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Agriculture under a Changing Climate: Challenges and Pathways for India

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Indian agriculture is entering a phase of heightened uncertainty as long-term climatic shifts increasingly influence natural resources, production stability, and farm livelihoods. Changes in thermal regimes, rainfall behaviour, and atmospheric composition are redefining crop–soil–water interactions and altering the biological balance within agro-ecosystems. These changes manifest as shortened crop life cycles, declining efficiency of applied inputs, increased vulnerability to pests and diseases, and growing pressure on soil and water resources. The cumulative impact threatens productivity across crops, livestock, and fisheries, particularly in climate-sensitive regions dependent on seasonal rainfall. Future agricultural sustainability therefore depends on the capacity to anticipate, absorb, and respond to climate-induced risks. Strategic interventions such as climate-responsive crop improvement, resource-conserving production systems, diversified land-use models, and data-driven risk management offer viable pathways to sustain output while minimizing environmental footprints. Integrating adaptation and mitigation within farm management is essential to ensure food system resilience, environmental integrity, and livelihood security under a changing climate.

Agriculture is the mainstay of the Indian economy where about 65-70 percent of the population is dependent on it for their livelihood. Therefore, the climate change has direct effect on India. There is strong evidence to suggest that change in climate has been occurring during the past 100 years. Global warming refers to the rise in average global temperatures mainly due to the increasing concentrations of greenhouse gases in the atmosphere. Climate change refers to the increasing changes in the measures of climate over a long period of time including precipitation, and wind patterns. Agriculture is highly sensitive to climate variability. Various climate driven extremes like high temperature stress, drought, elevated carbon dioxide and erratic rainfall patterns pose a serious challenge to global food grain production. Rise in temperature and drought significantly affects the crop yield. Because the livelihood system in India is based on agriculture, climate change could cause increased crop failure and more frequent incidences of pests and diseases. Increase in temperature will probably offset the likely benefits of increasing atmospheric concentrations of carbon dioxide on crop plants. The average surface temperature of the earth has been increased progressively by 0.7°C over the last 50 years along with frequency and intensity of extreme events. Besides that, gaseous composition of the atmosphere has undergone a significant change mainly through increased industrial emissions, fossil fuel combustion, widespread deforestation and burning of biomass which ultimately led to global warming. Climate extremities may hinder crop growth and productivity by affecting various physiological and biochemical mechanisms which finally impacts crop yield. Rising temperatures and lack of moisture may profoundly impact growth, yield, membrane stability, photosynthetic characters, water relations, anatomical changes, pollen and spikelet sterility and so forth.

Global warming

Global warming is phenomenon of gradual increase in the overall temperature of the earth's atmosphere generally attributed to the greenhouse effect caused by increased levels of carbon dioxide, CFCs, and other pollutants. Global warming is related to the more general phenomenon of climate change, which refers to changes in the totality of attributes that define climate. In addition to changes in air temperature, climate change involves changes to precipitation patterns, winds, ocean currents, and other measures of Earth's climate. Normally, climate change can be viewed as the combination of various natural forces occurring over diverse timescales. Since the advent of human civilization, climate change has involved an "anthropogenic," or exclusively human-caused, element, and this anthropogenic element has become more important in the industrial period of the past two centuries. The term global warming is used specifically to refer to any warming of near-surface air during the past two centuries that can be traced to anthropogenic causes.

Greenhouse effect

The average surface temperature of earth is maintained by a balance of various forms of solar and terrestrial radiation. Solar radiation is often called "shortwave" radiation because the frequencies of the radiation are relatively high and the wavelengths relatively short—close to the visible portion of the electromagnetic spectrum. Terrestrial radiation, on the other hand, is often called "longwave" radiation because the frequencies are relatively low and the wavelengths relatively long-somewhere in the infrared part of the spectrum. Downward-moving solar energy is typically measured in watts per square metre. The energy of the total incoming solar radiation at the top of Earth's atmosphere (the so-called "solar constant") amounts roughly to 1,366 watts per square metre annually. Adjusting for the fact that only one-half of the planet's surface receives solar radiation at any given time, the average surface insolation is 342 watts per square metre annually.

