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RESEARCH PAPER

Global warming's grip on agriculture: Strategies for sustainable production amidst climate change using regression based prediction

Chengping Zhang[1], Chengzhi Lyu[2], Tang Hao[3], Jinru Liu[3], Nadia Sarhan[4], Emad Mahrous Awwad[5], Yazeed Yasin Ghadi[6]

1 *Mechanical and Electrical Engineering College, Hainan Vocational University of Science and Technology, Haikou, 571126, China*
2 *Hubei University of Automotive Technology, Hubei, Hubei Province, China*
3 *School of information and Communication Engineering, Hainan University, Haikou, China*
4 *Department of Quantitative Analysis, College of Business Administration, King Saud University, Riyadh, Saudi Arabia*
5 *Department of Electrical Engineering, College of Engineering, King Saud University, P.O. Box 800, Riyadh 11421, Saudi Arabia*
6 *Department of Computer Science and Software Engineering, Al Ain University, Abu Dhabi, 12555, United Arab Emirates*

Corresponding author: Chengzhi Lyu (sanchilongquan1@outlook.com)

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Abstract

The intersection of climate change and food production is emerging as a critical area of research, focusing on both the potential benefits and the significant challenges posed by changing climate conditions. Elevated levels of carbon dioxide alongside rising global temperatures could theoretically boost crop yields, benefiting both human and animal consumption. This study examines the impact of various climate variables—temperature, humidity, precipitation, and soil moisture—on the primary production of essential foods such as rice, wheat, livestock, milk, eggs, vegetables, and fruits. Utilizing data from different countries spanning from 2000 to 2020, drawn from world development indicators, this research employs econometric analysis coupled with deep learning-based cluster analysis. Additionally, it projects future production trends up to 2100 using the moving average time series forecasting method. The findings reveal a direct correlation between climate variables and the production levels of vegetables and other food items, highlighting the immediate effects of climatic changes on agriculture. The study also points out the uneven distribution of these climate impacts, with developing countries facing more severe challenges due to their limited resources and adaptive capacities. This uneven impact contributes to increased uncertainty in food supply and affects market stability. Furthermore, concerns about food safety are intensifying under the influence of climate change, although some regions have implemented effective food conservation and control measures to mitigate these risks. This research underscores a complex landscape where the risks and benefits of climate change on food production are not uniformly distributed, but rather are influenced by a myriad of factors including geographic location, economic conditions, and the level of technological advancement in food safety practices. The nuanced understanding of these dynamics is crucial for developing targeted strategies to enhance food security in the face of a changing climate.

Keywords

Food Production, Deep Learning, Climate Change, Food Resources

Introduction

Climate change is profoundly affecting agricultural productivity and food security globally. As climate patterns shift, the direct and indirect impacts on crop yields, land suitability, and the incidence of pests and diseases become increasingly significant, posing challenges to sustaining global food systems (Skendžić S et al. 2021). A particular area of concern is the effect of climate change on critical agricultural water resources. With changes in precipitation patterns and rising temperatures, water scarcity is intensifying, especially in arid and semi-arid regions that rely heavily on irrigation. Research indicates that for every degree Celsius of warming, the water requirement for crops increases by about 10% due to higher evapotranspiration rates, making water resource management crucial for sustainable agriculture (Alotaibi 2023).

Additionally, climate change is altering crop phenology—the timing of life cycle events in plants (Habib-ur-Rehman et al. 2022; Nhemachen C et al. 2020; Gulzar et al. 2024). Warmer temperatures can cause earlier flowering and ripening of crops, which may not coincide with optimal growing conditions, leading to reduced yields and crop quality (Malhi GS et al. 2021). For example, in viticulture, the grape ripening period has advanced, affecting traditional flavor profiles and production techniques in the wine industry (Rouxinol MI et al. 2023; Semba RD et al. 2022). Another significant concern is the nutritional quality of crops; elevated CO_2 levels, a principal driver of climate change, have been shown to reduce protein and essential mineral content in staple crops like wheat and rice (Jobe TO et al. 2020; Wang et al. 2020). This 'CO_2 fertilization effect' has implications for global nutrition, particularly in developing countries where cereal grains are a primary food source (Ben Mariem S et al. 2021).

