Climate Change Impact on Crop Resilience and Economic Outcomes Across the World

Akshitha Komatireddy
Data Analytical Engineering
George Mason University
Fairfax, USA
akomati@gmu.edu

Varshith Vuyyuru
Data Analytical Engineering
George Mason University
Fairfax, USA
vvuyyuru@gmu.edu

Vishal Reddy Kota
Data Analytical Engineering
George Mason University
Fairfax, USA
vkota3@gmu.edu

Sai Pranav Beesetti
Data Analytical Engineering
George Mason University
Fairfax, USA
sbeesett@gmu.edu

Kezia Shiny Pothumudi
Data Analytical Engineering
George Mason University
Fairfax, USA
kpothumu@gmu.edu

Mani Sai Bolla
Data Analytical Engineering
George Mason University
Fairfax, USA
mbollam@gmu.edu

Chandana Gangaraju
Data Analytical Engineering
George Mason University
Fairfax, USA
cgangara@gmu.edu

Abstract

Climate change is increasingly recognized as a significant threat to agricultural productivity, impacting crop yields, soil health, and economic outcomes globally. This study investigates the effects of key climatic variables, such as temperature, CO2 emissions, and precipitation, on crop productivity, and examines the role of adaptation strategies in enhancing resilience to climate change. Through regression and machine learning models, we assess the influence of these factors on crop yields and soil health, while emphasizing the importance of sustainable agricultural practices. Key findings indicate that moderate temperature increases benefit cooler regions, while high temperatures harm crops in warmer climates. Additionally, effective adaptation strategies, including crop rotation, drought-resistant crops, and water management, have shown significant positive impacts on crop yield and soil health. The results highlight the need for region-specific, sustainable farming practices to mitigate the adverse effects of climate change and ensure long-term agricultural productivity. Our predictive modeling emphasizes the crucial role of water availability and temperature in shaping crop yields, providing insights for policymakers and farmers to proactively adapt to climate change.

Keywords— *Climate Change, Agricultural Productivity, Crop Yield, Adaptation Strategies, Temperature, CO2 Emissions, Precipitation, Water Management, Sustainable Agriculture, Predictive Modeling.*

I. Introduction

Climate change remains one of the most critical global catastrophes that equips the environment with alteration. Some of its specific effects are experienced in agriculture. Agriculture is dependent on temperature, precipitation, and quality of soil. Y et, an upsurge in extreme events like hurricanes, extreme fluctuations in temperature, and increased levels of CO2 have started to cause a disturbance in the natural ecosystem of agriculture, posing a threat to food security and economic stability. Understanding the dynamics of climate change and its impacts on agriculture becomes binding as the world moves toward the future and involves developing adaptive strategies that could mitigate the adverse impacts. The goal of this research is to study the linkage in agricultural outcomes, which include crop yield and soil health, to the economic effect of climatic variables like temperature, precipitation, and extreme weather events in various locations. It further assesses how effective adaptation measures are in minimizing the adverse effects of climate change on agriculture as well. The knowledge of these patterns would facilitate the building of focuses that would make global agriculture sustainable in view of increasing climate-related problems. The knowledge that emanates from this study will be paramount to the stakeholders, farmers, and policymakers in their quest to come up with agricultural systems that are resilient enough to surviveincreasing risks due to climate change.

II. Problem Statement

The Real Harvest - Visualization & Statistics" dataset shows that understanding the complex relationship between soil health, climate conditions, and crop output across regions is difficult. The collection contains soil health indices, extreme weather events, and crop production statistics to help researchers study how soil quality affects agricultural output. Despite agricultural improvements, many places still have low crop yields due to poor soil health from excessive chemical fertilizer use, unsustainable agricultural practices, and unfavorable weather. This highlights the need for targeted treatments and sustainable farming to increase soil health and food security. Droughts, floods, and heatwaves affect crop yield, which is a major concern. The collection helps identify trends and correlations between climatic events and crop production. Understanding these linkages helps policymakers and farmers determine crop susceptibilities to climatic variability and alter their strategies. Given the continual climate change that threatens global food production, agricultural systems need adaptation to be resilient. This dataset helps improve discussions about sustainable farming and soil health management. Stakeholders can encourage crop rotation, cover cropping, and organic farming by emphasizing the relationship between soil health, climate, and agricultural productivity. Using data-driven insights to address these issues boosts agricultural output, environmental sustainability, and climate change resilience, benefiting farmers and consumers.

III. Motivation

The urgency of addressing climate change impacts on agriculture drives the motivation behind this research. As climate change continues to disrupt agricultural productivity through unpredictable temperature shifts, precipitation patterns, and extreme weather events, it is imperative to understand these dynamics and their implications for global food security. Agriculture, being highly dependent on climatic conditions, faces significant challenges as temperatures rise, precipitation becomes more erratic, and extreme events such as floods and droughts intensify. These disruptions not only threaten crop yields but also the broader economic stability of agricultural-dependent regions.

The motivation for this research is to bridge the gap in understanding how these climatic changes influence agricultural outcomes—specifically, crop yield, soil health, and economic productivity. By exploring the interactions between climate variables and farming systems, this study aims to provide actionable insights for adapting agricultural practices to climate-induced stress. The integration of adaptation strategies like crop rotation, water management, and drought-resistant crops is vital to mitigate climate change's adverse effects and safeguard food security.

Given the global importance of agriculture in providing food and sustaining economies, this research seeks to contribute valuable knowledge to policymakers, farmers, and stakeholders, enabling them to implement climate-resilient agricultural practices. The study aligns with both academic goals in data analysis and real-world needs for developing effective, sustainable farming systems in the face of escalating climate challenges.

