

CHAPTER 1

Climate Change, Agriculture, Carbon, and Food Security

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Introduction

Throughout the course of Earth's existence, it has undergone alternating phases of warm periods and ice ages, resulting in a natural greenhouse effect. This effect is crucial for maintaining liquid water and supporting life, as the mean global annual temperature would have been -18°C in its absence (Voet and Voet, 2010). However, since the 1800s, human activities have emerged as the primary catalyst for an increase in the concentration of greenhouse gases (GHGs) in the troposphere, leading to significant impacts on global warming and climate change. These activities, such as the combustion of fossil fuels, household, commercial, and industrial practices, as well as deforestation and conventional agricultural activities, contribute to the release of heat-trapping gases (USEPA, 2023). The key GHGs include carbon dioxide (CO_2), carbon monoxide (CO), methane (CH_4), nitrous oxide (N_2O), water vapor, ozone (O_3), and fluorinated gases (Table 1).

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Table 1 Greenhouse gas emission, their global warming potential and tropospheric lifetime.
(Source: IPCC, 2014)

Greenhouse Gas	Chemical Formula	Emission Contrib. (%)	GWP in a 100 Yr. Time Span	Tropospheric Lifetime (Yr.)
Carbon Dioxide	CO ₂	76	1	100
Methane	CH ₄	16	25	12
Nitrous Oxide	N ₂ O	6	265	121
Fluorinated gases (F-gases)		2		
Chlorofluorocarbon-12 (CFC-12)	CCl ₂ F ₂		10,200	100
Hydrofluorocarbon-23 (HFC-23)	CHF ₃		12,400	222
Sulfur Hexafluoride	SF ₆		23,500	3,200
Nitrogen Trifluoride	NF ₃		16,100	500

With global warming potentials (GWPs) of emitted GHGs typically ranging from thousands to tens of thousands, they are termed high-GWP gases because, for a given mass, they trap more heat than CO₂. The GWP of CH₄ is 25 times greater, and N₂O is 296 times greater than CO₂ (GWP=1). However, the Earth’s troposphere contains significantly more CO₂ than CH₄ or N₂O (Table 1). The concentration of CO₂ has risen from the pre-industrial level of 280 $\mu\text{mol mol}^{-1}$ to the current level of 419 $\mu\text{mol mol}^{-1}$ and is projected to reach 700–800 $\mu\text{mol mol}^{-1}$ by 2100 (IPCC, 2021).

Human-induced global warming and climate change associated with the increasing accumulation of GHGs in the troposphere have broader impacts (Fig. 1). These include heightened frequency of extreme weather events, especially erratic precipitation, temperature rise, heatwaves, drought, and wet desertification, posing significant threats to ecosystem services and ecological functions (USEPA, 2023; Zhao et al., 2023). Notably, global temperatures have increased by 40% in the past 150 years, with half of this increase occurring in the last 30 years (IPCC, 2014). This could result in an average global temperature increase of 1–1.5°C sometime in the next century. As a response, climate zones may shift, polar ice may melt, and crops, forests, and animals may react differently by species. Some effects could be catastrophic.

Agriculture significantly contributes to the global carbon footprint, responsible for over 25% of anthropogenic GHG emissions linked to climate change effects on terrestrial ecosystems (IPCC, 2018; Zhao et al., 2023). While conventional agricultural practices generate substantial quantities of food, feed, and fiber (Fig. 2), they adversely impact soil health, water quality, and agroecosystem services (Islam and Didenko, 2019). Persistent annual tillage operations have demonstrated negative effects on biodiversity and efficiency, accelerating erosion, edge-of-field nutrient loss, compromising structural stability, increasing GHG emissions, diminishing soil organic carbon (SOC) content, and subsequently leading to soil health and land quality degradation (Aziz et al., 2013; Islam et al., 2021; Rahman et al., 2021). Specifically, accelerated soil organic matter (SOM) decomposition and crop residue burning, common in soil-crop management practices, are primary sources of CO₂ emissions in agriculture (Zhao et al., 2023). Methane emissions result from puddled and flooded rice production, intestinal fermentation in livestock digestive systems,

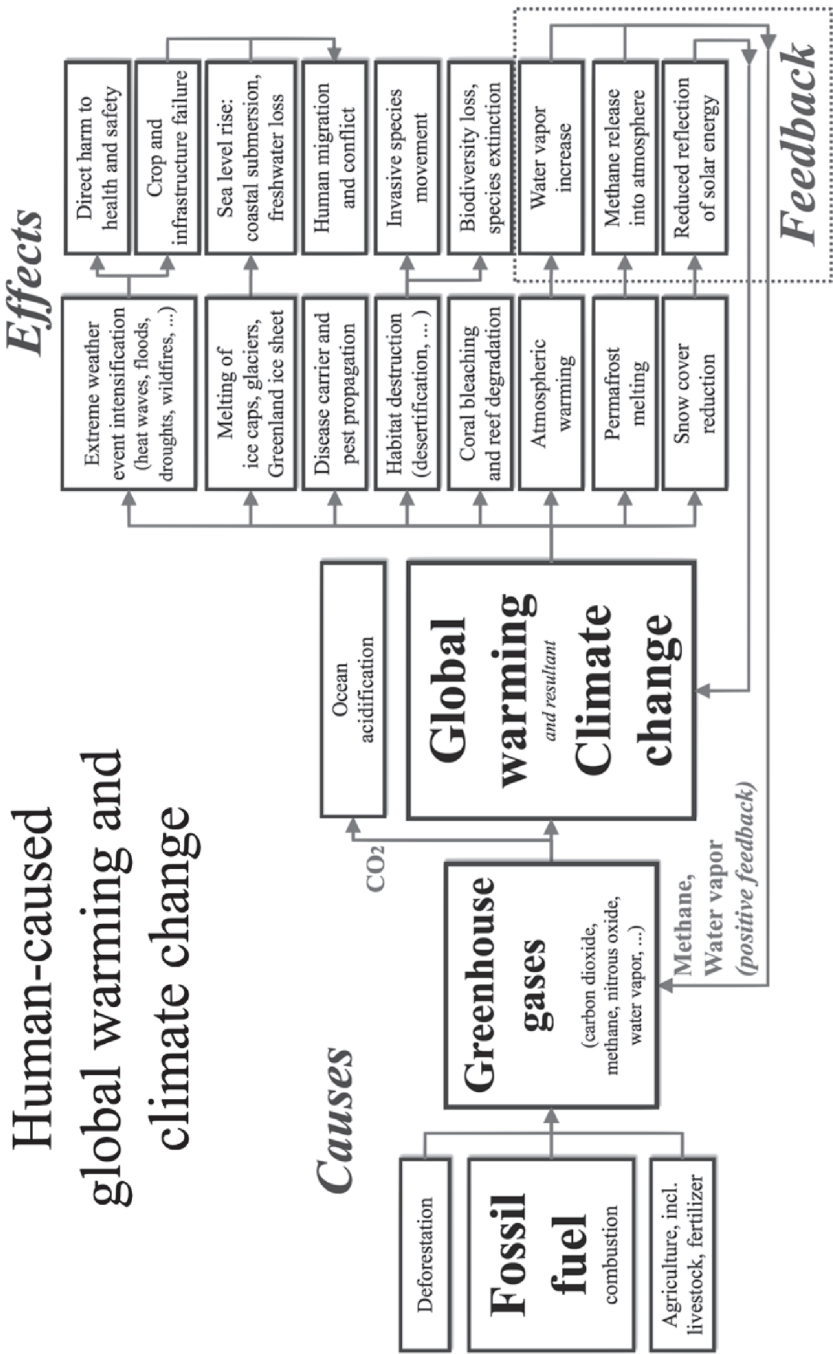


Fig. 1 Human-induced climate change effects on ecosystems
(https://en.m.wikipedia.org/wiki/File:20200101_Global_warming_-_climate_change_-_causes_effects_feedback.png).

and the decomposition of feces and crop residues in moist conditions. Similarly, N_2O emissions arise from intensively chemically fertilized soils, especially through nitrogen (N) fertilization, as well as from manure and compost amendments (Fig. 2). Globally, economic and population growth are pivotal factors driving the increase in GHG emissions, with projections indicating their continued rise, influencing future climate change (Jat et al., 2022).

