CLIMATE CHANGE AND GLOBAL FOOD SYSTEMS:

ENVIRONMENTAL TRANSFORMATIONS, AGRICULTURAL IMPACTS, AND SUSTAINABILITY CHALLENGES

iSPEC INSTITUTE

ISBN:
978-625-92098-2-1

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ISBN: 978-625-92098-2-1
DOI: 10.5281/zenodo.20315426

May / 2026
Ankara / Türkiye

UBAK International Academy of Sciences Association Publishing House®

(The Licence Number of Publicator: 2014/31220)

E mail: info@ispecbooks.com

www.ispecbooks.com

ISBN: 978-625-92098-2-1

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PREFACE

Climate change has emerged as one of the most significant global challenges affecting environmental stability, agricultural productivity, and food security. Increasing temperatures, changing precipitation patterns, and extreme climatic events continue to reshape ecosystems and influence the sustainability of food production systems worldwide.

The chapters in this volume explore the multidimensional relationship between climate dynamics and global food systems from interdisciplinary perspectives. The discussion on climate dynamics and food security highlights the growing vulnerability of agricultural systems and the urgent need for adaptive strategies to ensure sustainable food access. The examination of climate change impacts on coffee production reflects the challenges faced by one of the world's most economically and socially important agricultural commodities under changing environmental conditions. In addition, the analysis of global warming and climate-related environmental changes contributes to broader discussions surrounding ecological risks, sustainability, and future environmental resilience.

By integrating perspectives from environmental sciences, agricultural sustainability, and climate studies, this volume contributes to contemporary academic discussions on global environmental transformation and sustainable development. It also offers valuable insights for researchers, policymakers, and practitioners engaged in addressing the complex interactions between climate change, agriculture, and food systems.

It is hoped that this book will serve as a meaningful academic resource while encouraging further interdisciplinary research on climate resilience, sustainable agriculture, and global food security.

Editorial Team
May, 2026
Türkiye

CHAPTER 1

THE CONVERGENCE OF CLIMATE DYNAMICS AND GLOBAL FOOD SECURITY

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CLIMATE CHANGE AND GLOBAL FOOD SYSTEMS: ENVIRONMENTAL TRANSFORMATIONS, AGRICULTURAL IMPACTS, AND SUSTAINABILITY CHALLENGES

INTRODUCTION

The world agricultural environment is now experiencing a triple challenge of unparalleled proportions, namely, the need to nourish a population that is estimated to be growing to 9.7 billion by 2050, the need to becomes acculturated to more unpredictable weather patterns, and the dire need to decrease the environmental footprint of the sector. The food calories could be forced to rise by about 70 percent without any substantial new land within the country, which would demand increased productivity on the already available agricultural land (Wanglin and Rahut, 2024; Mizik, 2021). Extreme events, irregular rainfall, increasing temperatures and soil degradation are lowering the yields and enhancing food insecurity. An estimated 40 percent of agricultural land is already in degraded states, i.e. the term sustainability is no longer sufficient at this point regenerative practices are needed to restore soils, water and biodiversity. Agriculture is therefore left in a state of paradox- on the one hand it is a major target of climate change, and on the other it is a major contributor to climate change.

Because of these changes in the cryosphere which are in the form of melting of the polar ice caps the effects are experienced well beyond the Arctic circle directly affecting the global food systems. The availability, access, utilization, and stability as the pillars of food security are undermined by the changing weather patterns and the rising sea level. In the case of other parts of the world such as South Asia and Sub-Saharan Africa, this does not follow as a projection of what lies ahead but rather lived experience of deteriorating yields and broken lives.

The curtailment of agricultural output by the anthropogenically warmed climate commenced in the period between 1981 and 2010. Scientific evaluations indicate that primary staple crop yields have already been under a substantial down-pressure in the world, as illustrated in Table 1.

Table 1. Yield Impact of Major Staples (1981–2010)

Crop	Global Yield Decline	Vulnerability Factors
Maize	4.1%	High sensitivity to heat stress during pollination.
Wheat	1.8%	Vulnerable to shifting rainfall and early-season warmth.
Soybeans	4.5%	Significant declines observed in tropical zones.

Two-thirds of the world food production may be forced out of the safe climatic space, the set of temperature and rainfall levels, by mid-century, in which agriculture has long been successfully pursued.

Sub-Saharan Africa

The rates of hunger in Sub-Saharan Africa are higher than those in the rest of the world. Maize and sorghum are some of the staple crops that are continually threatened by the increasing droughts and unpredictable flooding. The exposure rate of the smallholder farmers to climate shocks in the Sahel region is 71 percent, which is directly correlated to acute food shortages. The recent cyclones at Madagascar and Mozambique have resulted in a dramatic increase in malnutrition rates obliterating decades of food-stability.

South Asia and the Monsoon Crisis

By the end of the century South and Southeast Asia are likely to lose 31 to 34 percent of their total food and livestock production. The area is highly dependent on the monsoon and as such, it is distinctly susceptible to unreliable rainfall. The combination of great population density and extreme weather events in Bangladesh make it a situation of a compounding risk, in which one failed harvest will cause turbulence in local markets and nutritional access to millions of Bangladeshi citizens.

1. THE POLAR CATALYST: ARCTIC AMPLIFICATION AND ATMOSPHERİC FEEDBACK LOOPS

The polar ice caps act as a thermostat in the entire world. Their degradation is not a localized environmental change, it is an influential and multi-pathway driver of the agricultural crises that breadbaskets are currently experiencing all around the globe. According to recent studies, there are four interrelated processes in the Arctic, including permafrost thaw and hydrological disturbance, greenhouse-gas feedback, Arctic-boreal fire and land-cover change, and ocean biogeochemical change, and each of which has either direct or indirect implications on food production.

Ambient temperature variations in the northern latitudes and highlands result in a temperature gradient between the northern and southern latitudes.

1.1 Arctic Amplification and the Albedo Effect

There is a temperature gradient between the northern and southern latitudes as a result of variations in ambient temperature in the northern latitudes and the highlands.

Arctic warming is 2-4 times the global mean rate, which is referred to as Arctic Amplification (You et al., 2021; Esau et al., 2023). This has been accelerated by the Albedo Effect: because white ice, being the most reflective ice, melts away, leaving behind dark ocean and land surface that absorbs much more solar radiation, causing the temperature to increase more rapidly in a self-decreasing feedback loop. Both ice sheets are proven to be losing mass over the long term by satellite and modeling, and have been doing so at least since the beginning of the 21st century, strongly correlated with increasing air and ocean temperatures (Box et al., 2019). The immediate impact is particularly harmful to agriculture, as the slowing of the Atlantic Meridional Overturning Circulation (AMOC), which changes the pattern of rainfall across Europe and the Americas, and the weakening of the polar temperature gradient, which causes the jetstream to curl and stick, trapping weather patterns in place and creating long heat or freezes that destroy crop cycles.

1.2 Permafrost Thaw, Hydrology, and the Carbon Feedback Loop

Permafrost permanently frozen ground covering vast stretches of Alaska, Canada, Siberia, and the Tibetan Plateau is thawing at an accelerating rate (Tao et al., 2025; Schuur et al., 2022). This process fundamentally alters soil structure, drainage, and surface water connectivity. Abrupt thaw and the formation of thermokarst landscapes create mosaics of waterlogged and drained land, increasing the lateral export of carbon and nutrients into rivers and coastal zones affecting water quality for irrigation and fisheries alike (Schuur et al., 2022). In many Arctic-boreal regions, thaw-driven drying is increasing soil moisture deficits and amplifying wildfire risk (Kim et al., 2024; Parmentier et al., 2024).

The carbon stakes are enormous. Permafrost regions contain an estimated ~1,300 Pg of carbon; when thawed under oxygen-poor conditions, this generates methane (CH_4) a greenhouse gas with far greater short-term warming potential than CO_2 (Knoblauch et al., 2017; Schuur et al., 2022). Current modeling estimates project Arctic methane emissions reaching up to 49 Tg CH_4 per year from thawing landforms, with projected growth under continued warming (Parmentier et al., 2024; Yang et al., 2024). This permafrost carbon feedback amplifies global temperature rise and intensifies compound agricultural stresses heat, drought, pest expansion, and soil erosion across temperate and subtropical farming regions (Yang et al., 2024; Hope & Schaefer, 2015).

1.3 Arctic-Boreal Fires, Land-Cover Change, and Atmospheric Teleconnections

Rapid permafrost thaw is projected to drive abrupt increases in wildfires across western Siberia and Canada, as soil drying and reduced atmospheric humidity create ideal ignition conditions (Kim et al., 2024). These fires are not merely regional hazards: smoke and black carbon deposit aerosols far downwind across North American and Eurasian grain belts, reducing photosynthetically active radiation for crops and altering snowmelt timing.

Land-cover change in the Arctic-boreal zone also modifies regional climate extremes producing more warm spells, longer dry spells, and fewer heavy precipitation events in ways that propagate through atmospheric circulation to affect precipitation reliability in adjacent agricultural regions of Canada, the northern United States, and northern Eurasia (Li et al., 2025; Box et al., 2019; Malik et al., 2025).

1.4 Ocean Biogeochemistry and Coastal Food Systems

Greater discharge of river systems in the north leads to the higher loads of carbon and nutrients in coastal water, altering the marine productivity and fisheries upon which food systems rely along the North Atlantic and North Pacific (Box et al., 2019; Esau et al., 2023; Parmentier et al., 2024). The release of methane through thawing marine sediments can also contribute to the local acidification, stressing calcifying species like shellfish, and has knock-on consequences on fisheries and food security and income of coastal populations (Parmentier et al., 2024).

1.5 Geographic Mapping of Agricultural Risk

Arctic change threatens agriculture not primarily through local cropping loss at high latitudes, but by amplifying global warming, destabilizing hydrology, intensifying fire regimes, and disrupting ocean biogeochemistry. Table 2 maps the key Arctic processes to their most directly at-risk agricultural regions.

It is also statistically correlated with interannual variations in the main crop yields in China (rice, maize, wheat and soybean) associated with the effect of Arctic sea-ice on the Arctic Oscillation and Eurasian temperature patterns (Chen and Sun, 2022). This worldwide connection highlights Arctic change is no longer an issue of remote worry among the agriculturalists of the tropics or subtropics, but a current contributor of unpredictability in yields in some of the most valuable food producing countries in the world today.

Table 2. Arctic Processes and Their Agricultural Risk Regions

Arctic Process	Most Affected High-Latitude Regions	Downstream Agricultural Risk Regions
Permafrost thaw, hydrology & fires	Alaska, western & eastern Siberia, Canadian boreal	Canadian Prairies, US Midwest, northern Europe, western Russia
Methane/CO_2 feedbacks	Pan-Arctic permafrost belt, wetlands & lakes	All major grain belts via added warming and extremes
River discharge & coastal change	Arctic coasts of Russia, Canada, Greenland	North Atlantic & North Pacific fisheries; coastal food systems

2. THE FRAMEWORK OF RESILIENCE: DEFINING CLIMATE-SMART AGRICULTURE

Climate-Smart Agriculture (CSA) is a complex method of landscape management, which involves managing landscapes (cropland, livestock, forests, and fisheries) in response to the interconnected problem of food security and fast climate change. CSA is extensively advocated as the means of increasing the resilience of the farming systems as well as maintaining the food production and reducing greenhouse gas (GHG) emissions. This has been narrowed down recently by focusing on vulnerability, social equity, and wider climate-resilient agriculture models.

2.1 The Three Pillars of CSA

Most research converges on CSA as a three-pillar framework:

- Productivity: Sustainably increase agricultural productivity and incomes.
- Resilience: Strengthen adaptation and resilience of people and food systems to climate change.
- Mitigation: Reduce or avoid GHG emissions where possible.

Table 3. Key Elements of CSA and Resilience

Dimension	What it Emphasizes
Productivity & Income	Higher yields, resource efficiency, and farm profitability.
Resilience & Adaptation	Coping with shocks; food security; livelihood stability.
Mitigation	Lower GHG, carbon sequestration, "net zero" potentials.
Social Equity	Who benefits/loses; smallholders; preventing maladaptation.

2.2 From Climate-Smart to Vulnerable-Smart and Climate-Resilient Agriculture

Critiques state that the traditional CSA may not capture the local realities of small-scale farmers, which will result in maladaptation in the event that the benefits are concentrated among the more advantaged groups. This has resulted in the evolution of framing:

- Vulnerable-Smart Agriculture (VSA): Re-conceptualizes resilience in terms of the capacity of the smallholder to anticipate the incidence, quantify the effects, and recognize coping mechanisms, expressly putting their voices to the forefront of decision-making (Azabi et al., 2021).
- Climate-Resilient Agriculture (CRA): Makes holistic agro-ecosystem resilience measurements (productivity, income, adaptability, green development) through multi-indicator measurements (Zong et al., 2022).
- Transformative Approaches: As opposed to making technical fixes, emphasize addressing structural inequity and power relations (Hellin et al., 2023; Dougill et al., 2021).

2.3 Practical Implementations

Transitioning to a climate-smart system involves a portfolio of site-specific practices:

- Regenerative Agriculture: Focusing on minimal soil disturbance (zero-tillage) to restore soil organic carbon.
- Agroforestry: Integrating trees and shrubs into crop and livestock systems to provide shade and windbreaks.

- Integrated Pest Management (IPM): Utilizing biological controls and resistant varieties to reduce chemical dependency.

3. THE DIGITAL RENAISSANCE: DRONE FARMING AND PRECISION MONITORING

Drone farming is now a fast-growing technology that has been developed as a significant part of precision farming, radically changing the approach of crops monitoring and managing.

Unmanned aerial vehicles (UAVs) allow farmers to observe crop and soil conditions in high-resolution and in real-time, and therefore provide greater productivity without a higher input consumption and environmental effects of farms. In the CSA framework, drone-based systems will lead to efficiency of resource utilization, climate variability resilience and reduction of emissions.

3.1 Global Deployment Patterns

The use of UAVs in agriculture is now common but not uniform geographically, and the use has been concentrated in three situations. Massive drone fleets used to protect plants on rice, wheat, maize, orchards, and in hilly-terrain settings (especially in China, Japan, or South Korea) are known to use drones because the challenging topography makes ground-based equipment impractical (Kim et al., 2019; Aslan et al., 2022; Nahiyoon et al., 2024). UAVs are mostly involved in monitoring and mapping in maize, soybean, wheat, vineyards, orchards, and vegetables on commercial farms and research stations in North America and Europe, with the repeat flights spanning hundreds of hectares (Istiak et al., 2023; Olson and Anderson, 2021; Kelleen et al., 2024). In smallholder systems in developing countries of Africa, Asia, and Latin America, early adoption is growing in irrigation scheduling, NDVI health mapping, and water productivity management systems, but at smaller scales (Gokool et al., 2023; Nhamo et al., 2020).

3.2 Crop and Soil Monitoring

UAVs are fitted with RGB, multispectral, hyperspectral, and thermal cameras, which enable them to identify small-scale changes in canopy vigor, water stress, nutrient deficiencies, pest infections, and disease occurrence before they manifest themselves. The vegetation indices including NDVI calculated using drone images enhance the promptness of detecting stress and maximizing agronomic treatment. UAV-based multimodal data fusion and deep learning prediction of soybean and corn yield have reported R 2 in the range of 0.7 to 0.8, which allows the targeted area of input to be done better within-field (Maimaitijiang et al., 2020; Killeen et al., 2024). Image-based CNN models on edge devices have also been shown to be more than 90-percent accurate in classifying crops and counting canopies as well as detecting pests (Chamara et al., 2023). This ability has been found especially useful in climate stress conditions, where the ability to respond quickly to heat or moisture extremes is essential.

3.3 Precision Spraying

Spraying of the pesticides, herbicides, fertilizers, and biological control agents can be applied site-specifically through drone based variable-rate spraying systems. Reviews of plant protection UAVs in East Asia are consistent in reporting higher operation efficiency and profitability when compared to ground based sprayers, particularly over rough or terraced landscapes due to lowered labour needs, faster turnaround time and reduced chemical oversprays (Kim et al., 2019; Aslan et al., 2022; Nahiyoon et al., 2024). On a larger level, a secondary meta-analysis of published UAV case studies revealed that farms using drones experience a reduction in the use of agrochemicals by about 2030 percent without affecting or worsening their control ability (Guebsi et al., 2024). The decreased chemical drift and the exposure to fewer operators contribute even more to the environmental and occupational safety.

3.4 Performance Measured: Yield, Water and Cost

In various crops and areas, there is synthesized evidence of substantial and significant benefits of UAV-assisted farm management.