Greenhouse gases

Carbon dioxide

Carbon dioxide (CO_2) is the most significant greenhouse gas. Natural sources of atmospheric CO_2 include outgassing from volcanoes, the combustion and natural decay of organic matter, and respiration by aerobic (oxygen-using) organisms. These sources are balanced, on average, by a set of physical, chemical, or biological processes, called "sinks," that tend to remove CO_2 from the atmosphere. Significant natural sinks include terrestrial vegetation, which takes up CO2 during photosynthesis.

Methane

Methane (CH_4) is the second most important greenhouse gas. CH_4 is more potent than CO_2 because the radiative forcing produced per molecule is greater. In addition, the infrared window is less saturated in the range of wavelengths of radiation absorbed by CH_4, so more molecules may fill in the region. However, CH_4 exists in far lower concentrations than CO_2 in the atmosphere, and its concentrations by volume in the atmosphere are generally measured in parts per billion (ppb) rather than ppm. CH_4 also has a considerably shorter residence time in the atmosphere than CO_2 (the residence time for CH_4 is roughly 10 years, compared with hundreds of years for CO_2).

Nitrous oxides and fluorinated gases

Additional trace gases produced by industrial activity that have greenhouse properties include nitrous oxide (N_2O) and fluorinated gases (halocarbons), the latter including CFCs, sulfur hexafluoride, hydrofluorocarbons (HFCs), and perfluorocarbons (PFCs). Nitrous oxide is responsible for 0.16 watt per square metre radiative forcing, while fluorinated gases are collectively responsible for 0.34 watt per square metre. Nitrous oxides have small background concentrations due to natural biological reactions in soil and water, whereas the fluorinated gases owe their existence almost entirely to industrial sources.

Water vapour

Water vapour is the most potent greenhouse gas in Earth's atmosphere, but its behaviour is fundamentally different from that of the other greenhouse gases. The primary role of water vapour is not as a direct agent of radiative forcing but rather as a climate feedback—that is, as a response within the climate system that influences the system's continued activity. This distinction arises because the amount of water vapour in the atmosphere cannot, in general, be directly modified by human behaviour but is instead set by air temperatures. The warmer the surface, the greater the evaporation rate of water from the surface. As a result, increased evaporation leads to a greater concentration of water vapour in the lower atmosphere capable of absorbing infrared radiation and emitting it back to the surface.

Sources of greenhouse gas emission

The primary sources of greenhouse gas emissions by economic sector are:

- **Transportation** (28% of 2022 greenhouse gas emissions) – The transportation sector generates the largest share of greenhouse gas emissions. Greenhouse gas emissions from transportation primarily come from burning fossil fuel for our cars, trucks, ships, trains, and planes. Over 94% of the fuel used for transportation is petroleum based, which includes primarily gasoline and diesel.
- **Electricity production** (25% of 2022 greenhouse gas emissions) – Electric power generates the second largest share of greenhouse gas emissions and includes emissions from electricity production used by other end use sectors (e.g., industry). In 2021, 60% of our electricity comes from burning fossil fuels, mostly coal and natural gas.
- **Industry** (23% of 2022 greenhouse gas emissions) – Greenhouse gas emissions from industry primarily come from burning fossil fuels for energy, as well as greenhouse gas emissions from certain chemical reactions necessary to produce goods from raw materials. If emissions from electricity use are allocated to the industrial end-use sector, industrial activities account for a much larger share (30%) of U.S. greenhouse gas emissions.
- **Commercial and Residential** (13% of 2022 greenhouse gas emissions) – Greenhouse gas emissions from the commercial and residential sector include fossil fuels burned for heat and the use of gases for refrigeration and cooling in buildings, and non-building specific emissions such as the handling of waste. Greenhouse gas emissions from commercial and residential buildings also increase substantially when emissions from electricity end-use are included, due to the relatively large share of electricity use (e.g., heating, ventilation, and air conditioning; lighting; and appliances) in these sectors When emissions from electricity use are allocated to the commercial and residential end-use sector, commercial and residential activities account for a much larger share (30%) of U.S. greenhouse gas emissions.
- **Agriculture** (10% of 2022 greenhouse gas emissions) – Greenhouse gas emissions from agriculture come from livestock such as cows, agricultural soils, and rice production.
- **Land Use and Forestry** (offsets 12% of 2022 greenhouse gas emissions) – While not shown in the figure, land areas can act as a sink (absorbing CO_2 from the atmosphere) or a source of greenhouse gas emissions. In the United States, since 1990, managed forests and other lands are a net sink, i.e., they have absorbed more CO_2 from the atmosphere than they emit.