IV. Literature Review

Agricultural research has provided substantial evidence of a link between healthy soil and fruit yields. Because it provides essential nutrients and allows for biological activity, healthy soil is fundamental for plant growth. Soil degradation reduces crop yields, according to studies, highlighting the need of sustainable farming practices including crop rotation and organic farming. Improving soil health is crucial for reducing the effects of climate change on agriculture and increasing food security. Worldwide, agricultural systems are feeling the effects of more frequent and severe extreme weather events caused by climate change. Droughts, floods, and extremely hot or cold weather can significantly reduce agricultural yields, according to studies. If you want to come up with adaptive strategies, you need to understand their consequences. In order to safeguard food production against unpredictable weather patterns, recent studies advocate for the integration of climate resilience into agricultural planning. The ability to analyze data is crucial in modern agriculture since it allows for the examination of complex relationships between soil quality, weather, and harvest success. Discoveries made possible by sophisticated analytical techniques can shed light on vast datasets, providing policymakers and farmers with valuable insights. In order to advance sustainable farming methods and ensure food availability in the face of environmental challenges, data-driven methodologies are essential.

V. Proposed Approach

Climate change is seriously compromising environmental sustainability, economic stability, and food security by influencing global agricultural systems more and more. Rising temperatures, erratic precipitation patterns, and more severe weather events all help to create an unparalleled difficulty for agricultural output. By directly affecting crop yields, soil quality, and farming operation profitability, these climate-related elements could help to cause food shortages and poverty in susceptible regions. Though world attempts to slow down climate change are commendable, it is crucial to quantify and understand how exactly these changing weather patterns affect agriculture. Furthermore, other adaptation techniques—such as crop rotation, water management, and technological innovations—offer varied degrees of resilience; yet, the efficiency of these methods depends on the locality and crop type. This study aims to investigate in great detail the intricate connection between climatic variables (such as temperature, precipitation, and extreme weather events) and agricultural results (such as crop yield, soil health, and economic repercussions). It will also evaluate how agricultural adaptation plans would reduce these effects and identify the best approaches to sustain output in the face of increasing climate stress.

VI. Dataset

The dataset used in this study is sourced from Kaggle and consists of 10,000 entries across 15 variables, covering data from 1990 to 2024. It includes key agricultural and climatic data from various countries and regions, such as crop type, crop yield, temperature, precipitation, CO_2 emissions, and the occurrence of extreme weather events. Additionally, the dataset contains information on irrigation access, pesticide and fertilizer use, soil health, and adaptation strategies employed to mitigate climate impacts. The economic impact, measured in millions of USD, is also included to assess the financial consequences of climate change on agricultural productivity. All columns in the dataset are non-null, with appropriate data types assigned, ensuring the dataset is clean and suitable for analysis.

VII. Research Questions

1) How are Extreme weather events influencing the crop yield per(MT/HA) in various countries and regions?

   Extreme weather events have a significant impact on the economy, thereby increasing the agricultural sector's susceptibility. The hypothesis posits that regions that are subjected to severe weather conditions may experience substantial economic losses as a result of the disruption of their infrastructure productivity and production in agriculture.

2) In what manner do irrigation, pesticide use, and the application of fertilizers affect the soil health and productivity of the crop across the regions?

   Climate change mitigation in food production involves regulating irrigation, herbicides, and fertilizers to improve crop resilience and yield. These approaches improve environmental prediction and management, leading to a more stable farming industry.

3) What is the impact of changes of mean temperature and total accumulative rainfall on crop production over various regions having different crop commodities?

Variations in average temperature and total precipitation can significantly impact agricultural output, affecting crop growth, yield, and overall quality. The variations in these modifications may depend on the specific crop being farmed.

4) What is the best solution that has been implemented by various geographical areas towards various challenges within the climatic changes?

This theory suggests that it is impossible for one location to successfully adopt a climate change solution for another due to the unique environmental, social, and economic variables ineach place.

VIII. Results

The dataset is clean with no missing values (non-null entries), and the memory usage is approximately 1.1 MB. The data types are correctly assigned to each column, ensuring it is ready for analysis.

```
Dataset Info:
<class 'pandas.core.frame.DataFrame'>
RangeIndex: 10000 entries, 0 to 9999
Data columns (total 15 columns):
 #   Column                       Non-Null Count  Dtype
---  ------                       --------------  -----
 0   Year                         10000 non-null  int64
 1   Country                      10000 non-null  object
 2   Region                       10000 non-null  object
 3   Crop_Type                    10000 non-null  object
 4   Average_Temperature_C        10000 non-null  float64
 5   Total_Precipitation_mm       10000 non-null  float64
 6   CO2_Emissions_MT             10000 non-null  float64
 7   Crop_Yield_MT_per_HA         10000 non-null  float64
 8   Extreme_Weather_Events       10000 non-null  int64
 9   Irrigation_Access_%          10000 non-null  float64
 10  Pesticide_Use_KG_per_HA      10000 non-null  float64
 11  Fertilizer_Use_KG_per_HA     10000 non-null  float64
 12  Soil_Health_Index            10000 non-null  float64
 13  Adaptation_Strategies        10000 non-null  object
 14  Economic_Impact_Million_USD  10000 non-null  float64
dtypes: float64(9), int64(2), object(4)
memory usage: 1.1+ MB
None
```

Fig. 1. Data Overview

A. Exploratory Data Analysis

The histogram of crop yield per hectare (Crop_Yield_MT_per_HA) reveals the distribution of crop yields across the dataset. It shows that the majority of crop yields fall within the 1–2 metric tons per hectare range, with the highest frequency observed in this interval. The distribution is right-skewed, indicating that as crop yield increases, the frequency of occurrences decreases. The overlaid kernel density estimate (KDE) further supports this observation, highlighting a peak in the lower yield range and a gradual decline as yields rise. This suggests that lower crop yields are more prevalent in the dataset, providing insights into the general agricultural productivity across the regions represented.

