# Comprehensive Assessment of Environmental Factors Influencing Crop Yields: Ozone, CO2, And Aerosols

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**Abstract.** The research explored how air pollution, particularly high ozone levels, negatively impacts sensitive crops like wheat, rice, and soybeans, posing significant threats to global food security. It emphasized the long-overlooked destructive effects of ozone and emphasized the immediate need for strategies to counter these impacts amid climate change. Furthermore, the study examined the crucial role of increased carbon dioxide ($CO_2$) levels on C4 crops, essential for global food security and biofuel production. Contrary to expectations, it challenged the belief that C4 crops inherently benefit from elevated CO2 levels in terms of enhanced photosynthesis. The study urged more experiments under changing climate conditions to refine predictions regarding crop yields. It emphasized the importance of focusing on ozone reduction, understanding how C4 crops respond to increased CO2, and assessing aerosol effects on specific crops. These insights aim to inform policies and strategies that can safeguard food security amidst rapid global economic growth and the challenges posed by climate changet.

**Keywords:** Ozone; $CO_2$; aerosols; climate change; C4 crop.

## 1. Introduction

In the wake of rapid global economic development, the pervasive issue of air pollution is a significant threat to agricultural productivity [1-3]. The escalating pace of industrialization and urbanization across diverse nations has unleashed a barrage of pollutants into the atmosphere, casting a shadow over crop yields. This phenomenon, rooted in the heavy burning of man-made fossil fuels, has been identified as a primary contributor to the reduction of agricultural outputs. Scientific investigations, such as those by Montes (2022) [1], underscore the harmful effects of high ozone levels on crop, particularly in disrupting the crucial process of carbon dioxide absorption essential for plant growth.

Ozone, a dual-role air pollutant and greenhouse gas, emerges as a key player in this complex narrative. The intricate interplay between ozone exposure and diminished crop yields necessitates a comprehensive understanding [4]. Air quality models, as proposed by Vlachokostas (2010), provide a valuable avenue for assessing the extent of crop yield losses attributable to ozone [5]. This analytical approach equips policymakers with the necessary tools to comprehend the economic implications of such losses and formulate strategic interventions [6].

Atmospheric aerosols, consisting of particles suspended in the air, are a significant source of uncertainty in climate research. They can directly and indirectly influence global or regional climate by altering radiation budgets through aerosol-radiation and aerosol-cloud interactions. These changes affect photosynthesis, surface heat fluxes, temperature, and regional precipitation patterns, consequently impacting crop physiological processes and yields. The rise in atmospheric aerosol emissions has drawn attention to its effects on crop production [7]. What's more, C4 crops, comprising maize, sorghum, millets, and sugar cane, stand as the backbone of global food security and emerging biofuel production. In 2006, C4 crops contributed a substantial 40% to the world's grain harvest, underscoring their paramount importance in the realm of agriculture (USDA-FAS) [6].

In this work, the effects of ozone on crops were first explored, then the effects of rising atmospheric $CO_2$ concentrations on C4 crops were analyzed, and finally the effects of aerosols on maize yields in China were assessed by radiative forcing analysis.

## 2. Impact of Ozone on Crops

Tropospheric ozone primarily emerges as a secondary pollutant, predominantly generated through the photochemical transformation of precursors like $NO_2$, volatile organic compounds, and carbon monoxide. The effects of ozone on some crops are clear and supported by various theories [2]. Ozone penetrates leaves through stomata and cascades with biomolecules in leaves to form reactive oxygen species. This initiates costly defense mechanisms within the metabolism, speeds up the aging of leaves, and diverts essential resources away from both growth and the production of seeds. Despite ozone's widespread impact on crop well-being, there has been notably insufficient emphasis from agronomists and policymakers on initiatives aimed at mitigating its harmful effects, particularly within the realm of climate change considerations.