Effects of global warming

Warmer temperatures over time are changing weather patterns and disrupting the usual balance of nature. This poses many risks to human beings and all other forms of life on earth

Hotter temperatures: nearly all land areas are seeing more hot days and heat waves; 2020 was one of the hottest years on record. Higher temperatures increase heat-related illnesses and can make it more difficult to work and move around. Wildfires start more easily and spread more rapidly when conditions are hotter.

More severe storms: changes in temperature cause changes in rainfall. This results in more severe and frequent storms. They cause flooding and landslides, destroying homes and communities, and costing billions of dollars.

Increased drought: water is becoming scarcer in more regions. Droughts can stir destructive sand and dust storms that can move billions of tons of sand across continents. Deserts are expanding, reducing land for growing food. Many people now face the threat of not having enough water on a regular basis.

A warming, rising ocean: the ocean soaks up most of the heat from global warming. This melts ice sheets and raises sea levels, threatening coastal and island communities. The ocean also absorbs carbon dioxide, keeping it from the atmosphere. More carbon dioxide makes the ocean more acidic, which endangers marine life.

These risks increase as temperatures climb. Forest fires, extreme weather, and invasive pests and diseases are among many threats. Some species will be able to relocate and survive, but others will not.

Scarcity of food: changes in climate and increases in extreme weather events are among the reasons behind a global rise in hunger and poor nutrition. Fisheries, crops, and livestock may be destroyed or become less productive. Heat stress can diminish water and grasslands for grazing.

More health risks: changing weather patterns are spreading diseases such as malaria. Extreme weather events increase diseases and deaths, and make it difficult for health care systems to keep up. Other risks to health include increased hunger and poor nutrition in places where people cannot grow or find sufficient food.

Poverty and displacement: climate change increases the factors that put and keep people in poverty. Floods may sweep away urban slums, destroying homes and livelihoods. Heat can make it difficult to work in outdoor jobs. Weather-related disasters displace 2.3 crore people a year, leaving many more vulnerable to poverty.

Impacts on agriculture

Heat waves and droughts: high temperatures during heatwaves can stress crops, leading to reduced yields and quality. Certain crops, such as wheat and corn, are particularly vulnerable to heat stress during critical growth stages. Droughts result in severe water shortages, impacting irrigation systems and reducing water availability for crops and livestock. Without sufficient water, crops wilt, yields decrease, and livestock suffer from dehydration and lack of forage.

Hastened organic matter decomposition: warmer temperatures accelerate microbial activity in the soil, leading to faster decomposition of organic matter. Microorganisms responsible for breaking down organic materials become more active and efficient in warmer conditions. Global warming can alter precipitation patterns, leading to changes in soil moisture levels. Drier conditions can concentrate microbial activity in pockets of moisture, accelerating decomposition in those areas. Conversely, increased precipitation in some regions can promote microbial growth and decomposition rates. Climate change can alter the composition and activity of soil microbial communities. Certain microbial species thrive in warmer conditions and may become more dominant, leading to increased rates of organic matter decomposition.