Land degradation linked to agriculture and other activities poses a threat to the distribution of productive soils worldwide (<https://www.globalagriculture.org>). On a global scale, 10–20% of drylands and 24% of productive lands are degraded. Annually, an estimated 24 billion tons of fertile soil are lost due to erosion, equating to 3.4 tons per person. Water (sheet and rill) erosion rates averaged 6.6 tons per hectare in 2017, while wind erosion rates averaged 4.8 tons per hectare in the U.S. (USDA, 2020). Furthermore, approximately 810 hectares of agricultural land in the United States are paved over, fragmented, and converted for uses that jeopardize farming (www.farmland.org).

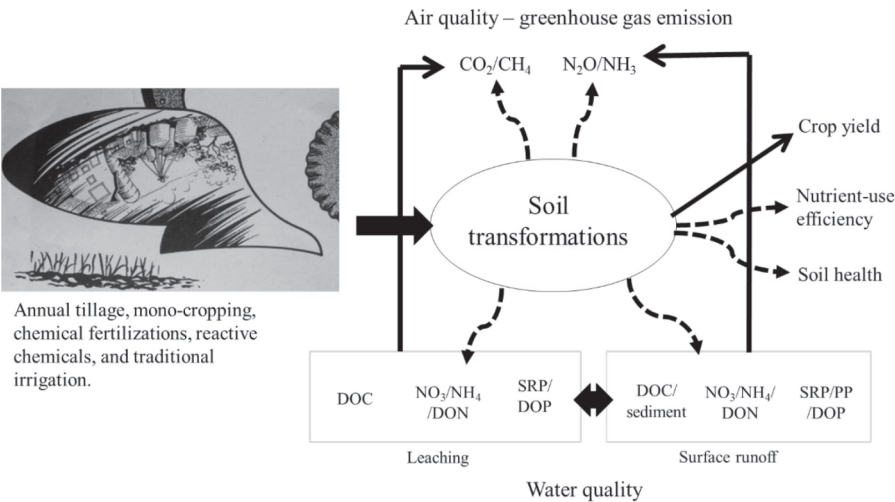


Fig. 2 Conventional agriculture’s impact on crop yield, soil health, greenhouse gas emission, and water quality associated with ecosystem services (DOC=dissolved organic C, DON=dissolved organic N, DOP=dissolved organic P, SRP=Soluble reactive P; and PP=particulate P).
Source: Rafiq Islam.

The European Union experiences an annual soil loss of 970 million tons due to water erosion, with the current cost of land degradation estimated at approximately US \$490 billion each year. Globally, 40% of degraded land is concentrated in regions with high poverty rates, directly affecting the health and livelihoods of around 1.5 billion people (<https://www.globalagriculture.org/>). A study supported by FAO, UNDP, and UNEP revealed that South Asian countries (India, Pakistan, Bangladesh, Afghanistan, Nepal, Sri Lanka, Bhutan) incur an annual loss of at least US \$10 billion due to land degradation (Khor, 2008; Spijkers, 2011). This accounts for 2% of the region’s GDP or 7% of its agricultural output. The study indicated that 43% of the region’s total agricultural land, approximately 140 million hectares, suffered from one or more

forms of degradation. Among these, 31 million hectares were highly degraded, and 63 million hectares were moderately degraded. Bangladesh ranked as the most severely affected country, with 75% of its agricultural land degraded, followed by Pakistan (61%), Sri Lanka (44%), Afghanistan (33%), Nepal (26%), India (25%), and Bhutan (10%) (Khor, 2008; Spijkers, 2011).

Climate Change and Agricultural Production

Agriculture stands as one of the most vulnerable sectors to the impacts of global warming and climate change (IPCC, 2021). The dependence of food production on climatic variables such as temperature, radiation, rainfall, moisture, and CO₂ concentration makes crop productivity susceptible to climate change (Nelson et al., 2009). Changes in climatic factors associated with crop production pose diverse challenges to addressing food security (Smith and Gregory, 2013; Lipper et al., 2014; Ziska, 2014).

Studies indicate an increase in the frequency and intensity of extreme events like droughts, heavy waves, intense rainfall, flooding, and high maximum temperatures, which are already occurring and expected to accelerate globally (IPCC, 2014; Lipper et al., 2014). Average and seasonal maximum temperatures are projected to rise with greater variability, while rainfall will become intensively variable, albeit unevenly distributed. Water scarcity and drought in dry regions are expected to increase by the end of the 21st century (IPCC, 2014). The impact of increased temperature on crops will vary based on each crop's optimal temperature for growth and reproduction (Hatfield et al., 2014). While some regions may benefit from global warming, others may experience adverse effects, impacting grain yield and food quality.

Studies suggest that despite short-term yield gains in some crops, increased temperatures will have a negative long-term impact, eventually reducing crop yields under future climate change (Bruinsma, 2003; IPCC, 2007). The effects of climate change on global agricultural production are expected to be unevenly distributed, with lower latitude and developing countries suffering more due to their geographical location, higher agricultural share in economies, and limited capacity to adapt. In contrast, high latitude regions may benefit from climate change (ADB, 2006). Global estimates predict a 15.9% reduction in agricultural productivity by the 2080s if global warming continues unabated, with developing countries experiencing a larger decline of 19.7% (Cline, 2007). According to Lipper et al. (2014), climate change has already reduced global maize and wheat yields by 3.8% and 5.5%, respectively. Paddy loss due to floods in Bangladesh and India is estimated at 4 million tons per year, enough to feed 30 million people (Asada and Matsumoto, 2009).

Increasing CO₂ concentration is expected to dilute N concentration, reducing protein quality via amino acids composition. Moreover, the concentration of essential nutrients in crops like wheat, soybeans, and rice may be affected, impacting food quality and posing a potential threat to human health and animal nutrition. Climate change is anticipated to encourage weed and pest proliferation, leading to increased likelihood of crop failures in the short-term and declines in food production in the long-term (Nelson et al., 2009; Ziska, 2014). Weeds, pests, and fungi are expected to thrive under warmer temperatures and wetter climates, posing new challenges to

crops previously unexposed to these conditions. Livestock faces risks from direct heat stress and reduced feed quality, affecting pasture and rangeland sustainability. Human health may be affected by reduced food quality and increased use of reactive chemicals (e.g., pesticides) due to heightened weed and pest pressures, alongside reductions in the efficacy of pesticides (Ziska, 2014). The IPCC (2021) reported that climate change negatively affects crop production more commonly than positively, with developing countries highly vulnerable to further negative impacts. Climate change is likely to affect agricultural production and food security globally, regionally, and locally by influencing soil-plant-water ecosystems (Brown et al., 2014; <https://www.globalagriculture.org>).

