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Climate change impact on soil health and crop production

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Abstract
Climate change has emerged as a defining challenge of the 21st century, profoundly affecting natural systems and human societies worldwide. One of the critical aspects of this phenomenon is its impact on carbon sequestration and crop production, which play vital roles in global carbon cycling and food security. The increase in greenhouse gas emissions due to human activities has led to a rise in global temperatures, altered precipitation patterns, and intensified extreme weather events like droughts and floods. Alterations in temperature, precipitation patterns, and the frequency of extreme weather events influence soil processes, accelerate microbial activity, moisture levels, disrupt soil structure, leading to the erosion of organic matter which impacts on carbon sequestration potential. Furthermore, the intricate relationship between climate change and crop production has significant implications for global food security. Altered temperature and precipitation patterns can disrupt plant phenology, water availability, and nutrient cycling, leading to yield variability and decreased agricultural productivity. Pests and diseases also find new opportunities for proliferation in a changing climate, adding additional stress to crop production systems. Shifts in suitable growing regions for various crops further complicate the dynamics of agricultural adaptation to a changing climate. Agriculture practices possesses the potential to mitigate them by acting as a carbon sink. The development and cultivation of climate-resilient crop varieties, precision agriculture technologies, and improved water management techniques are crucial for safeguarding crop production in a changing climate.

Keywords: Climate change, carbon sequestration, crop production

Introduction
Climate change is a complex and pressing global issue characterized by long-term alterations in Earth's climate patterns. At its core, it results from the excessive accumulation of greenhouse gases, such as carbon dioxide and methane, in the Earth's atmosphere due to human activities, primarily the burning of fossil fuels, deforestation, and industrial processes. These gases trap heat from the sun, causing the planet's average temperature to rise-a phenomenon known as global warming. According to the World Meteorological Organization's (WMO) annual report, climate change advanced from mountain summits to ocean depths in 2022-23. Droughts, floods, and heatwaves created disasters in communities across the globe, costing billions of dollars (Fig 1). The consequences of climate change are wide-ranging and include more frequent and severe weather events, rising sea levels, shifts in precipitation patterns, and disruptions to ecosystems and biodiversity.

Climate change is extensive and include rising global temperatures, which lead to more frequent and severe heatwaves, increased wildfires, and melting polar ice caps, contributing to rising sea levels and coastal erosion. Changes in precipitation patterns can result in droughts, water scarcity, and crop failures, threatening food security. More intense and frequent extreme weather events, such as hurricanes and floods, can lead to devastating economic losses and the displacement of communities. Furthermore, climate change disrupts ecosystems, leading to the loss of biodiversity and the spread of diseases.

Climate change is directly connected to agriculture, profoundly affecting the world's food production systems. Shifts in temperature and precipitation patterns, attributed to climate change, disrupt traditional growing seasons, leading to uncertainties for farmers. Extended heat waves, altered rainfall, and an increased frequency of extreme weather events like floods and droughts can damage crops, reduce yields, and compromise food security. Additionally, rising temperatures contribute to the expansion of pests and diseases, posing new challenges for crop and livestock management. Moreover, changes in climate can impact the availability and quality of water resources, which are critical for irrigation and livestock maintenance. In essence, climate change poses significant risks to agricultural productivity and sustainability, necessitating adaptation strategies and the development of climate-resilient farming practices to ensure a stable and secure global food supply.

Ultimately, addressing the complex relationship between climate change and agriculture is crucial for ensuring global food security and building a more sustainable and resilient agricultural sector.

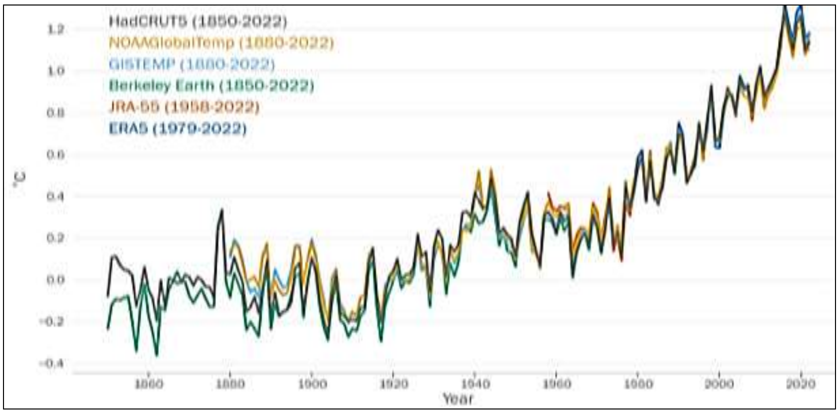

Fig 1: Global mean temperature increases to 1850-1900 (WMO Annual Report 2023)

