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Review Article

Climate Change and Sustainable Agriculture: Emerging Challenges and Future Perspectives

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ABSTRACT

Climate change poses significant challenges to agricultural productivity, food security, and environmental sustainability worldwide. Rising temperatures, irregular rainfall, droughts, floods, soil degradation, and increasing pest and disease pressures are affecting crop and livestock production systems. Sustainable agriculture offers promising approaches to address these emerging challenges through climate-smart practices, efficient resource management, conservation agriculture, agroforestry, precision farming, renewable energy, and resilient crop varieties. This paper highlights the major impacts of climate change on agriculture and examines innovative strategies for improving resilience and sustainability. Future perspectives emphasize technological advancements, integrated resource management, policy support, farmer participation, and climate-resilient agricultural systems for achieving long-term food security and environmental sustainability.

Keywords: *Climate change; Sustainable agriculture; Climate-smart agriculture; Food security; Adaptation and mitigation.*

INTRODUCTION

Agriculture is simultaneously a victim of climate change, a contributor to it and an indispensable part of its solution. This triple identity places the sector at the centre of the twenty-first-century sustainability agenda. The Intergovernmental Panel on Climate Change concluded that human activities have warmed the planet by approximately 1.1°C relative to the 1850–1900 baseline, and that global temperature will reach or exceed 1.5°C of warming within the following two decades under all considered emission scenarios (IPCC, 2021).

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Because crop growth, livestock physiology, soil biology and water availability are all temperature- and moisture-dependent, even modest shifts in mean climate and, more damagingly, in climate variability propagate directly into farm-level productivity and household food security. The stakes are considerable. The AR6 Synthesis Report confirmed that climate change is already widespread, rapid and intensifying, and identified food insecurity as a key global risk category (IPCC, 2023). Working Group II assessed with medium confidence that human-induced warming has already slowed the growth of agricultural productivity over the past fifty years across mid- and low-latitude regions, and that climate-related extremes have measurably reduced productivity in all agricultural and fishery sectors, with the frequency of sudden food-production losses rising since at least the mid-twentieth century (IPCC, 2022a). Under a high-emission pathway, more than 30% of the area currently used for crops and livestock could become climatically unsuitable by 2100, compared with less than 8% under a strong-mitigation pathway; approximately 10% of current areas are projected to become unsuitable as early as 2050 under a mid-range scenario (IPCC, 2022a).

These burdens are not evenly distributed. Impacts on food security, nutrition and livelihoods are most acute in sub-Saharan Africa, South and South-East Asia, small island states and the Arctic, and among small-scale food producers everywhere (IPCC, 2022a). In India, where more than half of the net sown area remains rainfed and monsoon behaviour governs the kharif season, projected increases in rainfall variability translate into direct income risk for millions of smallholders (Menon et al., 2013). At the same time, agriculture must feed a growing population while progress against hunger has stalled: between 690 and 783 million people faced hunger in 2022, a mid-range estimate of about 735 million, and the prevalence of undernourishment stood at 9.2% of the world population compared with 7.9% in 2019 (FAO et al., 2023).

Sustainable agriculture production that is simultaneously productive, resource-conserving, socially equitable and economically viable therefore has to be redefined under climatic non-stationarity. The historical assumption that yesterday's climate is a reliable guide to tomorrow's growing season no longer holds, and management recommendations, breeding targets, insurance products and policy instruments must all be recalibrated accordingly. The purpose of this review is threefold: to consolidate the observational and modelling evidence on how climate change is reshaping agricultural systems; to identify the emerging challenges that will dominate the coming decades; and to critically appraise the adaptation and mitigation pathways, together with their research and policy gaps, that constitute the future perspectives for climate-resilient agriculture. All data and literature considered here are drawn from sources published up to 2023.

2. Observed Trends in the Climate System

The physical basis of agricultural climate risk is unambiguous. The NASA Goddard Institute for Space Studies surface temperature analysis shows that the global mean surface temperature anomaly rose from about −0.18 °C in 1880 to +1.17 °C in 2023 relative to the 1951–1980 reference period, making 2023 the warmest year in the instrumental record (NASA GISS, n.d.). Warming over land exceeds the global mean, which is agronomically significant because crops and livestock experience terrestrial rather than globally averaged conditions (IPCC, 2021). Figure 1 presents the full annual series with a five-year running mean, revealing an accelerating trend since the late 1970s superimposed on interannual variability.