Increased competition from weeds: weeds may develop resistance to herbicides more rapidly under warmer conditions. Increased temperatures can accelerate the evolution of herbicide-resistant weed populations, making weed management more challenging and leading to greater competition with crops. Global warming can affect soil moisture levels, which can influence weed germination, growth, and competitiveness. Drier conditions may favour drought-tolerant weed species, while wetter conditions may promote the growth of water-loving weeds.

Increased crop residue rate: elevated atmospheric CO2 levels, a consequence of global warming, can stimulate plant growth and increase biomass production in crops. With more biomass being produced, there is a higher amount of crop residue left behind after harvest. Warmer temperatures and longer growing seasons associated with global warming can prolong the period during which crops accumulate biomass. This extended growing period allows crops to produce more biomass, resulting in higher crop residue rates.

Reduced crop duration: rising temperatures associated with global warming can lead to shorter growing seasons in certain regions. Higher temperatures can accelerate crop development, causing crops to mature more quickly. This acceleration may result in a shorter window of time for crops to complete their growth and development before adverse conditions, such as heat stress or drought, become limiting factors. Global warming can disrupt the timing of key phenological events in crop growth, such as flowering, fruiting, and maturity. Warmer temperatures can advance phenological stages, causing crops to progress through their growth cycle more rapidly. This acceleration can result in reduced crop duration if crops reach maturity before they have fully utilized available resources or accumulated sufficient biomass for optimal yield.

Pest and disease problem will increase: warmer temperatures can allow pests and diseases to expand their geographic ranges into regions where they were previously limited by temperature constraints. As temperatures rise, areas that were once too cold for certain pests or pathogens may become suitable habitats, increasing the likelihood of infestations or outbreaks. Global warming can disrupt the timing of phenological events in both plants and pests. Warmer temperatures can accelerate the development and reproduction of pests, causing them to emerge earlier in the growing season when crops are more vulnerable. Additionally, changes in the timing of flowering, fruiting, and other plant growth stages may create mismatches with the life cycles of pests, reducing natural pest control mechanisms.

Decrease nutrient use efficiency: warmer temperatures associated with global warming can accelerate evapotranspiration rates, leading to increased water loss from both plants and soil. As water availability becomes limited, plants may struggle to uptake nutrients efficiently, leading to nutrient deficiencies and reduced nutrient use efficiency. Elevated temperatures can influence soil microbial communities and their activity. Changes in microbial populations and metabolic processes may affect nutrient cycling dynamics in the soil, potentially leading to increased nutrient losses through leaching, volatilization, or microbial immobilization, thereby reducing nutrient availability to plants.

Soil degradation: prolonged droughts can lead to soil degradation, increased erosion, and reduced soil fertility, affecting long-term agricultural productivity.

Projected impacts of climate change on Indian agriculture

- Cereal productivity to decrease by 10-40 % by 2100
- Greater loss expected in *rabi*. Every 1 ^{o}C increase in temperature reduces wheat production by 4-5 million tons. Loss only 1-2 million tons if farmers could plant in time
- Increased water, shelter and energy requirement for livestock; implications for milk production
- Increasing sea and river water temperatures are likely to affect fish breeding, migration and harvests
- Considerable effect on microbes, pathogens and insects
- Increasing temperature would increase fertilizer requirement for the same production targets and result in higher emissions
- Food grains, oilseeds, pulses, plantation crops, vegetables, dairy, poultry, fisheries all sectors are effected

Adaptation strategies

I. Use of frontier biotechnological tools for improved biotypes
II. Developing Climate resilient genotypes

- Resistant to abiotic stress- heat, water, salinity
- Resistant to biotic stress- insects, diseases, weeds

III. Conservation agriculture based resource conservation technologies

- Laser-aided land levelling
- Zero tillage
- Rainwater harvest, drought management
- Crop Diversification and contingency crop planning and cropping system
- Furrow irrigated Raised-bed planting
- Soil health management
- Crop residue mulching
- Moisture conservation practices