### 2.1. Methods to Increase Wheat Production

Current trends in global wheat demand, coupled with stagnating yields in many wheat-producing regions, require a multifaceted approach to address the looming challenges. Enhancing water availability through techniques like water harvesting and expanding irrigation infrastructure represents key crop management strategies, offer potential avenues to increase yields, they also introduce complications. Increasing the uptake of carbon dioxide by stomata is beneficial for photosynthesis and may simultaneously increase ozone uptake, offsetting some of the positive gains. Efforts are underway to increase wheat yields through breeding programs with the goal of increasing photosynthesis, improving photosynthesis distribution to seeds, and increasing tolerance to various stresses. Strikingly, ozone tolerance has yet to find its place in these breeding schemes, and newer high-yielding wheat varieties often display increased sensitivity to ozone, partly attributed to their elevated stomatal conductance [8].

### 2.2. Early Research Limitation

Earlier studies predicted global wheat yield losses from ozone pollution, emphasizing a concentration-based approach. However, a paradigm shifts in considering methods based on stomatal absorption reveals a more nuanced understanding of the spatial distribution of ozone effects. Field evidence highlights the correlation between stomatal ozone uptake and yield effects, underscoring the need to accurately assess the effects of ozone on crop production.

### 2.3. Methods for Assessing Ozone and Crop Yield

Before delving into the results, the validity of the stomatal uptake modeling was rigorously assessed through three distinct approaches. Firstly, a comparison of time series data between daily maximum hourly mean ozone concentration and modelled data from global GAW network sites demonstrated the model's proficiency. Secondly, model's accuracy in estimating Dmax and M7 at GAW stations for the year 2012 was scrutinized, revealing a strong correlation between modelled and observed values. Thirdly, the model's estimation of stomatal conductance was validated using data from wheat-growing regions. These validation steps instilled confidence in the global applicability of the new modeling approach for assessing ozone effects on the yield based on stomatal absorption.

### 2.4. Yield and Production Losses Estimated

The analysis found that in the Northern Hemisphere, the average estimated yield losses were 9.9%, surpassing the Southern Hemisphere's 6.2%. The most significant percentage yield losses occurred in specific climatic zones, particularly in warm-temperate-moist in the Northern Hemisphere. Lower Middle-Income Countries and Territories experienced the highest average percentage yield losses at 10.7%. The study found that the effect of ozone on yields is exacerbated in climates where much of the wheat is rain-fed. Simulating conditions to remove soil moisture constraints exacerbates global yield losses. Developed Countries (DCs) and Middle-Income Countries would experience the highest additional production losses due to increased irrigation. The analysis highlighted the importance of soil moisture in mitigating ozone-induced yield losses, especially in dry climates where irrigation usage is limited. For instance, increased irrigation in the United States and China, among other major wheat producers, would result in notable additional losses, underscoring the intricate relationship between irrigation practices and ozone impact on wheat production [8].

## 3. Effects of Rising Atmospheric Carbon Dioxide Concentrations on C4 Crops

C4 crops are important for food security, especially in some tropical regions. As atmospheric $CO_2$ concentrations continue to rise, precipitating shifts in temperature and water availability that threaten future crop yields, a complex interplay of challenges and opportunities unfolds for C4 crops. While elevated $CO_2$ is a key driver behind climatic changes impacting agriculture, its potential direct benefits to crop physiology remain contentious, particularly for C4 plants [4].

Contrary to C3 crops, which typically experience direct photosynthetic enhancement in elevated $CO_2$, free-air $CO_2$ enrichment experiments provides evidence that challenges the notion that C4 photosynthesis is similarly stimulated. Instead, it is suggested that the primary advantage for C4 crops under elevated $CO_2$ lies in the amelioration of arid stress through reduced stomatal conductance and increased intercellular $CO_2$. This implies that the benefits of elevated $CO_2$ for C4 crops manifest primarily in times and regions characterized by drought stress, challenging the conventional assumption of universal photosynthetic enhancement in future crop yield projections.

Given the pivotal role of C4 crops in global food and biofuel production, understanding their responses to rising $CO_2$ becomes imperative. This paper navigates the evolving landscape of C4 crop physiology in the context of elevated $CO_2$, shedding light on the nuanced interactions between climate change, photosynthesis, and food security. The uncertainty surrounding the impact of rising $CO_2$ on C4 crops necessitates comprehensive evaluation through additional experiments, considering diverse growing conditions and genotypes to refine future crop yield projections [6].

