fertility. Meta-analytic synthesis of more than 1,700 published simulations indicates that yields of both C3 and C4 crops decline by roughly 4.9 per cent for each 1 °C rise in global mean temperature in the absence of adaptation (Challinor et al., 2014). Process-based estimates attribute yield losses of 4.1 per cent in maize and 4.5 per cent in soybean over 1981–2010 to warming, even after accounting for carbon dioxide fertilisation (IPCC, 2022a). The stimulatory effect of rising atmospheric carbon dioxide on C3 crops is real but is progressively offset by heat and water limitation and is accompanied by dilution of grain protein, zinc and iron, so that nutritional quality declines even where mass yield is maintained.

Regional signals are sharper than global means. Heat and rainfall extremes intensified by human-induced warming have reduced millet yields in West Africa by 10 to 20 per cent (Sultan et al., 2019), and farm productivity in Latin America and the Caribbean is projected to fall by 9.03 to 12.7 per cent over 2015–2050 (Lachaud et al., 2021). In South Asia, terminal heat stress during the reproductive phase of wheat and delayed monsoon onset affecting kharif sowing are the two most economically consequential expressions of climate variability. Figure 2 summarises the observed penalties on yields and productivity.

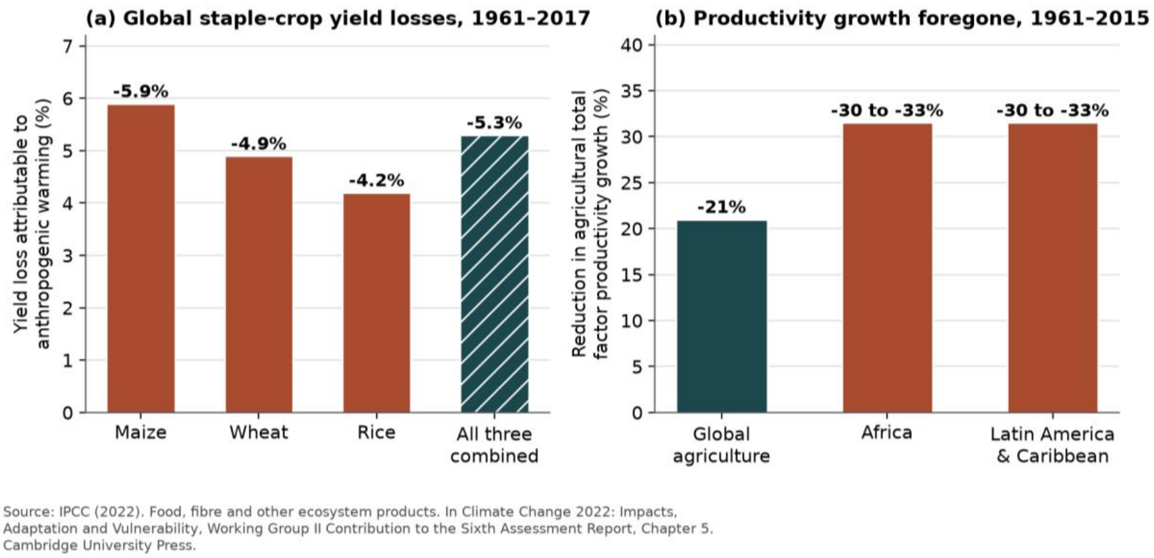

Fig. 2. Observed climate-change penalties on global staple-crop yields and agricultural total factor productivity. Panel (a) shows yield losses attributable to anthropogenic warming over 1961–2017; panel (b) shows the reduction in productivity growth over 1961–2015. Data from IPCC (2022a) and Ortiz-Bobea et al. (2021)

2.2 Soil, water and livestock systems

Warming accelerates the mineralisation of soil organic matter, depleting the carbon pool that underpins aggregate stability, cation exchange and water retention. Higher evaporative demand raises irrigation requirement precisely where surface water is becoming less reliable, and coastal salinity ingress is expanding under sea-level rise. Livestock face direct thermal stress that depresses feed intake, conception rate and milk yield, alongside indirect effects transmitted through the quantity and digestibility of forage and through the altered geography of vector-borne disease. Because livestock contribute a substantial share of farm-gate emissions while being highly climate-sensitive, they occupy the centre of both the impact and the mitigation agenda.