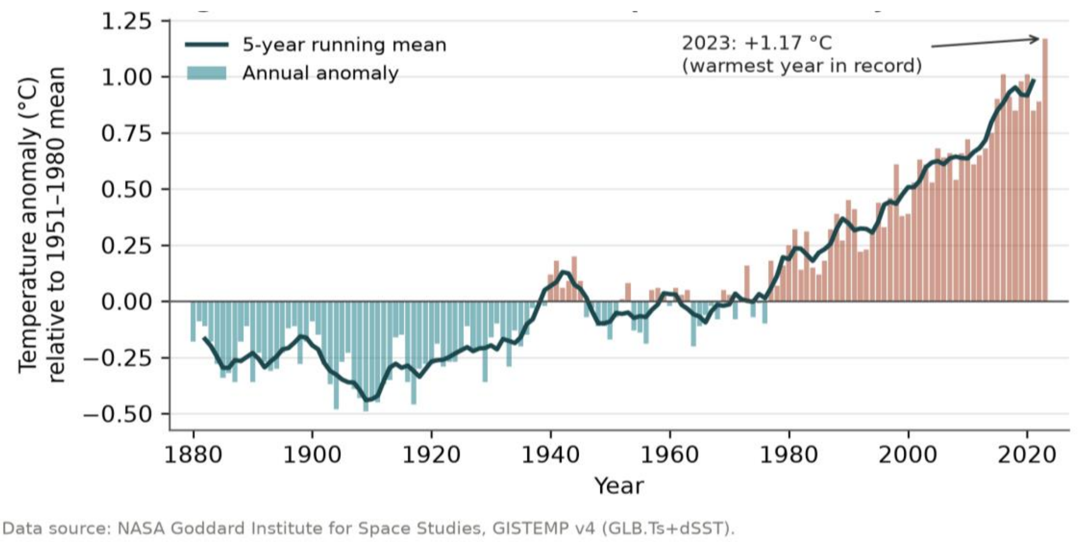

Fig.1. Global mean surface temperature anomaly, 1880–2023, relative to the 1951–1980 base period. Data source: NASA Goddard Institute for Space Studies, GISTEMP v4 (NASA GISS, n.d.)

The proximate driver of this trend is the accumulation of greenhouse gases. The Mauna Loa record, the longest continuous atmospheric carbon dioxide series available, shows an increase in the annual mean from 315.98 ppm in 1959 to 421.08 ppm in 2023 — a rise of roughly 105 ppm, or 33%, in sixty-four years (NOAA Global Monitoring Laboratory, n.d.). Critically, the rate of increase has itself accelerated, from roughly 5 ppm per decade in the 1960s to about 24 ppm over the decade to 2023 (NOAA Global Monitoring Laboratory, n.d.). Figure 2 illustrates this trajectory. Elevated carbon dioxide does exert a fertilisation effect on C3 crops such as wheat and rice, but experimental and modelling evidence indicates that this benefit is progressively offset by heat and water stress, and is frequently accompanied by declines in grain protein and micronutrient concentration.

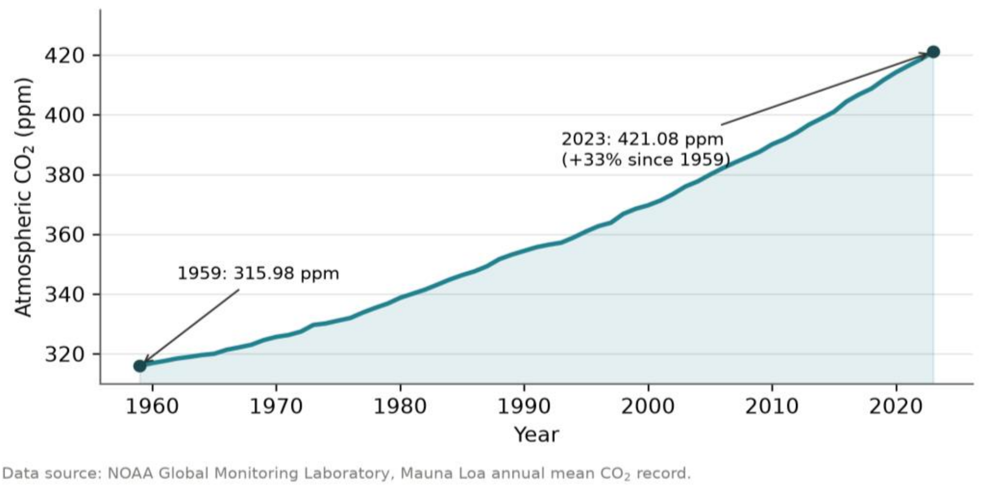

Fig.2. Annual mean atmospheric carbon dioxide concentration measured at Mauna Loa Observatory, 1959–2023. Data source: NOAA Global Monitoring Laboratory (n.d.)

Two features of these records matter most for agriculture. First, the signal is now large enough to exceed the adaptive range of many locally optimised cropping systems. Second, warming amplifies the hydrological cycle, so that the same aggregate trend manifests locally as more intense rainfall events interspersed with longer dry spells — a combination that undermines sowing decisions, irrigation scheduling and harvest logistics even where annual totals appear unchanged.