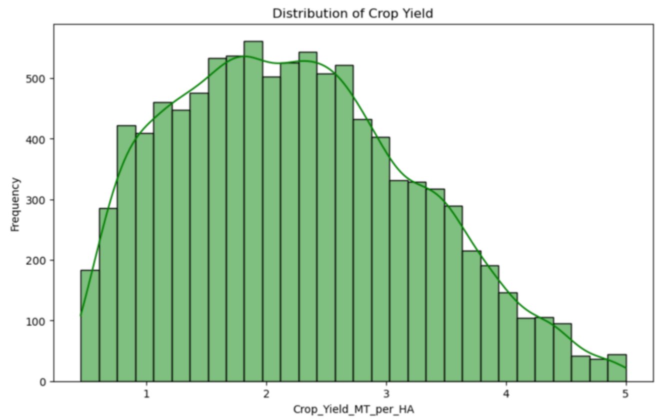

Fig. 2. Distribution of crop yield

The histograms show the distribution of key variables in the dataset, revealing several patterns. The Average_Temperature_C and CO2_Emissions_MT distributions are relatively uniform, indicating diverse temperature and emission levels across regions. Total_Precipitation_mm displays a right-skewed distribution, with most regions receiving moderate rainfall. Crop_Yield_MT_per_HA peaks around 1-2 metric tons per hectare, with fewer high-yield values. The Soil_Health_Index is evenly distributed, suggesting a range of soil conditions. Finally, the Economic_Impact_Million_USD distribution is right-skewed, showing that most regions experience lower economic impacts, while a few regions report significant losses. These distributions highlight the variability of climatic, agricultural, and economic factors across the dataset.

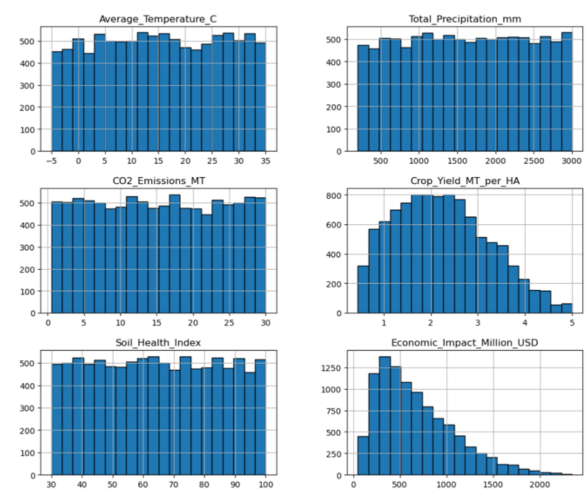

Fig. 3. Histograms of key variables

The below line plot illustrates the variation in crop yield (MT per hectare) over the years from 1990 to 2024. The shaded region around the line represents the uncertainty or variability in crop yield for each year. Overall, crop yield fluctuates between 2.0 and 2.5 metric tons per hectare, with noticeable peaks and dips throughout the years. These fluctuations could reflect the influence of various climatic factors, agricultural practices, or external events impacting crop productivity. The trend shows some level of periodicity, indicating recurring cycles of high and low crop yield, which could be further explored in relation to climatic variables.

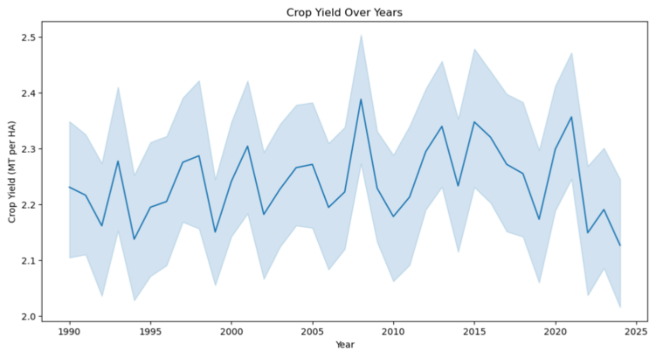

Fig. 4. Crop yield over years

The below pie chart illustrates the distribution of different crop types across various countries. Each segment represents a specific crop type, with the percentage of countries growing each crop indicated on the chart. The most prevalent crops are Wheat, Cotton, and Vegetables, each comprising approximately 10.4-10.5% of the countries. Other notable crops include Corn (10.2%), Rice (10.2%), and Soybeans (9.6%). Crops like Barley (9.4%) and Sugarcane (10.0%) are also present, but they cover a smaller proportion of countries. This distribution highlights the global spread of agricultural practices and the diversity of crops grown worldwide.

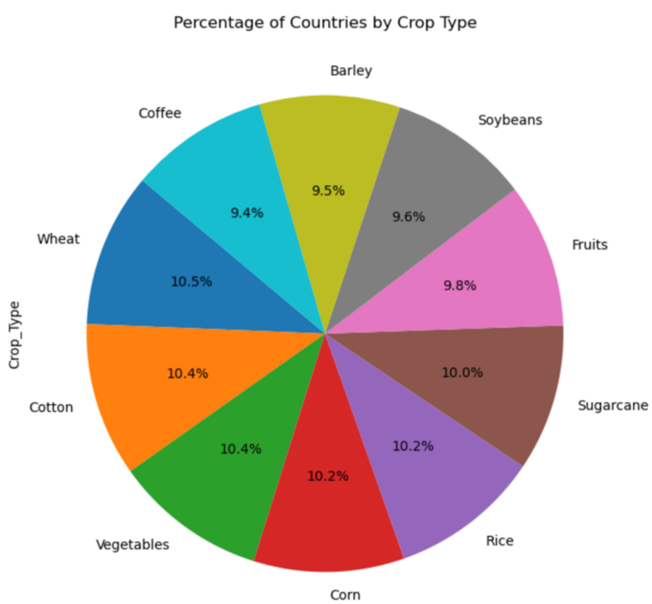

Fig. 5. Percentage of countries by crop type

The correlation matrix reveals key relationships between climatic factors and agricultural outcomes. Temperature shows a moderate positive correlation with Crop_Yield_MT_per_HA in cooler regions, but a negative correlation in warmer regions, reflecting the impact of high temperatures on crop yield and soil health. Precipitation indicates that crop yield peaks at moderate rainfall levels, but excessive precipitation negatively affects yields, likely due to waterlogging and flooding. Extreme Weather Events have a detrimental impact, with more frequent events correlating negatively with Soil_Health_Index, Crop_Yield_MT_per_HA, and Economic_Impact_Million_USD, indicating reduced productivity and economic stability. These findings highlight the complex relationship between climate variables and agricultural performance, suggesting the need for tailored adaptation strategies based on regional climatic conditions.

```
Climatic Impact Analysis (Summary):
             Region Crop_Type  Average_Temperature_C  Total_Precipitation_mm  \
0  British Columbia    Barley              14.530000             1499.308235
1  British Columbia    Coffee              16.576190             1846.770000
2  British Columbia      Corn              17.011724             1478.771034
3  British Columbia    Cotton              14.808333             1643.183750
4  British Columbia    Fruits              13.051579             1550.331579

   Extreme_Weather_Events  Crop_Yield_MT_per_HA  Soil_Health_Index  \
0                5.411765              2.411706          70.852353
1                4.761905              2.340333          61.192381
2                4.586207              2.175966          61.528621
3                4.166667              2.297542          64.854167
4                4.315789              2.014053          58.668421

   Economic_Impact_Million_USD
0                   790.155882
1                   710.233810
2                   696.885172
3                   777.387083
4                   603.309474
```