While climate change poses a significant risk to global agriculture, crop production in South Asia is particularly vulnerable in addressing food security (Aryal et al., 2020). Climatic variability, especially temperature and rainfall, explains 60% of crop yield variability and is a crucial factor influencing food production (Matiu et al., 2017; Aryal et al., 2020). The South Asian region is projected to experience a temperature rise of 0.5–1.2°C by 2020, 0.88–3.16°C by 2050, and 1.56–5.44°C by 2080. Heat-stressed areas in the region could increase by 21% in 2050, depending on future scenarios (IPCC, 2007; Tesfaye et al., 2017). These projected long-term changes in temperature and rainfall patterns are expected to impact land preparation, cropping seasons, crop types, planting suitability, fertilization, irrigation, disease and pest incidence, and weed infestations. For example, the growing periods for spring maize in Pakistan have shifted an average of 4.6 days per decade earlier between 1980–2014, while the planting of autumn maize has been delayed by 3 days per decade, significantly affecting crop yields (Abbas et al., 2017). Additionally, water availability, through rainfall and groundwater recharge, is anticipated to decline due to climate change, while agricultural water consumption is predicted to increase by 19% in 2050 (UN-Water, 2013).

Several studies, as summarized by Aryal et al. (2020), have reported the impacts of climate change on major food crops, including rice, wheat, and maize in South Asia (Tables 2, 3). Results show that crop yields in the region have been significantly influenced by changes in temperature and rainfall variability (Tables 2, 3). Comparing crop yields in the 1990s without climate change effects to those in the 2020s and 2050s, Parry et al. (2004) reported a reduction of 2.5–10% in several regions of Asia in the 2020s and 5–30% in the 2050s. The impacts of temperature and water stresses on agriculture, as reported by Lal (2011), indicate that summer crop productivity in South Asian countries is expected to decrease due to heightened climate variability and the widespread incidence and virulence of pests after 2050. Winter crops are expected to be more adversely affected by a temperature rise of 2°C. By the end of the 21st century, the net cereal production in South Asia is projected to decrease by at least 4–10% if the temperature increases by 3°C. Knox et al. (2012) suggested that the average yield of eight major crops would be reduced by 8% by the 2050s in South Asia. Specifically, maize and sorghum are anticipated to experience yield reductions of 16% and 11%, respectively, while rice is expected to be unaffected.

Aryal et al. (2020) documented a broad range of yield losses resulting from the impact of temperature changes on wheat, rice, and maize productivity in South Asia (Table 2). In India, crop yields decreased by 5%, 6–8%, and 10–30% in wheat, rice,

Table 2 Impact of change (increase) in temperature (ΔT) on crops in South Asian countries.

Country	ΔT (+)	Wheat	Rice	Maize	References*
India	<2°C	Yield decrease by 0.45 Mg/ha (1); yield decrease by 0.4 Mg/ha (2); yield decrease by 5.2% (6)	Yield decrease by 6% (3); yield decrease by up to 8.2% (4)	Yield decrease by 10–30% under 350 ppm CO ₂ (5)	¹ Sinha & Swaminathan (1991); ² Morey & Sadaphal (1981); ³ Saseendran et al. (2000); ⁴ Mathauda et al. (2000); ⁵ Kalra et al. (2007); ⁶ Gupta et al. (2017)
	2–3°C	Decrease in all regions (1)	Yield decrease by 0.75 Mg/ha (2); in % yield decrease by 8.4% (3)	Yield decrease by 10–30% under 350 ppm CO ₂ (4)	¹ Aggarwal & Sinha (1993); ² Sinha & Swaminathan (1991); ³ Mathauda et al. (2000); ⁴ Kalra et al. (2007)
	>3°C			Yield decrease by 10–30% under 350 ppm CO ₂ (3)	³ Kalra et al. (2007)
Bangladesh	<3°C	Yield loss exceed 60% (1)	Yield decrease by 2.6–13.5% (2)		¹ Karim et al. (1996); ² Basak et al. (2009)
	>3°C	Yield loss exceed 60% (1)	Yield decrease by 0.11–28.7% (2)		¹ Karim et al. (1996); ² Basak et al. (2009);
Nepal	4°C	Yield increases by 18.4% due to CO ₂ fertilization and by 8.6% with an increase in temperature (1)	Yield decrease by 1.8% in Terai and increase in hills by 5.3% and mountainous by 33.3% (1)	Yield decrease by 26.4% in Terai and by 9.3% in hills (2)	¹ Malla (2008); ² Prasai (2010)
Pakistan	<3°C	Yield decrease by 5–7% (1); Yield decrease by 7% in Swat district and 14% in Chitral district (2); yield decrease by 6–9% in sub-humid, semiarid, and arid zones (3)			¹ Aggarwal & Sivakumar (2010); ² Hussain & Mudasser (2007); ³ Sultana & Ali (2006)

Contd.

Table 2 *Contd.*

Country	ΔT (+)	Wheat	Rice	Maize	References*
	$>3^{\circ}\text{C}$	Yield decrease in arid, semiarid, and sub-humid zones, but increases in humid zone (1); yield decrease by 21% in Swat district and 23% in Chitral district (2)			¹ Sultana et al. (2009); ² Hussain & Mudasser (2007)
Sri Lanka	$\leq 1^{\circ}\text{C}$		A loss of 6% rice output (1); yield decrease by 1–5% (2)		¹ GoSL (2000); ² Vidanage & Abeygunawardane (1994)

Note: *Number in the parentheses refers to the corresponding reference mentioned (*Source:* Aryal et al., 2020).

and maize, respectively. Despite variations in input use and crop management in India, both season-long and terminal-heat stress negatively affected rice and wheat, with wheat proving more sensitive than rice (Arshad et al., 2017). In Nepal, rising temperatures positively impacted crop yields, especially for wheat. However, rice and maize yields in the mid-hills and Terai regions significantly decreased with increasing temperatures. In Bhutan, the impacts of climate change amplified crop losses due to unusual outbreaks of diseases and pests, erratic rainfall, windstorms, hailstorms, droughts, flash floods, and landslides (Chhogyel and Kumar, 2018). Similar responses to climate change-induced crop yield losses were observed in Bangladesh, Pakistan, and Sri Lanka. It is projected that almost half of the Indo-Gangetic Plains (Bangladesh and India), the major food basket of the South Asian region, may face severe wheat production challenges by 2050 due to heat stress (Ortiz et al., 2008; Dey et al., 2017).

Climate change, closely tied to rising temperatures, has a direct impact on water availability, significantly influencing crop productivity. For instance, if India continues to deplete its groundwater for irrigation, the adverse effects of increased warming and other climatic variations on crop production are expected to intensify by half (Fishman, 2018). Kumar et al. (2004) demonstrated that a 19% reduction in summer monsoon rainfall results in an approximately 18% decrease in food grain production (Table 3). Even a modest temperature rise (e.g., $1.5\text{--}2^{\circ}\text{C}$) in South Asia can critically affect water resources due to heightened monsoon variability and glacial meltwater, posing a substantial threat to future agricultural productions (Vinke et al., 2017).

Looking ahead to 2050, the global population is projected to surpass 10 billion, with approximately 10% of the current 8 billion people on Earth already facing undernourishment, and 3 billion lacking access to healthy diets (Nuccitelli, 2022). A staggering 75% of the world's poor reside in rural areas, where agriculture stands as their primary source of income. Schmidhuber and Tubiello (2007) reported that by 2080, anywhere between 5–170 million people worldwide may confront severe food scarcity, with over 95% of these individuals residing in developing countries

that are expected to be most affected by climate change. Concurrently, per capita food consumption is on the rise, anticipated to lead to a doubling of global meat consumption and a 60% increase in cereal consumption by 2050 (Zhai and Zhuang, 2009). Agriculture plays a pivotal role in Southeast Asia, contributing to more than 10% of the gross domestic product in most regional economies and offering employment to over one-third of the working population in the region (Zhai and Zhuang, 2009).