To mitigate these impacts, adaptive strategies in agriculture are crucial. Developing climate-resilient crop varieties, implementing sustainable water management practices, and employing advanced technologies such as precision agriculture are key to optimizing resource use and minimizing environmental impacts (Tétédé Rodrigue CK et al. 2024; Srivastav et al. 2021). Diversifying crops and farming practices can also reduce dependency on a few staple crops, enhancing food security amid changing climatic conditions (Mustafa et al. 2019; Chalmers K et al. 2020; Gulzar et al. 2023; Ünal et al. 2023). Ultimately, addressing the multifaceted impacts of climate change on agriculture requires an integrated approach, involving scientific research, policymaking, and collaboration across different sectors to ensure the resilience and sustainability of global agri-food systems in this unprecedented challenge (Tétédé Rodrigue CK et al. 2024; Loboguerrero AM et al. 2019). As global temperatures are projected to rise significantly by the end of the century due to escalating greenhouse gas emissions, the potential impacts on agricultural productivity and food security become increasingly dire. The elevated atmospheric CO_2 levels, while theoretically beneficial to plant growth, may not result in enhanced carbon assimilation as expected, potentially leading to diminished crop yields (Gonzalez Meler et al. 2004; Lloyd J and GD Farquhar 2024; Onyeaka et al. 2021). This poses a substantial challenge in meeting the food demands of a growing global population amidst ongoing climatic changes (Ebi KL and Ziska LH 2018; Wijerathna-Yapa A and Pathirana R 2022; Wheeler and Von Braun 2013; Thirukanthan CS et al. 2023; Allen Jr and Vu 2009).

The adverse effects of climate change extend beyond temperature increases and CO_2 levels; they also include biodiversity loss, soil degradation, and exacerbated water scarcity (Chevance G et al. 2023; Brandao J et al. 2022; Nicholls RJ et al. 2011; Strandmark A et al. 2015; Reid PC et al. 2009; Kay S et al. 2015; Strauss BH et al. 2015). These environmental impacts collectively contribute to the challenges of sustainable food production. According to the Intergovernmental Panel on Climate Change (IPCC), countries at lower latitudes are expected to suffer uniformly negative impacts on crop production due to climate change, whereas those at higher latitudes might see mixed effects (Godde CM et al. 2021; Varzakas T and Samaoui S 2024; Grigorieva E et al. 2023; Goyal SS et al. 2024; Michal Burzynski et al. 2022). In some northern regions, new areas may become available for crop cultivation, but these potential benefits are likely offset by limitations in soil quality and water availability (Altieri MA et al. 2015; Kumar et al. 2022). Predictive models under severe warming scenarios indicate a significant decline in global yields of key cereals like wheat and rice—up to 17% by 2050 compared to scenarios without climate change. This underscores the urgent need for efficient resource management and the development of strategic agricultural practices to mitigate the risks posed by current and future climatic conditions (Lobell David and Burke Marshall. 2010; Wang J et al. 2018; Ray Dk et al. 2019; Farooq A et al. 2023; Fletcher C et al. 2024).

The IPCC emphasizes the importance of adaptation measures—adjustments in both natural and human systems in response to climatic stimuli—to mitigate adverse impacts (Amri et al. 2024; Bhatti et al. 2024a, b). This necessitates localized research to understand the regional disparities in climate change effects on agriculture, as impacts can vary greatly depending on geographic and climatic conditions. Existing research on the impacts of climate change on agriculture is often limited by its spatial coverage and the variety of crops and models studied. Many studies focus on regional specifics and primarily examine staple crops like rice, which may not provide a global perspective. However, this review broadens its analysis to include the three most widely cultivated cereal crops—maize, wheat, and rice—across major producing countries. By overcoming limitations related to spatial and model coverage, this approach offers a more comprehensive view of the challenge's climate change poses to cereal crop production and explores a broader range of potential mitigation and adaptation strategies. This holistic perspective is crucial for developing effective global and local responses to the climatic challenges facing agriculture today.

The major contributions of this study are:

- Empirical Analysis of Climate Change Impact on Food Production: The study offers an in-depth empirical analysis of how climate change variables such as temperature, humidity, precipitation, and soil moisture have influenced primary food production (including rice, wheat, livestock, milk, egg, vegetables, and fruits) across 160 countries from 2000 to 2020.
- Integration of Deep Learning and Econometrics: A novel approach that combines deep learning-based cluster analysis with traditional econometric methods. This integration enhances the understanding of complex patterns and relationships between climate variables and food production.
- Forecasting Future Trends: Utilization of the ARIMA time series forecasting method to predict food production trends until 2100. This aspect of the study provides valuable insights into the long-term implications of climate change on food sustainability.
- Highlighting Geographical Disparities: The study underscores the uneven distribution of climate change effects, particularly
- emphasizing the challenges faced by developing countries due to limited resources and inadequate coping strategies.
- Market Speculation and Food Safety Concerns: It sheds light on the increased market uncertainty and concerns regarding food safety as indirect consequences of climate change, which are influenced by various factors including economic development and technological advancement in food conservation and control measures.

These contributions are significant in providing a comprehensive understanding of the multifaceted impacts of climate change on global food production and sustainability. The structure of the rest of this paper is as follows: Section 2 shares the methodology used in this study. Section 3 is results and discussion. The last section shares conclusions.