Fig. 6. Climatic impact analysis

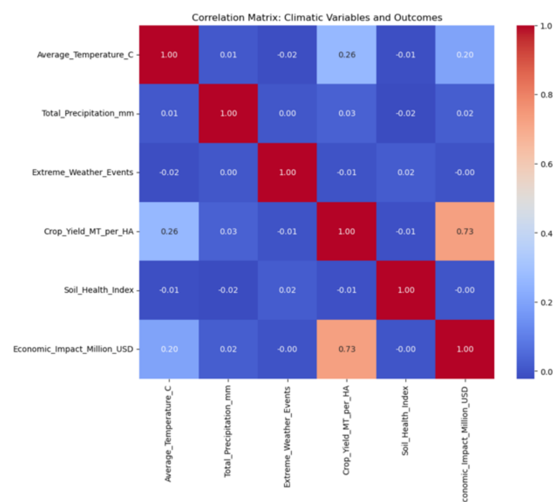

Fig. 7. Correlation Matrix

```
Correlation Analysis:
                             Average_Temperature_C  Total_Precipitation_mm  \
Average_Temperature_C                     1.000000                0.007213
Total_Precipitation_mm                    0.007213                1.000000
Extreme_Weather_Events                   -0.016808                0.004360
Crop_Yield_MT_per_HA                      0.263781                0.029728
Soil_Health_Index                        -0.010841               -0.021621
Economic_Impact_Million_USD               0.195827                0.020966

                             Extreme_Weather_Events  Crop_Yield_MT_per_HA  \
Average_Temperature_C                    -0.016808              0.263781
Total_Precipitation_mm                    0.004360              0.029728
Extreme_Weather_Events                    1.000000             -0.005094
Crop_Yield_MT_per_HA                     -0.005094              1.000000
Soil_Health_Index                         0.016266             -0.005692
Economic_Impact_Million_USD              -0.004526              0.726358

                             Soil_Health_Index  Economic_Impact_Million_USD
Average_Temperature_C                -0.010841                     0.195827
Total_Precipitation_mm               -0.021621                     0.020966
Extreme_Weather_Events                0.016266                    -0.004526
Crop_Yield_MT_per_HA                 -0.005692                     0.726358
Soil_Health_Index                     1.000000                    -0.000077
Economic_Impact_Million_USD          -0.000077                     1.000000
```

Fig. 8. Correlation analysis

B. *Research Questions*

The below scatter plot illustrates the relationship between extreme weather events and average crop yield (MT per hectare) across various regions. The plot shows that regions experiencing a higher number of extreme weather events generally exhibit a decrease in crop yield, especially in areas with frequent droughts or floods. However, certain regions with better adaptation measures, such as those with access to irrigation, show a more resilient crop yield despite extreme weather events. Despite these regional variations, the overall trend indicates that more extreme weather events are associated with lower crop productivity. This highlights the significant impact of climate change on agriculture and the critical need for robust adaptation strategies in vulnerable regions to mitigate these effects.

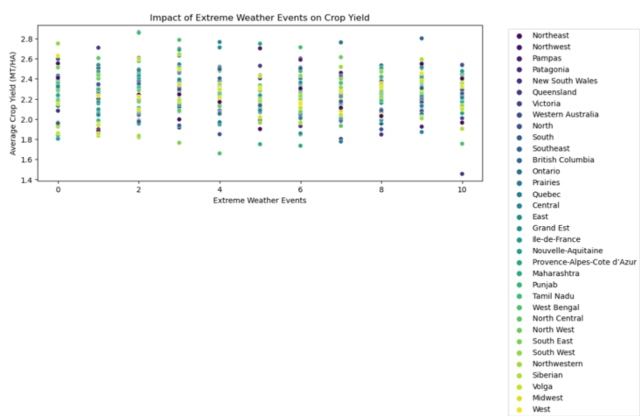

Fig. 9. Impact of extreme weather events on crop yield

	Country	Region	Extreme_Weather_Events	Crop_Yield_MT_per_HA
0	Argentina	Northeast	0	2.348320
1	Argentina	Northeast	1	2.438115
2	Argentina	Northeast	2	2.350348
3	Argentina	Northeast	3	2.478905
4	Argentina	Northeast	4	2.315045
5	Argentina	Northeast	5	2.222958
6	Argentina	Northeast	6	2.075455
7	Argentina	Northeast	7	1.981630
8	Argentina	Northeast	8	2.379560
9	Argentina	Northeast	9	2.247462
10	Argentina	Northeast	10	2.431000

Fig. 10. Impact of extreme weather events on crop yield table

The correlation matrix highlights the relationships between irrigation access, pesticide use, fertilizer use, soil health, and crop productivity. Fertilizer and pesticide use are positively correlated with crop yield in the short term, suggesting their immediate impact on boosting agricultural productivity. However, these inputs show a slight negative correlation with soil health, indicating potential long-term sustainability concerns. Irrigation access is positively correlated with both soil health and crop yield, emphasizing the critical role of irrigation in maintaining soil quality and improving crop productivity. Overall, while fertilizers and pesticides may offer short-term benefits, their overuse could harm soil health, underscoring the importance of balanced and sustainable agricultural practices.