An average 1520 percent yield improvement, a reduction of around 30 percent in water usage and a decrease of 1015 percent in operations on UAV-assisted farms compared to conventional farming were determined by a secondary meta-analysis of published case studies (Yeragera, 2024). Water productivity is also enhanced by UAV-controlled irrigation and water stress mapping in the smallholder systems to improve the estimation and scheduling of evapotranspiration (Gokool et al., 2023; Nhamo et al., 2020). Regardless of this positive development, cost-benefit datasets that are rigorously quantified and crop-and-country-specific are relatively rare and their wider implementation will require affordable, service-based models, better data workflows, and facilitating regulatory environment (Gokool et al., 2023; Guebsi et al., 2024).

Table 4. UAV Operational Roles and Performance Evidence

Role	**Dominant Regions / Crops**	**Key Performance Evidence**
Crop health & stress mapping	Maize, soybean, wheat, vegetables, orchards (N. America, Europe)	R^2 ~0.7–0.8 for yield prediction; improved input targeting (Maimaitijiang et al., 2020; Killeen et al., 2024)
Precision spraying	Rice, wheat, maize, orchards (esp. China, Japan)	Higher operational efficiency vs ground sprayers; reduced labor and chemical overuse (Kim et al., 2019; Nahiyoon et al., 2024)
Irrigation & water management	Smallholder cereals & vegetables (Africa, S. Asia)	Improved water productivity via ET estimates and scheduling (Gokool et al., 2023; Nhamo et al., 2020)
Overall UAV-aided farms (meta-analysis)	Multiple crops and regions	~15–20% average yield increase, ~30% water use reduction, ~10–15% lower operational costs (Yeragera, 2024)

4. SMART FARMING: INTERNET OF THINGS, AUTOMATION, AND ARTIFICIAL INTELLIGENCE

Smart farming is a paradigm shift in agricultural management and consists of a combination of Internet of Things (IoT) sensors, automated control systems, and artificial intelligence (AI) to form production systems that are constantly controlled and partially autonomous. Instead of periodic inspection and decision-making processes, smart farming allows collecting data and responding to it in real time, which allows farmers to maximize water, nutrients, energy, and labor and sustain or even improve yields.

4.1 IoT -Sensed and Connected

Smart farming is based on a network of soil moisture, soil temperature, humidity, light intensity, nutrient status, and, in certain situations, pest or disease indicators sensors.

The wireless sensor networks offer high frequency site-specific data, which can be used to capture spatial and temporal variation in a much better way than the traditional sampling. The delivery of these data streams is done via connectivity infrastructures such as LoRaWAN, 5G, Wi-Fi, and hybrid edge cloud. In this case, smallholder and commercial LoraWAN networks, in particular, have proven to be an affordable option to monitor fields in geographically distributed farms in real time at low energy costs (C et al., 2025). To minimize latency and bandwidth requirements, edge computing will enable preliminary data processing effectively near the field and cloud platforms will enable large-scale storage, integration, and analytics.

Drone farming has rapidly evolved from an experimental technology into a core component of precision agriculture, fundamentally transforming how crops are monitored and managed. Unmanned aerial vehicles (UAVs) enable high-resolution, real-time observation of crop and soil conditions, allowing farmers to increase productivity while reducing input use and environmental impact. Within the CSA framework, drone-based systems contribute directly to resource-use efficiency, resilience to climate variability, and emission reduction.

4.2 AI and Machine Learning: Model Types and Accuracy

The intelligence layer, powered by AI and machine learning, transforms raw sensor data into actionable insights. Several model architectures have demonstrated particularly strong results. Tabular deep models including Transformers and TabNet achieve approximately 99 percent accuracy in irrigation, soil, and fertilizer recommendation decision tasks, enabling fine-grained input control (Khaliq et al., 2025). Random Forest, linear regression, and LSTM models used for yield prediction and vegetation forecasting reach 95–96 percent accuracy in field conditions (Saha et al., 2025). CNN and deep CNN image models consistently achieve greater than 90 percent accuracy in crop classification, canopy cover estimation, counting, and pest and disease detection (Gurajada & Autade, 2025; Chamara et al., 2023). Crucially, AI enables anticipatory management forecasting risks before visible damage occurs a capability of particular value under the increasingly erratic weather patterns associated with climate change.

4.3 Field-Scale Deployments and Measured Outcomes

Moving beyond laboratory conditions, several field-scale deployments have now generated quantified results. End-to-end IoT–AI smart farm architectures integrating soil-climate sensor networks with edge computing and ML-based decision systems have reported +35 percent crop yield, +40 percent resource utilization efficiency, and −35 percent operating costs relative to conventional management (Gurajada & Autade, 2025). A combined LoRaWAN sensor network and UAV imaging system driven by AI analytics achieved +15 percent yield, −25 percent water use, and −20 percent pesticide use in field trials (C et al., 2025). A large-scale smart irrigation deployment in California using soil moisture and weather sensors with AI scheduling cut water use by 20 percent and raised yields by 15 percent (Singh et al., 2025). At the 5 ha scale, a modular IoT–AI wheat platform achieved 30 percent reduction in water use and 92 percent accuracy in early disease detection (Irfan et al., 2025). The most striking water savings come from integrated land mapping and fuzzy control systems combining satellite data with IoT sensors and LSTM models, reporting approximately 61 percent water savings and faster automated irrigation response (Saha et al., 2025).

4.4 Barriers to Large-Scale Adoption

Regardless of these constantly good outcomes, there are various limitations of its wide-scale application. Initial costs of investment, technical skills, network constraints in rural areas and problem of interoperability among platforms are still a significant impediment. Issues regarding data ownership, privacy and cybersecurity are rising with farms becoming more data-dense systems. The evidence in large part is based on short term trials or controlled settings, and thus long-term, large-scale validation is necessary, especially in the context of smallholder and resource-constrained settings where potential benefits are the highest, but the infrastructure to implement them is lacking.

Table 5. Representative Field-Scale IoT–AI Deployments and Outcomes

Deployment / Focus	Main Technology Stack	Key Outcomes vs Baseline
IoT–AI smart farm (end-to-end)	Sensors + edge computing + ML (yield, disease, irrigation)	+35% yield, +40% resource efficiency, –35% operating costs (Gurajada & Autade, 2025)
LoRaWAN + drone precision agriculture	LoRaWAN field sensors, UAV imaging, AI analytics	+15% crop yield, −25% water use, −20% pesticide use (C et al., 2025)
Smart irrigation – California	Soil moisture & weather IoT + AI irrigation scheduling	−20% water use, +15% yield (Singh et al., 2025)
Wheat smart farm pilot (5 ha)	Modular IoT–AI platform	−30% water use, 92% early disease detection accuracy (Irfan et al., 2025)
Integrated land mapping + fuzzy irrigation	Satellite + IoT + RF/LR/LSTM + fuzzy control	~61% water savings, faster automated control response (Saha et al., 2025)

5. DECOUPLING PRODUCTION: VERTICAL FARMING AND SOILLESS SYSTEMS

Vertical agriculture and the use of soilless agriculture technologies are a significant break with the traditional soil-based farming by actively separating crop production and land availability, weather effects, and natural soil dynamics. These systems depend on environments that are highly controlled, growing structures that are stacked upwards and recycled nutrient solutions to ensure that they are highly productive and resource-use efficient. With the pressure of climate change, urbanization, and soil degradation extracting a higher toll on the traditional farming systems, vertical agriculture and hydroponics are rapidly being called upon as climate-resilient solutions to grow high-value crops. The company has been pioneering in its global operations and crop concentration.

5.1 Leading Global Operations and Crop Focus

The majority of quantified information on performances is based on commercial or near-commercial leafy green systems that run in North America, Europe, and East Asia. City-states which are heavily dependent on food imports such as Singapore are major adopters, as well as large-scale operations in the Netherlands, the United Kingdom, Sweden, Japan, and the United States (Pensis et al., 2025; Van Delden et al., 2021). The primary products include lettuce and other leafy greens, herbs, and a few strawberries; research is in progress to introduce wheat and other cereals, but these are still pre-commercial (Zhu and Marcelis, 2023; Singh et al., 2025; Lubna et al., 2022). Other large vertical operations like AeroFarms and companies report a 10 to 390 productivity of land used to grow leafy greens (Singh et al., 2025; Van Delden et al., 2021). In an experimental study, wheat grown in an Infarm vertical facility achieved 11.7 kg grain m^2/year - or around 117 tonnes per hectare/year - hundreds of times the usual field yields - at a very high cost of electricity (Zhu & Marcelis, 2023).

5.2 Water-Use efficiency and Productivity

In the case of the commercially most developed crop, lettuce, commercial vertical farms obtain 60 to 105 kg fresh weight m 2 -1 per year, which is three to four times less than that of temperate open-field regimes (Pennisi et al., 2025; Van Delden et al., 2021). One of the strongest benefits is water-use efficiency: a vertical farm consumes about 7 litres of water per kilogram of lettuce grown, which means that it does not use more than 90 percent of water compared to open-field growing that requires 100 to 250+ litres per kilogram (Pinis et al., 2025; Singh et al., 2025). In comparative research, they claim that the yield is increased by 80 percent and that water saved in hydroponic and aquaponic systems is considerable as compared to soil production (Alizaeh et al., 2025). Closed-loop fertigation allows precise control of nutrient concentrations and minimizes leaching losses, making these systems particularly attractive in water-scarce or salinity-affected regions.

5.3 The Energy and Carbon Trade-Off

The critical limitation of vertical farming is its high electricity demand for artificial lighting and climate control. Life cycle assessment (LCA) studies consistently reveal that, under typical energy mixes, vertical farms carry a substantially higher carbon footprint than open-field or greenhouse production. A Dutch cradle-to-grave LCA of lettuce found vertical farming generating 2.9 kg CO_2e per kg fresh weight, compared with 0.19 to 0.46 kg CO_2e per kg for open-field and greenhouse systems, with electricity dominating all impacts (Blom et al., 2022; Pennisi et al., 2025). A Scottish case study similarly found vertical farming emitting 1.49 kg CO_2e per kg under the 2019 grid mix, falling to 0.42 kg CO_2e per kg under the more renewable 2020 grid—comparable to UK field lettuce (0.46 kg CO_2e per kg)—and reaching 0.33 kg CO_2e per kg under a 100 percent renewable energy scenario (Sandison et al., 2022). A large-scale Swedish commercial vertical farm showed lower GHG emissions than imported lettuce, though higher impacts in some categories due to electricity and infrastructure demands (Martin et al., 2023).

5.4 Renewable Energy Integration and the Path to Climate Competitiveness

The research consensus is unambiguous: vertical farming only becomes clearly climate-competitive when powered by very low-carbon energy sources (Pennisi et al., 2025; Stanghellini & Katzin, 2024; Lovat et al., 2025). Scenario modelling across contrasting energy contexts—Norway, China, and Dubai—confirms that near-carbon-free electricity allows vertical farming to match or outperform imported lettuce on CO_2e, but economic viability remains contingent on energy prices and the efficiency of LED lighting and HVAC systems (Ceccanti et al., 2025).

In response, recent research highlights a growing portfolio of renewable integration strategies: solar photovoltaic and wind coupling, waste heat recovery, demand response systems, and integration with municipal energy and waste networks (Erekath et al., 2024; Aborujilah, 2025; Kabir et al., 2023).

Agrivoltaic case studies embedding a vertical farm within a PV greenhouse have demonstrated a 13-fold increase in land productivity, with on-site PV covering 7 to 18 percent of the vertical farm's energy requirements though trade-offs between panel area and crop area persist (Cossu et al., 2023). AI-driven environmental control systems are also being deployed to minimize kilowatt-hours per kilogram of produce, gradually closing the gap between the technology's extraordinary productivity potential and its current carbon liability.

Table 6. Key Performance Metrics for Vertical Farming vs. Conventional Production (Lettuce)

Metric (Lettuce)	Vertical Farms (Typical)	Conventional Open Field
Yield (kg fresh weight m^{-2} yr^{-1})	60–105	~3–4 (temperate field)
Water use (L kg^{-1} fresh weight)	~7	100–250+
GHG (kg CO_2e kg^{-1} fresh weight)	~1.5–3.0 (current energy mix)	~0.3–0.5

6. SCALING RESILIENCE: POLICY, SOCIO-INSTITUTIONAL SUPPORT, AND DIGITAL ADVISORY

The transition to CSA requires a robust enabling environment beyond simple field-level changes. Three interconnected domains determine whether innovations reach the farmers who need them most.

- Socio-Institutional Support: Farmers require secure land tenure, access to credit, and climate-risk insurance to justify the initial investment in new technologies like drones or IoT sensors.
- Digital Advisory Services: ICT-based tools can provide smallholder farmers with real-time weather alerts and market information, significantly boosting their adaptive capacity.
- Policy Integration: A bridge must exist between global climate science (e.g., monitoring polar ice) and local farm-level decision-making to ensure long-term resilience.

Table 7. Climate-Smart Policy Strategies

Strategy	Climate Benefit	Economic Benefit
Zero Tillage	Reduces CO_2 release from soil	Lowers fuel and labor costs
Precision Nitrogen	Reduces N_2O (potent GHG)	Decreases input expenses
Diversified Cropping	Enhances biodiversity	Stabilizes income via risk-spreading

CONCLUSION

The clash of climatic processes with the world food security is the characteristic challenge of the 21 st century. The cryosphere melting serves as a catalyst to the global processes, not only due to the well-reported processes of sea-level rise and jet stream disturbance, but also due to the growingly important permafrost carbon feedbacks, Arctic-boreal fire regimes, and ocean biogeochemical restructuring that enhance warming and destabilize world breadbasket precipitation patterns. These are not risks in the future, they are present, available and quantifiable drivers of yield instability.

It is against this background that Climate-Smart Agriculture, precision UAV technology, AI-based IoT systems and soilless vertical production offers a plausible and more and more evidence-based way forward. Field-scale implementations invariably deliver double-digit productivity gains and significant savings on inputs in a wide range of agricultural settings, such as LoRaWAN-linked wheat farms realizing 30 percent water savings to East Asian plant-protection drone fleets that are reshaping terraced rice production. Although with an energy cost, vertical farming shows order-of-magnitude land and water productivity increases that would be climate-competitive with renewable energy systems.

The final success indicator will be whether these innovations will be adopted by the most vulnerable group of farmers, the smallholders, who will be impacted by the changing climatic safe space. It is not enough that technological maturation takes place.

This potential requires policy frameworks that are inclusive in order to harness the full potential of these systems including land tenure, financing, digital infrastructure and equitable access- and closing the gap between global Arctic science and local decisions made at the farm level. This crossroads requires a level of scientific knowledge, institutional capacity and political will never before seen.

REFERENCES

Aborujilah, A. (2025). Towards Sustainable Vertical Farming: A Systematic Review of Energy Return on Investment Efficiency and Optimization Strategies. Sustainability. https://doi.org/10.3390/su17188142

Alizaeh, P., Sodaeizade, H., Arani, A., & Hakimzadeh, M. (2025). Comparing yield, nutrient uptake and water use efficiency of Nasturtium officinale cultivated in aquaponic, hydroponic, and soil systems. Heliyon, 11. https://doi.org/10.1016/j.heliyon.2025.e42339

Aslan, M., Durdu, A., Sabancı, K., Ropelewska, E., & Gültekin, S. (2022). A Comprehensive Survey of the Recent Studies with UAV for Precision Agriculture in Open Fields and Greenhouses. Applied Sciences. https://doi.org/10.3390/app12031047

Azadi, H., Moghaddam, S., Burkart, S., Mahmoudi, H., Passel, S., Kurban, A., & López-Carr, D. (2021). Rethinking resilient agriculture: From Climate-Smart Agriculture to Vulnerable-Smart Agriculture. Journal of Cleaner Production, 319, 128602.

Bakirov, K., Tussupov, J., Tultabayeva, T., Makangali, K., Abdikerimova, G., & Yessenova, M. (2024). Advances in the design and optimization of smart irrigation systems for sustainable urban vertical farming. Scientific Journal of Astana IT University. https://doi.org/10.37943/20nnyr9391

Blom, T., Jenkins, A., Pulselli, R., & Van Den Dobbelsteen, A. (2022). The embodied carbon emissions of lettuce production in vertical farming, greenhouse horticulture, and open-field farming in the Netherlands. Journal of Cleaner Production.

Box, J., Colgan, W., Christensen, T., Schmidt, N., Lund, M., Parmentier, F., … & Olsen, M. (2019). Key indicators of Arctic climate change: 1971–2017. Environmental Research Letters, 14. https://doi.org/10.1088/1748-9326/aafc1b

C, J., B, M., J, J., K, H., E, J., & D, K. (2025). AI-Driven IoT-Enabled Precision Agriculture: Optimizing Resource Usage with LoRaWAN and Drone-Based Monitoring. 2025 International Conference on Data Science, Agents & Artificial Intelligence (ICDSAAI), 1–5.