Methodology

This section presents a comprehensive analysis of the dataset, methodologies, and strategies used to assess the effects of strict climate policies. It also includes a summary of various statistical tests applied to determine the relationships among different countries. The study utilized data from 2000 to 2020, sourced from the FAO and WDI, focusing on climate and food production variables. It employed econometric techniques alongside deep learning-based cluster analysis, and projected production up to the year 2100 using the ARIMA time series forecasting method. Fig. 1 shows the complete steps of the implementation strategy of workflow.

Dataset

This study incorporates data from two significant sources: the World Development Indicators (WDI) and the Food and Agriculture Organization (FAO). The WDI, managed by the World Bank, is a vast repository of data reflecting various developmental aspects across nations worldwide. This dataset is crucial for a diverse group of users including policymakers, academic scholars, and economic analysts, providing a wide range of statistical data. It spans several domains such as macroeconomic stability, social welfare, healthcare effectiveness, educational achievements, and infrastructural development. In terms of economic analysis, the WDI delves into essential metrics like Gross Domestic Product (GDP), inflation rates, and fiscal balances, which are key indicators of a nation's economic health and the impact of its policies. Additionally, it covers social indicators like literacy rates, infant mortality rates, and access to clean water, which help evaluate living standards and social progress. The WDI also includes environmental statistics, detailing carbon emissions and deforestation levels (Bhatti et al. 2023).

The FAO dataset, on the other hand, offers extensive data on global agriculture and food sectors. It provides detailed figures on the production volumes of various crops and livestock by country. It also sheds light on food security and nutrition, tracking food availability, access, and quality, as well as overall nutritional status worldwide. Furthermore, it includes data on land use and management, presenting insights into agricultural practices and cultivated areas. The dataset also covers fisheries and aquaculture production, along with forestry statistics like forest area, product output, and practices of sustainable forest management. Additionally, it encompasses global agricultural trade data, detailing both imports and exports. This dataset is an essential tool for stakeholders in agriculture, environmental science, and economics, offering a thorough and nuanced perspective on the state of global agriculture and food security.

Prediction method (ARIMA)

An ARIMA (AutoRegressive Integrated Moving Average) model is a popular statistical approach for time series forecasting. It combines autoregressive (AR) and moving average (MA) models and integrates differencing to make the data stationary. The model is defined by three parameters: p (autoregressive order), d (degree of differencing), and q (moving average order). The AR part uses the relationship between an observation and several lagged observations. The I part involves differencing the data to achieve stationarity. The MA part models the error of the observation as a linear combination of past errors. ARIMA models are widely used due to their flexibility and effectiveness in handling various types of time series data.

The ARIMA (AutoRegressive Integrated Moving Average) model for time series forecasting involves three key components: AR (p), I(d), and MA (g).