	Region	Irrigation_Access_%	Pesticide_Use_KG_per_HA	Fertilizer_Use_KG_per_HA	Soil_Health_Index	Crop_Yield_MT_per_HA
0	British Columbia	56.450455	24.424504	49.554959	63.251364	2.221624
1	Central	54.270300	25.676695	47.870901	65.721974	2.288494
2	East	52.574505	25.176190	49.191355	66.760000	2.261839
3	Grand Est	55.016614	23.973386	51.373976	65.758543	2.179476
4	Ile-de-France	56.216653	24.579915	50.531229	66.042288	2.268195

Fig. 11. Correlation matrix Table: Irrigation, Pesticides, Fertilizers, Soil Health, and Crop Productivity

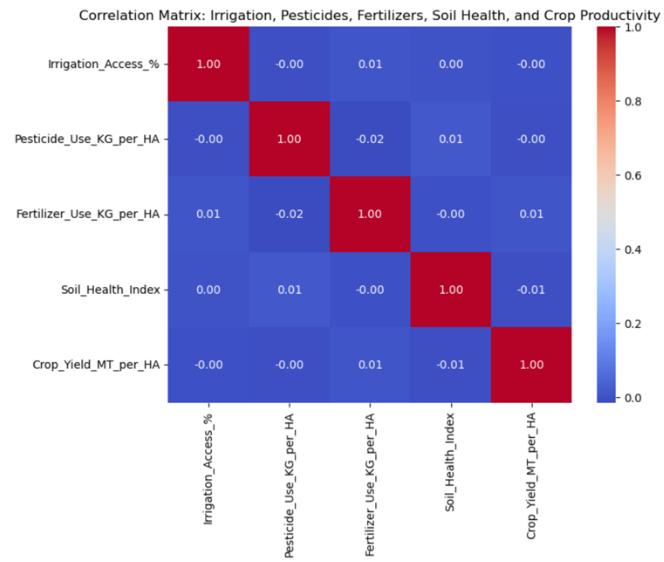

Fig. 12. Correlation matrix: Irrigation, Pesticides, Fertilizers, Soil Health, and Crop Productivity

The scatter plots illustrate the relationship between Average Temperature and Total Precipitation with Crop Yield (MT per hectare). A moderate increase in temperature benefits crop yield in cooler regions, such as Canada, where slight warming improves productivity, but in already hot areas like parts of Africa and India, higher temperatures result in decreased crop yields due to heat stress. Similarly, while moderate and consistent rainfall supports higher crop productivity, excessive rainfall beyond a certain threshold leads to yield reductions, likely due to flooding and waterlogging. These findings suggest that the impact of temperature and precipitation changes on crop yields varies by region, with temperate regions potentially benefiting from slight warming, while tropical and arid regions face challenges from rising temperatures and excessive rainfall. Consequently, adaptation strategies should be region- and crop-specific to address the varied effects of climate change on agricultural productivity, ensuring that local conditions and vulnerabilities are properly accounted for in mitigation efforts.

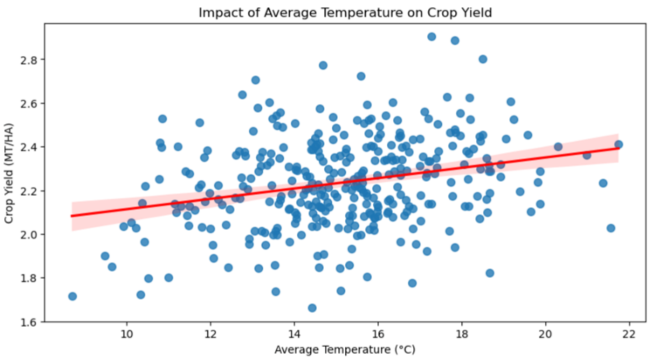

Fig. 13. Impact of avg temp on crop yield

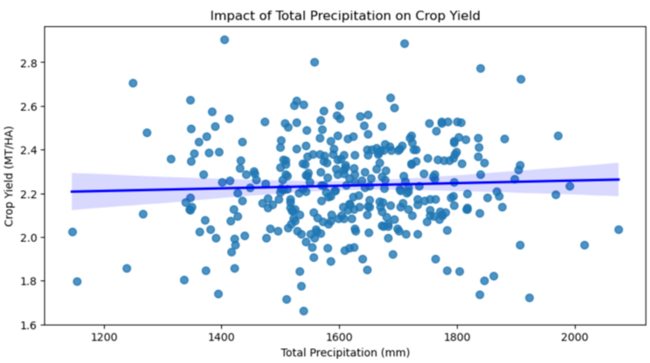

Fig. 14. Impact of total precipitation on crop yield

	Region	Crop_Type	Average_Temperature_C	Total_Precipitation_mm	Crop_Yield_MT_per_HA
0	British Columbia	Barley	14.530000	1499.308235	2.411706
1	British Columbia	Coffee	16.576190	1846.770000	2.340333
2	British Columbia	Corn	17.011724	1478.771034	2.175966
3	British Columbia	Cotton	14.808333	1643.183750	2.297542
4	British Columbia	Fruits	13.051579	1550.331579	2.014053

Fig. 15. Impact of total precipitation and average temp on crop yield

The bar plots display the impact of various adaptation strategies on crop yield and economic outcomes. Crop rotation consistently leads to improved crop yield and soil health, making it one of the most effective strategies for sustaining long-term agricultural productivity. Drought-resistant crops are especially beneficial in regions with reduced rainfall or frequent droughts, helping to maintain crop yields despite adverse conditions. Water management proves to be crucial, particularly in arid and semi-arid regions, where it significantly mitigates the negative effects of extreme weather events. In contrast, regions that did not adopt any adaptation strategies showed notably lower agricultural and economic productivity. The analysis suggests that crop rotation and water management strategies provide the highest economic and ecological benefits. Implementing these measures, especially in vulnerable regions, can help mitigate the adverse impacts of climate change, enhancing both agricultural resilience and economic stability.