### 3.1. Importance of $CO_2$ for Predicting Crop Yield

Efforts to predict future crop yields amidst climate change rely on process-based crop models integrated with projections from models across different economic scenarios [9]. The consensus among these projections is a forecasted decline in crop yields, particularly impacting lower latitudes earlier and more severely. At the heart of these assessments lies the significant influence of increased $CO_2$ on crop physiology.

The significance of the $CO_2$ fertilization effect is evident in model projections that differentiate between scenarios: One centered solely on climate change, neglecting $CO_2$ effects on crop physiology, while the other integrates these effects. These projections indicate that neglecting the positive impacts of increased $CO_2$ would lead to more substantial reductions in crop yields. However, when accounting for the beneficial effects of increased $CO_2$ on crop physiology, global yield declines are expected to be less severe, and some regions might even potentially witness increases.

Grasping the direct physiological reactions of plants to increased $CO_2$ levels is pivotal for precise modeling. There's widespread agreement on two main responses: an uptick in photosynthesis rates and a decrease in stomatal conductance. Elevated $CO_2$ fosters increased carbon uptake and growth through enhanced photosynthesis, while lower stomatal conductance limits water loss, preserving soil moisture and potentially alleviating drought stress. While these mechanisms are well-documented in most C3 species, the discussion becomes more contentious when addressing C4 species, particularly concerning their response to heightened $CO_2$ levels in photosynthesis.

The significance of C4 crops extends beyond their individual responses, as insights gained from studying them contribute to understanding C3 crop behavior. The ongoing debate around the accurate parameterization of $CO_2$ fertilization factors in crop models for C3 crops underscores the importance of comprehensive research on the reactions of C4 crops to heightened $CO_2$ levels. The current disparity in research focus, particularly the limited attention given to C4 crop responses to heightened

$CO_2$, emphasizes the urgency of bridging this knowledge gap for a holistic understanding of climate change impacts on global agriculture.

### 3.2. $CO_2$ Help Increase Crop Production

This section focuses on the potential effects of increased $CO_2$ on C4 plants, with a focus on water relationships and subsequent effects on photosynthesis, growth, and yield. Based on the conceptual model proposed by Ghannoum, the discussion incorporates the results of the free air $CO_2$ enrichment experiment [10]. Increased $CO_2$ continuously reduces stomatal conductance of C4 plants, resulting in decreased water use of the whole plant, decreased soil water retention, and higher leaf temperature rise. This mechanism can ameliorate drought stress, delay the stress caused by soil water depletion, and offset the decrease of photosynthesis caused by the decrease of intercellular $CO_2$ caused by the decrease of stomatal conductance induced by drought. Trap studies provide supporting evidence that water use is reduced in a variety of C4 plants under elevated $CO_2$, resulting in improved water status under drought conditions and enhanced photosynthesis and biomass accumulation. Significantly, research conducted on sorghum and maize in field settings has indicated that increased $CO_2$ levels could potentially lower stomatal conductance, retain more soil moisture, enhance resistance to drought stress, and consequently impact crop productivity. Despite these observed advantages, more experimental data is essential to comprehensively grasp the broader impacts of increased $CO_2$ on the behavior of C4 plants across various environmental conditions. This is crucial, especially considering uncertainties associated with climate change.

## 4. Assessing Aerosol Influence on Maize Yield through Radiative Impact Analysis in China

The intricate relationship between aerosols and agricultural productivity is a pressing concern in understanding the impact of environmental factors on crop yields. In this context, the utilization of data from global networks like Aerosol Robotic Network (AERONET, The global sun photometer network), providing crucial insights into aerosol properties, becomes instrumental. Complementing this data with sophisticated models that simulate crop growth and radiation dynamics offers a comprehensive framework for estimating crop yields under varying atmospheric conditions.

This interdisciplinary approach allows researchers to delve deeper into the complex interplay between aerosols and crop productivity. Previous studies have highlighted the detrimental effects of aerosols on optimal crop yields, suggesting that existing regulatory measures might fall short in mitigating these declines effectively.