3. Emerging Challenges for Agricultural Systems

3.1 Declining crop productivity and yield stability

The most rigorously quantified impact is the temperature sensitivity of staple cereal yields. Using four independent methods — global grid-based simulations, point-based simulations, field-warming experiments and statistical regressions — Zhao et al. (2017) estimated that, in the absence of carbon dioxide fertilisation, effective adaptation or genetic improvement, each 1 °C increase in global mean temperature reduces global average yields of wheat by 6.0%, rice by 3.2%, maize by 7.4% and soybean by 3.1%. Since these four crops supply roughly two-thirds of human caloric intake, the aggregate implication for food availability is substantial (Zhao et al., 2017). An independent thirty-model ensemble reached a closely matching conclusion for wheat, projecting a 6% production decline per degree of warming together with greater spatial and temporal variability of output (Asseng et al., 2015). Figure 3 summarises these sensitivities with their reported uncertainty ranges.

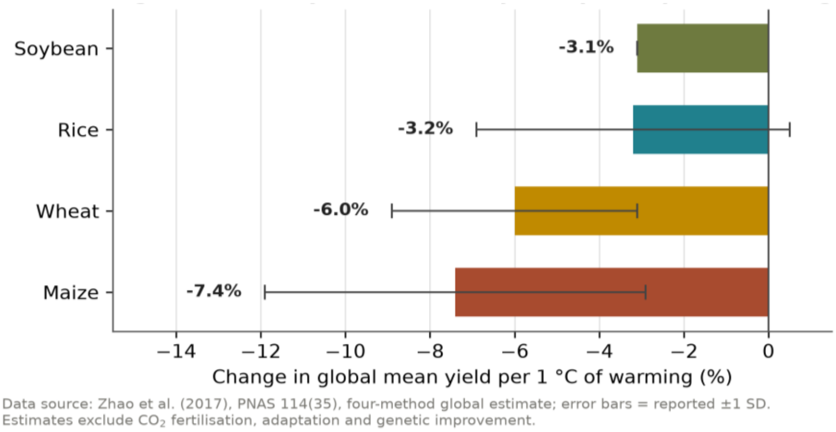

Fig.3. Estimated change in global mean yield of the four major staple crops per 1 °C of warming, with reported uncertainty. Data source: Zhao et al. (2017)

Adaptation moderates but does not eliminate these losses. A meta-analysis of crop-yield responses found that, without adaptation, aggregate production losses are expected for wheat, rice and maize in both temperate and tropical regions once local warming reaches 2 °C, whereas crop-level adaptations such as changing cultivars or shifting planting dates raise simulated yields by an average of 7–15%, with greater effectiveness for wheat and rice than for maize (Challinor et al., 2014). Increasing variability is as consequential as declining means, because it erodes the predictability on which credit, input purchase and insurance decisions depend.

3.2 Water scarcity and irrigation stress

Agriculture accounts for more than 70% of global freshwater withdrawals, the largest share of any sector (FAO, n.d.-a). Warming intensifies crop evapotranspirative demand at the same time that snowmelt-dependent and groundwater-dependent supplies become less reliable, producing a widening gap between irrigation requirement and availability. In much of South Asia, the expansion of tube-well irrigation that underpinned the Green Revolution now coexists with declining water tables, so that the conventional adaptation response of irrigating more is increasingly foreclosed. Water productivity — output per unit of water consumed — rather than land productivity alone is therefore emerging as the operative efficiency metric for sustainable intensification.

3.3 Soil degradation and loss of soil organic carbon

Soils mediate almost every climate-agriculture interaction, and they are being depleted. Warming accelerates the mineralisation of soil organic matter, while intensive tillage, residue removal and unbalanced fertilisation reduce carbon inputs; erosion, salinisation and compaction compound the loss. Because soil organic carbon simultaneously governs water-holding capacity, nutrient supply, aggregate stability and microbial function, its depletion reduces the buffering capacity of the system precisely when climatic shocks become more frequent. Lal (2004a) estimated the technical potential for carbon sequestration in agricultural and degraded soils at 0.6–1.2 Gt C per year, making soil restoration one of the few interventions that delivers adaptation, mitigation and productivity benefits simultaneously.

3.4 Shifting pest, disease and weed pressure

Biotic constraints are being redistributed by climate. Crop pests and pathogens spanning fungi, bacteria, viruses, nematodes and oomycetes have moved poleward at an average rate of 2.7 ± 0.8 km per year since 1960 (Bebber et al., 2013), exposing production regions to organisms against which local varieties and management practices were never selected. Warming also accelerates insect metabolism and voltinism. Global crop production currently loses an estimated 10–16% to insect pests, fungi and bacteria, and under 2 °C of warming, insect-driven losses are projected to increase by 46% for wheat, 31% for maize and 19% for rice, with each further degree adding a further 10–25% (Deutsch et al., 2018). Figure 4 depicts these projections. Notably, the largest proportional increases are expected in temperate regions such as Europe and North America, which include some of the world's most productive wheat belts (Deutsch et al., 2018).