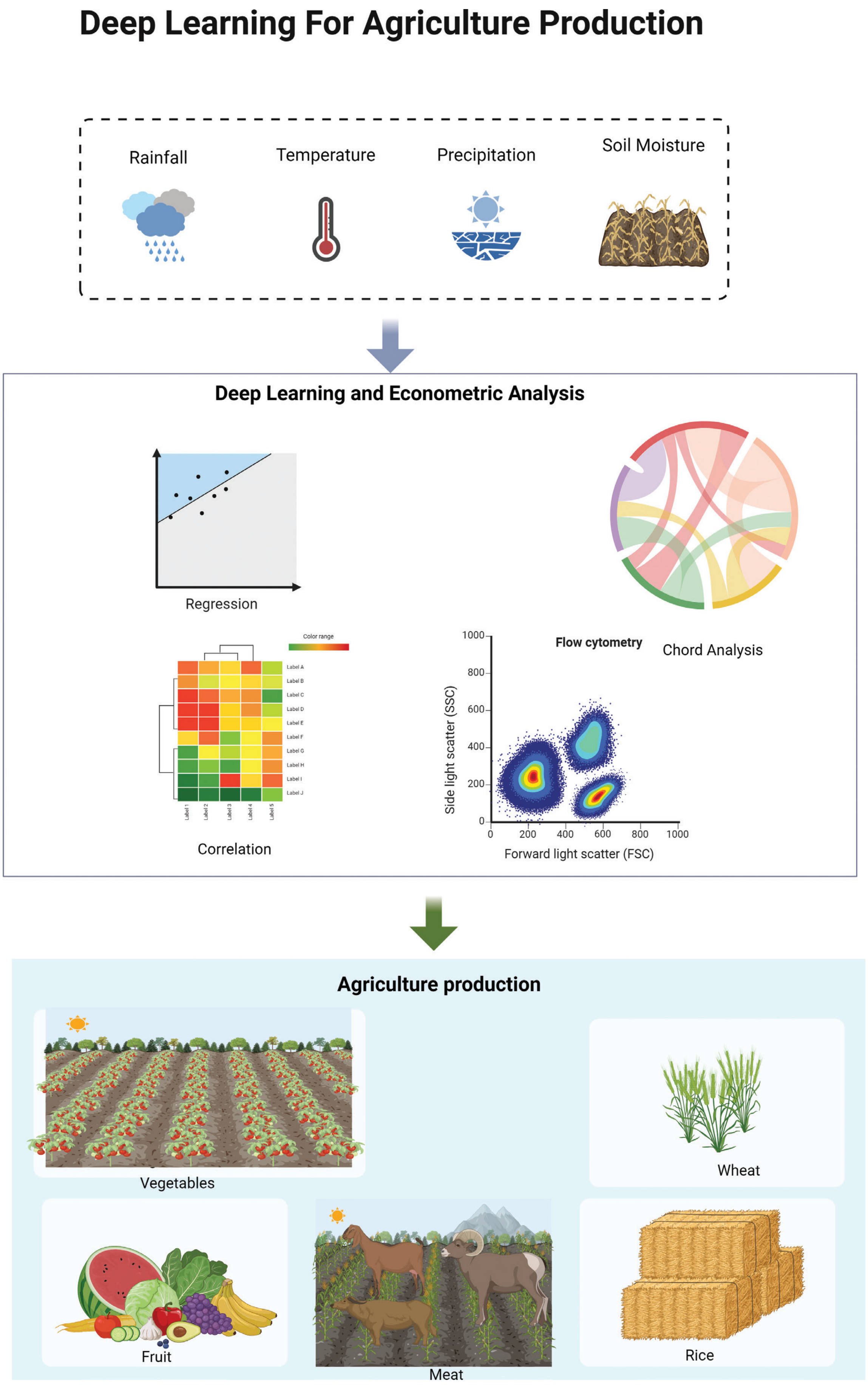


Figure 1. Implementation Model.

1.AR (p): AutoRegressive part, It models the dependency between an observation and a number of lagged observations. Represented as equation (1):

$$AR{:}Y_t = \alpha_1 Y_{t-1} + \alpha_2 Y_{t-2} + \cdots + \alpha_p Y_{t-p} + \epsilon_t \qquad (1)$$

where Y_t is the current value, $Y_{t-1} + Y_{t-2} + \ldots + Y_{t-p}$ are past values, αs are parameters, and ϵ_t is white noise.

2.I(d): Integrated part. It involves differencing the observations to make the time series stationary. Represented by d, the number of differences needed.

3.MA (q): Moving Average part. It models the error of the observation as a linear combination of error terms from the past. Represented as equation (2):

$$MA{:}\ Y_t = \epsilon_t + \theta_1 \epsilon_{t-1} + \theta_2 \epsilon_{t-2} + \cdots + \theta_q \epsilon_{t-q} \qquad (2)$$

where q ϵ s are error terms and 0s are parameters.

The ARIMA model combines these components to effectively forecast future values in a time series.

Results and discussion

Correlation analysis

Fig. 2 shows correlation heatmap, which is used to visualize the strength and direction of relationships between different variables, likely within an agricultural context. The dendrograms cluster the variables according to the similarity of their correlation profiles, grouping those with similar patterns closer together. This hierarchical clustering helps identify which variables share similar relationships across the dataset, suggesting they might be influenced by common factors or have similar effects on other variables. Without precise numerical values, detailed interpretations are challenging, but the overall patterns suggest intricate interdependencies among the variables that reflect the complex dynamics of agricultural production and environmental factors. Some variables that show a strong positive correlation move in the same direction. For instance, if Milk and Meat production show a strong positive correlation, it suggests that when milk production increases, meat production also tends to increase, which could be due to factors like increased livestock farming efficiency or growth in the agricultural sector. A moderate positive relationship indicates that the variables have a positive relationship, but it is not as strong. The variables still tend to move in the same direction, but there are more exceptions compared to a strong correlation. No correlation suggests there is no linear relationship between the variables. For example, Wheat and Eggs are white, it means that the production of wheat is not linearly related to the production of eggs. A strong negative suggests a strong inverse relationship. Such as rice and temperature were strongly negatively correlated, which could mean that higher temperatures are associated with lower rice yields.