Table 3 Impacts of change rainfall variability on crops in South Asian countries.

Country	Impacts	Crops	References*
Bangladesh	Positive and statistically significant effect	Rice	Sarker et al. (2012)
Bangladesh	Negatively affects rice yields	Rice	Alauddin and Hossain (2001)
Bangladesh	Variability in rice yields leading to Yield decrease by 8–17% by 2050	Rice	Rahman et al. (2009)
India	More rainfall leads to higher mNDVI in the drier western parts of the basin and lower mNDVI in the eastern parts of the basin (*)	Crops (vegetation)	Siderius et al. (2014)
India	Annual total yield were significantly correlated with all-India summer monsoon rainfall	Wheat and Rice	Kumar et al. (2007)
India	Statistical analysis of state-level Indian data confirms that drought and extreme rainfall negatively affected rice yield (harvest per hectare)	Rice	Aufhammer et al. (2012)
Nepal	The yield of individual cereals is correlated with the seasonal rainfall data	Paddy, maize, millet, wheat, and barley	Bhandari (2013)
India	All-India crop yield index shows a strong relationship with all-India summer monsoon rainfall	Food grains	Prasanna (2014)
Pakistan	Effect of rainfall on the yield of rice, wheat, and maize is negative and nonsignificant except for wheat, which is significant	Rice, wheat, and maize	Ali et al. (2017)
Pakistan	Normal precipitation during vegetative and maturity stages and their deviations from the historical mean (positive) exert a positive impact on the wheat yield	Wheat	Ahmad et al. (2014)

Note: NDVI is Normalized Difference Vegetation Index (*); for the Rabi season, the relationship for those areas with a significant impact is mostly positive (Source: Aryal et al., 2020).

Addressing the food security challenge in developing countries necessitates a substantial increase in cereal yields by 40%, along with a corresponding rise in irrigation water requirements by 40–50%. Additionally, there may be a need for an

additional 100–200 million hectares of land, particularly in Asia, sub-Saharan Africa, and Latin America (Lipper et al., 2014). The demographic landscape in developing countries is expected to witness an influx of an extra 2.4 billion people, concentrated in South Asia and sub-Saharan Africa, by 2050. While agriculture remains a pivotal economic sector and primary source of employment in these regions, the current reality is that over 20% of the population, on average, grapples with food insecurity (Wheeler and Braun, 2013; Lipper et al., 2014).

Projections underscore the global imperative to increase agricultural production by 60% by 2050 to meet escalating demand, with a major share of this augmentation required from enhanced crop productivity. However, an in-depth analysis based on South Asian countries' agricultural land area, population growth, and agricultural land per capita does not reveal economically viable options for the horizontal expansion of agriculture. Instead, the emphasis should be on achieving a vertical increase in crop productivity per unit of land (Table 4).

Table 4 Total and agricultural land distribution and population density in South Asian countries.

Country	Tot. Land Area (km ²)	Agric. Land (km ²)	Agric. Land/Total Land (%)	Total Population	Pop. Density (Person/km ²)	Agric. Land/Person
Afghanistan	652230	383130	58.7	42,239,854	65	0.91
Bangladesh	130170	100680	77.3	172,954,319	1329	0.06
Bhutan	38140	5130	13.5	787,424	21	0.65
India	2973190	1785279	60.0	1,428,627,663	481	0.12
Maldives	300	59	19.7	521,021	1737	0.01
Nepal	143350	41210	28.7	30,896,590	216	0.13
Pakistan	770880	363030	47.1	240,485,658	312	0.15
Sri Lanka	61860	28120	45.5	21,893,579	354	0.13
Total	4,708,260	2,706,638	—	1,938,406,108	412	—
Average	—	—	57.2	—	—	0.14

Source: <https://www.worldometers.info/world-population/southern-asia-population>. <https://data.worldbank.org/indicator/SP.POP.TOTL?locations=8S>.

By 2050, the global demand for food security is set to double, placing existing farming practices in a heightened dependency on reactive chemicals, freshwater, and energy inputs (Islam and Didenko, 2019). This intensification of farming under climate change is anticipated to have adverse consequences for agroecosystem services. The imperative to sustainably manage the world's climate-stressed and pollution-degraded agricultural system is paramount to meet the needs of the expected 9 billion people by 2050 (Nuccitelli, 2022). Addressing this challenge involves reducing GHG emissions to mitigate climate change effects and ensure food security for the growing population, making it one of the foremost challenges of the 21st century (Ziska et al., 2012). While increasing agricultural production is achievable, it is likely to come at a higher environmental cost and pose threats to biodiversity unless proactive measures are taken for climate change mitigation and adaptation.

Climate Change Mitigation and Adaptation

Climate-Smart Agriculture

Climate-smart agriculture (CSA) represents an integrated approach aimed at transforming and reorienting agricultural production systems to sustain food security in the face of climate change (Lipper et al., 2014). This approach harmonizes economic viability, social acceptability, and environmental compatibility to collectively address climate change-related threats to food security within the framework of sustainable agricultural development (FAO, 2013). The key objectives of CSA encompass:

1. **Increased Productivity:** Producing more high-quality food to enhance nutrition security and boost incomes, especially for the 75% of the world's low-income population residing in rural areas reliant on agriculture for their livelihoods.
2. **Enhanced Resilience:** Reducing vulnerability to drought, pests, diseases, and other climate-related risks and shocks, while improving the capacity to adapt and thrive in the face of longer-term stresses such as shortened seasons and erratic weather patterns.
3. **Reduced Emissions:** Pursuing lower emissions for each calorie or kilogram of food produced, avoiding deforestation from agriculture, and identifying ways to sequester tropospheric CO₂ via plants as SOM to enhance soil health and sustain crop production for food security.

Carbon within SOM plays a crucial role in the earth's carbon cycle and is vital for mitigating the effects of climate change (Sundermeier et al., 2011; Raphael, 2024). Mitigating emitted CO₂ as SOM is a pivotal strategy to enhance soil health and increase crop production within the context of climate-smart agriculture.

Conservation Tillage

While conventional tillage (CT) offers benefits such as field workability, seed bed preparation, weed and soil-borne disease suppression, and higher crop yields, it adversely affects soil biology by fragmenting fungal hyphae and mycorrhizal associations (Islam and Weil, 2000; Sundermeier et al., 2011). CT degrades soil health and accelerates GHG emissions, especially CO₂ (Sundermeier et al., 2011). Transitioning from CT to no-till (NT) or minimum tillage emerges as a proactive strategy to enhance soil functional capacity in the CO₂ source-to-sink pathway (Sundermeier et al., 2011; Islam et al., 2022). Under NT, crop residues accumulate on the surface, acting as mulch to mitigate rising soil temperature, reduce evaporative demand, control soil erosion, retain moisture longer, and limit O₂ diffusion. Additional benefits encompass increased biodiversity with fungal dominance (higher C-use efficiency), slower decomposition of residues and native SOM, augmented aggregate formation and stability, greater SOC sequestration, and improved soil quality (Islam and Weil, 2000; Islam et al., 2022).