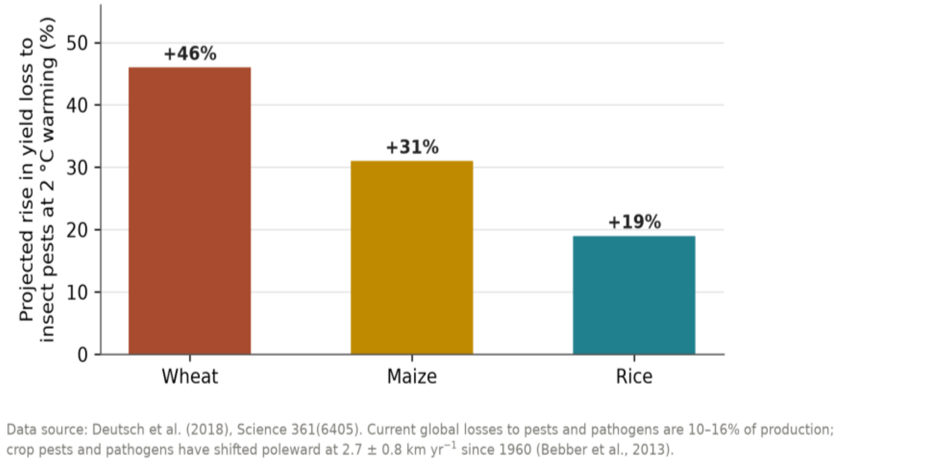

Fig.4. Projected increase in insect-pest-driven crop losses at 2°C of warming
Data source: Deutsch et al. (2018)

3.5 Livestock, fisheries and nutritional quality

Livestock systems face direct thermal stress that depresses feed intake, growth, fertility and milk yield, alongside indirect effects on forage quantity and quality and on the distribution of vector-borne disease. The IPCC assessed that at 2 °C of warming, heat extremes would more frequently exceed critical tolerance thresholds for agriculture and for human health, and that food production in already-hot lower-latitude regions would be further compromised relative to a 1.5 °C world (IPCC, 2021, & 2022a). Comparable risks apply to capture fisheries and aquaculture through ocean warming, deoxygenation and acidification. A further, often neglected dimension is nutritional: climate stress and elevated carbon dioxide can dilute the protein, zinc and iron content of staple grains, so that calorie-adequate diets may nonetheless become less nutritious.

3.6 Food security, equity and smallholder vulnerability

Aggregate production statistics conceal distributional harm. More than 3.1 billion people could not afford a healthy diet in 2021, and over 122 million more people were pushed into hunger after 2019 as pandemic, conflict and climate shocks interacted (FAO et al., 2023). Smallholders, who are typically rainfed, undercapitalised and weakly insured, bear disproportionate exposure. In flood-prone parts of India alone, more than 4.8 million people are exposed to river-flood risk annually (CEGA, n.d.). Vulnerability is thus a function of socio-economic capacity as much as of climate hazard, and adaptation that ignores tenure, gender, credit access and extension reach will not reach those most at risk.

4. Agriculture as a Driver of Climate Change

Agriculture's mitigation obligation follows from its emission footprint. Activities under agriculture, forestry and other land use accounted for approximately 23% of total net anthropogenic greenhouse gas emissions, or 12.0 ± 2.9 Gt CO2-equivalent per year, during 2007–2016; within this, the sector contributed about 13% of anthropogenic carbon dioxide, 44% of methane and 81% of nitrous oxide emissions (IPCC, 2019). When pre- and post-production activities such as processing, transport, retail, consumption and waste are included, total food-system emissions rise to an estimated 21–37% of net anthropogenic emissions (IPCC, 2019). Contemporary FAOSTAT accounting places global agrifood-system emissions at 16.2 Gt CO2-equivalent in 2022, roughly one-third of the global total and about 10% higher than in 2000 (FAO, 2023a). Figure 5 presents the gas-wise contribution.