Contribution of Agriculture to Climate Change

On a worldwide scale, agriculture is one of the major sources of GHG emissions. (Khanal 2009) [23]. Multiple climate pollutants contribute to anthropogenic climate change, with CO_2, CH_4, and N_2O being the three main individuals responsible for global warming. (Myhre *et al*. 2014**)** [29]. All three of these gases are related to agriculture and food production, but direct agricultural emissions are exceptional in that CH_4 and N_2O predominate (Fig 2.) (Lynch *et al*. 2021) [25]. Following the application of urea and lime, a tiny quantity of CO_2 emissions is produced directly from agricultural production; however, these sources account for a very small percentage of global CO_2 emissions. Emissions from the food chain can also include energy-use CO_2 from agricultural operations (For example, tractor fuel) or incorporated in inputs (For example, fertilizer manufacture and transportation), although these emissions are very unknown. Nitrous oxide emissions support both the warming effect and the ozone hole in the stratosphere. Nearly 90% of the world's atmospheric N_2O is produced by microbes in soils and water when they break down nitrate (NO_2^-) and ammonia (NH_4^+). Globally, agriculture accounts for 65-80% of all N_2O emissions, primarily from livestock, feedlots, and nitrogenous fertilizers applied to cultivated soils. Because of the unproductive loss of mobile N, soils emit CH_4. Any nitrogen intake, including crop residues, mineral and organic fertilizers, biologically fixed nitrogen, and fertilizers with other nitrogen sources, all contribute to the emission of CH_4. Increased N_2O production, particularly in agricultural soils, depends on the amount of nitrogen fertilization (Khanal *et al*. 2009) [23]. About two-thirds of all human-made methane (CH_4) emissions are thought to come from agriculture, primarily from paddy rice fields, burning biomass, and ruminants (Enteric fermentation and animal waste disposal). But aerobic agricultural soils are thought of as atmospheric CH_4 sinks based on the level of nitrogen fertilization (Khanal *et al*. 2009) [23].

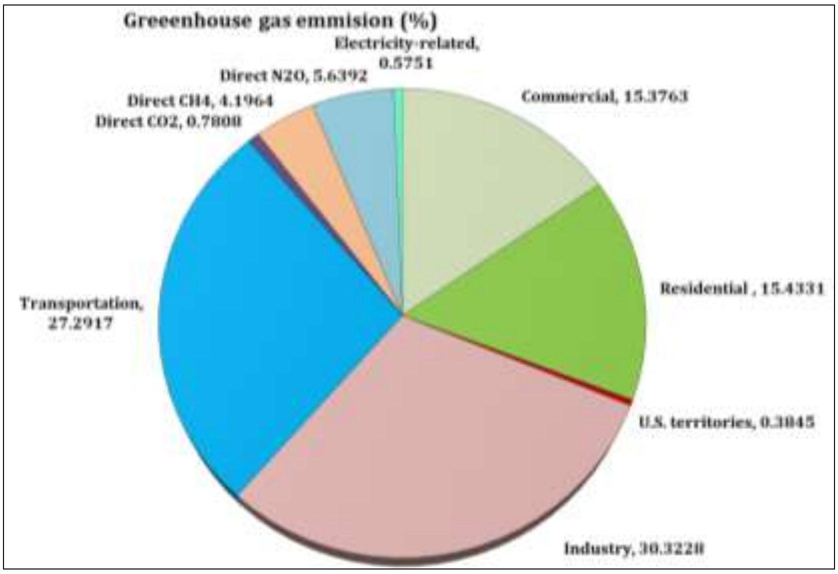

Fig 2: Greenhouse gas emission from agriculture and other sectors (USDA ERS - Climate Change)