3. ADAPTATION STRATEGIES

3.1 Genetic and varietal adaptation

Breeding for abiotic stress tolerance remains the most scalable adaptation entry point because it requires no change in farmer practice beyond seed replacement. Marker-assisted and genomic selection have compressed the breeding cycle for drought, submergence, heat and salinity tolerance. In India, over 2,900 crop varieties were released in the decade to 2024, of which 537 were specifically bred for tolerance to drought, flood, heat, cold and salinity (Government of India, 2024). Submergence-tolerant rice carrying the Sub1 locus, short-duration pulses that escape terminal drought, and heat-tolerant wheat lines illustrate how a single trait can convert a total crop failure into a harvestable yield. Complementary strategies include shifting to inherently resilient crops such as millets, pseudo-cereals and pulses, and conserving landraces as donors of adaptive alleles.

3.2 Agronomic and crop-management adaptation

Adjusting sowing dates to realign the sensitive reproductive phase away from the period of peak heat or erratic rainfall is a low-cost, high-return adaptation. Crop diversification, intercropping and legume-based rotations spread climatic risk across species with differing stress sensitivities while improving nitrogen economy. Mulching moderates soil temperature and conserves moisture, with maize yield response in Uganda maximised at a 6 cm mulch depth (Zizinga et al., 2022). Laser land levelling, raised-bed planting and residue retention improve water-use efficiency, and in India the combination of improved varieties, diversification, laser levelling and zero tillage raised both rice and wheat yields (Khatri-Chhetri et al., 2017). Real-time contingency crop planning, which specifies alternative crops and varieties for defined delays in monsoon onset, converts these individual practices into a coherent seasonal decision system (Venkateswarlu & Shanker, 2009).

3.3 Water management adaptation

Water is the medium through which most climate risk is transmitted to the crop. In situ conservation through contour bunding, broad-bed furrows and conservation furrows, combined with ex situ storage in farm ponds and recharge structures, buffers intra-seasonal dry spells. Micro-irrigation raises water productivity substantially: global synthesis of alternate wetting and drying in rice reports a 33.9 per cent reduction in irrigation water consumption, a 20.3 per cent gain in irrigation water efficiency and a 29.6 per cent gain in water productivity for a marginal yield penalty of 1.56 per cent (Wang et al., 2024). Because such interventions simultaneously cut methane emissions, they belong to the co-benefit zone discussed in Section 5.

3.4 Information, insurance and institutional adaptation

Adaptation fails without timely information. Seasonal and extended-range forecasts translated into crop-specific agro-advisories, delivered through mobile platforms and village-level knowledge centres, allow farmers to modify sowing, irrigation and spray decisions within the operational window. Weather index-based insurance transfers residual risk that no agronomic measure can absorb, and evidence from climate-smart village pilots indicates that bundling advisories, insurance and technology adoption produces greater resilience than any single component (Aggarwal et al., 2018). Systematic review evidence further confirms that extension services are the decisive determinant of climate-smart agriculture adoption, operating in synergy with credit and secure land tenure (Zheng et al., 2024).

4. MITIGATION STRATEGIES

The agriculture, forestry and other land-use sector offers an economic mitigation potential of 8 to 14 Gt CO2eq per year over 2020–2050 at costs up to USD 100 per tonne of carbon dioxide equivalent, the largest of any sector, with roughly half arising from measures that also strengthen resilience (IPCC, 2022b). Figure 3 disaggregates this potential by option.