Conservation tillage, a practice that mandates leaving a minimum of 30% of crop residues, is pivotal for controlling edge-of-field soil loss (Kanicki, 2014; Bergtold and Sailus, 2020). With approximately 40% of crop residues remaining in the soil under conservation tillage (30% recommended residues and 10% as root biomass),

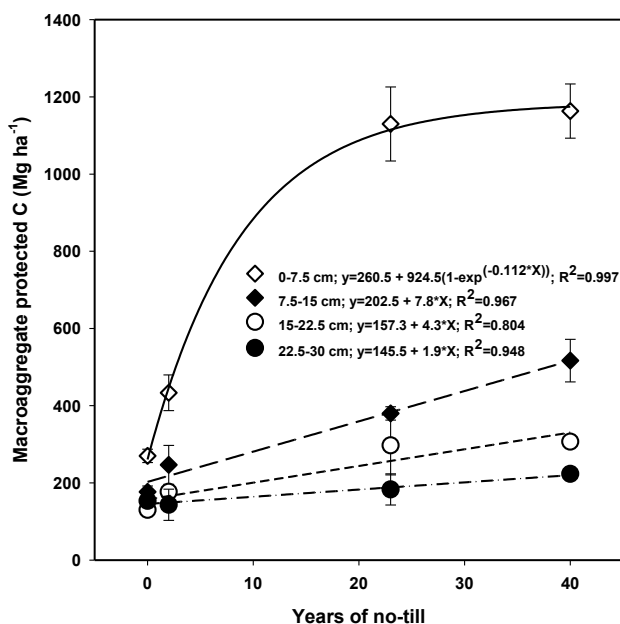


Fig. 3 Impact of long-term no-till on aggregate protected carbon sequestration at different depths of soil. (Source: Sundermeier et al. (2011))

equivalent to 1.6 tons of residue per hectare annually. Calculating the conversion rate of crop residues to SOM at 30% (Hann, 1977), SOM amounts to 0.48 tons per hectare per year. Given that SOM comprises about 58% total carbon (C), SOC equates to 0.28 tons per hectare per year. Using the coefficient “ r ” as the percentage of native SOC left in the second year after the decomposition of SOC formed in the first year, assuming r as 99% (Hann, 1977), the SOC stock in 10 years will be:

$$Y = [\text{SOC} * (1 - r^n)] / (1 - r)$$

$$Y = [0.28 * (1 - 0.99^{10})] / (1 - 0.99)$$

$$Y = 2.68 \text{ tons C/ha.}$$

Results indicate that aggregate-protected C was 24%, 80%, and 92% higher in 2, 23, and 44-year no-till (NT), respectively, compared to conventional tillage (CT) (Sundermeier et al., 2011). Over a 50+ year period, NT at 10-year intervals resulted in aggregate-protected C sequestration rates of 92, 63, 47, and 37 kg/ha/yr. at depths of 0–7.5, 7.5–15, 15–22.5, and 22.5–30 cm, respectively, when compared to CT (Fig. 3). It has been reported that C sequestration associated with soil health improvement sustains agricultural productivity (Islam et al., 2022). Reduced tillage with residue management has proven beneficial in increasing labile C and SOC stocks in intensive rice-based cropping systems in Bangladesh (Sarker et al., 2023).

In the South Asian region, especially Bangladesh, India, Nepal, and Pakistan, rice-wheat rotation dominates, covering more than 13.5 million hectares of CT lands (Zahid et al., 2020). In recent years, the productivity of rice-wheat has declined due to repeated plowing, unbalanced chemical fertilization, and increased pest and soil-borne

disease pressures (Bhatt et al., 2016). It has been reported that average wheat yield and irrigation efficiency in zero-till were higher than in CT for rice-wheat rotation and rice-wheat systems with the inclusion of legumes, owing to enhanced wheat rooting after unpuddled rice (Chaki et al., 2021).

Cropping Diversity and Cover Crops

Cropping diversity emerges as a solution to mitigate climate change while addressing the demand for food security (Moss et al., 2020). Diversifying crops through mixed cropping, intercropping, relay crops, or crop rotation with cover crops reduces the environmental impact of agriculture by enhancing microbial efficiency, labile carbon, and nutrients, thereby improving soil health to sustain crop productivity (Moss et al., 2020; Islam et al., 2021; Sarker et al., 2023).

Plants primarily fix tropospheric CO₂ through two photosynthetic processes: The C₃ and C₄ pathways, C₃ plants, such as rice, wheat, soybeans, small grains, and legumes, respond more effectively to increasing CO₂ concentration than C₄ plants, such as maize, millet, sorghum, sugarcane, and many grasses, as C₄ plants are already efficient users of CO₂ at ambient levels. An increase in CO₂ concentration positively impacts C₃ crop yields by stimulating photosynthesis and reducing water loss via transpiration. It is reported that crop yield may increase by 10–25% for C₃ crops and by 0–10% for C₄ crops when CO₂ levels reach 550 ppm (IPCC, 2007). Therefore, managed agroecosystems containing both C₃ and C₄ plants may provide a competitive advantage for C₃ plants under increased CO₂ in the troposphere. A meta-analysis revealed that cropping diversity with cover crops reduced GHG emissions by 8% while increasing SOC sequestration (Poeplau and Don, 2015). Cover crops also suppress weeds, capture residual N, and improve crop yield (Islam et al., 2021). The benefits and services provided by cropping diversity with cover crops are outlined in Fig. 4 and Table 5.

In South Asia, agriculture is characterized by rice monocropping or rice-wheat rotation, with or without cover crops. Numerous studies have highlighted the substantial benefits of diversified legume-based cropping systems, including significantly higher crop yields and SOC content. These positive outcomes are attributed to the N recycling effects facilitated by leguminous crop residues. The existing lack of crop diversification emerges as a key factor contributing to the gradual decline in agricultural production over time. This decline serves as a crucial warning sign for stakeholders in South Asia, emphasizing the need to formulate appropriate national policies. These policies should aim at fostering agricultural diversification as a strategic approach to ensure sustainable food and nutritional security in the region.

Chemical Fertilization

The Green Revolution, facilitated by chemical fertilization, has significantly contributed to a global increase of approximately 50% in crop yields, with a more pronounced impact in developing countries (Yousaf et al., 2017; Anonymous, 2019). Optimizing NPK fertilizations has been reported to result in a notable 19–41% increase in rice yields and a substantial 61–76% boost in rapeseed yields (Yousaf et al., 2017). Without N fertilizations, maize yields could have experienced a 40%