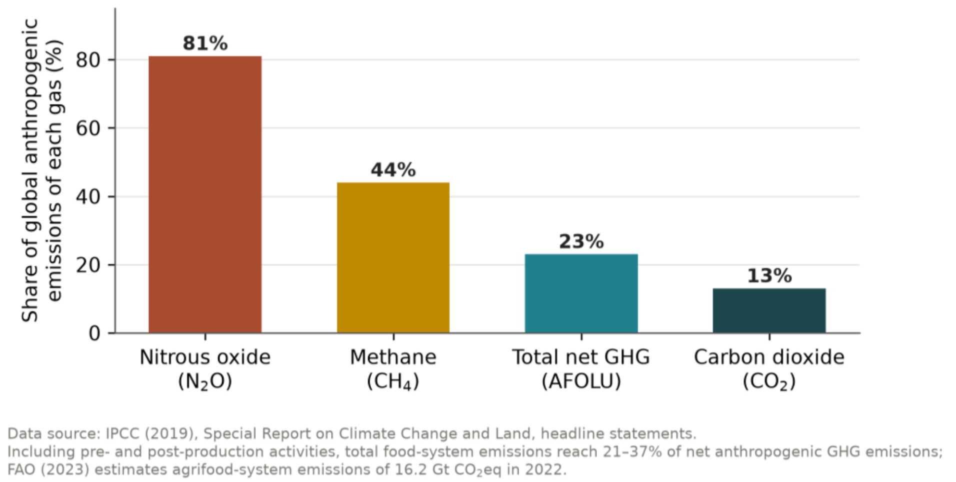

Fig.5. Contribution of agriculture, forestry and other land use to global anthropogenic greenhouse gas emissions, 2007–2016. Data source: IPCC (2019); FAO (2023a)

The gas-wise pattern is strategically important. Because methane and nitrous oxide dominate agricultural emissions, and because their principal sources — enteric fermentation, flooded rice soils, manure management and nitrogen fertilisation — are amenable to management change, targeted interventions can deliver disproportionate climate returns. Nitrous oxide deserves particular attention: manure and fertiliser nitrogen have been the dominant cause of its atmospheric increase since 1860 (Davidson, 2009), and because it has a long atmospheric lifetime and a high global warming potential, improving nitrogen use efficiency is among the highest-value mitigation levers available. The AFOLU sector's economic mitigation potential at costs up to US$100 per tonne CO2-equivalent has been assessed at 4.1 (1.7–6.7) Gt CO2-equivalent per year for agricultural measures and 7.3 (3.9–13.1) Gt CO2-equivalent per year for forests and other ecosystems over 2020–2050 (IPCC, 2022b). The land sink is also large — about 11.2 Gt CO2 per year, equivalent to 29% of total carbon dioxide emissions during 2007–2016 — but its persistence under continued warming is uncertain (IPCC, 2019).

5. Sustainable Agriculture Pathways and Response Options

Climate-smart agriculture provides the organising framework for response, integrating three objectives: sustainably increasing productivity and incomes, adapting to climate change, and reducing emissions where possible. Figure 6 synthesises the linkages between climate drivers, emerging challenges, impact endpoints and response pathways discussed in this review.

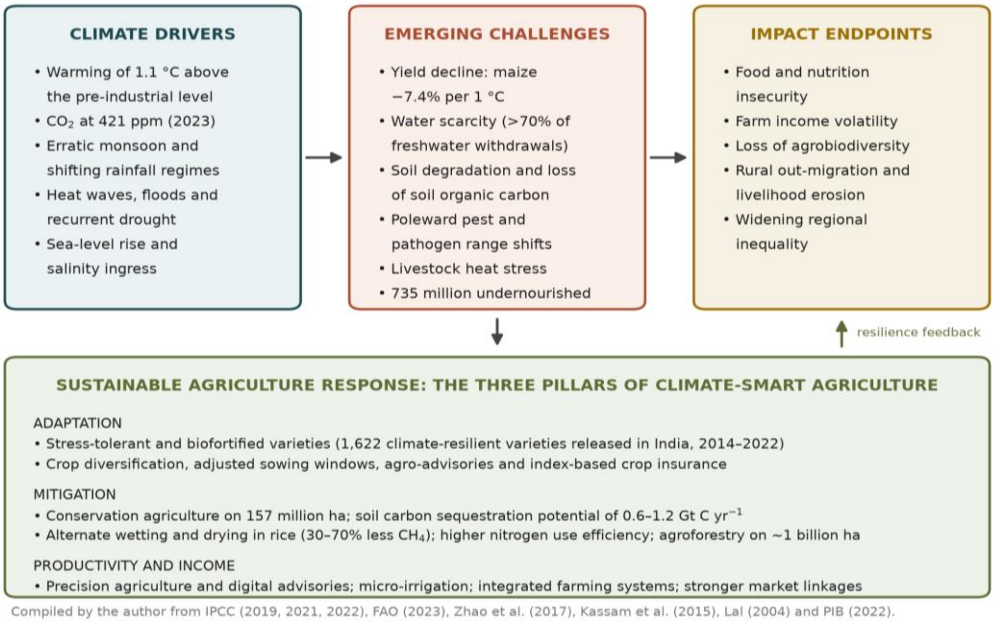

Fig.6. Conceptual framework linking climate drivers, emerging agricultural challenges, impact endpoints and climate-smart response pathways Compiled from IPCC (2019, 2021, 2022a), FAO (2023a), Zhao et al. (2017), Kassam et al. (2015), Lal (2004a) and PIB (2022)