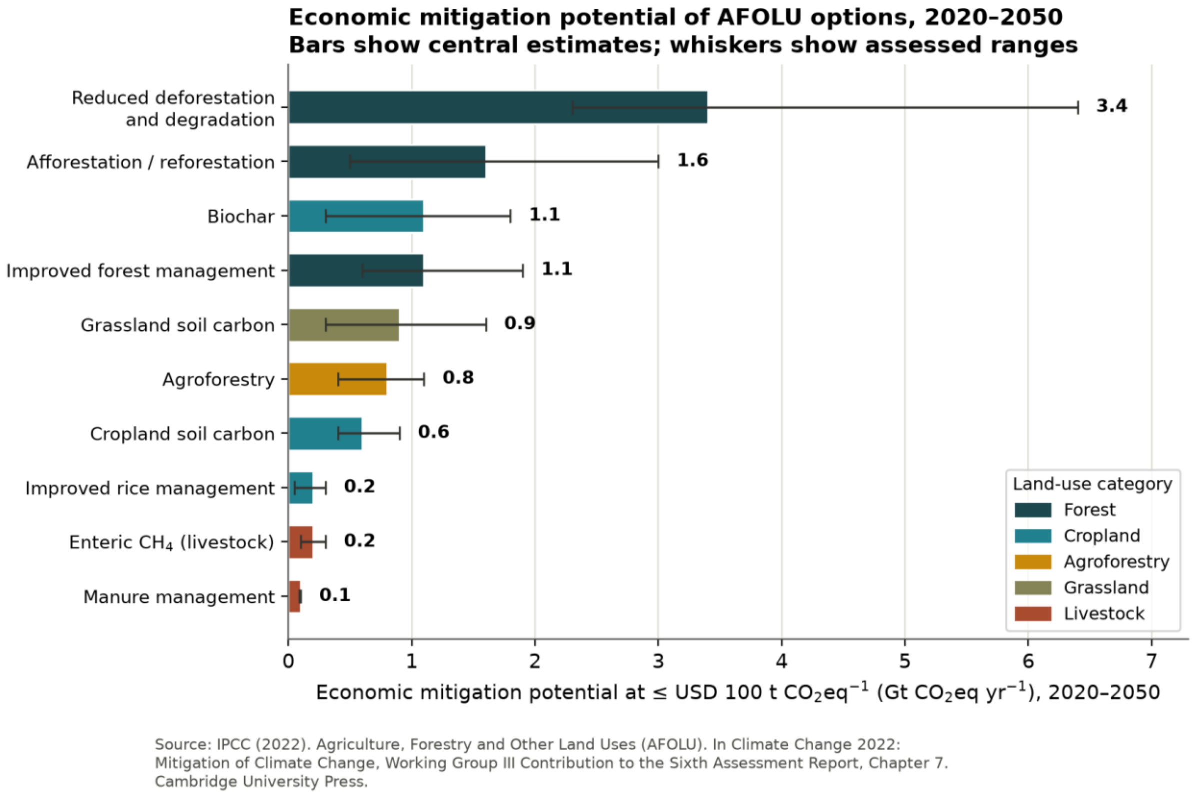

Fig. 3. Economic mitigation potential of principal agriculture, forestry and other land-use options at costs up to USD 100 per tonne CO2eq for the period 2020–2050. Bars show central estimates and whiskers the assessed ranges; compiled from IPCC (2022b)

4.1 Soil carbon sequestration and conservation agriculture

Conservation agriculture, defined by minimum mechanical soil disturbance, permanent organic soil cover and diversified crop rotation, is the flagship practice linking mitigation to resilience. Cropland and grassland soil carbon management together with agroforestry and biochar carry an economic potential of about 3.4 Gt CO2eq per year (IPCC, 2022b). Global meta-analytic estimates of sequestration under conservation agriculture range from 0.57 to 1.8 t C per hectare per year, with an average potential of 0.5 to 0.9 t C per hectare per year, and long-term no-tillage experiments in southern Brazil have recorded 1.24 t C per hectare per year over nineteen years (Corsi et al., 2012; & Lal, 2004). Adoption has expanded rapidly, from approximately 106 million hectares in 2008/09 to 205 million hectares in 2018/19, with extrapolation indicating 250 to 270 million hectares, close to 20 per cent of global cropland, by 2024 (Kassam et al., 2019; & Kassam, 2024). Figure 4 traces this trajectory.