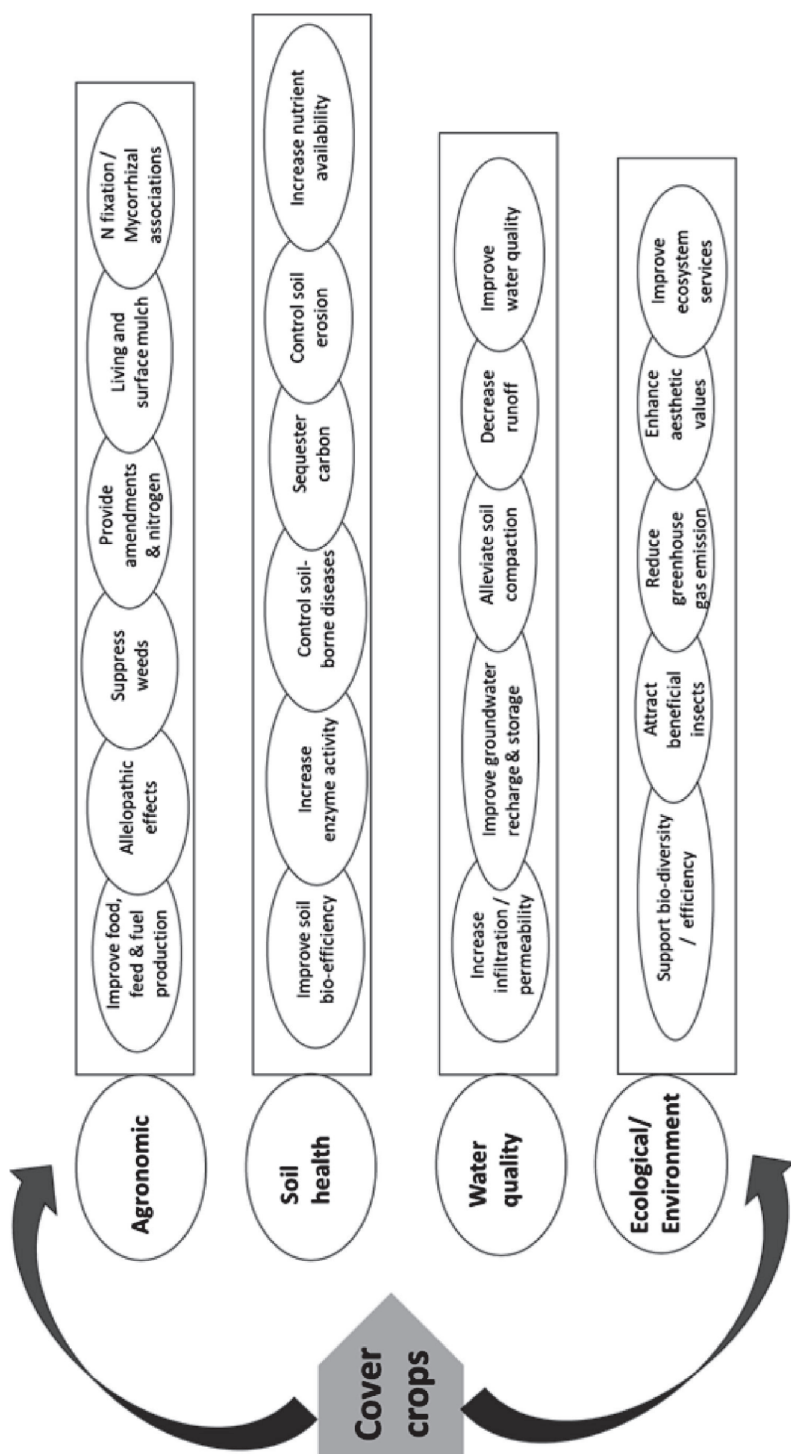


Fig. 4 Cover crops functions and benefits in agroecosystems (*Source*: Islam and Sherman, 2021).

Table 5 Biomass production, nitrogen and carbon contents, and biomass nitrogen contribution and/or recycling by legume and non-legume cover crops.

<i>Cover Crop</i>	<i>Dry Biomass (Mg/ha)</i>	<i>Nitrogen (%)</i>	<i>Carbon (%)</i>	<i>C: N of Biomass</i>	<i>Biomass N (kg/ha)</i>
Legumes					
Alfalfa	4.8	3.72	41.9	11.3	400
Cowpea	3.2	2.97	42.6	14.3	101
Crimson clover	1.8	1.97	41.7	21.2	36
Hairy vetch	2.1	2.33	44.3	19.0	53
Jumbo Ladino clover	0.7	3.26	42.8	13.1	55
Medium red clover	0.9	2.77	43.7	15.8	53
Mammoth red clover	0.8	2.00	43.5	21.7	35
Mung bean	2.9	3.92	40.4	10.7	124
White clover	1.3	2.92	43.3	14.8	38
Austrian winter pea	3.1	3.60	44.1	12.3	111
Non-legumes					
Annual ryegrass	1.3	2.11	43.2	20.5	62*
Cereal rye	1.4	0.89	42.6	48.1	26*
Coriander	0.5	1.52	41.4	27.3	18*
Oilseed radish	3.9	2.11	41.1	19.5	82*
Sorghum Sudan grass	12.2	0.68	43.3	63.3	85*
Spelt	2.1	0.99	42.7	43.3	45*

(Source: Rafiq Islam).

decline, and long-term studies suggest a potential 40–57% decrease in wheat yield without chemical fertilizations (Anonymous, 2019).

Despite these positive outcomes, it is crucial to recognize that the excessive or unbalanced use of chemical fertilization can contribute to significant carbon and N footprints, accelerating GHG emissions and exacerbating the effects of climate change. Therefore, optimizing chemical fertilization practices for crop growth is essential to minimize carbon and N footprints and mitigate associated GHG emissions.

In a study by Ortas and Islam (2018), the optimization of phosphorus (P) fertilization emerged as a crucial factor in supporting economically viable crop production. The research revealed a significant non-linear increase in corn yields with higher rates of P fertilization. Corn yields showed a notable improvement, increasing from 4.3 Mg/ha in the control to 5.6, 5.7, and 6.1 Mg/ha with P fertilization rates of 50, 100, and 200 kg of P_2O_5 /ha, respectively. However, the extrapolation of the relationship suggested that 100 kg P_2O_5 /ha was optimal for achieving near-maximum economic corn production, approximately 95%. Similarly, the relationship indicated that applying 50 kg P_2O_5 /ha resulted in achieving 90% of the corn yield.

A 2-year field study evaluating variable combinations of NP fertilization on irrigated beans demonstrated consistent grain yield increases of 25–30% under $N_{45}P_{45}$

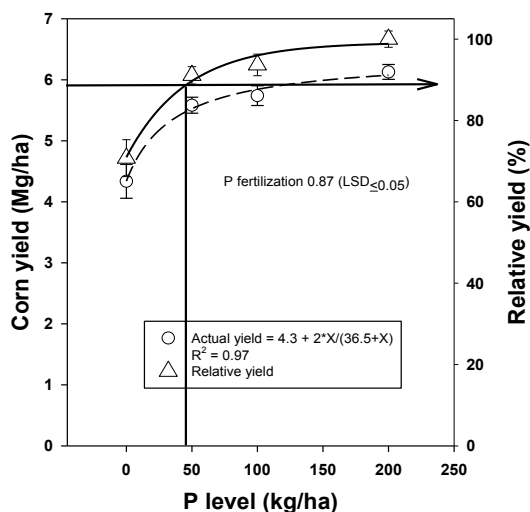


Fig. 5 Impact of phosphorus fertilization on corn yields (*Source: Ortas and Islam, 2018*).

(kg/ha) and $N_{90}P_{90}$ (kg/ha) compared to the control (Lavrenko et al., 2021). The $N_{45}P_{45}$ combination produced near-maximum economic bean production (95%) compared to $N_{90}P_{90}$. Additionally, under $N_{45}P_{45}$, there was a reduction of 45 kg/ha in both N and P fertilizers under both deep and shallow tillage systems. Furthermore, the water-use efficiency of beans increased by 22–27% due to the optimization of NP fertilization.

Soil Amendments – Gypsum, Lime, Biochar, and Compost

To minimize the impacts of climate change and conventional agriculture, proactive recycling of both inorganic and organic soil amendments, including gypsum, lime, biochar, and compost, has been identified as a sustainable alternative (Amoakwah et al., 2020; Wright et al., 2022; Islam et al., 2022; Khangura et al., 2023).