5.1 Conservation agriculture and soil carbon management

Conservation agriculture, based on minimum soil disturbance, permanent organic soil cover and diversified rotations, expanded from 2.8 million hectares in 1973/74 to about 157 million hectares by 2013, equivalent to roughly 11% of global cropland, with the rate of expansion accelerating to about 10 million hectares per year after 2008/09 (Kassam et al., 2015). Its benefits — improved infiltration, reduced erosion, lower fuel use and rising soil carbon — align adaptation with mitigation. Complementary soil carbon strategies include organic amendment, cover cropping, integrated nutrient management and residue retention. The 4 per 1000 initiative proposes that an annual 0.4% increase in soil organic carbon stocks in the upper 30–40 cm could offset a meaningful share of anthropogenic emissions, although Minasny et al. (2017) caution that attainable rates vary greatly with climate, soil type, initial carbon status and management intensity, and that the target should be interpreted as an aspiration rather than a uniform prescription. Lal (2004b) further emphasised that soil carbon restoration is a precondition for food security in degraded tropical landscapes, not merely a carbon accounting exercise.

5.2 Water-smart and emission-smart practices

Alternate wetting and drying in rice illustrates how a single practice can address several objectives at once. By periodically draining paddies to approximately 15 cm below the soil surface before re-flooding, the practice suppresses methanogenic activity during dry phases, reducing water consumption by about 30% and methane emissions by 30–70%

without a systematic yield penalty (IRRI, n.d.). Micro-irrigation, laser land levelling, deficit irrigation and improved scheduling similarly raise water productivity. On the nitrogen side, split and site-specific application, nitrification inhibitors, deep placement and legume integration reduce nitrous oxide losses while often lowering input costs — an important consideration for adoption where subsidies distort fertiliser price signals.

5.3 Genetic improvement and crop diversification

Breeding remains the most scalable adaptation instrument. Submergence-tolerant rice carrying the SUB1 gene, exemplified by Swarna-Sub1, yields comparably to conventional varieties under normal conditions while surviving flooding for up to two weeks; seed production of such improved varieties by a single state seed corporation in Odisha, India, rose from 300 tonnes in 2012 to more than 6,000 tonnes in 2015 (CEGA, n.d.). India's National Agricultural Research System, coordinated by the Indian Council of Agricultural Research, released 1,956 field-crop varieties and hybrids between 2014 and 2022, of which 1,622 were climate-resilient, including 175 for drought and moisture stress, 43 for flood and submergence tolerance, 36 for salinity and alkalinity, 25 for heat tolerance and 7 for cold tolerance (PIB, 2022). Genome editing tools such as CRISPR/Cas systems offer a route to accelerate abiotic-stress tolerance beyond the pace of conventional selection (Zafar et al., 2020). Diversification through pulses, millets, agroforestry and integrated crop–livestock systems spreads risk; agroforestry practices already occur on more than 43% of global agricultural land, supporting the livelihoods of over 900 million people (FAO, n.d.-b).

5.4 Precision agriculture and digital advisories

Precision technologies improve resource use efficiency by matching inputs to spatial and temporal variability. Even in the most advanced adopter market, however, penetration is uneven: guidance and auto-steer systems were used on 58% of United States corn acres in 2016 and 64.5% of cotton acres in 2019, whereas variable-rate technology reached only 37.4% of corn acres in 2016 and 25.3% of soybean acres in 2018 (McFadden et al., 2023). This gradient indicates that adoption follows labour savings and immediate cost reduction more readily than agronomic optimisation, a pattern with clear implications for how climate-smart technologies should be designed and incentivised for smallholder contexts.

6. Future Perspectives and Research Priorities

Five priorities emerge from the evidence reviewed. First, adaptation and mitigation must be planned jointly rather than sequentially, since practices such as conservation agriculture, agroforestry and alternate wetting and drying deliver both, and since a mitigation-only focus risks displacing the adaptation needs of the most vulnerable producers. Second, resilience must be measured, not asserted: long-term, multi-location experiments and harmonised indicators of yield stability, water productivity, soil carbon change and net emission intensity are required to distinguish genuinely climate-smart practices from locally contingent successes. Third, scenario-consistent, downscaled regional projections remain scarce; much of the available regional yield literature aggregates heterogeneous scenarios and horizons, as in the widely cited African and South Asian meta-analysis reporting mean declines of about 17% for wheat, 15% for sorghum and 5% for maize (Knox et al., 2012; & Wheeler, 2013), which limits its use for investment planning.

Fourth, the enabling environment determines whether technical options translate into practice. Index-based insurance, climate-informed advisories delivered through mobile platforms, reform of input subsidies that entrench emission-intensive practices, secure land tenure, and results-based finance for soil carbon and methane abatement all condition adoption. Extension systems require reorientation from message delivery towards participatory co-design, since climate adaptation is inherently location-specific. Fifth, equity and nutrition must be integral objectives rather than co-benefits. Given that agrifood systems account for about one-third of global emissions (FAO, 2023a) and that hunger has stalled at 9.2% of the population (FAO et al., 2023), demand-side measures — reducing food loss and waste, moderating overconsumption of resource-intensive products in high-income settings, and diversifying diets towards climate-resilient crops such as millets — belong within the sustainable agriculture agenda alongside supply-side innovation. Persistent uncertainties, particularly the durability of the land carbon sink, the interaction of carbon dioxide fertilisation with heat and nutrient limitation, and the socio-economic determinants of adoption, define the frontier of research.