Ceccanti, F., Bischi, A., Desideri, U., & Baccioli, A. (2025). Beyond yield: integrating energy, water, cost, and carbon to benchmark indoor vertical farming viability. Energy Conversion and Management.

Chamara, N., Bai, G., & Ge, Y. (2023). AICropCAM: Deploying classification, segmentation, detection, and counting deep-learning models for crop monitoring on the edge. Computers and Electronics in Agriculture, 215, 108420. https://doi.org/10.1016/j.compag.2023.108420

Chate, G., Bhosale, H., Bhagat, S., & Chaudhari, S. (2025). Smart Farming: An Integrated Approach Using IoT and AI. International Journal on Science and Technology. https://doi.org/10.71097/ijsat.v16.i2.4321

Chen, D., & Sun, Q. (2022). Impact of rapid Arctic sea ice decline on China's crop yield under global warming. Environment, Development and Sustainability, 26, 1263–1280. https://doi.org/10.1007/s10668-022-02757-x

Cossu, M., Tiloca, M., Cossu, A., Deligios, P., Pala, T., & Ledda, L. (2023). Increasing the agricultural sustainability of closed agrivoltaic systems with the integration of vertical farming: A case study on baby-leaf lettuce. Applied Energy. https://doi.org/10.1016/j.apenergy.2023.121278

Dong, C., & Ren, S. (2025). Research on Precision Agriculture Monitoring System Based on Internet of Things and Artificial Intelligence. Applied and Computational Engineering. https://doi.org/10.54254/2755-2721/2025.po25380

Dougill, A., Hermans, T., Eze, S., Antwi-Agyei, P., & Sallu, S. (2021). Evaluating Climate-Smart Agriculture as Route to Building Climate Resilience in African Food Systems. Sustainability. https://doi.org/10.3390/su13179909

Erekath, S., Seidlitz, H., Schreiner, M., & Dreyer, C. (2024). Food For Future: Exploring Cutting-Edge Technology and Practices in Vertical Farm. Sustainable Cities and Society.

Esau, I., Pettersson, L., Cancet, M., Chapron, B., Chernokulsky, A., Donlon, C., … & Johannessen, J. (2023). The Arctic Amplification and Its Impact: A Synthesis through Satellite Observations. Remote Sensing, 15, 1354. https://doi.org/10.3390/rs15051354

Gokool, S., Mahomed, M., Kunz, R., Clulow, A., Sibanda, M., Naiken, V., Chetty, K., & Mabhaudhi, T. (2023). Crop Monitoring in Smallholder Farms Using Unmanned Aerial Vehicles to Facilitate Precision Agriculture Practices: A Scoping Review and Bibliometric Analysis. Sustainability. https://doi.org/10.3390/su15043557

Guebsi, R., Mami, S., & Chokmani, K. (2024). Drones in Precision Agriculture: A Comprehensive Review of Applications, Technologies, and Challenges. Drones. https://doi.org/10.3390/drones8110686

Gurajada, H., & Autade, R. (2025). Integrating IOT And AI For End-To-End Agricultural Intelligence Systems. 2025 International Conference on Engineering, Technology & Management (ICETM), 1–7. https://doi.org/10.1109/icetm63734.2025.11051863

Hellin, J., Fisher, E., Taylor, M., Bhasme, S., & Loboguerrero, A. (2023). Transformative adaptation: from climate-smart to climate-resilient agriculture. CABI Agriculture and Bioscience, 4.

Hope, C., & Schaefer, K. (2015). Economic impacts of carbon dioxide and methane released from thawing permafrost. Nature Climate Change, 6, 56–59. https://doi.org/10.1038/nclimate2807

Irfan, E., Zaka, E., Rehman, E., Sattar, B., Haider, S., & Hayat, M. (2025). An IOT-Driven Smart Agriculture Framework for Precision Farming, Resource Optimization, and Crop Health Monitoring. ACADEMIA International Journal for Social Sciences.

Istiak, M., Syeed, M., Hossain, M., Uddin, M., Hasan, M., Khan, R., & Azad, N. (2023). Adoption of Unmanned Aerial Vehicle (UAV) imagery in agricultural management: A systematic literature review. Ecological Informatics, 78, 102305. https://doi.org/10.1016/j.ecoinf.2023.102305

Kabir, M., Reza, M., Chowdhury, M., Ali, M., Ali, M., Lee, K., & Chung, S. (2023). Technological Trends and Engineering Issues on Vertical Farms: A Review. Horticulturae. https://doi.org/10.3390/horticulturae9111229

Khaliq, A., Khan, A., Jan, S., Umair, M., Gulshair, A., Ali, A., & Shah, U. (2025). AI-Driven Smart Agriculture: An Integrated Approach for Soil Analysis, Irrigation, and Crop-Fertilizer Recommendations. IEEE Access, 13, 141124–141138.

Kim, I., Timmermann, A., Kim, J., Rodgers, K., Lee, S., Lee, H., & Wieder, W. (2024). Abrupt increase in Arctic-Subarctic wildfires caused by future permafrost thaw. Nature Communications, 15.

Kim, J., Kim, S., Ju, C., & Son, H. (2019). Unmanned Aerial Vehicles in Agriculture: A Review of Perspective of Platform, Control, and Applications. IEEE Access, 7, 105100–105115. https://doi.org/10.1109/access.2019.2932119

Knoblauch, C., Beer, C., Liebner, S., Grigoriev, M., & Pfeiffer, E. (2017). Methane production as key to the greenhouse gas budget of thawing permafrost. Nature Climate Change, 8, 309–312. https://doi.org/10.1038/s41558-018-0095-z

Killeen, P., Kiringa, I., Yeap, T., & Branco, P. (2024). Corn Grain Yield Prediction Using UAV-Based High Spatiotemporal Resolution Imagery, Machine Learning, and Spatial Cross-Validation. Remote Sensing, 16, 683. https://doi.org/10.3390/rs16040683

Li, S., Yang, D., He, Y., Parazoo, N., & Liu, W. (2025). The biogeophysical impacts of land cover change on climate extremes in the Arctic and Boreal regions. Environmental Research Letters, 20. https://doi.org/10.1088/1748-9326/adeba0

Lovat, S., Noor, E., & Milo, R. (2025). Vertical farming limitations and potential demonstrated by back-of-the-envelope calculations. Plant Physiology, 198. https://doi.org/10.1093/plphys/kiaf056

Lubna, F., Lewus, D., Shelford, T., & Both, A. (2022). What You May Not Realize about Vertical Farming. Horticulturae.

Maimaitijiang, M., Sagan, V., Sidike, P., Hartling, S., Esposito, F., & Fritschi, F. (2020). Soybean yield prediction from UAV using multimodal data fusion and deep learning. Remote Sensing of Environment, 237, 111599. https://doi.org/10.1016/j.rse.2019.111599

Makam, S., Komatineni, B., Meena, S., & Meena, U. (2024). Unmanned aerial vehicles (UAVs): an adoptable technology for precise and smart farming. Discover Internet of Things, 4. https://doi.org/10.1007/s43926-024-00066-5

Malik, I., Ahmed, R., Ford, J., & Hamidi, A. (2025). Arctic Warming: Cascading Climate Impacts and Global Consequences. Climate. https://doi.org/10.3390/cli13050085

Martin, M., Elnour, M., & Siñol, A. (2023). Environmental life cycle assessment of a large-scale commercial vertical farm. Sustainable Production and Consumption. https://doi.org/10.1016/j.spc.2023.06.020

Miller, T., Mikiciuk, G., Durlik, I., Mikiciuk, M., Łobodzińska, A., & Śnieg, M. (2025). The IoT and AI in Agriculture: The Time Is Now—A Systematic Review of Smart Sensing Technologies. Sensors, 25. https://doi.org/10.3390/s25123583

Mizik, T. (2021). Climate-Smart Agriculture on Small-Scale Farms: A Systematic Literature Review. Agronomy, 11, 1096.

Nájera, C., Gallegos-Cedillo, V., Ros, M., & Pascual, J. (2023). Role of Spectrum-Light on Productivity, and Plant Quality over Vertical Farming Systems: Bibliometric Analysis. Horticulturae.

Nahiyoon, S., Ren, Z., Wei, P., Li, X., Li, X., Xu, J., Yan, X., & Yuan, H. (2024). Recent Development Trends in Plant Protection UAVs: A Journey from Conventional Practices to Cutting-Edge Technologies. Drones. https://doi.org/10.3390/drones8090457

Nhamo, L., Magidi, J., Nyamugama, A., Clulow, A., Sibanda, M., Chimonyo, V., & Mabhaudhi, T. (2020). Prospects of Improving Agricultural and Water Productivity through Unmanned Aerial Vehicles. Agriculture, 10, 256. https://doi.org/10.3390/agriculture10070256

Olson, D., & Anderson, J. (2021). Review on unmanned aerial vehicles, remote sensors, imagery processing, and their applications in agriculture. Agronomy Journal. https://doi.org/10.1002/agj2.20595

Parmentier, F., Thornton, B., Silyakova, A., & Christensen, T. (2024). Vulnerability of Arctic-Boreal methane emissions to climate change. Frontiers in Environmental Science.

Pennisi, G., Gianquinto, G., Marcelis, L., Martin, M., & Orsini, F. (2025). Vertical farming: productivity, environmental impact, and resource use. A review. Agronomy for Sustainable Development, 45. https://doi.org/10.1007/s13593-025-01055-w

Radoglou-Grammatikis, P., Sarigiannidis, P., Lagkas, T., & Moscholios, I. (2020). A compilation of UAV applications for precision agriculture. Computer Networks, 172, 107148.

Saha, G., Shahrin, F., Khan, F., Meshkat, M., & Azad, A. (2025). Smart IoT-driven precision agriculture: Land mapping, crop prediction, and irrigation system. PLOS One, 20.

Sandison, F., Yeluripati, J., & Stewart, D. (2022). Does green vertical farming offer a sustainable alternative to conventional methods of production?: A case study from Scotland. Food and Energy Security.

Schuur, E., Abbott, B., Commane, R., Ernakovich, J., Euskirchen, E., Hugelius, G., … & Turetsky, M. (2022). Permafrost and Climate Change: Carbon Cycle Feedbacks From the Warming Arctic. Annual Review of Environment and Resources. https://doi.org/10.1146/annurev-environ-012220-011847

Shi, Y., Thomasson, J., Murray, S., Pugh, N., Rooney, W., Shafian, S., … & Yang, C. (2016). Unmanned Aerial Vehicles for High-Throughput Phenotyping and Agronomic Research. PLoS ONE, 11. https://doi.org/10.1371/journal.pone.0159781

Singh, A., Barman, S., M, A., M, M., Babu, S., Satheeshkumar, N., Ramasamy, M., & K, T. (2025). Integration of AI and IoT for Yield Optimization in Precision Farming. Journal of Experimental Agriculture International. https://doi.org/10.9734/jeai/2025/v47i33331

Singh, S., Rawat, A., Deshwal, A., Yadav, Y., Kumar, D., Rai, P., & Gangwar, V. (2025). Vertical Farming: A Modern and Sustainable Approach to Horticultural Crop Growth. Journal of Scientific Research and Reports. https://doi.org/10.9734/jsrr/2025/v31i42991

Stanghellini, C., & Katzin, D. (2024). The dark side of lighting: a critical analysis of vertical farms' environmental impact. Journal of Cleaner Production. https://doi.org/10.1016/j.jclepro.2024.142359

Tao, J., Liljedahl, A., Burn, C., Grosse, G., Noetzli, J., Goetz, S., Douglas, T., & Yang, Y. (2025). Permafrost vulnerability to climate change: understanding thaw dynamics and climate feedback of permafrost degradation. Environmental Research Letters, 20. https://doi.org/10.1088/1748-9326/adfc7e

Van Delden, S., SharathKumar, M., Butturini, M., Graamans, L., Heuvelink, E., Kacira, M., … & Marcelis, L. (2021). Current status and future challenges in implementing and upscaling vertical farming systems. Nature Food, 2, 944–956. https://doi.org/10.1038/s43016-021-00402-w

Van Gerrewey, T., Boon, N., & Geelen, D. (2021). Vertical Farming: The Only Way Is Up? Agronomy. https://doi.org/10.3390/agronomy12010002

Wanglin, W., & Rahut, D. (2024). Climate-smart agriculture: adoption, impacts, and implications for sustainable development. Mitigation and Adaptation Strategies for Global Change, 29. https://doi.org/10.1007/s11027-024-10139-z

Yang, Y., Tilman, D., Jin, Z., Smith, P., Barrett, C., Zhu, Y., … & Lobell, D. (2024). Climate change exacerbates the environmental impacts of agriculture. Science, 385. https://doi.org/10.1126/science.adn3747

Yeragera, C. (2024). Evaluating the Technological Impact of Unmanned Aerial Vehicles on Efficiency Metrics in Precision Agriculture: A Secondary Data Analysis. International Journal of Scientific Research in Engineering and Management. https://doi.org/10.55041/ijsrem37996

You, Q., Cai, Z., Pepin, N., Chen, D., Ahrens, B., Jiang, Z., … & Zhang, Y. (2021). Warming amplification over the Arctic Pole and Third Pole: Trends, mechanisms and consequences. Earth-Science Reviews, 217, 103625. https://doi.org/10.1016/j.earscirev.2021.103625

Zhu, X., & Marcelis, L. (2023). Vertical farming for crop production. Modern Agriculture, 1. https://doi.org/10.1002/moda.4

Zong, X., Liu, X., Chen, G., & Yin, Y. (2022). A deep-understanding framework and assessment indicator system for climate-resilient agriculture. Ecological Indicators. https://doi.org/10.1016/j.ecolind.2022.108597

CHAPTER 2

IMPACTS OF CLIMATE CHANGE ON COFFEE PRODUCTION

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INTRODUCTION

Coffee production is one of the most important agricultural value chains worldwide, sustaining the livelihoods of more than 25 million smallholder families and constituting a strategic commodity for developing economies (Silva et al., 2024; Li et al., 2026). In the global market, Coffea arabica accounts for approximately 60% of coffee traded, whereas C. canephora represents nearly all of the remaining volume, with Brazil occupying a prominent position by exporting roughly one third of the coffee marketed worldwide (Xu et al., 2026; Silva et al., 2024; Lorençone et al., 2021).

From a biological standpoint, the genus Coffea exhibits high sensitivity to meteorological conditions. Arabica coffee, originating from humid montane forests, requires mean temperatures between 18 °C and 23 °C, whereas C. canephora shows greater thermal resilience, with an optimal range between 22 °C and 27 °C (Megerssa et al., 2025). Changes in altitude, rainfall and temperature range directly regulate phenology, and temperatures above physiological thresholds intensify respiration and reduce net photosynthesis, thereby affecting growth, fruit set and carbohydrate accumulation (Urugo et al., 2024; Akafu et al., 2026).

Climate change, driven by increasing concentrations of greenhouse gases, has emerged as the main agricultural challenge of the twenty first century (Akafu et al., 2026). With mean global warming already close to 1 °C and a higher frequency of extreme events, projections from the IPCC and sector specific studies indicate reductions of up to 50% in climatically suitable areas for arabica cultivation at the global scale (Lorençone et al., 2021; Megerssa et al., 2025; Thom et al., 2026). In Brazil, thermal and water constraints are likely to force altitudinal and latitudinal shifts in coffee production areas in search of more moderate microclimates, a process limited by land scarcity, land use conflicts and overlap with conservation areas (Lorençone et al., 2021; Akafu et al., 2026; Megerssa et al., 2025).

The impacts are not restricted to yield. Warming accelerates fruit maturation, shortens the period between flowering and harvest, and compromises the accumulation of sugars and aromatic precursors, thereby degrading the sensory quality of the beverage (Megerssa et al., 2025; Xu et al., 2026).

In parallel, the dynamics of pests and diseases such as coffee leaf rust, coffee leaf miner and coffee berry borer are profoundly altered, increasing management costs and exerting pressure on international competitiveness, particularly for smallholders (Megerssa et al., 2025; Ayalew et al., 2024).

In this context, strategies such as agroforestry systems, genetic improvement targeting tolerance to abiotic stresses, efficient water management, and climate risk management instruments are emerging as key pillars for building a climate resilient coffee sector. This chapter provides an integrated analysis of (i) the climatic characteristics and physiological sensitivity of the coffee plant, (ii) projections of land suitability and the effects on yield, quality and plant health, (iii) the socioeconomic dimensions of vulnerability in coffee production, and (iv) the main adaptation and mitigation strategies, discussing research challenges and prospects for the long term sustainability of the sector.