How Climate is related with Soil

Climate not only influences soil, but soil can also influence climate. The current scientific issue is global climate change. Greenhouse gas emissions, such as carbon dioxide and methane, contribute to climate change (Pareek 2017) [33]. According to projections, the direct as well as indirect impacts of climate change on crops, soils, animals, and pests would have a considerable influence on agriculture. It is anticipated that changes in the moisture content of soil and a rise in soil temperature as well as carbon dioxide (CO_2) levels would be the primary consequences of climate change on soils. Temperature affects microbial activity and organic matter decomposition rates in soil, impacting nutrient availability and overall soil health. Precipitation patterns determine soil moisture levels, influencing the type of vegetation that can thrive and the degree of erosion or leaching that occurs (Pareek 2017) [33]. Reduced rainfall may lead to drier top soils and reduce soil structure, more frequent extreme weather events will bring heavy downpours.

Impact of climate change on different soil parameters

1. **Soil Water:** Climate change can affect soil water in a variety of ways, including precipitation that causes rapid changes in the amount of water in the soil. The field water balance and soil moisture regime reflect the combined impact of changes in climate, hydrology, vegetation, and land use. (Dutta & Rakshit 2016) [11].
2. **Soil Temperature**: Soil temperature trends are crucial yet underreported indicators of climate change. Air temperature and soil temperature are inextricably linked, and an increase in air temperature will certainly result in a rise in soil temperature. (Dutta & Rakshit 2016) [11]. Warmer soil temperatures will accelerate soil processes such as organic matter decomposition, greater microbiological activity, faster nutrient release, enhanced nitrification rate, and overall chemical weathering of minerals. However, soil temperatures will be influenced by the sort of plant that grows on its surface, which may vary due to climate change or adaptive management. (Patil 2018) [34]
3. **Soil Texture and Structure Differentiation**: Although soil texture is a relatively consistent soil feature, it has a substantial impact on soil qualities and determines how susceptible soil is to climatic variations. Because frequent soaking and drying of the soil significantly enhances fracture formation, shrinking, and swelling, clay soils are vulnerable to climate change if the number of wetting and drying cycles rises. (Mondal 2021) [28]
4. **Porosity**: Future climate change scenarios (increased CO_2 and temperature, varied and extreme rainfall events) could affect root development and soil biological activities. Soil porosity and pore size distribution are likely to influence soil functioning in unanticipated ways (Weil & Magdoff 2004) [47]
5. **Bulk Density**: In general, bulk density is inversely related to soil organic matter (SOM) or soil organic carbon (SOC) concentration (Weil & Magdoff 2004) [47]. The loss of organic carbon due to increased decomposition due to elevated temperature (Davidson and Janssens 2006) [9] may lead to an increase in bulk density, making soil more susceptible to compaction, namely land management activities and climate change stresses from variable and high intensity rainfall and drought events (Birkas *et al*. 2009) [4].
6. **Chemical Processes in Soils:** Under changing external conditions, the most rapid processes of chemical or mineralogical change would be salt and nutrient cation loss, where leaching increases salinization, where upward water movement occurs due to increased evapotranspiration or decreased rainfall or irrigation water supply. (Dutta & Rakshit 2016) [11]. Climate change may have an impact on the development of acid sulphate soils through sea level rise, changes in precipitation patterns, and flood flows. (Mondal 2021) [28]
7. **Soil pH:** Most soils would not be susceptible to rapid pH variations caused by climate change factors such as rising temperatures, increasing CO_2, variable precipitation, and atmospheric N deposition. However, these climate change drivers will have an impact on organic matter status, C and nutrient cycling, plant accessible water, and hence plant production, which will have an impact on soil pH (Reth *et al*. 2005) [35].
8. **Electrical Conductivity:** Electrical conductivity (EC) of soil is a measure of salt concentration. It can provide information on salinity, crop performance, nutrient cycle, and biological activity trends. Together with pH, it can be used as an indirect indicator of soil structural degradation, particularly in sodic soils (Arnold *et al*. 2005) [2]. Under climate change scenarios, increasing temperatures and decreasing precipitation increase electrical conductivity (Smith *et al*. 2002) [39].
9. **Carbon Sequestration**: As global temperatures rise and weather patterns become increasingly erratic, the delicate balance of carbon stored in soils is disrupted. Higher temperatures and changing precipitation patterns can accelerate the decomposition of organic matter, releasing carbon dioxide into the atmosphere. Additionally, extreme weather events like floods and droughts can disturb soil structures, further compromising carbon storage. Conversely, elevated carbon dioxide levels in the atmosphere can stimulate plant growth, potentially leading to increased organic matter input to soils (Bossio *et al*. 2020) [5]. Due to the widely varied patterns of plant C allocation in various plant-soil systems, the response of soil microorganisms to changes in plant productivity under higher CO_2 is highly variable. Under increasing CO_2, there is a great deal of variation in microbial biomass, gross N mineralization, microbial immobilization, and net N mineralization. Soil microorganisms are often C-limited and therefore, increased C availability stimulates microbial growth and activity. (Pareek 2017) [33].
10. **Soil Organic Matter:** Soil organic matter (SOM), a major regulator of soil fertility, affects the majority of soil processes such as cation exchange and water holding capacity and has a significant influence on soil ph. Furthermore, it promotes soil aggregation and water retention for plant use. As a result, a loss in SOM may impair soil fertility and biodiversity while also deteriorating soil structure, which reduces water retention capacity, makes the soil prone to erosion, and increases bulk density, which leads to soil compactness (Mondal 2021) [28]
11. **Nutrient Transformation in Soil:** Plants absorb nutrients from the soil solution pool, and nutrients must be in solution in order to move through the soil. Because biological transformation between organic and inorganic pools is significantly driven by moisture and temperature, global climate change may have a significant impact on N and S solution concentrations (Pareek 2017) [33].