Regression

Table 1 and Fig. 3 show the intricate relationships between environmental factors and agricultural output across five

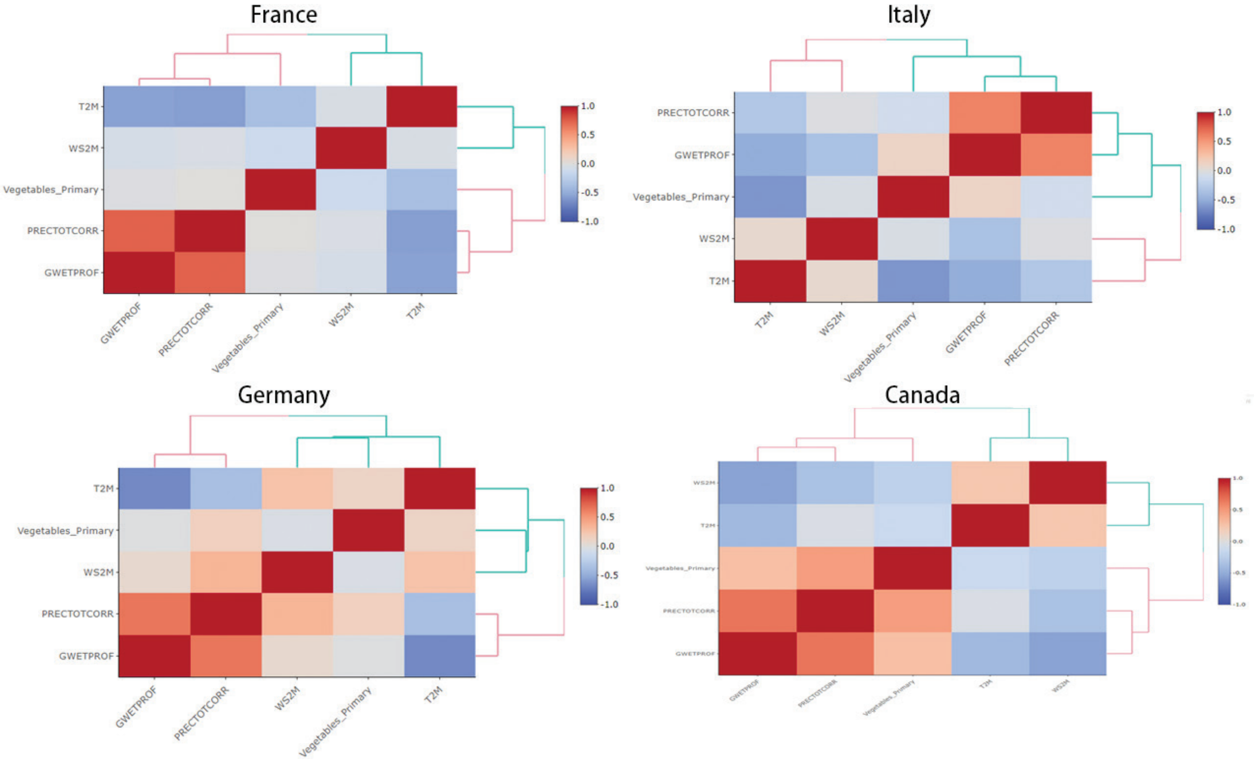


Figure 2. Correlation Diagram.