1. CLIMATIC CHARACTERISTICS OF COFFEE CULTIVATION

1.1. Thermal and Water Requirements of *Coffea arabica* and *C. canephora*

Global coffee production is based on the cultivation of Coffea arabica and Coffea canephora (Li et al., 2026). Arabica coffee, originating from montane forests in Ethiopia, evolved under thermal buffering and constant humidity, whereas C. canephora is native to low altitude equatorial regions and exhibits greater resilience to harsh thermal conditions (Urugo et al., 2024; Megerssa et al., 2025; Silva et al., 2024). Currently, arabica accounts for 60–70% of global trade, and the economic distribution of the species reflects their intrinsic evolutionary adaptations (Xu et al., 2026; Salojärvi et al., 2024).

Thermal requirements are the main biological dividing line between the two species: arabica requires annual mean temperatures between 18 °C and 23 °C, whereas the optimal range for C. canephora is 22 °C to 27 °C (Megerssa et al., 2025; Silva et al., 2024). Temperatures above 24 °C for arabica increase respiration rates and reduce net photosynthesis, thereby compromising vegetative growth and yield stability (Akafu et al., 2026; Lorençone et al., 2021).

With respect to water regimes, arabica requires annual rainfall between 1,200 and 2,000 mm, whereas robusta demands higher amounts, often above 1,400–1,600 mm (Silva et al., 2024; Megerssa et al., 2025). Both species need a dry period of two to four months as a trigger for floral induction (Urugo et al., 2024). However, the combination of prolonged droughts and thermal anomalies is currently the major constraint on productivity (Akafu et al., 2026).

As a C3 plant, coffee is subject to oxidative stress and reproductive abortion under heat waves above 30 °C (Megerssa et al., 2025). Biennial bearing and the partitioning of photoassimilates are sensitive to meteorological variability, making climate monitoring indispensable for technical planning (Silva et al., 2024; Akafu et al., 2026). Altitude plays a compensatory role: at higher elevations, slow maturation favors the accumulation of sugars and aromatic precursors, whereas heat at lower altitudes accelerates metabolism, resulting in beans with lower density and inferior quality (Urugo et al., 2024; Xu et al., 2026; Megerssa et al., 2025).

Climate change is projected to reduce suitable areas for arabica cultivation by up to 50% by the end of the century, forcing latitudinal and altitudinal shifts (Thom et al., 2026; Megerssa et al., 2025). In this context, strategies such as agroforestry systems, irrigation and the use of resilient varieties are mandatory to mitigate impacts and ensure the livelihood of communities dependent on this commodity (Silva et al., 2024; Akafu et al., 2026).

Table 1 below summarizes the climatic ranges considered ideal in the contemporary scientific literature and serves as a basis for agroclimatic zoning and for the planning of adaptation strategies (Lorençone et al., 2021; Megerssa et al., 2025).

It is important to note that exceeding these upper thermal limits induces a critical increase in plant respiration rates, thereby compromising net photosynthesis and, consequently, the sensory quality of the beans produced (Akafu et al., 2026; Megerssa et al., 2025). Likewise, although a short dry period is necessary for the synchronization of flowering, prolonged droughts associated with high temperatures currently represent the main limiting factor for global coffee production (Silva et al., 2024; Megerssa et al., 2025).

Therefore, the parameters presented here should be interpreted as indicators of biological resilience in a context of accelerated climate change (Megerssa et al., 2025).

Table 1. Reference agroclimatic parameters for *Coffea arabica* and *Coffea canephora*

Parameter	**Coffea arabica**	**Coffea canephora**	**References**
Optimal mean temperature (°C)	18–23	22–27	Silva et al. (2024); Megerssa et al. (2025)
Upper tolerated limit (average) (°C)	~24–25 (affects productivity)	~30 (high risk of stress)	DaMatta et al. (2018); Megerssa et al. (2025)
Annual rainfall (mm)	1200–2000	1400–2500	Silva et al. (2024); Bunn et al. (2015)
Dry period (months)	2–4 months (floral induction)	1–3 months (lower tolerance)	Silva et al. (2024); Megerssa et al. (2025)
Typical altitude (m)	800–2000 (tropical regions)	0–800 (humid tropical regions)	Bunn et al. (2015); Xu et al. (2026)

1.2. Physiological Sensitivity to Heat And Drought

The vulnerability of the genus Coffea to thermal and water fluctuations is linked to its C3 photosynthetic metabolism (DaMatta & Ramalho, 2006; Silva et al., 2024). Temperatures above the optimal range (18 °C to 23 °C for arabica) increase respiration rates and reduce the efficiency of net photosynthesis, destabilizing the carbohydrate balance essential for bud differentiation and grain filling (Akafu et al., 2026; Megerssa et al., 2025; Urugo et al., 2024). Heat waves exceeding 30–32 °C during flowering cause flower abortion and drop of young fruits, while nighttime warming accelerates cellular respiration, limiting the photoassimilates available for production (Camargo, 2010; Ayalew et al., 2024b; Megerssa et al., 2025). The response to water deficit is based on early stomatal closure to preserve leaf water potential (DaMatta et al., 2018; Akafu et al., 2026). Although this mechanism reduces transpiration, it limits CO_2 diffusion and carbon assimilation, and may cause leaf and fruit abscission (DaMatta et al., 2018; Lorençone et al., 2021).

Prolonged droughts inhibit branch growth, compromising the current harvest and the potential of the following year due to the crop's biennial bearing (Schlosser, 2026; Silva et al., 2024).

The timing of these anomalies is critical: while moderate drought can synchronize flowering, insufficient rainfall may impair fruit development (Akafu et al., 2026; DaMatta & Ramalho, 2006). At low altitudes, warming accelerates maturation, preventing the accumulation of aromatic precursors and degrading beverage quality (Xu et al., 2026; Megerssa et al., 2025). To mitigate these risks, strategies such as agroforestry systems, supplemental irrigation and genetic improvement for heat tolerance are essential to ensure biological resilience and the economic viability of the sector (Silva et al., 2024; Martinelli et al., 2025; Megerssa et al., 2025).

2. CLIMATE PROJECTIONS AND SUITABILITY OF CULTIVATION ÁREAS

2.1. Global Reduction of Suitable Areas

At the international level, scientific evidence converges toward a severe and widespread reduction of land suitable for coffee cultivation in the coming decades (Thom et al., 2026). Estimates indicate that the global area suitable for Coffea arabica production may decline by approximately 50% by 2050 under high emission scenarios (Thom et al., 2026). Traditional coffee growing regions in Latin America, Africa and Asia are facing climatic constraints that will compromise the viability of current plantations (Megerssa et al., 2025). Leading exporting nations such as Brazil, Vietnam and Colombia rank among the most vulnerable to these territorial losses (Thom et al., 2026). This geographic contraction is driven by increases in annual mean temperature beyond the thermal comfort limits of the coffee plant (Megerssa et al., 2025).

The species Coffea canephora will likewise experience significant contractions in its climatically suitable range in response to global warming (Thom et al., 2026). Although it exhibits greater biological resilience to heat than arabica, robusta is projected to undergo area reductions of similarly alarming magnitude in many producing countries (Thom et al., 2026). In some locations, however, there may be an expansion into newly favorable higher altitude areas that will become climatically suitable (Megerssa et al., 2025).

The dynamics of loss of suitability for conilon reflects the sensitivity of plants to new patterns of potential evapotranspiration and water deficit (Akafu et al., 2026). Thus, the displacement of production zones is becoming a defining feature of twenty first century coffee cultivation (Megerssa et al., 2025).

In Brazil, agroclimatic zoning projects profound changes in the geography of arabica coffee production (Lorençone et al., 2021). Simulations for the period between 2040 and 2080 indicate an average reduction of 50% in the total area suitable for cultivation in the country (Lorençone et al., 2021). States with a strong coffee tradition, such as Minas Gerais and São Paulo, are expected to face sharp yield losses due to thermal excess and persistent water deficit (Lorençone et al., 2021). Conversely, regions in southern Brazil may shift from being unsuitable due to insufficient heat to suitable for commercial cultivation (Lorençone et al., 2021). These changes in suitability pose an unprecedented challenge for family farming and national supply chains (Silva et al., 2024).

Figure 1 below presents projections of climatic zoning for arabica coffee in Brazil for future periods, highlighting potential changes in the spatial distribution of areas that are suitable, suitable with irrigation, and restricted by thermal or water limitations.

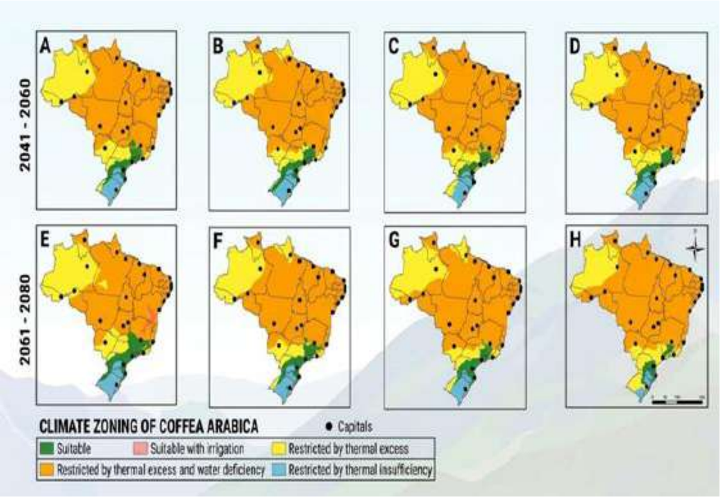

Figure 1. Climatic zoning of Coffea arabica for Brazil under different climate change scenarios. Source: Adapted from Lorençone et al., 2021

The loss of climatic suitability exacerbates the socioeconomic vulnerability of rural families that depend on coffee monoculture (Silva et al., 2024). In regions such as El Salvador, it is projected that the area of optimal production may be reduced by up to 40% within this century (Teodoro et al., 2024). Uncertainty in rainfall regimes and the higher incidence of pests such as coffee berry borer and coffee leaf rust increase management costs and reduce producers' profit margins (Megerssa et al., 2025). Strategies such as the adoption of agroforestry systems and the implementation of supplemental irrigation thus become indispensable pillars for community resilience (Silva et al., 2024). The integration of technological solutions with meteorological knowledge is a mandatory pathway to keep coffee cultivation viable in a rapidly changing climate (Megerssa et al., 2025).

2.2. Altitudinal And Latitudinal Shifts

The shift of coffee growing zones is the most frequently cited adaptive strategy to mitigate global warming (Megerssa et al., 2025). In mountainous landscapes, production migrates to higher elevations in search of microclimates that preserve the optimal thermal range for arabica coffee (18 °C to 23 °C), ensuring balanced maturation and preventing oxidative stress (Silva et al., 2024; Akafu et al., 2026). In Andean countries and in Ethiopia, areas above 1,500 meters are becoming progressively more favorable, whereas zones below 1,200 meters face severe constraints that hinder the accumulation of aromatic precursors and degrade the sensory quality of the beverage (Läderach et al., 2017; Megerssa et al., 2025; Xu et al., 2026).

However, this geographic transition encounters practical barriers such as rugged topography, shallow soils and socio environmental conflicts (Megerssa et al., 2025). Many high altitude areas are legally protected as conservation units, such as Kilimanjaro National Park, which limits agricultural expansion (Grabs et al., 2026). In addition, high population density and poor logistical infrastructure in remote regions increase production and transportation costs (Megerssa et al., 2025).

Latitudinally, there is an observed gain in suitability in regions farther from the equator, where warming reduces frost risk, as simulated for southern Brazil (Bunn et al., 2015; Lorençone et al., 2021).

In these new frontiers, Coffea canephora may gain prominence due to its greater thermal tolerance, although challenges such as photoperiod and erratic rainfall persist (Bunn et al., 2015; Silva et al., 2024). Thus, the reconfiguration of the global terroir requires technical support and mitigation policies, such as the use of agroforestry systems, to safeguard the economic viability of millions of rural families facing the forced displacement of coffee plantations (Silva et al., 2024; Teodoro et al., 2024; Martinelli et al., 2025). Figure 2 presents a schematic model of the shift in climatically suitable zones toward higher altitudes as a compensatory response to rising global temperatures.

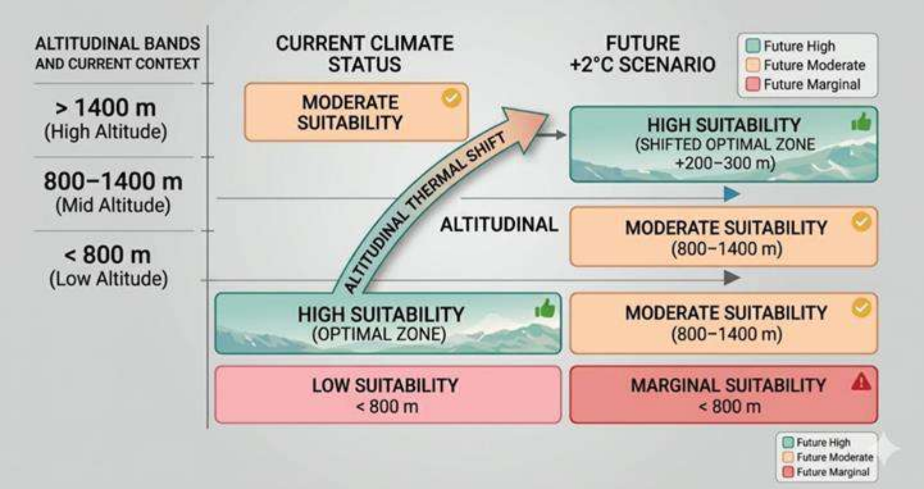

Figure 2. Conceptual scheme of the altitudinal shift of Coffea arabica cultivation zones under global warming. Source: Authors

3. IMPACTS ON PRODUCTIVITY

3.1. Empirical Relationships Between Climate and Yield

Coffee yield shows a close biophysical correlation with meteorological variables, with mean temperature, accumulated precipitation and water balance being the main determinants of final productivity (Silva et al., 2024). Empirical studies indicate that prolonged thermal stress reduces photosynthetic efficiency and compromises flowering, resulting in substantial yield declines (Megerssa et al., 2025).

In Tanzania, for example, a reduction of approximately 137 kg ha^{-1} in arabica coffee yield was observed for each 1 °C increase in minimum temperature during the reproductive phase (Ayalew et al., 2024b). Such evidence reinforces that even subtle thermal fluctuations can destabilize plant metabolism and compromise the economic viability of the production system (Akafu et al., 2026). Continuous agroclimatic monitoring is therefore indispensable for risk mitigation (Silva et al., 2024).

In Brazil, analyses of historical time series show that the occurrence of prolonged dry spells during the rainy season, especially in the critical grain filling stage, is associated with yield losses that often exceed 20–30% (Assad et al., 2004). Severe water deficit inhibits the growth of new vegetative branches and reduces the number of fruits per node, directly affecting the export potential of coffee beans (Schlosser, 2026). In addition, localized extreme weather events, such as hail and frost, can lead to total crop losses in specific areas, generating high variability even among neighboring farms (Thom et al., 2026). This vulnerability requires the adoption of technologies that make plantations more resilient to climatic shocks (Silva et al., 2024).

An additional complexity factor in yield analysis is physiological biennial bearing, an intrinsic characteristic of coffee plants that alternate between years of high and low production (Schlosser, 2026). Climate exerts a direct influence on this process, since water or thermal stresses occurring in high yield years can deplete plant reserves and exacerbate yield decline in the subsequent cycle (Silva et al., 2010; Silva et al., 2024). Climate change tends to amplify this natural variability by increasing the frequency of years with unfavorable meteorological conditions (Silva et al., 2024). This scenario significantly complicates production, logistical and financial planning for both rural families and the export industry (Grabs et al., 2026).

3.2. Yield Projections Under Future Scenarios

Projections based on crop models suggest that, in the absence of robust adaptation measures, average coffee yields will undergo severe declines in already warm tropical regions (Megerssa et al., 2025).

Simulations for Brazil indicate that a 3 °C increase in mean temperature could render arabica coffee cultivation unviable in traditional areas of Minas Gerais and São Paulo (Zullo et al., 2011; Lorençone et al., 2021). Accelerated warming distorts flowering and maturation cycles, exacerbating problems such as flower abortion and the formation of malformed beans (Megerssa et al., 2025). Thus, even in regions that remain climatically suitable, water and thermal stress may reduce individual plant yield (Bunn et al., 2015).

The progressive increase in water deficit and potential evapotranspiration points to a future of growing challenges for the water security of coffee plantations (Humphries et al., 2024). Numerical modeling indicates that cash crops such as coffee are among the most sensitive to changes in aridity indices, facing more severe water stress than annual grain crops (Adane et al., 2026). Under extreme drought scenarios, crop water requirements may increase by up to 13%, surpassing the natural replenishment capacity of rainfall (Adane et al., 2026). To ensure the continuity of coffee cultivation in vulnerability hotspots, the implementation of supplemental irrigation and soil conservation practices becomes a strategic priority (Martinelli et al., 2025).