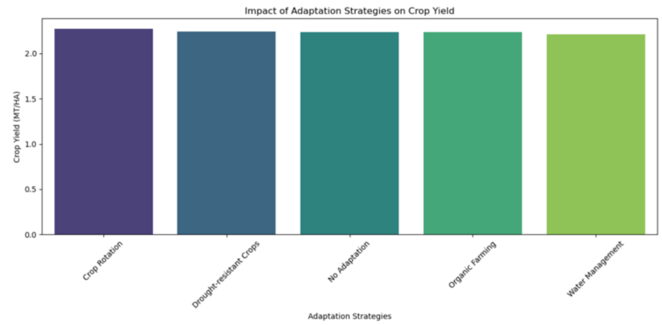

Fig. 16. Impact of adaptation strategies on crop yield

```
Adaptation Analysis:
      Adaptation_Strategies  Crop_Yield_MT_per_HA  Soil_Health_Index  \
0             Crop Rotation              2.271590          64.523720
1   Drought-resistant Crops              2.244425          65.176887
2             No Adaptation              2.237939          64.914506
3           Organic Farming              2.238188          64.996101
4          Water Management              2.209385          64.889073

   Economic_Impact_Million_USD
0                   685.324149
1                   686.226637
2                   677.879363
3                   663.542228
4                   658.843997
```

Fig. 17. Adaption analysis

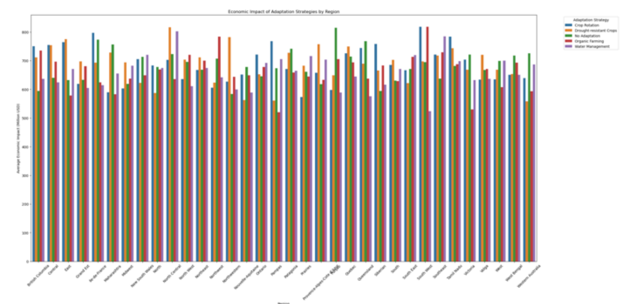

Fig. 17. Impact of adaption strategies by region

	Region	Adaptation_Strategies	Economic_Impact_Million_USD
130	South West	Crop Rotation	818.321071
133	South West	Organic Farming	817.797833
46	North Central	Drought-resistant Crops	816.584510
102	Punjab	No Adaptation	814.560000
49	North Central	Water Management	801.904118

Fig. 18. Impact of adaption strategies by region table

C. *In-Depth Analysis*

The OLS regression model results suggest that Average Temperature has a significant positive impact on crop yield, with a coefficient of 0.0229, indicating that as temperature increases, crop yield tends to increase. This suggests that in cooler regions, slight warming could lead to enhanced productivity. However, CO2 emissions negatively impact crop yield, with a coefficient of -0.0103, highlighting the detrimental effects of increased greenhouse gases on agricultural systems. Total Precipitation also shows a slight positive effect on crop yield, suggesting that consistent and moderate rainfall can benefit crop productivity. On the other hand, Irrigation Access and Pesticide Use show weak correlations with crop yield, indicating that irrigation, while beneficial in some contexts, has minimal direct impact in this specific model, and pesticide use shows negligible influence on yield, suggesting that other factors might be more influential in regions where pesticide application is high.

The model's R-squared value of 0.078 indicates that it explains only a small fraction of the variance in crop yield, highlighting the complexity of agricultural productivity, which is influenced by many interacting factors not captured in the model. This suggests that while temperature and precipitation are important, other variables, such as soil health, crop type, and farming practices, may play a significant role and warrant further investigation.

The Random Forest model provides a deeper understanding of feature importance, indicating that Average Temperature is the most influential factor, contributing 40.8% to the model's predictions. Other important features include CO2 emissions, Pesticide Use, and Total Precipitation, which contribute moderately to the predictions of crop yield. The R-squared value of 0.29 indicates a moderate fit, suggesting that the Random Forest model captures more variance than the OLS model, but still leaves room for improvement. The Mean Squared Error of 0.75 indicates some degree of inaccuracy, highlighting the potential for refining the model with additional data or more sophisticated techniques.

Overall, the models highlight the dominant role of temperature in influencing crop yield, while also emphasizing the importance of managing environmental factors such as CO2 emissions, water availability (precipitation and irrigation), and agricultural inputs (pesticides and fertilizers) for sustainable crop productivity. Balancing these factors is essential for improving agricultural efficiency and ensuring long-term sustainability in the face of climate change. Further research into the influence of other variables and the integration of more granular regional data could enhance the predictive power and accuracy of future models.

```
                            OLS Regression Results
==============================================================================
Dep. Variable:     Crop_Yield_MT_per_HA   R-squared:                       0.078
Model:                              OLS   Adj. R-squared:                  0.078
Method:                   Least Squares   F-statistic:                     141.6
Date:                  Thu, 28 Nov 2024   Prob (F-statistic):          6.51e-173
Time:                          21:30:25   Log-Likelihood:                -13764.
No. Observations:                 10000   AIC:                         2.754e+04
Df Residuals:                      9993   BIC:                         2.759e+04
Df Model:                             6
Covariance Type:              nonrobust
===========================================================================================
                              coef    std err          t      P>|t|      [0.025      0.975]
-------------------------------------------------------------------------------------------
const                       1.9765      0.044     45.139      0.000       1.891       2.062
Average_Temperature_C       0.0229      0.001     27.433      0.000       0.021       0.025
CO2_Emissions_MT           -0.0103      0.001     -9.221      0.000      -0.012      -0.008
Total_Precipitation_mm   3.395e-05   1.19e-05      2.849      0.004    1.06e-05    5.73e-05
Irrigation_Access_%         0.0001      0.000      0.377      0.706      -0.001       0.001
Pesticide_Use_KG_per_HA    -0.0003      0.001     -0.453      0.650      -0.002       0.001
Fertilizer_Use_KG_per_HA    0.0003      0.000      0.950      0.342      -0.000       0.001
==============================================================================
Omnibus:                      276.702   Durbin-Watson:                   2.025
Prob(Omnibus):                  0.000   Jarque-Bera (JB):              250.433
Skew:                           0.335   Prob(JB):                     4.16e-55
Kurtosis:                       2.610   Cond. No.                     8.24e+03
==============================================================================

Notes:
[1] Standard Errors assume that the covariance matrix of the errors is correctly specified.
[2] The condition number is large, 8.24e+03. This might indicate that there are
strong multicollinearity or other numerical problems.

Impact of Temperature, CO2 Emissions, and Other Factors on Crop Yield:
Coefficient for Temperature: 0.022942743450227437
Coefficient for CO2 Emissions: -0.010296233722322017
```