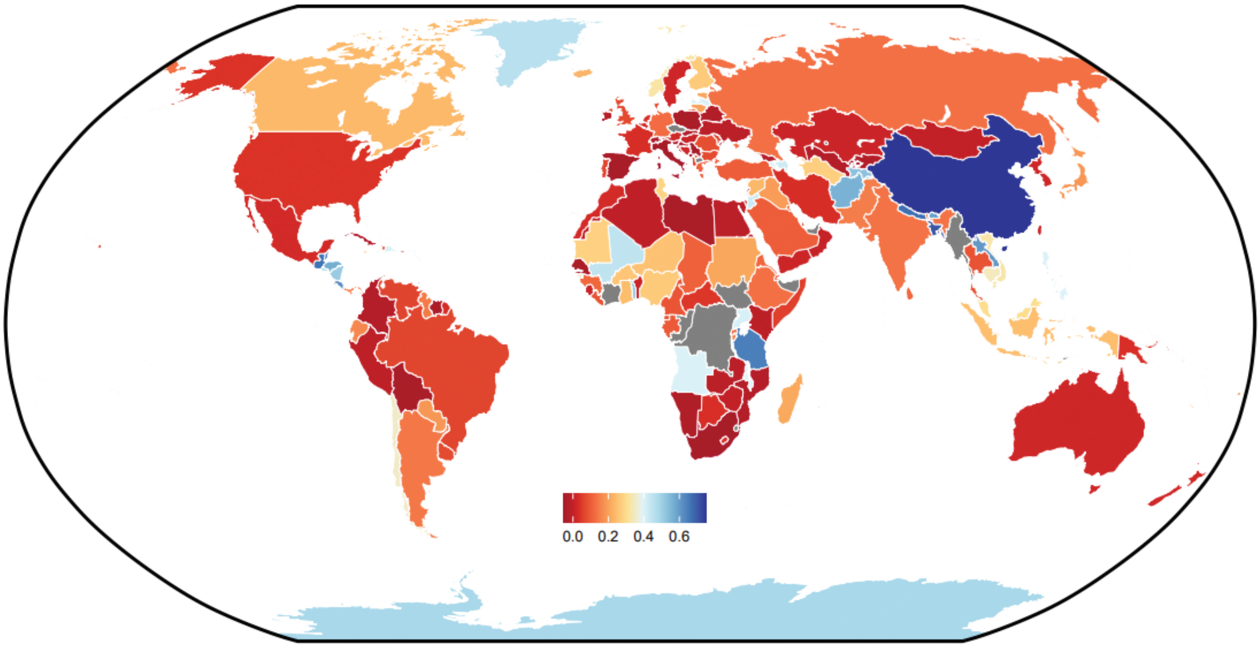
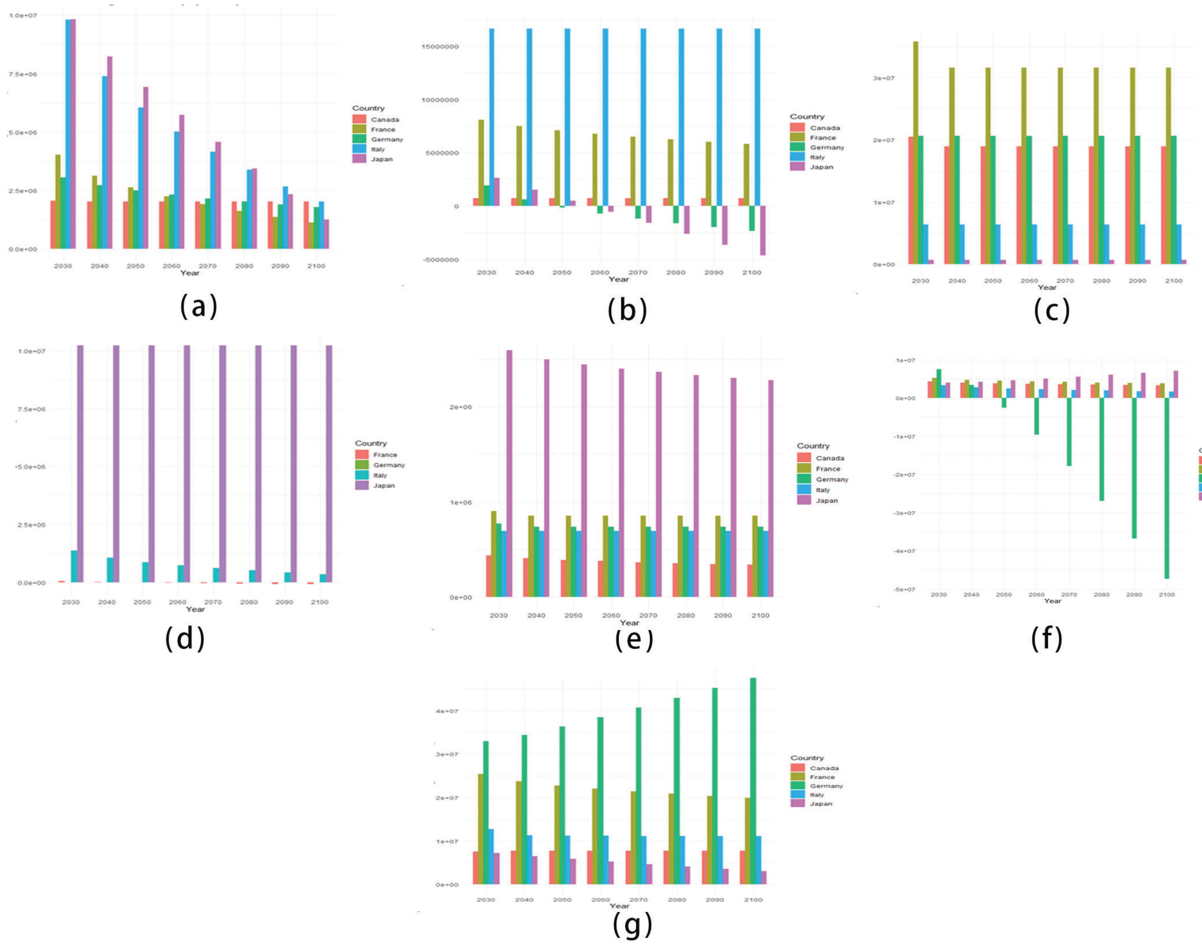


Figure 3. Regression analysis for different countries on all productions.



(a)
(b)
(c)
(d)
(e)
(f)
(g)

Figure 4. Forecasting the patterns.

countries: Canada, France, Germany, Italy, and Japan. Through rigorous statistical analysis, significant associations between soil moisture, temperature, wind speed, precipitation, and various types of agricultural products were uncovered. Notably, vegetables demonstrated consistent sensitivity to environmental conditions across all countries, with soil moisture and precipitation emerging as significant influencers of yield. Fruit production displayed mixed effects, underscoring the nuanced nature of agricultural systems and the need for localized management approaches. Wheat yields were significantly influenced by soil moisture levels, highlighting the

Table 1. Regression analysis.