IV. Alternative land-use systems, IFS

V. Risk management through early warning system and crop insurance

Mitigation opportunities

I. Reducing emission

II. Increasing Nitrogen use efficiency

III. Livestock management

IV. Aerobic rice and SRI method

V. Enhancing removals(Sinks)

- Agroforestry systems
- Carbon trading
- Displacing emission
- Biofuel, application of biochar
- Energy from residues

Climate-smart agriculture

Climate-smart agriculture (CSA) is an integrated approach to managing landscapes—cropland, livestock, forests and fisheries--that address the interlinked challenges of food security and climate change. CSA is a set of agricultural practices and technologies which simultaneously boost productivity, enhance resilience and reduce GHG emissions. Although it is built on existing agricultural knowledge, technologies, and sustainability principles, CSA is distinct in several ways. First, it has an explicit focus on addressing climate change in the agrifood system. Second, CSA systematically considers the synergies and tradeoffs that exist between productivity, adaptation, and mitigation. And third, CSA encompasses a range of practices and technologies that are tailored to specific agro-ecological conditions and socio-economic contexts including the adoption of climate-resilient crop varieties, conservation agriculture techniques, agroforestry, precision farming, water management strategies, and improved livestock management. By implementing these practices, triple win results can be achieved:

- Increased productivity
- Enhanced resilience
- Reduced emissions

Global initiatives to reduce the greenhouse gas emission and global warming

Kyoto Protocol: The Kyoto Protocol implemented the objective of the UNFCCC to reduce the onset of global warming by reducing greenhouse gas concentrations in the atmosphere to "a level that would prevent dangerous anthropogenic interference with the climate system". The Kyoto Protocol applied to the seven greenhouse gases listed in Annex A: carbon dioxide (CO_2),methane(CH_4), nitrousoxide(N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PF Cs), sulfur hexafluoride (SF_6), nitrogen trifluoride (NF_3).Nitrogen trifluoride was added for the second compliance period during the Doha Round.

Paris Agreement: The Paris Agreement is a legally binding international treaty on climate change. It was adopted by 196 Parties at the UN Climate Change Conference (COP21) in Paris, France, on 12 December 2015. It entered into force on 4 November 2016.

Its overarching goal is to hold "the increase in the global average temperature to well below 2°C above pre-industrial levels" and pursue efforts "to limit the temperature increase to 1.5°C above. That's because the UN's Intergovernmental Panel on Climate Change indicates that crossing the 1.5°C threshold risks unleashing far more severe climate change impacts, including more frequent and severe droughts, heatwaves and rainfall.

Indian initiatives to reduce the greenhouse gas emission and global warming

- **Harit Dhara' (HD):** Indian Council of Agricultural Research (ICAR) has developed an **anti-methanogenic feed supplement** 'Harit Dhara' (HD), which can cut down cattle methane emissions by 17-20% and can also result in higher milk production.
- **India Greenhouse Gas Program:** The India GHG Program led by WRI India (non-profit organization), Confederation of Indian Industry (CII), and The Energy and Resources Institute (TERI) is an industry-led voluntary framework **to measure and manage greenhouse gas emissions.**
- **National Action Plan on Climate Change (NAPCC):** It was launched in 2008 and aimed at creating awareness among the representatives of the public, different agencies of the government, scientists, industry, and the communities on the **threat posed by climate change** and **the steps to counter it.**

Conclusion

Climate change is steadily reshaping the foundations of Indian agriculture by intensifying environmental stress and reducing production stability. Sustaining food systems under such conditions requires a shift from reactive practices to resilient, knowledge-driven farming approaches. Integrating climate-responsive technologies, efficient resource management, and supportive policies will be crucial to safeguard productivity, farmer livelihoods, and ecological balance in the face of a warming future.