CONCLUSION

The evidence assembled in this review indicates that climate change has moved from a projected to a realised constraint on agriculture. Global temperatures reached 1.17 °C above the 1951–1980 mean in 2023 and atmospheric carbon dioxide reached 421.08 ppm, while each degree of warming is estimated to reduce maize yields by 7.4% and wheat yields by 6.0%, pest-driven losses are projected to rise sharply at 2 °C, water and soil resources are under compounding pressure, and about 735 million people remain hungry. Agriculture is also responsible for roughly a quarter of net anthropogenic emissions and the great majority of nitrous oxide, which makes it central to mitigation as well as adaptation. The technical repertoire required is largely known — conservation agriculture, soil carbon restoration, water- and nutrient-smart practices, stress-tolerant varieties, diversification and precision tools — and the binding constraints are institutional, financial and equity-related rather than purely agronomic. Sustainable agriculture under climate change must therefore be pursued as an integrated systems transformation, evaluated by resilience, emission intensity, nutritional quality and inclusiveness alongside yield. Doing so within this decade is the decisive determinant of whether food systems remain able to meet the needs of a growing population on a warming planet.

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REFERENCES

Asseng, S., Ewert, F., Martre, P., Rötter, R. P., Lobell, D. B., Cammarano, D., Kimball, B. A., Ottman, M. J., Wall, G. W., White, J. W., Reynolds, M. P., Alderman, P. D., Prasad, P. V. V., Aggarwal, P. K., Anothai, J., Basso, B., Biernath, C., Challinor, A. J., De Sanctis, G., & Zhu, Y. (2015). Rising temperatures reduce global wheat production. *Nature Climate Change*, *5*(2), 143–147. https://doi.org/10.1038/nclimate2470

Bebber, D. P., Ramotowski, M. A. T., & Gurr, S. J. (2013). Crop pests and pathogens move polewards in a warming world. *Nature Climate Change*, *3*(11), 985–988. https://doi.org/10.1038/nclimate1990

Center for Effective Global Action. (n.d.). Stress-tolerant rice in India. *University of California*, Berkeley. https://cega.berkeley.edu/feature/stress-tolerant-rice-in-india/

Challinor, A. J., Watson, J., Lobell, D. B., Howden, S. M., Smith, D. R., & Chhetri, N. (2014). A meta-analysis of crop yield under climate change and adaptation. *Nature Climate Change*, *4*(4), 287–291. https://doi.org/10.1038/nclimate2153

Davidson, E. A. (2009). The contribution of manure and fertilizer nitrogen to atmospheric nitrous oxide since 1860. *Nature Geoscience, 2*(9), 659–662. https://doi.org/10.1038/ngeo608

Deutsch, C. A., Tewksbury, J. J., Tigchelaar, M., Battisti, D. S., Merrill, S. C., Huey, R. B., & Naylor, R. L. (2018). Increase in crop losses to insect pests in a warming climate. *Science, 361*(6405), 916–919. https://doi.org/10.1126/science.aat3466

Food and Agriculture Organization of the United Nations (2023a). Greenhouse gas emissions from agrifood systems: Global, regional and country trends, 2000–2022 (FAOSTAT Analytical Brief No. 50). *FAO*. https://www.fao.org/statistics/highlights-archive/highlights-detail/greenhouse-gas-emissions-from-agrifood-systems.-global--regional-and-country-trends--2000-2022/en

Food and Agriculture Organization of the United Nations (2023b). The state of food and agriculture 2023: Revealing the true cost of food to transform agrifood systems. *FAO*. https://www.fao.org/publications/fao-flagship-publications/the-state-of-food-and-agriculture/en

Food and Agriculture Organization of the United Nations (n.d.-a). Water use: AQUASTAT methodology. FAO. https://www.fao.org/aquastat/en/overview/methodology/water-use/

Food and Agriculture Organization of the United Nations (n.d.-b). Agroforestry. *FAO*. https://www.fao.org/agroforestry/en

Food and Agriculture Organization of the United Nations, International Fund for Agricultural Development, United Nations Children's Fund, World Food Programme, & World Health Organization (2023). The state of food security and nutrition in the world 2023: Urbanization, agrifood systems transformation and healthy diets across the rural–urban continuum. *FAO*. https://doi.org/10.4060/cc3017en

Intergovernmental Panel on Climate Change (2019). Climate change and land: An IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. *IPCC*. https://www.ipcc.ch/srccl/