12. **Soil Erosion:** Soil erosion rates will be affected by climate change. Reduced rainfall due to climate change may result in drier top soils and a loss of soil structure. Soil erosion is primarily caused by downpours, or heavy rain that falls quickly. When it rains severely enough, the soil is unable to absorb it, and the water rushes across the surface, carrying a layer of topsoil with it (Ternkathy 2022) [42].
13. **Soil Organic Carbon**: Soil organic carbon (SOC) is an important determinant of soil health. Many favorable characteristics are connected with it, including nutrient availability, high biological activity, soil physical structure, water-holding capacity, and aeration. SOC is also involved in climate change mitigation. Changes in the amount of carbon stored in soil can have an impact on the global carbon cycle and change carbon dioxide levels in the atmosphere. As a result, reductions in soil carbon may increase greenhouse gas levels in the atmosphere, contributing to climate change. (Bossio *et al*. 2020) [5]
14. **Soil Formation:** Numerous elements influence soil formation, including environmental factors such as temperature and precipitation. These climate characteristics have a direct impact on soil formation by supplying biomass and weathering conditions. The main climate elements that have a direct impact on soil formation are the sum of active temperatures and the precipitation-evaporation ratio. (Pareek 2017) [33].
15. **Plant Nutrient Availability and Acquisition:** Plant availability of nutrients in soil is determined by soil chemical characteristics, ion position relative to the root surface, and the length of the pathway the nutrient must travel in the soil to reach the root surface. Changes in precipitation and temperature have a substantial impact on root zone temperature and moisture regimes. Given that soil moisture and temperature are important regulators of nutrient availability and root growth and development, and that carbon allocation to roots drives nutrient uptake, it is logical to expect process outputs to reflect the changing environment. (Pareek 2017) [33].
16. **Soil Biological Activities:** The impacts of increased atmospheric CO_2 concentration on soil microbial community structure are frequently characterized by increased mycorrhizal colonization as a result of increased plant nutrient demand, combined with enhanced C absorption rates. CO_2 enrichment should increase mycorrhizal biomass because plant N and P demands will rise in tandem with C assimilation rates, and plants will allocate additional photosynthates belowground to the roots and mycorrhizal fungi to help meet this increased nutrient requirement**.** (Pareek 2017) [33].

Climate changes can disrupt essential processes such as nutrient cycling, water retention, and carbon sequestration, with potential consequences for agricultural productivity, food security, and ecosystem health. Table 1 summarizes the effect of climate change on soil properties.