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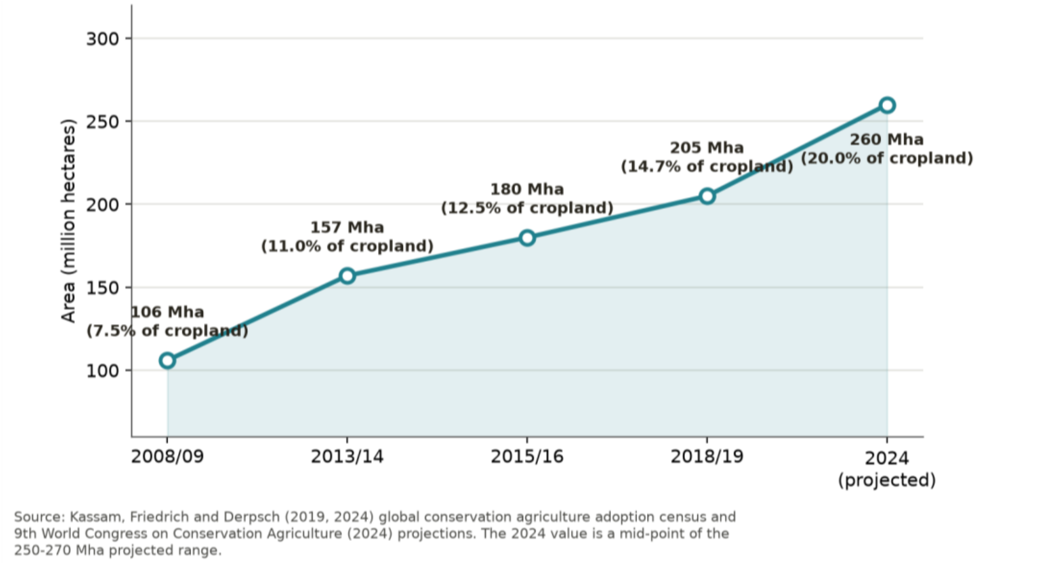

Fig. 4. Global expansion of cropland under conservation agriculture from 2008/09 to 2024. Values compiled from Kassam et al. (2019) and Kassam (2024); the 2024 figure is the mid-point of the projected 250–270 million hectare range

4.2 Methane mitigation in rice and livestock

Flooded rice is the single largest agricultural methane source amenable to management change. Alternate wetting and drying reduces methane emissions by 47 to 52 per cent and the combined global warming potential of methane and nitrous oxide by approximately 47 per cent relative to continuous flooding, although nitrous oxide emissions rise by 44 to 52 per cent, so the net benefit depends on nitrogen management and soil conditions (Zhao et al., 2024; & Wang et al., 2024). Improved rice management carries an economic potential of 0.2 Gt CO2eq per year (IPCC, 2022b). In livestock, enteric methane mitigation through improved feed quality, balanced rations, feed additives and genetic selection for feed efficiency offers 0.2 Gt CO2eq per year economically and up to 0.8 Gt CO2eq per year technically, while covered anaerobic manure storage and biogas digesters add a further 0.1 Gt CO2eq per year (IPCC, 2022b). Because most of these interventions raise productivity per animal, emission intensity per litre of milk or kilogram of meat falls even where absolute herd emissions are unchanged.

4.3 Nitrogen and nutrient management

Nitrous oxide from synthetic fertiliser and manure has a global warming potential far exceeding that of carbon dioxide, and global nitrogen use efficiency in cereals rarely exceeds half of applied nitrogen. Site-specific nutrient management guided by soil testing, leaf colour charts, chlorophyll meters and decision-support tools, combined with deep placement, split application, slow-release formulations and nitrification inhibitors, reduces emissions while sustaining or raising yield. Field evidence indicates that leaf colour charts, soil test kits, organic amendment and intermittent irrigation together raise yields by 0.7 to 1.9 t per hectare (Ariani et al., 2018), and cost-effective nutrient and water management options could abate a large share of Indian agricultural emissions at negative or zero net cost (Sapkota et al., 2019).

4.4 Agroforestry, biochar and farm energy

Agroforestry integrates woody perennials with crops and livestock, sequestering carbon in biomass and soil while diversifying income and buffering microclimate. Its economic potential is 0.8 Gt CO2eq per year against a technical potential of 4.1 Gt CO2eq per year, and trees on farms already sequester an estimated 0.74 billion tonnes of carbon dioxide annually (IPCC, 2022b; & Zomer et al., 2016). Biochar, produced by pyrolysis of crop residue, offers 1.1 Gt CO2eq per year economically, simultaneously providing a stable carbon pool, improving water retention and offering an alternative to residue burning (IPCC, 2022b; & Woolf et al., 2010). Substituting diesel pumps with solar-powered irrigation and improving on-farm energy efficiency addresses the fast-growing pre- and post-production emission component identified in Figure 1.