Intergovernmental Panel on Climate Change (2021). Climate change 2021: The physical science basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. *Cambridge University Press*. https://www.ipcc.ch/report/ar6/wg1/

Intergovernmental Panel on Climate Change (2022a). Climate change 2022: Impacts, adaptation and vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. *Cambridge University Press*. https://www.ipcc.ch/report/ar6/wg2/

Intergovernmental Panel on Climate Change (2022b). Climate change 2022: Mitigation of climate change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. *Cambridge University Press*. https://www.ipcc.ch/report/ar6/wg3/

Intergovernmental Panel on Climate Change (2023). Climate change 2023: Synthesis report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. *IPCC*. https://doi.org/10.59327/IPCC/AR6-9789291691647

International Rice Research Institute (n.d.). Alternate wetting and drying. IRRI Greenhouse Gas Mitigation in Rice. https://ghgmitigation.irri.org/mitigation-technologies/alternate-wetting-and-drying

Kassam, A., Friedrich, T., Derpsch, R., & Kienzle, J. (2015). Overview of the worldwide spread of conservation agriculture. *Field Actions Science Reports*, *8*. https://journals.openedition.org/factsreports/3966

Knox, J., Hess, T., Daccache, A., & Wheeler, T. (2012). Climate change impacts on crop productivity in Africa and South Asia. *Environmental Research Letters, 7*(3), 034032. https://doi.org/10.1088/1748-9326/7/3/034032

Lal, R. (2004a). Soil carbon sequestration to mitigate climate change. *Geoderma, 123*(1–2), 1–22. https://doi.org/10.1016/j.geoderma.2004.01.032

Lal, R. (2004b). Soil carbon sequestration impacts on global climate change and food security. *Science, 304*(5677), 1623–1627. https://doi.org/10.1126/science.1097396

McFadden, J., Njuki, E., & Griffin, T. (2023). Precision agriculture in the digital era: Recent adoption on U.S. farms (Economic Information Bulletin No. 248). *United States Department of Agriculture, Economic Research Service*. https://ers.usda.gov/sites/default/files/_laserfiche/publications/105894/EIB-248.pdf

Menon, A., Levermann, A., Schewe, J., Lehmann, J., & Frieler, K. (2013). Consistent increase in Indian monsoon rainfall and its variability across CMIP-5 models. *Earth System Dynamics*, *4*(2), 287–300. https://doi.org/10.5194/esd-4-287-2013

Minasny, B., Malone, B. P., McBratney, A. B., Angers, D. A., Arrouays, D., Chambers, A., Chaplot, V., Chen, Z. S., Cheng, K., Das, B. S., Field, D. J., Gimona, A., Hedley, C. B., Hong, S. Y., Mandal, B., Marchant, B. P., Martin, M., McConkey, B. G., Mulder, V. L., & Winowiecki, L. (2017). Soil carbon 4 per mille. *Geoderma*, *292*, 59–86. https://doi.org/10.1016/j.geoderma.2017.01.002

NASA Goddard Institute for Space Studies (n.d.). GISS surface temperature analysis (GISTEMP v4): Global land–ocean temperature index [Data set]. *National Aeronautics and Space Administration*. https://data.giss.nasa.gov/gistemp/

NOAA Global Monitoring Laboratory (n.d.). Trends in atmospheric carbon dioxide: Mauna Loa annual mean data [Data set]. *National Oceanic and Atmospheric Administration*. https://gml.noaa.gov/ccgg/trends/

Press Information Bureau, Government of India (2022, July 26). High yielding variety of seeds. *Ministry of Agriculture and Farmers Welfare*. https://www.pib.gov.in/Pressreleaseshare.aspx?PRID=1845109

Wheeler, T. (2013). Climate change impacts on global food security. *Food and Agriculture Organization of the United Nations*. https://www.fao.org/fileadmin/templates/est/meetings/climate_2013/Wheeler_CC_impacts_on_FoodSecurity.pdf

Zafar, S. A., Zaidi, S. S. A., Gaba, Y., Singla-Pareek, S. L., Dhankher, O. P., Li, X., Mansoor, S., & Pareek, A. (2020). Engineering abiotic stress tolerance via CRISPR/Cas-mediated genome editing. Journal of Experimental Botany, 71(2), 470–479. https://doi.org/10.1093/jxb/erz476

Zhao, C., Liu, B., Piao, S., Wang, X., Lobell, D. B., Huang, Y., Huang, M., Yao, Y., Bassu, S., Ciais, P., Durand, J.-L., Elliott, J., Ewert, F., Janssens, I. A., Li, T., Lin, E., Liu, Q., Martre, P., Müller, C., & Asseng, S. (2017). Temperature increase reduces global yields of major crops in four independent estimates. *Proceedings of the National Academy of Sciences*, *114*(35), 9326–9331. https://doi.org/10.1073/pnas.1701762114