Table 1: Effect of different extreme temperature and rainfall on soil

Increasing temperature	Increasing CO_2 concentration	Increasing rainfall	Reduction in rainfall
Soil organic matter loss Decrease in the SOM labile pool A decrease in the moisture content Increase in the rate of mineralization Soil structure loss Higher soil respiration rate	Augmentation of soil organic matter More efficient use of water Increased carbon availability for soil microbes Nutrient cycling that is accelerated	An increase in soil dampness or moisture Enhanced erosion and surface runoff Augmentation of soil organic matter Leaching of nutrients Increased nitrate and iron decrease Increased nitrogen loss via volatilization An increase in arid regions' productivity	Lower levels of soil organic matter Salting of the soil Reduced availability of nutrients

Impact of Climate Change on Crop Production

Climate change may result in better or worse crop-growing conditions in certain places. For example, growing seasons are becoming longer in almost every state due to increases in temperature, precipitation, and frost-free days. (Gowda *et al*. 2018) [15]. A longer growing season could have both positive and negative consequences on food production. While some farmers may be able to plant crops with longer maturities or more crop cycles in general, others may need to irrigate their fields more regularly during a longer, hotter growing season. Air pollution has the potential to harm crops, plants, and forests. Plants exposed to high levels of ozone at the ground level grow slower, produce less photosynthesis, and are more susceptible to disease. (Nolte *et al*. 2018) [30] Effect of climate change in different crop in different location is presented in Table 2.

1. **Photosynthesis**: As plant matures more quickly due to a rise in temperature, it has less time to complete photosynthesis, which results in fewer grains and lower yields. (Cho 2022) [7]
2. **Soil moisture:** As soil moisture levels continue to drop, agriculture may require more irrigation, which could result in lower yields and perhaps desertification, which could have a significant impact on food production. Thirteen EU members have stated that desertification is a problem in their countries. (Yang *et al*. 2015) [49]
3. **High concentrations of** CO_2**:** Increased temperatures may affect the carbon cycle by reducing the amount of water available and lowering photosynthesis rates. In contrast, higher temperatures might result in more productive plants when water is not a concern, which would have an effect on the carbon balance. (Ontl & Schulte 2012) [32].
4. **Yield:** Depending on the crop's ideal temperature for growth and reproduction, an increase in temperature will have different effects on different crops. The types of crops that are traditionally cultivated there may benefit from warming in some areas, or farmers may be able to switch to crops that are now grown in warmer regions. Conversely, production will decrease if the higher temperature exceeds the crop's optimal temperature (EPA 2017) [13]. Higher carbon dioxide concentration increase yield by 30% or more in case of wheat and soybean, smaller response to maize and other crops. Mainly high carbon dioxide concentration increases yield. (Stockle *et al*. 1992) [41]
5. **Pest & disease infestation:** Elevated CO_2 can cause leaves to contain less nitrogen and more simple carbohydrates. These can exacerbate the harm done by numerous insects, who will eat more leaves to fulfill their nitrogen-dependent metabolic needs. Any attack will therefore be more damaging. A greater number of pests will survive the winter months as a result of higher temperatures brought on by

global warming, which is mostly caused by increased CO_2. Pathogens will be able to overwinter more easily with increased CO_2, whereas thermophilic fungi will benefit from warmer temperatures. Many illnesses and pests will expand poleward as a result of rising temperatures in both hemispheres. In the temperate climate zone, this will result in more attacks occurring for longer periods of time (Venkataraman 2016) [46]. In North Africa, Middle Eastern and European countries F. *oxysporum* infestation will increase in future. (Shabani *et al*. 2014) [38].

6. **Weed problem:** Due to their broad gene pool and higher physiological plasticity, weeds are predicted to exhibit greater resilience and adaptation to rising carbon dioxide (CO_2) concentration and temperature than crops. C3 and C4 plants in agroecosystems respond differently to high CO_2 and temperature, which can affect crop-weed competition and the effectiveness of herbicides. The majority of C3 plants increase their photosynthetic rate and biomass production in response to CO_2. The production and quality of food are significantly reduced by weed competition for nutrients, water, and light with crops. In order to secure sustainable agricultural production, more focus is therefore required on crop-weed interaction and management under changing climatic conditions. (Sreekanth *et al*. 2023**)** [40]