5. SYNERGIES, TRADE-OFFS AND ENABLING CONDITIONS

The strategic value of climate-resilient agriculture lies in the overlap between the two pillars rather than in either alone. Practices that build soil organic carbon simultaneously sequester greenhouse gases and increase plant-available water capacity, which is precisely the buffer required during intra-seasonal dry spells. Alternate wetting and drying saves water, cuts methane and lowers pumping energy. Agroforestry sequesters carbon while moderating canopy temperature and diversifying household income. A comprehensive review of climate-smart practices concluded that such measures can raise farm productivity and income, strengthen resilience and reduce emissions concurrently, although effect sizes are strongly conditioned by agro-ecology, farm size and the quality of extension support (Zheng et al., 2024). Figure 5 organises these relationships into a single framework.

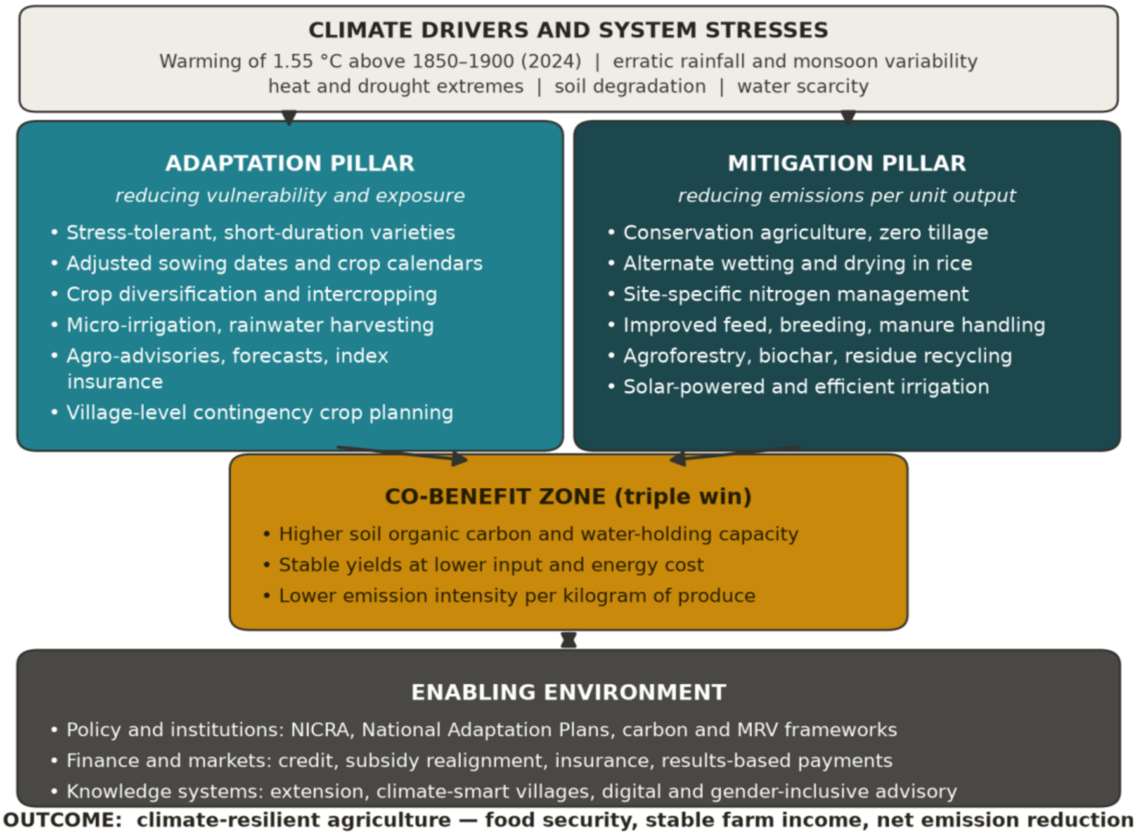

Fig. 5. Conceptual framework linking the adaptation pillar, the mitigation pillar, their co-benefit zone and the enabling environment required to deliver climate-resilient agriculture. Compiled from FAO (2013, 2024), Lipper et al. (2014), IPCC (2022b) and Venkateswarlu and Shanker (2009)

Trade-offs must nevertheless be acknowledged rather than assumed away. Alternate wetting and drying reduces methane but increases nitrous oxide, and yields a marginal yield penalty that risk-averse smallholders may reasonably refuse. Zero tillage without adequate residue cover can depress yields on poorly drained or compacted soils in early transition years. Bioenergy expansion competes with food production for land and water. Soil carbon gains are reversible on resumption of tillage, and their measurement carries genuine uncertainty, which complicates their inclusion in carbon markets. Recognising these tensions is essential because overstated co-benefits erode farmer trust once field results diverge from advisory claims.