Countries →	Canada		France		Germany		Italy		Japan	
Variables Relationship ↓	**P-value**	**R^2**	**P-value**	**R^2**	**P-value**	**R^2**	**P-value**	**R^2**	**P-value**	**R^2**
1st result set (Vegetables ~ Soil Root Moisture + Temperature + Wind Speed + Precipitation)	0.0026	0.0332	0.0369	0.0317	0.0909	0.0137	0.0041	0.0581	0.0398	0.0304
2nd result set (Fruit ~ Soil Root Moisture + Temperature + Wind Speed + Precipitation)	0.0113	0.0240	0.1096	0.0075	0.1010	0.0105	0.0082	0.0511	0.0242	0.0379
3rd result set (Wheat ~ Soil Root Moisture + Temperature + Wind Speed + Precipitation)	0.0005	0.0422	0.0426	0.0293	0.1005	0.0107	0.0012	0.0683	0.0759	0.0182
4th result set (Rice ~ Soil Root Moisture + Temperature + Wind Speed + Precipitation)	0.1123	0.0064	0.0076	0.0520	0.0000	0.0000	0.1123	0.0064	0.0042	0.0579
5th result set(Eggs ~ Soil Root Moisture + Temperature + Wind Speed + Precipitation)	0.0001	0.0488	0.0550	0.0248	0.0355	0.0323	0.1030	0.0099	0.0082	0.0511
6th result set (Meat ~ Soil Root Moisture + Temperature + Wind Speed + Precipitation)	0.0000	0.0830	0.0147	0.0444	0.0700	0.0200	0.0043	0.0578	0.0043	0.0576
7th result set (Milk ~ Soil Root Moisture + Temperature + Wind Speed + Precipitation)	0.0000	0.0702	0.0073	0.0524	0.0134	0.0456	0.0309	0.0344	0.0435	0.0289

importance of water management strategies in optimizing production. In contrast, rice production appeared less sensitive to environmental factors, suggesting potential resilience in rice cultivation practices or the presence of unaccounted variables. Livestock production, including eggs, meat, and milk, also exhibited significant relationships with environmental variables, emphasizing the interconnectedness of agricultural and climatic systems. These findings have implications for agricultural management and policy development, enabling stakeholders to implement targeted interventions to enhance productivity, resilience, and sustainability. Moving forward, further research should explore the underlying mechanisms driving these relationships and employ advanced modeling techniques to improve predictive accuracy. Overall, this study contributes to our understanding of the complex dynamics shaping agricultural systems, laying the groundwork for evidence-based decision-making to ensure food security amidst evolving environmental challenges.

Time series prediction

Japan, an island nation in East Asia, offers insights into the impacts of climate change on agricultural practices in a maritime climate with limited arable land. Additionally, these countries are economically significant in the global food production landscape, with advanced agricultural technologies and practices. This diverse mix of geographical, climatic, and technological factors makes these countries ideal for studying the multifaceted impacts of climate change on food production, providing valuable lessons that can be applied to other regions globally.

- 1st Result Set (Vegetables): Shows a significant relationship in Canada and Italy ($P < 0.05$) with moderate explanatory power (R-squared around 0.27 and 0.48, respectively). For France, Germany, and Japan, the relationship is not significant.
- 2nd Result Set (Fruit): None of the countries show a significant relationship and the explanatory power is generally low.
- 3rd Result Set (Wheat): Significant in Canada and Italy with moderate to high explanatory power. Other countries show no significant relationship.
- 4th Result Set (Rice): Shows a significant relationship in Italy ($P < 0.05$) with moderate explanatory power. Other countries, including Germany, show no significant relationship.
- 5th Result Set (Eggs): Significant in Canada with high explanatory power. Other countries show no significant relationship.
- 6th Result Set (Meat): Highly significant in Canada with high explanatory power. Other countries show no significant or a weak relationship.
- 7th Result Set (Milk): Significant in Canada, France, and Germany with moderate to high explanatory power. Italy and Japan show no significant relationship.

These results suggest varying degrees of impact of the selected climate variables on different types of agricultural outputs in the studied countries. The significance and strength of these relationships differ across countries and types of agricultural products.

Policy recommendation

Policy recommendations for addressing the interplay between food production and climate change should be multifaceted, considering both the need to adapt agricultural practices to changing environmental conditions and the necessity to mitigate the contribution of agriculture to climate change. Here are some detailed policy recommendations:

- Promote Sustainable Agricultural Practices: Encourage farming methods that are environmentally sustainable and resilient to climate change. This includes practices like conservation agriculture, integrated pest management, and organic farming. Policies should incentivize farmers to adopt these practices through subsidies, technical assistance, and access to sustainable farming resources.