Table 2: Effect of climate change in different crop in different location

Sl. No.	Name of crop	Area of study	Effect	Reference
1	Rice and wheat	Asia	If the temperature rises by 2 °C above the critical temperature of 24 °C, rice is sensitive to it and will yield and biomass will decrease by 16-52%.	Habib-ur-Rahman *et al*. 2022 [17]
2	Maize, wheat, and rice	China	Therefore, we draw the conclusion that if concurrent modifications are implemented in a variety of cropping systems, the warming caused by climate change may have a favorable effect on crop production in China.	Yang *et al*. 2015 [49]
3	Maize, wheat, rice, peas	Rwanda (Africa)	According to a number of recent research, crops in Africa will likely see a range of effects from increased to decreased yield.	Mikova *et al*. 2015 [27]
4	Rice	South Korea	The occurrence of rice diseases, which account for around 8% of the yearly output losses in South Korea's rice crop, is likely to be impacted by weather changes brought on by global warming.	Kim *et al*. 2015 [24]
5	Grape	France	Climate change influence in occurrence and development of Downy mildew.	Caubel *et al*. 2014 [6]

How soil and plants are linked with climate change

Soil and plants are intricately linked to climate change through a series of complex interactions. On one hand, climate change impacts soil health and composition. Rising temperatures, altered precipitation patterns, and increased frequency of extreme weather events can lead to soil degradation, erosion, and reduced nutrient availability, ultimately affecting plant growth and agriculture.

On the other hand, plants play a crucial role in mitigating climate change. They absorb and store carbon dioxide through photosynthesis, acting as carbon sinks that help offset greenhouse gas emissions. Additionally, plant cover can help prevent soil erosion and maintain soil moisture, contributing to overall soil resilience. Therefore, the relationship between soil, plants, and climate change is a dynamic one, where the health and functioning of each component have profound implications for the Earth's climate system and its ability to adapt to and mitigate the impacts of climate change.

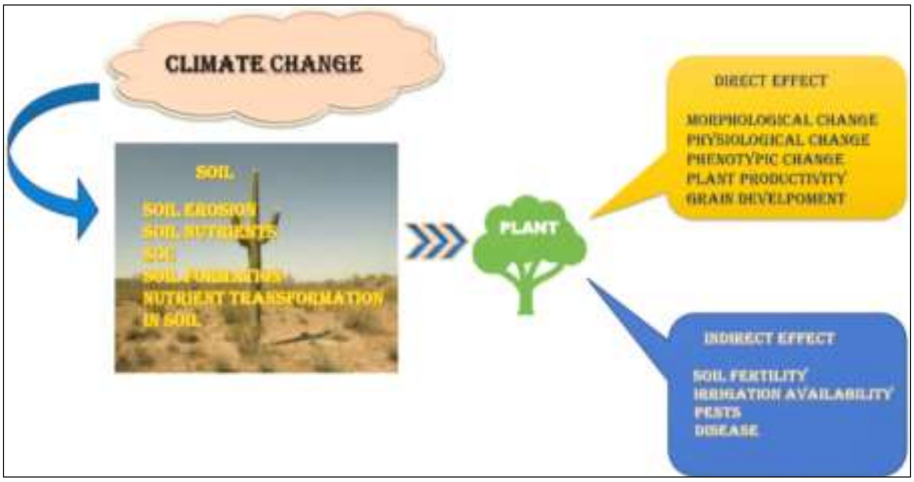

Fig 3: Climate change linked with soil and plant

Agricultural practices to mitigate climate change

1. **Climate-smart Crops:** Climate-smart plants are more resistant to adverse climatic conditions. They use less pesticides and fertilizers and are more resistant to flooding and drought. Reduced chemical inputs help to maintain nature, and hence resistant species are a win-win solution for climate change and agriculture (Reynolds & Ortiz 2010) [36].
2. **No-Tillage:** In cropping systems, reduced tillage and no-till may help maintain soil moisture, reducing erosion and protecting crop plants from drought (Vanden-Bygaart 2016) [45]. They can be promoted as an approach of reducing greenhouse gas emissions (Greenhouse Gas Working Group 2010) [16]. Conservation tillage, in which crop residue is left on the soil surface, enhances soil moisture retention and protects the soil from erosion (Henneron *et al*. 2015) [18]. Farmers that use continuous conventional till use not over 6 gallons of diesel fuel per acre annually. Continuous no-till uses less than two litres of water per acre. Fields that have been managed utilizing no-till for several years have a

higher water retaining capacity than traditionally tilled fields (Creech 2017) [8].