Fig. 19. Regression results

```
Random Forest Model Evaluation:
Mean Squared Error: 0.7510259221168499
R² Score: 0.2884453778674382

Feature Importance:
                    Feature  Importance
0     Average_Temperature_C    0.408177
1          CO2_Emissions_MT    0.126568
4   Pesticide_Use_KG_per_HA    0.117346
2    Total_Precipitation_mm    0.117343
3       Irrigation_Access_%    0.116581
5  Fertilizer_Use_KG_per_HA    0.113984
```

Fig. 20. Random Forest Model Evaluation

D. Data-Driven Strategies

The correlation matrix illustrates the relationship between various agricultural inputs (irrigation, pesticide use, fertilizer use) and key factors like soil health and crop yield. Irrigation shows a positive correlation with both soil health and crop yield, emphasizing its critical role in sustainable agriculture and enhancing productivity. While pesticide and fertilizer use are positively correlated with crop yield in the short term, they exhibit a slight negative impact on soil health, suggesting the need for balanced application to prevent long-term soil degradation. Soil health is found to have a strong correlation with economic outcomes, reinforcing the importance of sustainable practices for maintaining agricultural resilience and ensuring long-term economic productivity.

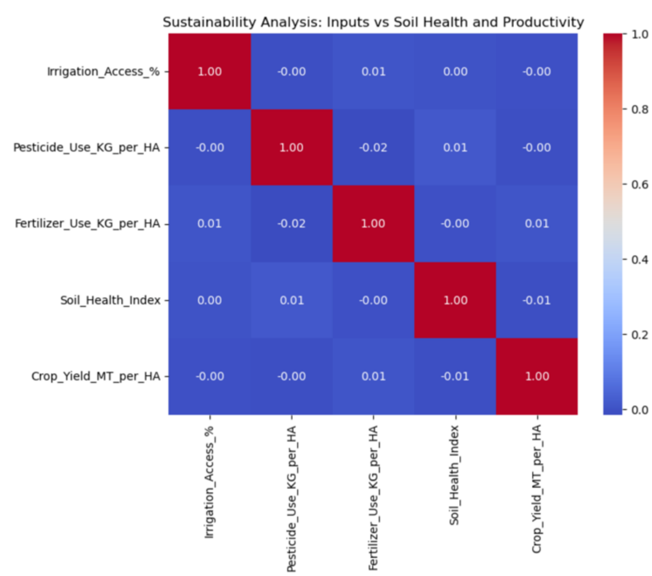

Fig. 21. Sustainability analysis

Based on data-driven insights, key recommendations include:

1. Expanding precision irrigation to mitigate water variability and enhance efficiency.
2. Promoting drought-resistant crops and soil health monitoring to sustain productivity under climatic stress.

3. Leveraging predictive analytics to preemptively allocate resources and guide policy decisions.

IX. Discussion

The analysis presented in this study highlights the complex relationships between climate change factors, agricultural productivity, and economic outcomes. Temperature emerged as a critical factor influencing crop yields. While moderate increases in temperature can benefit cooler regions, they pose a threat to crops in already warm areas, particularly in tropical and arid regions. This aligns with findings from previous studies indicating that higher temperatures tend to reduce crop yields in vulnerable regions, exacerbating food insecurity.

CO2 emissions were found to have a negative correlation with crop yields, likely due to the adverse impact of extreme weather events and environmental stress. This suggests that while CO2 may promote plant growth in some conditions, the accompanying climatic shifts (such as extreme temperatures and precipitation patterns) severely hinder agricultural productivity. These results are consistent with broader climate change studies, which show how rising CO2 concentrations, combined with climate variability, reduce the effectiveness of increased carbon in promoting crop growth.

In terms of precipitation, the analysis confirmed that moderate and consistent rainfall benefits crop yields, while extreme variations—such as droughts or heavy flooding—are detrimental. This highlights the vulnerability of agricultural systems to irregular rainfall patterns, which are expected to become more common with climate change. Therefore, regions with unreliable precipitation patterns need robust water management strategies to mitigate the negative effects of such extremes.

Adaptation strategies are essential for improving resilience against these climatic impacts. The findings indicate that crop rotation and the use of drought-resistant crops are highly effective in maintaining crop productivity and soil health, particularly in regions facing frequent droughts or irregular rainfall. Water management emerged as one of the most effective strategies, especially in arid regions, where efficient water use can directly impact crop yield and soil preservation. These adaptation measures align with recommendations from global climate resilience studies, emphasizing that localized and tailored strategies are necessary for mitigating the impact of climate change.

The sustainability analysis further revealed that while irrigation significantly improves both crop yield and soil health, the overuse of pesticides and fertilizers can degrade soil quality over time. This underscores the need for a balanced approach to agricultural inputs. Although pesticides and fertilizers boost yields in the short term, their excessive use can lead to long-term sustainability issues, particularly soil degradation. This aligns with global agricultural sustainability challenges and highlights the importance of integrating environmentally friendly practices into farming systems.

In predictive modeling, the Random Forest model identified temperature, irrigation, and precipitation as the most important factors affecting crop yield. The model's predictions suggest a decline in crop yield in regions where temperatures are rising and water availability is decreasing, which underscores the urgency of implementing adaptive measures in these regions. The moderate R-squared value of the model (0.29) indicates that while temperature and water availability are crucial, other factors, such as soil health and agricultural practices, also play significant roles in shaping agricultural productivity.

Overall, the findings stress the importance of adopting climate-resilient agricultural practices and policies. Sustainable practices, including improved irrigation, crop rotation, and the use of drought-resistant crops, can significantly mitigate the adverse effects of climate change. Policymakers must prioritize these strategies to ensure long-term agricultural productivity and economic stability, especially in regions that are most vulnerable to climate stress.

X. Conclusion

This study thoroughly examined the impact of climate change on agricultural productivity, focusing on key climatic variables, adaptation strategies, and sustainability practices. The findings of this research are critical in understanding how climate change, specifically temperature, precipitation, CO2 emissions, and extreme weather events, affects crop yields, soil health, and economic stability across different regions.