However, in high altitude regions that are currently considered cold, global warming may initially exert a neutral or even slightly positive effect on productivity (Megerssa et al., 2025). Latitudinal shifts toward southern Brazil also suggest the opening of new cultivation areas where the risk of lethal frosts will be reduced by rising minimum temperatures (Lorençone et al., 2021). Nonetheless, these geographical gains are often constrained by soil limitations, rugged topography and environmental protection legislation (Megerssa et al., 2025; Grabs et al., 2026). Therefore, the sector's resilience will depend on the integration of genetic improvement aimed at heat tolerance with the adoption of microclimate management systems, such as shade provision (Akafu et al., 2026).

4. IMPACTS ON COFFEE QUALITY

High coffee quality results from the interaction among genotype, terroir and post harvest management, with meteorological variables controlling the biosynthesis of chemical precursors (DaMatta et al., 2018; Silva et al., 2024; Xu et al., 2026).

At high altitudes, mild temperatures slow down maturation, favoring the accumulation of sugars, lipids and organic acids, which are essential for dense beans and layered aromatic profiles (Urugo et al., 2024; Megerssa et al., 2025). However, global warming accelerates respiratory metabolism and shortens the cycle between anthesis and harvest, leading to forced maturation, lower sucrose accumulation and degradation of lipid fractions that are crucial for the retention of volatile compounds (Akafu et al., 2026; Xu et al., 2026; DaMatta & Ramalho, 2006).

Metabolomic studies indicate that thermal stress reduces the biosynthesis of terpenes such as linalool and limonene, thereby compromising the floral and citrus notes of premium varieties (Xu et al., 2026; Aung Moon et al., 2025). In parallel, severe water deficit induces the formation of malformed beans and sensory defects that devalue the lot (DaMatta & Ramalho, 2006; Megerssa et al., 2025). Evidence from Tanzania and Brazil confirms that rising minimum temperatures and more intense heat waves reduce bean size, density and final cupping scores (Craparo et al., 2015; Assad et al., 2004; Lorençone et al., 2021).

In addition to these direct effects (Table 2), changes in plant health dynamics act as a further driver of quality degradation. The upslope expansion of coffee leaf rust (Hemileia vastatrix) and coffee berry borer into previously unaffected high altitude areas alters the original flavor of the beverage due to biochemical damage (Ayalew et al., 2024b; Megerssa et al., 2025). In Ethiopia, thermal increases in lowland zones and higher vapor pressure deficit (VPD) have produced coffees with greater bitterness and lower acidity, disrupting the terroir of specialty coffees (Megerssa et al., 2025; Xu et al., 2026). To mitigate these impacts, agroforestry systems and genetic improvement for thermal resilience are essential, as shade reduces temperature peaks and ensures the uniform maturation required for the economic sustainability of producers (Lin, 2007; Martinelli et al., 2025; DaMatta et al., 2018).

Table 2. Main effects of climate change on the physicochemical and sensory quality of Coffea arábica

Climatic factor	Effect on the plant	Coffee quality outcome
Increase in mean temperature	Metabolic acceleration; shortened phenological cycle; higher nighttime respiration	Reduced bean density; lower accumulation of sucrose and trigonelline; loss of fine acidity and aromatic complexity
Intensification of heat waves (> 30–32 °C)	Oxidative stress; severe stomatal closure; bud and young fruit abortion	Marked heterogeneity in maturation; presence of black, green and over-roasted-tasting beans; loss of sensory uniformity
More frequent and severe droughts	Reduced net photosynthesis; carbohydrate partitioning imbalance; water stress	Shriveled or malformed beans; increased sensory defects; reduced body and sweetness of the beverage
Intense or erratic rainfall (during harvest)	Nutrient leaching; uncontrolled microbial fermentations	Undesirable fermented flavors; degradation of green bean color; risk of mycotoxin contamination
Post-harvest fluctuations in humidity and temperature	Altered hygroscopic equilibrium of stored beans; accelerated lipid oxidation	“Stale” aroma; degradation of volatile compounds; lower final cupping score

Source: Prepared by the authors based on DaMatta & Ramalho (2006); Camargo (2010); DaMatta et al. (2018); Urugo et al. (2024); Aung Moon et al. (2025); Megerssa et al. (2025); Akafu et al. (2026); Schlosser (2026); Xu et al. (2026)

Water instability, particularly dry spells during the fruit expansion stage, inhibits full endosperm development, resulting in beans with lower weight and inferior physical grading (Megerssa et al., 2025). In addition, the proliferation of fungal diseases and pests such as coffee berry borer and coffee leaf rust—whose life cycles are accelerated by heat—acts as an indirect driver of quality degradation, causing mechanical damage that alters roasting chemistry (Ayalew et al., 2024b; Megerssa et al., 2025). Strategies such as the use of agroforestry systems therefore become indispensable to mitigate these thermal impacts and preserve the sensory integrity of the beverage (Akafu et al., 2026; Martinelli et al., 2025).

5. DYNAMICS OF PESTS AND DISEASES UNDER CLIMATE CHANGE

Climate change profoundly alters the phytosanitary balance of coffee plantations by modifying plant metabolism and pathogen virulence (Silva et al., 2024; Ayalew et al., 2024b). Coffee leaf rust (Hemileia vastatrix) and coffee leaf miner (Leucoptera coffeella) cause severe defoliation, reducing photosynthetic capacity and resilience to water stress (Silva et al., 2024; Ayalew et al., 2022, 2024b). In parallel, coffee berry borer (Hypothenemus hampei) compromises yield and bean quality by directly boring into the fruits (Megerssa et al., 2025; Grabs et al., 2026). Global warming disrupts traditional patterns: higher minimum temperatures and erratic rainfall favor the germination of rust uredospores, while heat accelerates coffee berry borer metabolism, shortening its life cycle and allowing a greater number of generations per year (Akafu et al., 2026; Megerssa et al., 2025; Grabs et al., 2026).

Geographic expansion of pests is one of the most visible consequences of shifting thermal isotherms. High altitude regions previously protected by cold conditions are becoming favorable ecological niches for coffee berry borer and rust, increasing infestation pressure and chemical control costs (Megerssa et al., 2025; Silva et al., 2024). In Africa, rising nighttime temperatures are driving diseases such as coffee berry disease (Colletotrichum kahawae) and coffee wilt disease (Gibberella xylarioides), whose xylem colonization is facilitated by soil warming (Ayalew et al., 2024b, 2025; Megerssa et al., 2025). Conversely, warming may reduce the virulence of pathologies such as Armillaria root rot (Armillaria mellea), highlighting the complexity of microclimatic responses (Ayalew et al., 2024b, 2025).

Given this vulnerability, phytosanitary management requires integrated and sustainable strategies. The use of agroforestry systems and shade trees contributes to thermal regulation, acts as a physical barrier against spore dispersal and favors natural biological control by predators (Akafu et al., 2026; Ayalew et al., 2022, 2024b). Adaptation through genetic breeding for resistance and climate education for farmers are fundamental pillars to anticipate epidemic outbreaks and ensure the economic viability of global coffee production in the face of emerging biotic challenges (Silva et al., 2024; Akafu et al., 2026; Megerssa et al., 2025).

6. SOCIOECONOMİC AND GEOGRAPHIC DIMENSIONS OF COFFEE CULTIVATION

Vulnerability in the coffee sector disproportionately affects smallholder farmers in developing countries, whose dependence on rainfed systems exposes them directly to rainfall irregularities and extreme events (Silva et al., 2024; Akafu et al., 2026; Humphries et al., 2024). The adaptive capacity of these communities is constrained by institutional barriers such as limited access to credit, crop insurance and technical assistance, as well as demographic factors that influence the perception of climate risk (Megerssa et al., 2025; Akinkuolie et al., 2024; Sarkar et al., 2026). Yield and quality declines induced by thermal stress often result in indebtedness, food insecurity and migration from rural areas to urban centers or to agricultural frontier zones with precarious infrastructure (Megerssa et al., 2025; Teodoro et al., 2024; Schlosser, 2026).

Geographically, the search for new ecological niches at higher altitudes creates imminent risks of deforestation in sensitive biomes and land use conflicts in conservation areas (Megerssa et al., 2025; Grabs et al., 2026). Farmers unable to migrate or adopt mitigation technologies face economic marginalization and loss of competitiveness in the specialty coffee market (Silva et al., 2024; Megerssa et al., 2025). This spatial reconfiguration is accompanied by heightened exposure to international market volatility, where climate shocks in major producing countries such as Brazil and Vietnam trigger sharp price fluctuations that disproportionately squeeze the profit margins of small coffee growers (Li et al., 2026; Teodoro et al., 2024; Grabs et al., 2026).

Climate change thus acts as a catalyst for a new geopolitics of coffee. Regions that invest in innovation and genetic improvement tend to consolidate their commercial position, while less resilient origins lose market share to new frontiers at higher latitudes and altitudes (Bunn et al., 2015; Thom et al., 2026). Moreover, instability in the supply of high quality coffees may force the industry to alter blend composition, increasing the share of robusta to reduce costs, which in turn puts downward pressure on premiums paid to arabica producers (Silva et al., 2024; Irawan et al., 2026). The sector’s resilience depends on a coordinated approach that integrates meteorological science with climate justice policies and economic sustainability (Teodoro et al., 2024; Martinelli et al., 2025; Grabs et al., 2026).

7. ADAPTATION STRATEGIES

Adaptation is the central pillar for addressing the negative impacts of climate change on coffee production, involving the adjustment of biological and human systems to actual or expected climatic stimuli (Kassa et al., 2026). Although the risks are significant, the scientific literature shows that there is considerable scope for adaptive actions at multiple levels: genetic (plant), agronomic (management), territorial (landscape) and institutional (public policies) (Läderach et al., 2017; Teodoro et al., 2024). The adoption of these strategies is influenced by socioeconomic factors such as access to credit, farm size, education level and farmers' risk perception (Akafu et al., 2026; Megerssa et al., 2025). Smallholders in tropical countries, despite being the most vulnerable, are already implementing local measures based on traditional knowledge and incremental innovations (Silva et al., 2024; Kassa et al., 2026). However, the effectiveness of these actions depends on an integrated approach that connects meteorological science with the practical realities of farming systems (Silva et al., 2024; Megerssa et al., 2025).

7.1 Genetic Improvement and Cultivar Selection

The development and dissemination of cultivars tolerant to abiotic stresses are fundamental strategies to ensure future productivity under global warming (Kassa et al., 2026; Xu et al., 2026). Modern technologies such as Marker Assisted Selection (MAS) and Genomic Selection (GS) have accelerated the identification of genes associated with the biosynthesis of aroma precursors and resistance to water deficit (Xu et al., 2026). F1 hybrid cultivars of Coffea arabica show superior performance in both full sun and shaded systems, exhibiting greater biological resilience than traditional pure lines (Akafu et al., 2026; Kahsay et al., 2023). Hybridization of arabica with robust C. canephora lines is a promising pathway to combine desirable sensory quality with the thermal adaptability required under climate change (Xu et al., 2026). The use of resistant varieties has proven more effective in controlling diseases such as coffee leaf rust and coffee berry disease (CBD) than interventions based solely on microclimate management (Ayalew et al., 2024b; Ayalew et al., 2025).

The species Coffea canephora (robusta/conilon), due to its greater intrinsic heat tolerance, is gaining relative importance as an alternative crop in low altitude regions where arabica becomes unviable (Bunn et al., 2015; Thom et al., 2026). However, the adoption of new varieties faces barriers such as the high cost of seedlings and the need for greater fertilizer investment to reach yield potential (Akafu et al., 2026; Putra et al., 2026). Sustainable seedling production in nurseries should prioritize vegetative propagation methods, which have a lower carbon footprint than grafting based systems (Putra et al., 2026). Beyond resistance, genetic improvement should focus on preserving sensory profiles, avoiding situations where adaptation compromises beverage quality and the price premiums paid in the specialty coffee market (Xu et al., 2026; Urugo et al., 2024).

7.2. Agroforestry Systems and Shade Management

Agroforestry systems (AFS) are among the most resilient and widely studied adaptation measures, as they provide a stable microclimate that buffers peaks in air and soil temperature (Lin, 2007; Ayalew et al., 2025). Planned shading reduces direct radiation on the plants, lowers respiration rates and maintains higher relative humidity, allowing slower and more uniform fruit maturation (Lin, 2007; Oliva-Cruz et al., 2024). In qualitative terms, coffees grown under shade exhibit higher bean density and elevated concentrations of sucrose and trigonelline, attributes that are essential for high sensory scores (Urugo et al., 2024; Xu et al., 2026). In addition, the presence of native trees in AFS is crucial for biodiversity conservation and atmospheric carbon sequestration, thereby integrating adaptation with climate change mitigation (Wynter et al., 2025; Li et al., 2026).

Biological diversification in coffee plantations, such as intercropping with macadamia trees (Macadamia integrifolia), has shown significant benefits for soil structure, increasing porosity and water holding capacity (Amorim et al., 2026). Conservation systems that use cover crops such as Urochloa decumbens act as net carbon sinks and improve nutrient cycling (Martinelli et al., 2025; Sousa et al., 2025).

Shade management also functions as a physical barrier against pest and pathogen dispersal, although it requires careful planning to avoid excessive humidity that could favor certain fungal diseases (Akafu et al., 2026; Ayalew et al., 2024b). Despite these benefits, farmers face challenges such as competition for resources between trees and coffee plants and greater operational complexity of harvesting in diversified systems (Kassa et al., 2026; Grabs et al., 2026).

The following Table 3 summarizes the main benefits and technical challenges associated with the implementation of agroforestry systems in a context of accelerated global warming.

Table 3. Potential benefits and trade-offs of agroforestry systems in coffee cultivation under climate change

Aspect	**Potential Benefit**	**Possible Trade-off or Limitation**
Canopy temperature	Buffering of heat peaks and reduction of respiratory stress	Reduced photosynthetically active radiation may limit maximum productivity
Soil structure and moisture	Increased water infiltration; reduced erosion; higher organic carbon stocks	Possible competition for water and nutrients between trees and coffee plants during dry periods
Sensory quality	Slower phenological maturation; higher bean density and greater aromatic complexity	More complex post-harvest management due to heterogeneous maturation under dense shade
Ecosystem services	Biodiversity conservation; biological pest control; income diversification	High technical knowledge requirements; long financial payback time for timber trees

Source: Prepared by the authors based on em Lin (2007), DaMatta et al. (2018), Oliva-Cruz et al. (2024), Akafu et al. (2026), Amorim et al. (2026)

For these management and genetic strategies to be adopted at scale, institutional support through climate adapted agricultural credit and qualified technical assistance is imperative (Quiroga et al., 2020; Megerssa et al., 2025). Meteorological monitoring tools and the use of digital agriculture are emerging technologies that can improve the precision of pruning, fertilization and harvesting under conditions of uncertainty (Chaichana et al., 2024; Humphries et al., 2024). In sum, the sustainability of global coffee production will depend on a transition toward more resilient and diversified systems that secure not only the flow of the commodity, but also the dignity of rural communities (Grabs et al., 2026; Teodoro et al., 2024).

7.3. Water Management: Irrigation and Soil Conservation

In regions characterized by increasingly erratic rainfall regimes, the implementation of irrigation is consolidating as an indispensable adaptation technology, provided its economic and environmental feasibility is ensured (Läderach et al., 2017; Adane et al., 2026). The use of supplemental irrigation systems targeted at critical phenological stages such as post flowering and grain filling can drastically reduce interannual yield variability (Silva et al., 2024; Humphries et al., 2024). Studies in producing regions show that negative water balance during flowering can be mitigated through irrigation schedules adjusted to the specific needs of each locality (Humphries et al., 2024; Megerssa et al., 2025). Technologies such as solar powered drip irrigation have shown significant advantages, enabling water savings of up to 80% and yield increases exceeding 100% in arid zones (Kassa et al., 2026; Adane et al., 2026). In addition, water planning must account for the increase in potential evapotranspiration induced by global warming, which raises the overall water demand of the crop (Humphries et al., 2024; Adane et al., 2026).

Complementarily, the adoption of soil conservation practices is vital to maximize water use efficiency and strengthen crop resilience to drought periods (Silva et al., 2024; Martinelli et al., 2025). Mulching with plant residues or straw protects the soil surface from direct radiation, reducing evaporative losses and keeping root zone temperatures at adequate levels (Akafu et al., 2026; Megerssa et al., 2025).