Gypsum application, when combined with cover crops, was found to enhance bio-efficiency, chemical balancing, and physical stability, leading to improved soil health under corn-soybean rotation (Islam et al., 2021). The application of gypsum at 2.2 Mg/ha increased microbial biomass, active carbon, carbon pool index (carbon accumulation), and influenced the carbon management index (carbon accumulation and lability) across degraded fields in Alabama, Indiana, and Ohio (Islam et al., 2022). The results indicated that SOC accumulation increased, contributing to enhanced soil health on degraded or marginal lands.

Biochar and compost, as carbon-enriched recyclable soil amendments, have shown promise in improving soil health and sustaining crop productivity (Amoakwah et al., 2020; Khairo and Farhan, 2024). Biochar, when applied at 30 tons/ha, increased the fungal-to-bacterial ratio, promoting greater SOC sequestration due to the higher C-use efficiency of fungi compared to bacteria (Amoakwah et al., 2020). In a study in Iraq, biochar applied at 5% of the soil significantly increased maize yield, harvest index, N-use efficiency, and water-use efficiency compared to the control. Similarly, compost, when applied at 5%, led to a significant increase in maize yield, harvest

Table 6 Compost and biochar amendments effect on grain yield, grain nutrient content, and nitrogen- and water-use efficiency of irrigated maize.

Compost (% Soil)	Biochar (% Soil)	Irrigation (% FMC)	Grain Yield (g/plant)	Harvest Index	Total N (%)	Total P (%)	Total K (%)	NUE (kg/kg)	WUE (kg/m ³)
0			26.3c	0.35c	1.97b	0.31c	2.87c	0.38b	1.27c
2			33.9b	0.40b	2.73a	0.39b	3.46b	0.86a	1.48b
5			41.1a	0.43a	2.91a	0.58a	4.10a	0.93a	1.69a
	0		31.6y	0.38x	2.31z	0.38x	3.21y	0.59x	1.39y
	2		32.2xy	0.39x	2.40y	0.37x	3.27xy	0.61x	1.42xy
	5		33.0x	0.39x	2.44x	0.39x	3.33x	0.60x	1.45x
		50	30.3C	0.38B	2.09C	0.33B	3.25B	0.69B	2.13A
		75	33.0B	0.39B	3.11A	0.59A	3.95A	0.62B	1.32B
		100	37.9A	0.41A	2.41B	0.35B	3.23B	0.86A	0.98C

index, N-use efficiency, and water-use efficiency. The combined application of compost and biochar demonstrated positive effects on growth, yield, N-use efficiency, and water-use efficiency of irrigated corn, particularly under the expected climate change effects (Khairo and Farhan, 2024).

Yelikbayev et al. (2023) found that after 3, 11, 18, and 29 years, SOC storage increased by 5.3–6.2 times under alfalfa-organic amendments compared to the control. SOC sequestration rates were observed at 614 ± 129 , 710 ± 69 , and 744 ± 161 kg/ha/yr. at 0–10 cm depth under alfalfa, alfalfa-manure, and alfalfa-vermicompost treatments, respectively, in contrast to the control. However, the SOC rates were lower at 10–20 cm depth. Particularly, the alfalfa-vermicompost treatment significantly accumulated SOC, indicating the potential of rejuvenating degraded soils derived from loess materials in Kazakhstan through SOC sequestration to mitigate the effects of climate change.

Chemical Inducing/Acquired Resistance

Climate change poses threats to agricultural sustainability through abiotic and biotic stresses on plants. Chemical inducers have been proposed as environmental stress alleviators in response to climate change effects and soil-crop environmental degradations (Khan et al., 2015; Didenko et al., 2019; Irkitbay et al., 2023). Studies have reported that dilute solutions of salicylic acid improve abiotic and biotic stress tolerance in plants, sustaining crop growth and yield (Khan et al., 2015; Yakhin et al., 2017; Islam and Didenko, 2019). In Ukraine, the application of 0.02 M salicylic acid as a chemical inducer exerted positive effects on crop productivity under both CT and NT systems. Soybean yield increased by 14% with salicylic acid treatment compared to the control, with a more pronounced effect under CT than NT (Didenko et al., 2019).

Irkitbay et al. (2023) reported that both salicylic acid (at concentrations of 0.25 and 0.50 mM) and oxalic acid (at concentrations of 0.10 and 0.20 mM) treatments influenced the abiotic stress tolerance of wheat. The effect of oxalic acid was more pronounced than that of salicylic acid in improving stress tolerance of wheat (Fig. 5). Wheat grain yield increased by 5–8% with 0.25- and 0.50-mM salicylic acid, respectively, compared to the control. Similarly, grain yield significantly increased by 9–19% with 0.10- and 0.20-mM oxalic acid, respectively. Hence, chemical inducing of crops could offer a novel and integrated approach to improve crop growth and yield in dry and seasonally drought-prone areas in South Asia.

Water Management

Effective water management, involving soil moisture replenishment and irrigation, plays a crucial role in mitigating climate change effects and enhancing crop productivity. According to Khairo et al. (2024), irrigating corn at 100% field-moisture capacity (FMC) significantly increased corn yield (10–25%) and harvest index compared to corn irrigated at 50% FMC. However, deficit irrigation at 50% FMC notably enhanced water-use efficiency (35–54%) of corn compared to higher irrigation rates.

In South Asia, improved water management practices, such as managing soil under alternate wetting-drying cycles and avoiding continuous water-logging, can reduce

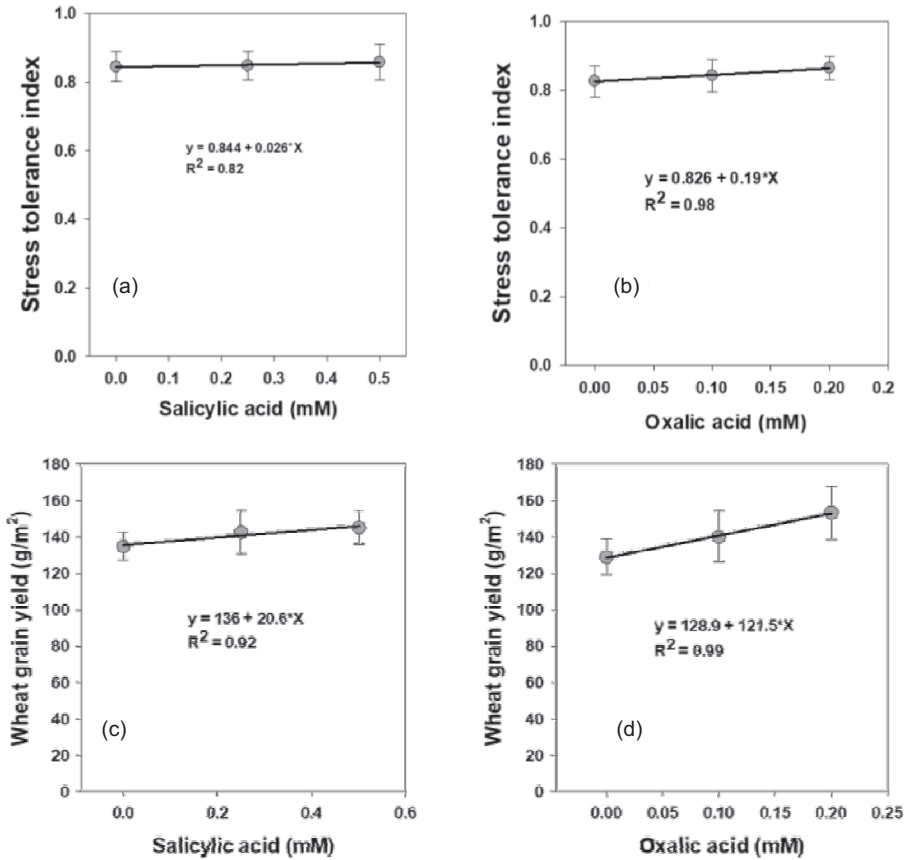


Fig. 6 Relationship of salicylic acid with (a) stress tolerance and (c) yield of wheat. Oxalic acid treatments with (b) stress tolerance and (d) yield of wheat.