3. **Organic mulching:** Farmers address the problem by covering inter-rows with straw, dry hay, or mulches. It not only suppresses weeds owing to a lack of light, but it also collects moisture and protects plant roots from the hot sun, and it helps in carbon sequestration via straw decomposition (Finney *et al*. 2017) [14].
4. **Cover Cropping:** Cover crops (Finney *et al* 2017) [14] minimize erosion, conserve water, and may reduce greenhouse gas emission (Kaye & Quemada 2017, Greenhouse Gas Working Group 2010) [22, 16].
5. **Nutrient Management Practices:** Biochar is a soil additive that serves to increase soil organic carbon while also lowering greenhouse gas emissions from acidic and carbon-depleted soils (Dickie *et al*. 2014) [10].
6. **Water Management Practices:** Irrigation and irrigation are two agricultural water management practises that have been shown to have an effect on crop pests (Madegwa *et al*. 2016, Altieri *et al*. 2015) [26, 1] and the rice intensification system (SRI) (Thakur *et al*. 2016) [43]. Collecting rainfall is also a cost-effective means of obtaining water in drought-prone areas (Ivanchuk 2023) [21].
7. **Sustainable agriculture:** Sustainable agriculture may help in the reduction of greenhouse gas emissions from the agricultural sector. It can also reduce the usage of synthetic fertilizer and pesticides. Furthermore, by utilizing solar, wind, biogas, or biofuel technologies, sustainable agriculture can improve energy efficiency and renewable sources while reducing fossil fuel usage and waste. Furthermore, it can encourage the use of agroforestry and silvopasture systems, which integrate trees, crops, and livestock to provide benefits such as carbon storage, biodiversity conservation, and income diversification (El-Ramady *et al*. 2013) [12].
8. **Precision Farming:** Precision farming is one such tool that can help make agriculture more 'climate smart' by minimizing its environmental impact. By capturing the variety of the land at a minute scale, this farming technique applies the proper management practices at the right location and right time (Roy & K. 2020) [37] by employing high-tech equipment have the potential to minimize agricultural inputs through site-specific applications, as they better focus inputs to the spatial and temporal needs of the fields, potentially resulting in lower greenhouse gas emissions. (Balafoutis and colleagues 2017) [3].
9. **Conservation Agriculture:** Conservation agriculture (CA) promotes water infiltration and soil penetration by roots, allowing crops to better adapt to decreasing rainfall and use irrigation water more efficiently. CA also reduces water and wind erosion since the soil surface is protected, and water runoff is minimized as more water penetrates the soil profile. Growing rice with less water and implementing CA practices reduces N_2O emissions. CA can also significantly reduce CO_2 emissions by reducing diesel usage and increasing C sequestration in soil (Hobbs & Govaerts 2010) [20]. Conservation agriculture will improve soil moisture, allowing crops to survive seasonal dry spells, reduce the effects of drought, reduce crop failure risk, and safeguard livelihoods in the region (Thierfelder & Wall 2010) [44].

Conclusion
In conclusion, this review paper has shed light on the profound and intricate relationship between climate change, soil health, crop production, and the imperative need for sustainable agricultural practices to mitigate its adverse effects. Climate change-induced alterations in temperature, precipitation patterns, and extreme weather events have undeniable repercussions on soil quality and crop yields. However, through the adoption of innovative and climate-resilient agricultural strategies such as conservation tillage, crop rotation, agroforestry, and the integration of cover crops, there exists a promising pathway to both adapt to and mitigate the impacts of climate change. Furthermore, the judicious application of precision farming technologies and organic farming practices can play a pivotal role in reducing greenhouse gas emissions from the agriculture sector. To secure global food security and preserve our planet's fragile ecosystems, the synergy between sustainable agriculture and climate change mitigation must remain at the forefront of agricultural research and policy agendas, with an unwavering commitment to fostering resilience in our farming systems while curbing the emissions driving climate change.

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