Physical structures such as terracing and contour planting are fundamental on sloping land to reduce surface runoff, prevent erosion and promote water infiltration into the soil profile (Kassa et al., 2026; Akafu et al., 2026). In the Brazilian context, intercropping coffee with grasses such as Urochloa decumbens has proven an effective strategy to improve soil porosity and nutrient cycling (Martinelli et al., 2025; Sousa et al., 2025). The integration of these practices leads to a substantial increase in soil water holding capacity, acting as a biological buffer against meteorological extremes (Silva et al., 2024; Martinelli et al., 2025).

Sustainable water resource management also requires investment in water harvesting infrastructure, such as small reservoirs and rainwater harvesting systems, especially in smallholder communities (Kassa et al., 2026; Gemeda et al., 2026). These low cost solutions allow the storage of surplus water during the rainy season for use during periods of critical deficit (Kassa et al., 2026; Gemeda et al., 2026). Watershed protection and riparian forest restoration are essential landscape level measures to secure water quality and availability in the long term (Gemeda et al., 2026; Silva et al., 2024). Therefore, resilient water management must combine the precision of irrigation engineering with the ecological wisdom of soil conservation practices (Humphries et al., 2024; Martinelli et al., 2025).

7.4. Climate Risk Management and Climate Information

Strategic climate risk management in contemporary coffee production depends fundamentally on the availability and proper interpretation of high quality meteorological data (Silva et al., 2024; Akafu et al., 2026). Seasonal climate forecast tools and early warning systems enable farmers to anticipate planting windows, pruning and phytosanitary applications, thereby minimizing losses from extreme events (Kassa et al., 2026; Megerssa et al., 2025). Integrating global circulation models with local ecological knowledge makes it possible to generate tailored recommendations that respect the microclimates of each terroir (Humphries et al., 2024; Megerssa et al., 2025). It is imperative that technical information on the probability of frost, dry spells or rainfall during harvest be communicated in accessible language to support decision making in the field (Quiroga et al., 2020; Silva et al., 2024).

The rapid dissemination of such information through digital technologies, such as text messages and mobile apps, has proven a cost effective way to reach farmers in remote regions (Kassa et al., 2026; Chaichana et al., 2024).

Farmers' risk perception, shaped by their lived experiences with climate variability, is a crucial determinant of adaptation uptake (Akafu et al., 2026; Sarkar et al., 2026). Educational programmes focused on training in agrometeorology can raise perceived adaptive capacity, reduce cognitive barriers and promote technological innovation (Quiroga et al., 2020; Kassa et al., 2026). However, the lack of access to reliable climate information remains a major bottleneck, especially for smallholder coffee farmers in developing countries (Läderach et al., 2017; Akinkuolie et al., 2024). Strengthening rural extension services, combined with continuous monitoring by automatic weather stations, is the foundation for building resilient coffee growing communities (Kassa et al., 2026; Silva et al., 2024).

Beyond technical support, financial instruments such as weather index insurance are emerging as modern solutions for risk transfer (Läderach et al., 2017; Humphries et al., 2024). These products, based on objective meteorological indices (such as precipitation deficits or hours above a given temperature threshold), simplify indemnity processes and secure producer liquidity after severe climate shocks (Humphries et al., 2024; Silva et al., 2024). However, the expansion of these financial mechanisms faces challenges such as high premium costs and limited data infrastructure for risk parametrization (Akinkuolie et al., 2024; Kassa et al., 2026). Successful implementation of risk management strategies therefore requires strong coordination among research institutions, public authorities and the private sector (Megerssa et al., 2025; Grabs et al., 2026). Ultimately, the economic security of global coffee production will depend on the convergence between advanced meteorological science and public policies that support climate transition (Silva et al., 2024; Megerssa et al., 2025).

8. EMISSION MITIGATION AND SUSTAINABILITY

Although coffee cultivation is often framed primarily in terms of vulnerability, the sector holds significant potential to contribute to climate change mitigation through carbon sequestration and improved management practices (Martinelli et al., 2025; Silva et al., 2024). The transition from conventional conservation agriculture systems (CAS) has proven effective, with practices such as intercropping with Urochloa decumbens and the use of organic residues leading to substantially lower greenhouse gas emissions (Martinelli et al., 2025). Agroforestry systems for coffee (AFS) stand out as critical carbon reservoirs, enabling sequestration in both tree biomass and soil, often resulting in a net negative carbon balance (Jawo et al., 2024; Martinelli et al., 2025). Studies show that shade grown coffee can sequester up to 70% more carbon than full sun systems, while also delivering ecosystem services such as biodiversity conservation (Jawo et al., 2024; Wynter et al., 2025). Maintaining forest cover and halting deforestation in expanding coffee frontiers is a mandatory measure for reducing global CO_2 emissions (Silva et al., 2024; van der Vossen, 2005).

Reducing the carbon footprint of the production chain also depends on the rational use of inputs, especially nitrogen fertilizers, which are the main source of emissions in conventional systems (Thom et al., 2026; Basavalingaiah et al., 2022). The adoption of organic agriculture and integrated production systems can reduce emissions by about 65%, while improving on farm energy efficiency (Basavalingaiah et al., 2022; Li et al., 2026). In the post harvest stage, proper management of by products such as parchment and pulp, together with water reuse and automation of wet processing, supports circularity and reduces pollutant loads (Li et al., 2026; Antonio et al., 2023). Growing demand in niche markets for sustainably certified coffees—such as Fairtrade and Rainforest Alliance—creates direct economic incentives for producers to adopt mitigation practices (Jones et al., 2024; Martinelli et al., 2025). Thus, mitigation is not only an environmental objective but also a strategy for resilience and market differentiation in the global coffee sector (Li et al., 2026; Martinelli et al., 2025).

9. RESEARCH CHALLENGES AND KNOWLEDGE GAPS

Despite substantial scientific progress, important knowledge gaps persist that limit the effectiveness of adaptive interventions in coffee production (Thom et al., 2026; Silva et al., 2024). First, coffee specific crop models still lack the detailed parameterization available for major annual crops, hindering precise projections of thermal and water stress impacts at local microclimatic scales (Thom et al., 2026; Humphries et al., 2024). It is imperative to improve the representation of plant physiological processes, such as night time respiration and carbohydrate partitioning, to better inform technical planning (Thom et al., 2026; Silva et al., 2024). In addition, the diversity of varieties and the range of post harvest management systems are often neglected in current modelling efforts, generating uncertainty about the resilience of specific cultivars (Thom et al., 2026; Urugo et al., 2024).

A second critical challenge lies in understanding the interaction between climate change and the sensory quality of coffee (Xu et al., 2026; Urugo et al., 2024). The literature still lacks long term time series that integrate granular climatic variables, chemical metabolic parameters of the beans and standardized sensory scores across different terroirs (Xu et al., 2026; Urugo et al., 2024). Third, there is an urgent need for interdisciplinary studies that connect meteorological scenarios to socioeconomic dimensions, spanning international price dynamics, rural migration and gender equity within the sector (Grabs et al., 2026; Silva et al., 2024). The adaptive capacity of smallholders is often overestimated, overlooking structural barriers in access to finance and technical information (Akafu et al., 2026; Teodoro et al., 2024).

Finally, the assessment of large scale adaptation strategies remains an emerging field, requiring analyses that quantify costs, adoption barriers and actual effectiveness under extreme climate scenarios (Akafu et al., 2026; Teodoro et al., 2024). Strengthening transformative capacity—which enables farmers to diversify income sources or transition out of coffee when cultivation becomes unviable—is a research frontier that remains little explored (Grabs et al., 2026; Teodoro et al., 2024). Science must therefore pursue a more farmer centred approach, co designing technological solutions that integrate academic knowledge with the contextual realities of the field (Teodoro et al., 2024; Akafu et al., 2026).

Only by addressing these gaps will it be possible to build a truly sustainable and climate resilient coffee sector for the 21st century (Silva et al., 2024; Megerssa et al., 2025).

CONCLUSION

The evidence synthesized in this chapter shows that global coffee production is facing an unprecedented structural challenge. The high climate sensitivity of the Coffea genus particularly C. Arabica points to a potential reduction of up to 50% of suitable areas in traditional regions over the course of this century under pronounced warming scenarios. This process implies a major geographic reconfiguration, marked by altitudinal and latitudinal shifts that are likely to destabilize long established production systems and the incomes of millions of rural households.

The impacts extend beyond the strictly productive dimension and reach the very sensory identity of coffee. Thermal and water stress accelerate fruit metabolism, reduce bean density and compromise the accumulation of key compounds for beverage quality, while the expansion and intensification of pests and diseases such as coffee leaf rust and the coffee berry borer exacerbate economic losses and increase dependence on external inputs. In this context, the socioeconomic vulnerability of smallholders especially in developing countries is amplified by barriers to accessing credit, technical assistance and agricultural insurance. These constraints mean that the adaptive and mitigation options documented in the scientific literature are often unevenly accessible across regions and producer profiles.

At the same time, coffee production has a broad repertoire of adaptation and mitigation strategies at its disposal. Agroforestry systems and conservation practices can buffer microclimatic extremes, improve soil structure and enhance carbon sequestration; genetic improvement offers pathways to combine heat tolerance, disease resistance and the preservation of sensory quality; and water management and climate risk governance, supported by high quality meteorological information, reduce exposure to droughts, mid season dry spells and extreme events. Innovative financial instruments and markets that reward socio environmental attributes can further strengthen economic incentives for the transition toward more sustainable systems.

Important knowledge gaps nonetheless remain, particularly regarding integrated modelling that links climate, plant physiology, sensory quality and socioeconomic responses across diverse regional contexts. Progress toward a truly resilient coffee sector requires that scientific research become more participatory, co developing solutions with farmers and incorporating their perceptions and concrete constraints. The continuity of this sector in the twenty first century will depend on the convergence of technological innovation, territorial governance and climate justice, in order to reconcile productivity, ecosystem conservation and the dignity of the communities whose livelihoods are grounded in coffee.

REFERENCES

Adane, Z. et al. Modeling the future of rainfed agriculture: Climate change impacts on water resources and crop production in Ethiopia. Journal of Hydrology: Regional Studies, v. 64, n. 103301, 2026. DOI: 10.1016/j.ejrh.2026.103301.

Akafu, T. et al. Exploring climate change adaptation in coffee-based farming systems across diverse regions worldwide. Climate Services, v. 42, n. 100647, 2026. DOI: 10.1016/j.cliser.2026.100647.

Amorım, H. C. S. et al. Soil structure and organic carbon dynamics from agroforestry versus conventional coffee systems. Agriculture, Ecosystems and Environment, v. 397, n. 110042, 2026. DOI: 10.1016/j.agee.2025.110042.

Andualem, A. M. et al. Exploring the local knowledge of farming and pastoral communities in Ethiopia regarding climate change adaptation: a systematic review. Scientific African, v. 29, n. e02794, 2025. DOI: 10.1016/j.sciaf.2025.e02794.

Assad, E. D. et al. Impacto das mudanças climáticas no zoneamento agroclimático do café no Brasil. Pesquisa Agropecuária Brasileira, v. 39, n. 11, p. 1057–1064, 2004.

Ayalew, B. et al. Impact of climate and management on coffee berry disease and yield in coffee’s native range. Basic and Applied Ecology, v. 76, p. 25–34, 2024. DOI: 10.1016/j.baae.2024.01.006.

Ayalew, B. et al. The impact of climate, local habitat, surrounding landscape and management on coffee wilt disease. Basic and Applied Ecology, v. 89, p. 59–70, 2025. DOI: 10.1016/j.baae.2025.10.005.

Basavalıngaıah, K. et al. Energy flow and life cycle impact assessment of coffee-pepper production systems: An evaluation of conventional, integrated and organic farms in India. Environmental Impact Assessment Review, v. 92, n. 106687, 2022. DOI: 10.1016/j.eiar.2021.106687.

Bunn, C. et al. A bitter cup: climate change profile of global production of Arabica and Robusta coffee. Climatic Change, v. 129, p. 89–101, 2015. DOI: 10.1007/s10584-014-1306-x.

Camargo, M. B. P. The impact of climatic variability and climate change on Arabic coffee crop in Brazil. Bragantia, v. 69, n. 1, p. 239–247, 2010. DOI: 10.1590/S0006-87052010000100030.

Craparo, A. C. W. et al. Coffea arabica yields decline in Tanzania due to climate change: Global implications. Agricultural and Forest Meteorology, v. 208, p. 1–10, 2015. DOI: 10.1016/j.agrformet.2015.04.011.

Damatta, F. M. et al. Coffee tree growth and environmental acclimation. Burleigh Dodds Science Publishing, p. 1–28, 2018. DOI: 10.19103/AS.2017.0012.04.

Damatta, F. M. et al. Physiological and agronomic performance of the coffee plant in the context of climate change and global warming: a review. Journal of Agricultural and Food Chemistry, v. 66, n. 21, p. 5264–5274, 2018. DOI: https://doi.org/10.1021/acs.jafc.7b04537

Damatta, F. M.; Ramalho, J. D. C. Impacts of drought and temperature stress on coffee physiology and production: a review. Brazilian Journal of Plant Physiology, v. 18, n. 1, p. 55–81, 2006. DOI: https://doi.org/10.1590/S1677-04202006000100006

Fılho, J. de D. G. et al. Spatial and temporal variability of coffee fruit detachment force in selective mechanized harvesting. Smart Agricultural Technology, v. 12, n. 101394, 2025. DOI: 10.1016/j.atech.2025.101394.

Grabs, J. et al. Resilience of what and for whom? Climate change mitigation and adaptation in the global, Ethiopian, and Tanzanian coffee sectors. World Development, v. 200, n. 107299, 2026. DOI: 10.1016/j.worlddev.2025.107299.

Humphrıes, U. W. et al. Determination of crop water requirements and potential evapotranspiration for sustainable coffee farming in response to future climate change scenarios. Smart Agricultural Technology, v. 8, n. 100435, 2024. DOI: 10.1016/j.atech.2024.100435.

Jaramıllo, J. et al. Some like it hot: the influence and implications of climate change on coffee berry borer (Hypothenemus hampei) and coffee production in East Africa. PLOS ONE, v. 6, n. 9, e24528, 2011. DOI: https://doi.org/10.1371/journal.pone.0024528

Kassa, A. et al. Climate change impacts and adaptations in Eastern and Western Africa. Climate Services, v. 42, n. 100644, 2026. DOI: 10.1016/j.cliser.2026.100644.

Läderach, P. et al. Climate change adaptation of coffee production in space and time. Climatic Change, v. 141, p. 47–62, 2017. DOI: 10.1007/s10584-016-1788-9.

Li, X. et al. An overview of carbon footprint reduction in the global coffee supply chain. Applied Food Research, v. 6, n. 101716, 2026. DOI: 10.1016/j.afres.2025.101716.

Lın, B. B. Agroforestry management as an adaptive strategy against potential microclimate extremes in coffee agriculture. Agricultural and Forest Meteorology, v. 144, p. 85–94, 2007.

LorençonE, J. A. et al. Impacto das mudanças climáticas no período 2040-2080 sobre a aptidão do cultivo de Coffea arabica no Brasil. In: CONGRESSO BRASILEIRO DE AGROINFORMÁTICA (SBIAGRO), 13., 2021, Evento Online. Anais [...]. Porto Alegre: Sociedade Brasileira de Computação, 2021. p. 374-377.

Lorençone, J. A. et al. Impacto das mudanças climáticas no período 2040-2080 sobre a aptidão do cultivo de Coffea arabica no Brasil. Revista Contemporânea, v. 3, n. 10, p. 17811–17821, 2023. DOI: 10.56083/RCV3N10-063.

Martınellı, G. et al. Carbon balance in coffee farming: A life cycle case study of conservationist versus conventional systems. Cleaner Production Letters, v. 9, n. 100106, 2025. DOI: 10.1016/j.clpl.2025.100106.

Megerssa, G. R. et al. Impact of climate change on Ethiopian Arabica coffee production. Sustainable Futures, v. 10, n. 101459, 2025. DOI: 10.1016/j.sftr.2025.101459.

Ovalle Rıvera, O. et al. Projected shifts in Coffea arabica suitability among major global producing regions due to climate change. PLOS ONE, v. 10, n. 4, e0124155, 2015.

Sarkar, S. et al. Evaluating farmers' strategies and socioeconomic drivers for adaptation to climate uncertainty: A case study in the Himalayan region of West Bengal, India. Regional Sustainability, v. 7, n. 2, 2026. DOI: 10.1016/j.regsus.2026.100334.

Sılva, J. B. C. da; PINTO, P. A. L. de A. Socio-economic impacts of climate change on coffee production: a systematic literature review. Revista Brasileira de Climatologia, v. 35, 2024. DOI: 10.55761/rbclimatol.v35i0.16543.