off-rice season greenhouse gas emissions (Zhao et al., 2023). Large areas in South Asia, especially in India, Bangladesh, and Pakistan, depend heavily on groundwater for irrigated rice agriculture. However, increasing climatic aridity poses challenges to soil health and crop yields in these regions. In areas like western India, northern Bangladesh, and Pakistan, the scarcity of freshwater for dry-season irrigation hinders agricultural production (Rushton et al., 2020). In Bangladesh, approximately 79% of irrigated lands rely on groundwater, with the northwest region utilizing groundwater for about 95% of Boro rice irrigation (Peña-Arancibia et al., 2020). Boro rice, crucial for food security, accounts for over 55% of total rice production in Bangladesh. Excessive water use for Boro rice irrigation, up to 45%, contributes to water loss. Proactive strategies, including cultivating drought-resistant Boro rice varieties, precision irrigation, and chemical inducing (using salicylic acid), are essential for ensuring groundwater sustainability and sustaining dry-season agriculture in South Asia, particularly in semi-arid regions of Bangladesh.

Grasslands and Grazing Management

Grassland ecosystems cover one-third of the global terrestrial carbon stocks, and maintaining or restoring their health is crucial for mitigating climate change effects. Human disturbances, such as overgrazing and agriculture, and climate change threaten grasslands, leading to CO₂ emissions (Ontl and Janowiak, 2017). To enhance natural climate solutions in global grasslands, best management practices are recommended (Bai and Cotrufo, 2022). Restoring degraded grasslands through limiting soil disturbance, improving grazing management, using prescribed fire, increasing biodiversity, and planting native species can boost SOC stocks (Ontl and Janowiak, 2017; Chatterjee, 2021).

Grazing livestock, especially in rotational systems, can contribute to soil carbon sequestration by encouraging deeper roots and stabilizing biomass carbon in the ground. Strategies like planting grass with legumes as cover crops improve root production and soil fertility. Fertilization and irrigation practices positively impact plant diversity and SOC stocks, particularly in grasslands managed as pasture. Prescribed fire helps prevent invasive species and increases plant productivity. The global potential for carbon sequestration in grasslands is significant, ranging from 2.3–7.3 billion tons of CO₂e/yr. for biodiversity restoration, 148–699 megatons of CO₂e/yr. for improved grazing management, and 147 megatons of CO₂e/yr. for planting legumes in pasturelands (Bai and Cotrufo, 2022). Livestock raised on grasslands contribute to food security, supporting livelihoods and dietary diversity globally, including in South Asia.

Forest Management – Reforestation and Afforestation

Photosynthesis by terrestrial vegetation absorbs approximately 120 billion tons of carbon from the troposphere annually, surpassing the carbon released by fossil fuel burning by over 20 times and constituting about a sixth of the total carbon in today's troposphere. Forest ecosystems have been proposed as significant repositories of the “missing carbon” in the global carbon budget imbalance (Dixon et al., 1994).

The carbon fertilization effect resulting from increased tropospheric CO₂ concentration strongly influences C₃ plants, including most forest species, which exhibit a lower rate of photosynthetic efficiency compared to C₄ plants. The competition between CO₂ and O₂ for the active site of the enzyme Ribisco/bisphosphate-carboxylase oxygenase (Rubisco) plays a pivotal role. An increase in CO₂ shifts the balance towards carboxylation rather than oxygenation, reducing photorespiration in C₃ plants. This process conserves carbon that would otherwise be oxidized by the glycolate pathways, leading to an increased quantum yield of CO₂ assimilation in C₃ plants, where Rubisco is the sole CO₂-fixing enzyme. Most forests utilize the C₃ pathway, acting as net carbon sinks to mitigate greenhouse effects (Musselman and Fox, 1991).

For instance, approximately 1.25 tons of residues per hectare are deposited annually on the surface of temperate forests. Assuming a conversion rate of residues to SOM of about 50% (Gabriel and Michelis, 1991), the SOM formation is $1.25 * 0.5 \Rightarrow 0.625$ tons. As SOM contains about 58% carbon, the SOC content will be $0.625 * 0.58 \Rightarrow 0.3625$ tons per hectare per year. Considering the SOC decomposition

coefficient (r) as 99.3% in forest ecosystems (Gabriel and Michelis, 1991), the amount of SOC stored in a 10-year cycle will be:

$$Y = [0.3625 * (1 - 0.993^{10}) / (1 - 0.993)] \Rightarrow 3.51 \text{ tons C/ha.}$$

Therefore, forest soils can accumulate substantial amounts of carbon over time to mitigate climate change effects. Additionally, the current level of CO₂ in the troposphere is not sufficient to increase SOC accumulation beyond 40% of its capacity (Wallace, 1994).

It has been reported that forests, especially mangrove forests in the coastal areas of tropical and subtropical regions, play a crucial role in protecting coastlines from erosion and storm surges. They provide a vital habitat for a wide variety of plant and animal species and serve as a sink of CO₂ (<https://vnvadvisory.com/mangrove-reforestation>). In the South Asian region, particularly in Southern Bangladesh and India, a significant portion of the coastal region is covered under mangrove forests. In Bangladesh, afforestation and reforestation programs to green up newly raised islands (char lands) within the river channel/estuary or attached land to the riverbanks and the eroded mangrove forests primarily using Sunderi (*Heritiera fomes*) and the mangrove apple (*Sonneratia caseolaris*), all native tropical and mangrove species, have been successfully implemented over the years (<https://www.earthday.org/campaign/the-canopy-project-bangladesh>). The average annual C sequestration rate for mangrove forests is estimated to range between 6–8 Mg CO₂e/ha. These rates are about two to four times greater than the global rates observed in mature tropical forests.

Carbon finance can play a crucial role in mangrove afforestation and reforestation programs by providing a financial incentive for the conservation and restoration of these fragile ecosystems. Carbon finance mechanisms, such as carbon offsetting and carbon credits, allow for the generation of income from the carbon sequestered by the trees and in soils of the afforested and reforested areas. This income can be utilized to cover the costs of afforestation and reforestation activities. Despite the immense pressure from global population growth and urbanization to convert forests to agriculture and from agriculture to urban uses, resulting in increased ecosystem disservices, sustainable forest management holds the potential to positively address these challenges with greater economic viability and environmental compatibility.

Conclusions

The global carbon cycling involves a mix of natural steady-state rates and reservoirs, along with changing rates and reservoirs affected by human activities. Human activities release billions of tons of GHGs, especially CO₂, annually into the troposphere through fossil fuel combustion, deforestation, agriculture, and urbanization, contributing to global warming. While agriculture accounts for approximately 24% of anthropogenic GHG emissions, climate change adversely affects agriculture and food security. Mitigating and adapting to climate change are crucial for sustainable agriculture to ensure global food security amidst a growing population. Agriculture must be economically viable, environmentally compatible, and socially acceptable, with a focus on proactive climate-smart practices, drought-tolerant crops, chemical inducing, precision fertilization, optimized irrigation, carbon sequestration, and soil

health improvement. Although South Asian countries have formulated national and local policies to address climate change challenges, there is a need for enhanced coordination across different institutions to implement effective adaptation policies in the future.

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