5.1 Adoption barriers

Adoption of climate-resilient practices remains far below technical potential. The dominant constraints are the mismatch between immediate establishment costs and delayed, uncertain returns; limited access to credit and to specialised machinery such as zero-till seed drills; insecure tenure that discourages long-horizon soil investment; thin extension coverage relative to farm numbers; competing demand for crop residue as livestock fodder and household fuel; and gendered inequalities in access to land, information and inputs. Small and marginal holdings, which dominate South Asian and sub-Saharan agriculture, face the sharpest version of each constraint.

5.2 Policy and institutional enablers

Effective policy realigns incentives so that resilience becomes the rational private choice. Priority instruments include redirecting input subsidies toward practices and outcomes rather than commodities, expanding index-based insurance with transparent triggers, financing farm mechanisation through custom-hiring and service-provider models, strengthening seed systems for stress-tolerant varieties, and investing in agrometeorological infrastructure. Mission-mode public programmes demonstrate what is possible: in India, the National Innovations in Climate Resilient Agriculture initiative has combined vulnerability mapping, technology demonstration in climatically vulnerable districts and the release of stress-tolerant varieties, and district agriculture contingency plans now provide standing operational guidance for aberrant weather (Government of India, 2024; & Venkateswarlu & Shanker, 2009). Comparable approaches in West Africa underscore that climate-smart interventions must be co-designed with farmers to be adopted (Zougmoré et al., 2016). Credible measurement, reporting and verification systems, along with results-based payments, are prerequisites if the substantial soil carbon potential is to be financed at scale.

6. RESEARCH GAPS AND FUTURE DIRECTIONS

Five gaps constrain progress. First, long-term factorial experiments quantifying the joint yield, water and greenhouse gas outcomes of practice bundles across contrasting agro-ecologies remain scarce, so most published effect sizes derive from short-duration single-practice trials. Second, breeding pipelines still prioritise single stresses, whereas field conditions impose combined heat, drought and salinity stress. Third, livestock and fisheries adaptation is markedly under-researched relative to crops. Fourth, low-cost, verifiable soil carbon measurement protocols suited to smallholder plots are lacking, blocking access to carbon finance. Fifth, socio-economic analysis of who adopts, who benefits and who is excluded, disaggregated by gender, farm size and tenure, remains thin. Addressing these gaps requires multi-location networks, integration of crop, livestock and hydrological models with downscaled climate projections, and participatory on-farm research that treats farmers as co-investigators.

CONCLUSION

Agriculture stands simultaneously as the sector most exposed to climate change and as the source of nearly one-third of global anthropogenic emissions, a position that makes it indispensable to any credible climate response. The evidence assembled in this review demonstrates that anthropogenic warming has already cost global staple crops between 4.2 and 5.9 per cent of their yield and has suppressed agricultural productivity growth by about 21 per cent, while agrifood-system emissions of 16.2 Gt CO_2eq per year continue to grow within the farm gate and along the supply chain. The response cannot be sequential. Adaptation without mitigation locks in escalating hazard, whereas mitigation without adaptation exposes farm households to losses they cannot absorb.

The encouraging finding is the breadth of the overlap between the two objectives. Stress-tolerant varieties, adjusted crop calendars, diversification and micro-irrigation reduce vulnerability, while conservation agriculture, alternate wetting and drying, site-specific nutrient management, agroforestry, biochar and improved livestock husbandry reduce emissions, and a substantial subset of these practices delivers both outcomes together with higher and more stable incomes. The technical potential is large, exceeding 8 Gt CO2eq per year in the land-use sector, and the expansion of conservation agriculture to nearly 20 per cent of global cropland by 2024 shows that scaling is achievable when incentives and machinery access align.

The binding constraint is therefore not technological but institutional. Realising resilience at scale requires location-specific technology portfolios rather than universal prescriptions, subsidy and credit structures that reward resilience-building practice, insurance that absorbs residual risk, extension systems dense enough to reach smallholders, and measurement systems credible enough to attract carbon finance. Equity must be central, since the households least responsible for emissions are the most exposed to their consequences. Climate-resilient agriculture, pursued as an integrated adaptation and mitigation agenda embedded in supportive policy, offers the most practical pathway to feeding a growing population within a narrowing climatic and ecological envelope.

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