- Enhance Research and Development: Invest in agricultural research focused on developing climate-resilient crop varieties and innovative farming techniques. This also includes improving forecasting tools to better predict climate-related impacts on agriculture.
- Strengthen Water Management: Implement policies for efficient water use in agriculture, given that water scarcity is exacerbated by climate change. This can involve investment in efficient irrigation systems, rainwater harvesting, and water recycling practices.
- Support for Smallholder Farmers: Smallholder farmers are often the most vulnerable to climate change. Policies should focus on providing them with financial support, access to climate-resilient technologies, and training in adaptive agricultural practices.
- Reduce Agricultural Emissions: Implement strategies to reduce greenhouse gas emissions from agriculture, such as promoting low-emission livestock farming, better manure management, and reducing the use of nitrogenous fertilizers.
- Enhance Food Supply Chain Efficiency: Invest in infrastructure to reduce post-harvest losses, improve storage facilities, and enhance transportation systems to ensure efficient movement of food from farms to markets.
- Promote Dietary Shifts: Encourage shifts towards more sustainable diets, which have lower environmental impacts. This can be achieved through public awareness campaigns and by altering food procurement policies in public institutions.
- International Collaboration: Climate change is a global issue and requires international cooperation. Policies should promote the sharing of knowledge, technology, and resources between countries to tackle the challenges posed by climate change on a global scale.
- Risk Management and Insurance: Develop and promote insurance products for farmers to protect them against climate-related risks, such as droughts, floods, and extreme weather events.
- Policy Integration: Ensure that policies related to agriculture, climate change, water, energy, and land use are integrated and aligned to address the interconnectedness of these issues effectively.

These policies, collectively, aim to create a sustainable and resilient food production system that can withstand the challenges posed by climate change while also contributing to its mitigation.

Conclusion

The study presents a nuanced view of the impact of climate change on global food production. Although increased CO_2 levels and warmer temperatures could theoretically enhance crop yields, the actual data from 160 countries, analyzed using econometric and deep learning cluster methods, frequently indicate a decline in agricultural output. This reduction is largely attributed to the rising occurrence of extreme weather events, adversely affecting the production of essential food items such as rice, wheat, livestock, milk, eggs, vegetables, and fruits. The effects of climate change are disproportionately felt by developing countries, which often lack the resources and adaptive strategies to cope with these changes, leading to greater food provision uncertainty and market instability. The study also considers the implications of climate change on food safety, noting some regional successes in countering these effects through improved food conservation and control measures. Using ARIMA time series forecasting, the research predicts persistent challenges up to the year 2100, illustrating a scenario where the risks and benefits of climate change on food production are unevenly distributed across different regions, influenced by factors such as geographical location, economic status, and advancements in food safety technology. This complex landscape necessitates region-specific mitigation strategies to counteract the adverse effects of climate change on food production and ensure global food security. It urges governments to use these findings for strategic planning and policy making, focusing on research, infrastructure development, risk management, and international cooperation to bolster agricultural resilience against climate variability.

Future research directions include:

- Model Refinement: Improving predictive models by integrating more data, including detailed climate projections and local farming practices.
- Impact Studies: Undertaking comprehensive studies to assess the effects of specific climate variables on crop yields and livestock productivity.
- Adaptation Strategies: Formulating and evaluating adaptive approaches for different agricultural sectors and climatic regions.
- Technological Innovation: Investing in technologies that enhance agricultural resilience, such as drought-resistant crops and precision farming techniques.
- Policy Frameworks: Developing adaptable policy frameworks that can respond to evolving predictions and circumstances.
- International Collaboration: Fostering cross-border cooperation to share knowledge and resources for climate adaptation in agriculture.
- Education and Training: Equipping current and future generations of agricultural professionals with the necessary skills and knowledge through targeted educational programs.
- Sustainability Practices: Promoting research into and adoption of sustainable farming practices that minimize environmental impacts.

Authors' contributions

Chengping Zhang was responsible for conceptualization, methodology, supervision, and original draft preparation. Chengzhi Lyu contributed to data curation, formal analysis, and review and editing of the manuscript. Tang Hao handled investigation, validation, and visualization. Jinru Liu was in charge of resources, software, and project administration. Nadia Sarhan contributed to review and editing of the manuscript and secured funding. Emad Mahrous Awwad was involved in investigation, methodology, and validation. Yazeed Yasin Ghadi provided resources, data curation, and software support. Each author has approved the submitted version of the manuscript and agrees to be personally accountable for their own contributions.

Data and materials availability

Data will be available on request from corresponding author.

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