Teodoro, J. D. et al. Co-designing a research agenda for climate adaptation in El Salvador’s coffee sector: A transdisciplinary perspective. Environmental Science and Policy, v. 153, n. 103678, 2024. DOI: 10.1016/j.envsci.2024.103678.

Thom, B. et al. Beyond the average: understanding the heterogeneity of environmental impacts in coffee supply chains. Journal of Cleaner Production, v. 546, n. 147805, 2026. DOI: 10.1016/j.jclepro.2026.147805.

Urugo, M. M. et al. Associations of Arabica coffee cup quality with green bean density and chemical composition. Journal of Agriculture and Food Research, v. 18, n. 101549, 2024. DOI: 10.1016/j.jafr.2024.101549.

Van Der Vossen, H. A. M. A critical analysis of the agronomic and economic sustainability of organic coffee production. Experimental Agriculture, v. 41, n. 4, p. 449–473, 2005.

Wynter, V. et al. A global comparison of the biodiversity impacts of coffee agroforestry systems. Agricultural Systems, v. 229, n. 104449, 2025. DOI: 10.1016/j.agsy.2025.104449.

Xu, X. et al. Exploring the chemistry and craft behind coffee flavour. Journal of Food Composition and Analysis, v. 150, n. 108886, 2026. DOI: 10.1016/j.jfca.2026.108886.

Zullo, J. et al. Potential for growing Arabica coffee in the extreme south of Brazil in a warmer world. Climatic Change, v. 109, n. 3–4, p. 535–548, 2011. DOI: https://doi.org/10.1007/s10584-011-0058-0

CHAPTER 3

CLIMATE CHANGE, CAUSES, EFFECTS AND GLOBAL WARMING

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INTRODUCTION

Climate change is a serious challenge that is facing our planet, leading to various industrial revolution (Osariemen & Obehi, 2024). Changes in the earth's climate, resulting from human activities which is anthropogenic climate change or natural processes that are already occurring or predicted to occur in the near future (IPCC, 2014). These include increasing air and sea surface temperatures, changes in the rainfall patterns, sea level rise, ocean acidification, and changes in frequency and intensity of extreme events such as droughts, floods, and tropical cyclones (Grinning Planet, 2007). Greenhouse gases emissions has increased the climate change issues, and thus making our weather more threatening (IPCC, 2021). Climate change which can also be called global warming has deteriorated the environment and the world at large posing a serious health risks to the living things by decreasing the essential ingredients of good health, for example; clean air, safe drinking water, nutritious food supply, and safe environment (NOAA, 2024; Mi et al., 2019). Climate change resulting from natural and anthropogenic activities has pose escalating threats to global biodiversity, with tropical regions facing ecological disruptions due to ecosystem complexity as shown in Figures 1 below (Shaw et al., 2018). It can be from natural and man-made causes, the natural causes are many including ocean currents, volcanic eruption, earth's orbital changes and solar variations, the man-made causes include burning of fossil fuels, land-use and deforestation (Global Carbon Project, 2024; Paehler, 2007). The burning of fossil fuels for industrial purposes has increased greenhouse gas (GHG) emission which has altered the temperature and precipitation patterns (Osariemen & Obehi, 2024). NOAA, 2020 reported that carbon dioxide (CO2) and methane levels in the atmosphere continued to rise in 2020, with CO2 level reaching their highest point in 3.6 million years, according to calculations by the (National Oceanic and Atmospheric Administration). The global surface average for carbon dioxide (CO2), collected and calculated from measurements at the remote sampling locations of NOAA, it was seen to be 412.5 parts per million (ppm) in 2020, rising by 2.6 ppm during the year (National Oceanic and Atmospheric Administration, NOAA, 2020).

Several researchers have agreed to fact that, the effects of greenhouse gas emissions have changed the natural ecosystems, weather patterns, food supplies, lives and economies already. Many cases of severe drought and wildfires to rising seas and eroding coastlines, warnings from decades ago have manifested globally as shown in Figures1-8 below. Climate Scientists agrees to the fact that the earth is currently having challenges of increase/rapid warming which is caused by rising levels of greenhouse gases in the environment/atmosphere, and it is causing threat for humans and its environment as shown in Figures 1-8 below.

Figure 1. Picture of severe coastal erosion (Getty images)
Source: EST/CBS News

Figure 2. Picture of dried forests (Getty images)
Source: EST/CBS News

What is Climate change?

Climate change is defined as any change in climate over time whether due to natural variability or as a result of anthropogenic activity (Suarez, 2022). Climate change also refers to long-term shifts in temperature and weather patterns over a long period of time (Kaddo and Jameel, 2016). Climate change is also defined as changes in regional climate characteristics over a long period, including temperature, humidity, rainfall, wind and serious weather events (http://www.climatechangechallenge.org/).

Climate has always changed due to natural processes interaction with the sun such as the water and energy cycles. In previous years, these changes were natural and caused by phenomena such as slow shifts in the Earth’s orbit and changes in solar and volcanic activity (USEPA, 2016; USGCRP, 2017).

What is Global Warming?

Global warming is defined as the increase in the Earth's average temperature that occurs when the concentration of greenhouse gases in the atmosphere increases (IPCC, 2020; 2021). These gases absorb more solar radiation and trap more heat, thus causing the planet to get hotter. Greenhouse gases are increased whenever, the burning fossil fuels (coal, oil, and gas), deforestation (cutting down forest), livestock farming (overgrazing), and urbanization are practiced (Tao et al., 2021).

Causes of Climate Change and Its Effect

The causes of climate change are natural and man-made (anthropogenic)causes (Crowley, 2000; Paehler, 2007). The main causes or contributors to climate change are human activities on a daily basis while some of these causes may be natural (Kaddo and Jameel, 2016; USEPA, 2016). Heat waves, unprecedented flooding and wildfires have cost billions in damages already on earth which are identified as the effect of climate change as shown in Figure 3 below.

Figure 3. Picture of wildfire (Getty images)
Source: EST/CBS News

1. NATURAL CAUSES OF CLIMATE CHANGE

The earth's climate is changed through the following natural causes such as;

- Ocean current
- Volcanic eruptions
- Earth's orbital changes
- Solar variations

Ocean Current

According to Onoja et al. (2011) who reported in their findings on climate change and its causes that, the oceans have indicated to be the important part of the larger whole of the climate system. Ocean currents have change position by transferring large amounts of heat from one side to the other around the globe. The wind push horizontally against the sea surface and drive ocean current patterns. Ocean and atmosphere can affect each other by ways of interaction to produce El-Nino which usually takes place every 2 to 6 years. Observation have shown that, deep ocean circulation of cold water moves from pole towards the equator while warm water returns from the equator to the poles, and without this movement, the water from the poles would be colder and the equator warmer (Brown, 2010).

Oceans plays a major part in determining the atmospheric concentration of CO2. Ocean circulation experience causes changes that may affect the climate through the movement of CO2 into or out of the atmosphere (Hoffman et al., 2010; Shanta Barley, 2010).

Volcanic Activities

Volcanic eruptions releases large quantity of sulphur dioxide (SO2), dust, ash and water vapour into the atmosphere (Onoja et al., 2011). It is known that large volumes of gases and ash can influence climate patterns for years by increasing planetary reflectivity, causing atmospheric cooling. Tiny particles called aerosols are produced by volcanoes (Bowen, 2010). Due to these reflect of solar energy back into space, they possess a cooling effect on the earth's surface (Ammann et al., 2010; Paehler, 2007). The sun is said and known to be the source of energy for the planet's climate system. Sun's energy output appears constant from an everyday point of view, small changes over an extended period of time can lead to climate changes (Onoja et al., 2011).

Earth's Orbital Changes

The Earth makes one revolution around the sun once a year, tilted at an angle of 23.5 to the perpendicular plane of its orbital path. Changes in the tilt of the Earth can lead to small but climatically important changes in the strength of the seasons, more tilt means warmer summers and colder winters; less tilt means cooler summers and milder winters. Slow changes in the Earth's orbit lead to small but climatically important changes in strength of the seasons over tens of thousands of years. Climate feedbacks have been shown to amplify these small changes, thereby producing ice ages (Crowley, 2000; Paehler, 2007; Perkins, 2010).

Solar Variation

The sun is known to be the source of energy for the planet's climate system. Although the sun's energy output appears constant from an everyday point of view, small changes over an extended period of time can lead to climate changes. It has been speculated that a portion of the warming in the first half of the 20 Century was due to an increase in the output of solar energy.

As the sun is the fundamental source of energy that is instrumental in our climate system, it would be reasonable to assume that changes in the sun's energy output would cause climate to change. But studies by Crowley (2000) and Paehler (2007) have shown that if this were so it would be expected to see warmer temperatures in all layers of the atmosphere. On the contrary, the cooling was observed in the upper atmosphere, a warming at the surface and in the lower parts of the atmosphere. This was shown to be due to greenhouse gases capturing heat in the lower atmosphere.

2. MAN-MADE (ANTHROPOGENIC) CAUSES OF CLIMATE CHANGE

According to Paehler, (2007), it has been shown that climate is changing due to man-made greenhouse gases from burning of fossil fuels (gas, oil, and coal) and other industrial activities, which are known to be the main producers of carbon dioxide (CO2). Even the use of land and deforestation adds pressure to greenhouse gases. The real cause of current climate change is man-made (human activities), which contributes to the build-up of greenhouse gases in the atmosphere. The heat emitted by the sun's radiation heats the globe. Some atmospheric gases play key role as greenhouse gas by encasing this heat into the atmosphere (Global Carbon Project, 2024; Li et al., 2016; Gerber et al., 2013). The main gases causing global warming are methane, carbon dioxide, and water vapour. When greenhouse gases absorb heat and release part of it into the atmosphere, then the surface temperatures will increase the radiation (NOAA, 2024; Black et al., 2017).

Effect of Climate Change

One aspect that has been greatly affected by climate change is the weather (Kaddo and Jameel, 2016). The effects of climate change are list below;

- Desertification and Land Degradation: Desertification and land degradation results from overgrazing, deforestation, and poor agricultural practices, leading to loss of arable land, reduced agricultural productivity, and heightened poverty.

- Rising sea level and flooding: This is caused by heavy rainfall, storm surges, and poor urban planning, leading to displacement of people, damage to infrastructure, and loss of livelihoods. Several findings have shown that, if sea-levels should rise by a metre or more, then many coastal marshes would be submerged by seawater, even those that continue to accrete sediment (Hoffman et al, 2010; Walton, 2010; Walton Jr & Dean, 2010). The researchers maintained that coastal marshes are not just passive casualties of rising sea levels but respond dynamically to changes in inundation, vegetation and sedimentation.

The worker concluded that if the sea- level rise is restricted to around 30cm, with minimal ice- sheet contributions over the coming century, many marshes will be able to keep pace with rising seas and maintain their position. However, a sea-level rise of more than a metre would permanently submerge most coastal marshes, including many that will continue to grow by accretion (Brown, 2010). They reported that an increase in air temperature can cause glacier melt-water production to rise and this would worsen climate change.

Figure 4. Picture of human beings affected with flood (Getty images)Source: EST/CBS News

- Heat wave: According to the World Meteorological Organization (WMO, 2023), heat wave is a period during which daily maximum temperature exceeds for more than five consecutive days the maximum normal temperature by 9 degrees Fahrenheit (5 degrees Celsius), the normal period being defined as 1961-1990.

Due to global warming, the frequency, duration, and severity of heat waves are predicted to increase in most parts of the world. The impacts on human health, regional economies, and ecosystems may be important. Heat wave is also defined as an extended period of unusually high temperatures and often high humidity that causes temporary medication in lifestyle and may have adverse health effects on the affected population. Heat waves are mainly caused by urbanization and industrialization, poor urban planning which leads to heat-related illnesses, increased mortality, and decreased economic productivity in the world (https://www.ifrc.org/sites/default/files/2021-06/10-HEAT-WAVE-HR.pdf).

- Drought: Drought is defined as a deficiency in precipitation over an extended period, usually a season or more, resulting in a water shortage causing adverse impacts on vegetation, animals and humans (https://droughtreporter.unl.edu/). It is different than aridity, which is a permanent feature of climate in regions or areas where low precipitation is the norm, as in a desert. Droughts are among the most expensive weather-related events, in terms of economics and loss of life (https://droughtreporter.unl.edu/).

Human activities in the area of water demand and water management, can exacerbate the impact drought has in a location or region. This is caused by irregular rainfall patterns, and inefficient water management as shown in Figure 4 below, resulting in water scarcity, reduced agricultural productivity, and increased food insecurity.

Figure 5. Picture of drought (Getty images)

Source: EST/CBS News

In practice, drought can be defined in a number of ways that reflects various perspectives and interests. There are three types of common droughts, which are;

- Agricultural drought
- Meteorological drought
- Hydrological drought

Agricultural Drought

Agricultural drought is linked to various characteristics of meteorological (or hydrological) drought to agricultural impacts, focusing mainly on precipitation shortages, soil water deficits, decreased ground water or reservoir levels needed for irrigation and for other purposes (https://droughtreporter.unl.edu/).

Meteorological Drought

Meteorological drought definition is based on the degree of dryness (in comparison to some normal or average) and the duration of the dry period. It onset generally occurs with a Meteorological drought (https://droughtreporter.unl.edu/).

Hydrological Drought

Hydrological drought mostly occurs following periods of extended precipitation shortfalls that impact water supply (that is, streamflow, reservoir and lake levels, ground water), potentially resulting in important societal impacts. Due to regions interconnections by hydrologic systems, the impact of meteorological drought may proceed well above the borders of the precipitation-deficient area (https://droughtreporter.unl.edu/).

Greenhouse Gases (GHGs)

Greenhouse gases are said to be the main contributor to climate change (The Greenhouse Effect). They are very efficient in trapping heat into the atmosphere; therefore, resulting in greenhouse effect.

According to report by the United Nations Framework Convention on Climate Change (UNFCCC), all the below listed greenhouse gases are covered by UNFCCC. There are six greenhouse gases which include;

- Carbon dioxide (CO2)
- Methane (CH4)
- Nitrous oxide (N2O)
- Hydrofluorocarbons (HFCs)
- Sulphur hexafluoride (SF6)

The solar energy is absorbed by the earth's surface and then reflected back to the atmosphere as heat. Then as the heat goes out to space, greenhouse gases absorb a part of the heat. After that, they radiate the heat back to the earth's surface, to another greenhouse gas molecule, or to space (The Greenhouse Effect).

Greenhouse Effect

The energy coming in from the Sun can pass through the clear atmosphere without any change or alteration, and therefore sending direct heat to the surface of the Earth. The infrared radiation emanating from the surface of the Earth is partly absorbed by some gases in the atmosphere, and some of it is re-emitted downwards (USGCRP, 2017). The effect of this is to warm the surface of the Earth and lower part of the atmosphere, this is called the greenhouse effect. Greenhouse effect is simply defined as a phenomenon in which greenhouse gases absorb heat and releases part of it into the atmosphere which rises the surface temperature (Osariemen and Obehi, 2024; Black et al., 2017). The greenhouse effect is caused by anthropogenic activities which increases the level of atmospheric concentrations of greenhouse gases, most especially carbon dioxide (CO2) (Onoja et al., 2011).

The burning of fossil fuels (gas, oil, and coal) and other industrial activities are the core manufacturers of carbon dioxide. By increasing the concentration of the greenhouse gases, we are increasing the amount of heat that is in our atmosphere (NASA). Hurricanes have also become more aggressive largely because of warmer temperatures that mainly resulted from the emission of greenhouse gases.

Berbisi et al. (2016) reported that “Methane leakage from evolving petroleum systems: Masses, rates and inferences for climate feedback,” the present-day warming trend has been attributed to an annual increase in the atmospheric methane concentration and CO2. Warmer temperatures result in warmer water in the oceans. As the result of warmer oceans, hurricanes and tornados become more intense. According to NASA, who reported that, warmer atmosphere result in more energy in the atmosphere and when hurricanes start, they usually pick up energy from the oceans and as the result of warmer water in the oceans because of greenhouse effect, more energy is given to hurricanes.