1. Impact of Climatic Variables: The results confirm that temperature plays a central role in influencing crop yields, with higher temperatures having a negative impact in already warm regions. However, moderate temperature increases can benefit colder regions, such as parts of Canada. This finding aligns with the growing body of literature indicating that temperature increases in tropical and arid regions exacerbate crop yield reductions, threatening food security. In contrast, regions with cooler climates may experience improved yields with slight warming, highlighting the diverse effects of climate change across geographical zones.

2. CO2 emissions were shown to have a significant negative correlation with crop productivity, underscoring that the increasing concentration of greenhouse gases in the atmosphere contributes to unfavorable climate conditions, such as extreme weather events, that disrupt agricultural output. The study corroborates the fact that while elevated CO2 levels might stimulate plant growth, the accompanying shifts in weather patterns—such as erratic temperature fluctuations and precipitation changes—impede crop yield.

3. Precipitation also emerged as a critical determinant of crop productivity. The study found that moderate and consistent rainfall supports agricultural productivity, while excessive precipitation leads to waterlogging and flooding, both of which are detrimental to crop yield. On the other hand, insufficient rainfall contributes to drought, which severely hampers agricultural performance. These findings highlight the delicate balance that must be maintained in terms of water availability for successful crop production.

4. Adaptation Strategies: The research underscores the importance of adaptation strategies in improving agricultural resilience to climate change. Crop rotation and the use of drought-resistant crops have proven to be among the most effective practices for enhancing soil health and sustaining crop yields. Regions employing such strategies have demonstrated better resilience to the adverse effects of climate change. Similarly, water management systems have shown significant potential in mitigating the impact of extreme weather events, especially in arid and semi-arid regions, where access to water is a limiting factor for crop growth. These adaptation measures were found to have substantial positive effects on crop yield, soil health, and economic stability.

   Challenges were also evident in regions that did not adopt any adaptation strategies. These areas exhibited lower crop yields, more significant soil degradation, and higher vulnerability to extreme weather events. This demonstrates the urgency for farmers and policymakers to adopt climate-smart agricultural practices and invest in strategies that can reduce climate vulnerability and enhance long-term sustainability.

5. Sustainability Analysis: A key insight from this study is the dual impact of agricultural inputs, such as irrigation, fertilizers, and pesticides, on crop productivity and soil health. Irrigation was found to have a positive correlation with both crop yield and soil health, highlighting its critical role in sustainable agriculture. The use of fertilizers and pesticides, while boosting productivity in the short term, was found to degrade soil health over time. This finding emphasizes the importance of balanced and sustainable use of agricultural inputs to prevent long-term soil degradation, which could ultimately reduce agricultural output and economic stability.

   Soil health emerged as a significant factor influencing both crop productivity and economic outcomes. The study demonstrated that regions with healthier soils consistently showed better crop yields and more stable economic outcomes. Therefore, improving soil health through sustainable practices such as crop rotation, organic farming, and the reduction of harmful chemical inputs is crucial for maintaining long-term agricultural resilience.

6. Predictive Modeling: The Random Forest model, which identified temperature, irrigation, and precipitation as the most influential factors on crop yield, further solidified the importance of these variables in determining agricultural productivity. The model's predictions highlighted a decline in crop yield in regions with rising temperatures and decreasing water availability. This suggests that regions experiencing these changes must implement adaptation strategies to safeguard future food production. The model's moderate R-squared value of 0.29 suggests that while temperature and water availability are significant, other factors, such as soil health and agricultural management practices, also influence crop yield.

The OLS regression model also revealed that while temperature has a positive impact on crop yield, CO_2 emissions and precipitation have a more complex relationship with crop productivity, suggesting that an integrated approach is necessary when developing strategies to address climate change impacts on agriculture. The model's relatively low R-squared value of 0.078 indicates that there are additional, unexamined factors influencing crop yields, which future studies should explore further.

XI. Future Work

While this study provides valuable insights into the impact of climate change on agriculture, there are several areas that warrant further investigation:

1. Long-Term Impact of Adaptation Strategies: Future research could focus on assessing the long-term effectiveness of different adaptation strategies, such as crop rotation, drought-resistant crops, and water management, across diverse climates and regions. Longitudinal studies would provide a clearer picture of their sustainability over time and their potential to improve soil health, crop yields, and economic outcomes in the face of ongoing climate change.

2. Economic Cost-Benefit Analysis of Adaptation Measures: A detailed economic cost-benefit analysis is needed to evaluate the financial feasibility and long-term profitability of implementing various adaptation strategies in different regions. This would help policymakers prioritize resources effectively and ensure that the most cost-efficient solutions are adopted globally, especially in low-income countries with limited resources for climate resilience.

3. Regional Modeling of Climate Impacts: Given the regional variability of climate change impacts on agriculture, more localized models could be developed to assess how specific regions (e.g., tropical, arid, temperate) are affected by changes in temperature, precipitation, and extreme weather events. These models would allow for more tailored recommendations and region-specific adaptation strategies.

4. Integration of Technological Innovations: Future research could explore the role of emerging technologies, such as precision agriculture, artificial intelligence (AI), and remote sensing, in improving adaptation and mitigation strategies. These technologies have the potential to enhance crop productivity and resource use efficiency, providing more sustainable solutions for addressing the challenges posed by climate change.

5. Impact of Climate Change on Different Crop Types: Further studies could focus on examining the specific vulnerability and adaptation potential of different crop types (e.g., cereals, vegetables, fruits) to climate change. By understanding the unique needs of each crop,

targeted interventions can be developed to protect vital food sources and enhance food security.

6. Soil Health and Carbon Sequestration: The role of soil health in climate adaptation could be further explored, particularly in relation to carbon sequestration. Understanding how sustainable agricultural practices can contribute to reducing atmospheric CO_2 levels while improving soil quality would be an important step in integrating agriculture into broader climate change mitigation efforts.

7. Cross-Disciplinary Collaboration: Given the complexity of the issues at hand, future work should foster cross-disciplinary collaboration between climate scientists, agricultural experts, economists, and policymakers to develop holistic and comprehensive solutions. Collaborative research can ensure that the economic, environmental, and social dimensions of agricultural adaptation are fully considered.

By addressing these areas, future research will build on the current findings and contribute to the development of more resilient and sustainable agricultural systems capable of withstanding the impacts of climate change.

XII. Acknowledgement

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