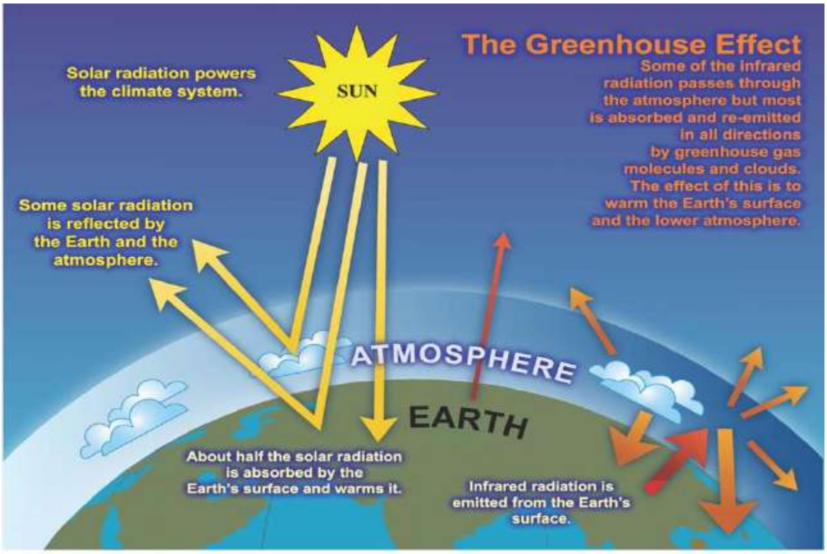

Figure 6. Intergovernmental Panel on Climate Change (2007) IPCC Fourth Assessment Report. Climate Change. [Accessed June 2009]. Available from World Wide Web: http://ipcc.ch/graphics/graphics/ar4-wg1/jpg/faq-2-1-fig-1.jpg

3. IMPACTS OF CLIMATE CHANGE ON ECOSYSTEMS AND HUMANS

Rising Temperatures

This rising in temperature drives extreme weather, wildfires, flooding, severe drought and melting glaciers (NOAA, 2024).

The manifestation of climate change, such as rising temperatures, brings about heatwaves that threaten livestock as well as the lives of human beings, and thereby causing heat stress which increases animals' vulnerability to diseases and reduces fertility and milk production.

Changing Rainfall Patterns

Climate change alters rainfall patterns, causing droughts in some areas and floods in others, leading to soil erosion and landslides. This change in rainfall patterns is posing a serious threat on the ecosystems thereby affect the agricultural yield.

Loss of Biodiversity

This loss of biodiversity is endangering the climate in different ways such as extinction of species, reduction in population sizes, thereby diminishing the nature's ability to provide essential services such as water, food, clean air, and risking the lives of human as well as ecological stability. Climate change is projected to cause loss of up to 30% of plants and animals by 2050 due to habitat destruction and interruption on the normal operation of an ecosystems.

Shifts in Species Distribution

Climate change alters the distribution of plants and animals, disrupting ecosystems and potentially leading to extinctions. These extinctions are very dangerous to the environment and the lives of humans.

Water Scarcity

Changes in precipitation patterns and increased evaporation due to warmer temperatures lead to water scarcity, affecting agriculture, industry, and human consumption. Water scarcity is a global challenges and urgent provisions must be available in order to address this ugly situation.

Increased Risk of Natural Disasters and Food Insecurity

Increased risk of natural disasters and food insecurity is affected by poor agricultural practices, and inefficient food systems, leading to reduced access to nutritious food, increased malnutrition, and decreased economic productivity as seen in Figure 7 below.

Figure 7. Picture of Mysterious die-offs (Getty Images)
Source: EST/CBS News

Climate change also resulted in playing a major role in shrinking of ice sheets (Riebeek, 2016) as shown in Figure 8 below. The melting of ice results in the rise of sea levels and that endangers many islands to disappear completely (Riebeek, 2016). According to NASA, up to 10 percent of the world's population lives in areas where there about 30 feet above sea level (NASA).

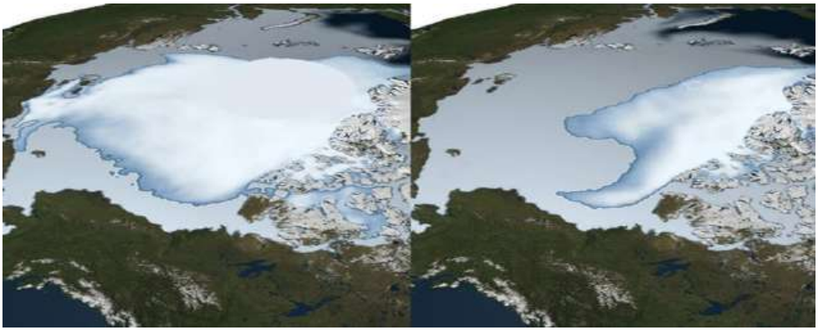

Figure 8. Picture of ice cap disappearing (NASA)

Source: NASA

4. MITIGATION AND ADAPTATION STRATEGIES

Rolnick et al., (2022) reported that emissions of heat-trapping greenhouse gases can be decreased by lowering their sources of origin (for example; the use of fossil fuels for transportation, heating, or electricity) or "sinking" them through absorption and storage. United Nations Climate Change Mitigation (UNCCM) Report in 2014, also states prompt recovery of greenhouses can help ecosystems to adapt naturally to climate change, thereby stabling the effects of gas concentrations. The best option to avert climate change and its disasters is to reduce the effect of human activities worldwide.

Seagrass, mangroves, and salt marshes are examples of distinctive coastal ecosystems that serve as marine habitats and natural water filters and they ought to be kept (Fawzy et al., 2020). By soaking up storm surges and floods, it shields coastlines from the consequences of increasing sea levels. It also stores considerable amounts of carbon in plant roots and soil. More than two years' worth of global emissions are released by mangrove forest destruction, worsening the effects of climate change (Schaftel, 2022).

The entire world has applauded the Copenhagen and Kyoto agreements to bring down the atmospheric temperature rise caused by GHGs emission to below 2oC by 2050 due to the obvious consequences of its effects (http://www.climatechangechallenge.org/). The identified climate change mitigation measures are many including:

Irrigation

According to Perkins, (2010) who reported in research findings that through enhanced evaporation, irrigation cools the earth's surface and provides a counter balance to global warming, especially in the higher latitudes but additional warming from the tropics if not looked into is capable of throwing that balance off-kilter.

Trading Plants for Carbon

According to West et al., (2010), it was reported that a complex trade-off exists between expanding agriculture and maintaining carbon on the farm land.

Perkins (2010) advised that farmers particularly those in the tropics should concentrate on boosting crop production on already cleared land to prevent carbon emissions. This is because in the tropics, farmers engage in bush- burning and other farming practices that boost carbon dioxide emissions. According to the report, Paul West and his colleagues at the University of Wisconsin- Madison used soil and agricultural data gathered worldwide to estimate the carbon that would be lost if natural ecosystems are cleared for farming food or bio-fuel crops. They discovered that the carbon lost from clearing differs widely between the temperate region and the tropics (West et al., 2010). In the temperate region, each hectare of forest cleared would release about 63 metric tons of carbon, whereas in the tropics the same area would release about 120 metric tons of stored carbon.

Clean Biomass Systems

Research has shown that a great potential exists for clean biomass systems to reduce greenhouse gas (GHG) emissions (Onoja et al., 2011). Whiteman and Lehmann (2010) observed that when biomass is burned inefficiently as in conventional cooking stoves, some carbon which was hitherto regarded as carbon-neutral is returned to the atmosphere in the form of methane and carbon monoxide – greenhouse gases that are even more powerful than carbon dioxide, but when these conventional stoves were replaced by cleaner-burning types, a reduction of about 30 per cent greenhouse gases (GHGs) was achieved (Perkins, 2010; Bowen, 2010).

Climate change is one part of adaptation to living in a changing environment, according to the National Academy of Sciences, NAS (2020). Less exposure to the harmful effects of climate change is the aim (rising sea levels, flooding, more extreme weather events, food insecurity, et cetera). This entails making the most of the anticipated advantages of climate change, such as; longer growing season and better yields in some regions (Fortuny, 2022). Adaptation strategies include, the following;

- Improving drainage pavements globally to deal with floods and run-offs.
- Increasing water storage and consumption
- Preparing for heat waves

- Constructing flood defences and high temperatures (Devine-Wright, 2013; Hoenkamp, et al., 2011).

CONCLUSION

Based on this findings, it was concluded that the climate is changing due to man-made greenhouse gases from burning of fossil fuels (gas, oil, and coal) and other industrial activities, which are known to be the main producers of carbon dioxide (CO2). However, human activity has caused an unexpected shift in the climate system thereby releasing billions of tonnes of carbon dioxide (CO2) into the atmosphere and adding substantially to the greenhouse effect. Greenhouse Gas (GHG) emissions have increased rapidly since the industrialization and urbanization revolution have reached the highest level. These changes on the climate are posing serious threats on the ecosystem and humans. The future climate change will aggravate the likelihood of drought or violent thunderstorms in the region, boosting soil erosion and decreasing crop production/yields, if the above mentioned mitigation and adaptation strategies are not implemented globally.

REFERENCES

Alderman, H. (2010). Safety net can help address the risks to nutrition from increasing variability. The Journal of Nutrition, 140, 148–152.

Ammann, C. M., Washington, W. M., Meehl, G. A., Buja, L., & Teng, H. (2010). Climate engineering through artificial enhancement of natural forcings: Magnitudes and implied consequences. Journal of Geophysical Research, 115(D22109). https://doi.org/10.1029/2009JD012878

Berbesi, L. A., et al. (2014). Methane leakage from evolving petroleum systems: Masses, rates and inferences for climate feedback. Earth and Planetary Science Letters, 387, 219–228.

Black, I. R., Shaw, D., & Trebeck, K. (2017). A policy agenda for changing our relationship with consumption. Journal of Cleaner Production, 154, 12–15.

Bloem, M. W., Semba, R. D., & Kraemer, K. B. (2010). Castel Gandolfo workshop: An introduction to the impact of climate change, the economic crisis, and the increase in food prices on malnutrition. The Journal of Nutrition, 140, 132–135.

Bowen, A., Romani, M., & Stern, N. (2010). Challenge of the century. Finance and Development, 47(4), 24–25. http://www.imf.org/fandd

Brown, A. (2010). Mitigation: Compensatory cooling. Nature Climate Change. https://doi.org/10.1038/nclimate1021

Crowley, T. J. (2000). Connecting environment, nutrition and health. Science, 289(5477), 270–277. https://doi.org/10.1126/science.289.5477.27

Devine-Wright, P. (2013). Think global, act local? The relevance of place attachments and place identities in a climate changed world. Global Environmental Change, 23, 61–69.

DifferenceBetween.com. (2012). Difference between climate change and global warming. http://www.differencebetween.com/difference-between-climate-change-and-global-warming/

Fawzy, S., Osman, A. I., Doran, J., & Rooney, D. W. (2020). Strategies for mitigation of climate change: A review. Environmental Chemistry Letters, 18(6), 2069–2094.

Fortuny, L. (2022). Climate change mitigation and adaptation. https://www.iaia.org/wiki-details.php?ID=6

Gerber, P. J., Steinfeld, H., Henderson, B., Mottet, A., Opio, C., Dijkman, J., et al. (2013). Tackling climate change through livestock: A global assessment of emissions and mitigation opportunities. Food and Agriculture Organization of the United Nations.

Global Carbon Project. (2024). Fossil fuel CO2 emissions increase again in 2024. https://globalcarbonbudget.org/fossil-fuel-CO2-emissions-increase-again

Grinning Planet. (2007). Global warming vs. climate change. http://www.grinningplanet.com/2007/01-02/global-warming-vs-climate-change.htm

Hoffman, R. N., et al. (2010). An estimate of increases in storm surge risk to property from sea level rise in the first half of the twenty-first century. Weather, Climate, and Society.

Hoenkamp, R., Huitema, G. B., & de Moor-van Vugt, A. (2011). The neglected consumer: The case of smart meter roll-out in the Netherlands. Renewable Energy Law and Policy Review, 4, 269–282.

Intergovernmental Panel on Climate Change. (2007). Climate change 2007: Fourth assessment report. http://ipcc.ch/graphics/graphics/ar4-wg1/jpg/faq-2-1-fig-1.jpg

Intergovernmental Panel on Climate Change. (2014). Working Group III contribution to the Fifth Assessment Report: Chapter 5.

Intergovernmental Panel on Climate Change. (2020). Global warming of 1.5°C: An IPCC special report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways. IPCC.

Intergovernmental Panel on Climate Change. (2021). Summary for policymakers. In V. Masson-Delmotte et al. (Eds.), Climate change 2021: The physical science basis (pp. 3–32). Cambridge University Press. https://doi.org/10.1017/9781009157896.001

Intergovernmental Panel on Climate Change. (2023). Summary for policymakers. In H. Lee & J. Romero (Eds.), Climate change 2023: Synthesis report (pp. 1–34). IPCC. https://doi.org/10.59327/IPCC/AR6-9789291691647.001

International Federation of Red Cross and Red Crescent Societies. (2016). Small and simple actions to address climate change. IFRC.

Kaddo, J. R. (2016). Climate change: Causes, effects, and solutions (Honors project No. 164). Parkland College. http://spark.parkland.edu/ah/164

Li, Y., Zou, B., Changwen, H., & Minhua, C. (2016). Nitrogen-doped porous carbon nanofiber webs for efficient CO2 capture and conversion. Carbon, 99, 79–89.

Mi, Z., Guan, D., Liu, Z., Liu, J., Viguié, V., Fromer, N., & Wang, Y. (2019). Cities: The core of climate change mitigation. Journal of Cleaner Production, 207, 582–589.

National Academy of Sciences. (2020). Climate change: Evidence and causes. https://royalsociety.org/~/media/royal_society_content/policy/projects/climate-evidence-causes/climate-change-evidence-causes.pdf

National Centers for Environmental Information. (2024). Annual 2024 global climate report. National Oceanic and Atmospheric Administration. https://www.ncei.noaa.gov/access/monitoring/monthly-report/global/202413

National Oceanic and Atmospheric Administration. (n.d.). Seasonal drought outlook.

National Aeronautics and Space Administration. (2008, June 15). Global climate change: Effects. https://climate.nasa.gov/effects/

Onoja, U. S., Dibua, U. M. E., & Enete, A. A. (2011). Climate change: Causes, effects and mitigation measures—A review. Global Journal of Pure and Applied Sciences, 17(4), 469–479.

Osariemen, M. I., & Obehi, O. I. (2024). Causes and consequences of climate change: A theoretical approach. Journal of Academic Research in Economics, 16(2), 375–386.

Paehler, H. K. (2007). Causes of climate change in Nigeria (Country report series).

Perkins, S. (2010a). Adaptation: Identifying obstacles. Nature Climate Change. https://doi.org/10.1038/nclimate1027

Perkins, S. (2010b). Agriculture: Trading crops for carbon. Nature Climate Change. https://doi.org/10.1038/nclimate1011

Perkins, S. (2010c). Atmospheric science: Clouds' contribution. Nature Climate Change. https://doi.org/10.1038/nclimate1026

Perkins, S. (2010d). Economics: Costly storm surges. Nature Climate Change. https://doi.org/10.1038/nclimate1020

Riebeek, H. (2010, June 3). Global warming. NASA Earth Observatory. https://earthobservatory.nasa.gov/features/GlobalWarming

Rolnick, D., Donti, P. L., Kaack, L. H., Kochanski, K., Lacoste, A., Sankaran, K., et al. (2022). Tackling climate change with machine learning. ACM Computing Surveys, 55(2), 1–96.

Shaftel, H. (2022). Responding to climate change. NASA. https://climate.nasa.gov/solutions/adaptation-mitigation/

Shaw, D., Cumbers, A., McMaster, R., & Crossan, J. (2018). Scaling up community action for tackling climate change. British Journal of Management, 29(2), 266–278.

Suarez, I. (2022). 5 strategies that achieve climate mitigation and adaptation simultaneously. World Resources Institute. https://www.wri.org/insights/5-strategies-achieve-climate-mitigation-and-adaptation-simultaneously

Tao, Y., Steckel, D., Klemeš, J. J., & You, F. (2021). Trend towards virtual and hybrid conferences may be an effective climate change mitigation strategy. Nature Communications, 12(1), 1–14.

U.S. Environmental Protection Agency. (2016). Causes of climate change. https://www.epa.gov/climate-change-science/causes-climate-change

U.S. Global Change Research Program. (2017). Climate science special report: Fourth national climate assessment (Vol. I).

Walton, T. L., Jr., & Dean, R. G. (2010). Shoreline: News from the Florida Shore & Beach Preservation Association. http://bit.ly/br57im

West, P. C., et al. (2010). Trading carbon for food: Global comparison of carbon stocks vs. crop yields on agricultural land. Proceedings of the National Academy of Sciences. https://doi.org/10.1073/pnas.1011078107

Whiteman, T. L., & Lehmann, C. J. (2010). Systematic under- and overestimation of GHG reductions in renewable biomass systems. Climatic Change. https://doi.org/10.1007/s10584-010-9984-5

World Meteorological Organization. (2023). Eight warmest years on record witness upsurge in climate change impacts. https://public.wmo.int/en/media/press-release/eight-warmest-years-record-witnss-upsurge-

ISBN: 978-625-92098-2-1