AERONET offers essential data on aerosol optical properties, crucial for understanding their characteristics. Integrating process-based crop growth models with radiation models allows estimation of crop yields under evolving atmospheric conditions. Research demonstrates that aerosols can notably diminish optimal crop yields, and current legislative measures may not suffice in preventing such declines. Leveraging AERONET and other radiative model, this study evaluates aerosol impacts on radiation levels during China's maize growing season. Utilizing the APSIM crop model, the research scrutinizes how aerosols affect maize production. These findings hold significance for regional policymakers and guide national agricultural strategies in adapting to climate change challenges in China.

### 4.1. Spatial Variability and Implications for Agricultural Adaptation in China

The crucial aspects revolve around how atmospheric aerosols impact solar radiation and their shared effects on maize biomass and yield in China. Analyzing data from 10 sites in the corn-growing region between 2002 and 2014 revealed a fluctuating downward trend in annual solar radiation without aerosols (Fig. 1). However, the presence of aerosols caused a more significant reduction in solar radiation, averaging a decrease of 166.34 $W \cdot m^{-2}$. The decrease rate of each station is different, the decrease rate of Xianghe station is the smallest, and the decrease rate of Hefei, Nanjing and

Xuzhou station is larger. Using the APSIM model, the study simulated influence of aerosols on corn yield and found significant reductions, especially in summer corn. The average biomass and yield of summer maize decreased by 19.72% and 20.56% respectively during 2002-2014, while that of spring maize decreased by 10.36% and 5.16% respectively. The study highlights the spatial variability of aerosol effects on maize and highlights the need to understand these effects in detail to effectively adapt agriculture to changing climatic conditions. These findings provide valuable insights for Chinese policymakers and national agricultural strategies [7].

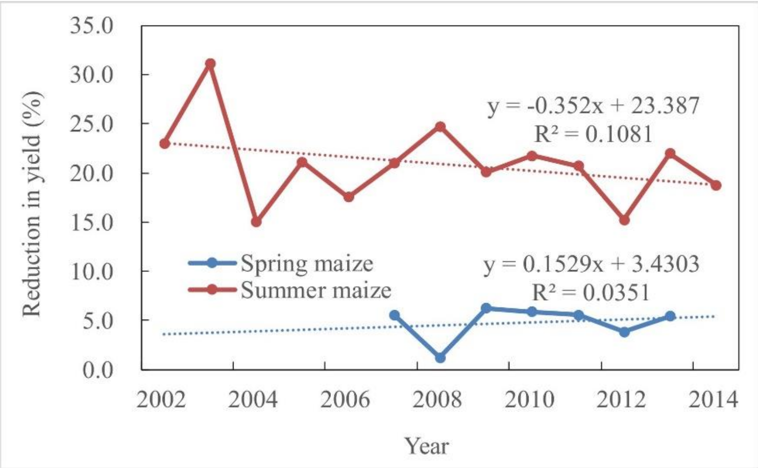


**Fig. 1** Modeling the Influence of Aerosols on Spring and Summer Maize Average Yields across Ten Stations. https://pubmed.ncbi.nlm.nih.gov/32135295/

### 4.2. Impact of Aerosols on the Growth of Vegetation

The impact of aerosols on vegetation growth, particularly on maize, yielded conclusions similar to previous estimates of reduced yields in eastern China. Empirical models show significant losses in wheat and rice yields due to reduced radiation caused by aerosols. The results show that the average corn yield decreased by 15.10% between 2002 and 2014 due to the radiation effects of aerosols alone, which is consistent with similar research findings.

### 4.3. limitations and Uncertainties

The omission of other meteorological changes caused by aerosols and potential model uncertainties caused by assumptions, simplifications, and parameterizations. The study highlights the need for future research to address these limitations, considering factors such as diffuse radiation and various meteorological elements. Furthermore, it underscores current investigations delving into how crops respond to aerosol pollution. This research aims to deepen our comprehension of the detrimental effects on corn production and alleviate potential overestimations. The study also provides more ideas into the overall impact of aerosol radiation on corn production in China.

## 5. Conclusion

Major wheat producing countries, including China, India, and the United States are facing significant yield losses, indicating that ozone's impact on wheat production is of global significance. The Free Air Carbon Dioxide Enrichment experiment provide evidence to suggests that carbon dioxide does not directly trigger C4 photosynthesis. In an elevated $CO_2$ environment, stomatal conductance of all plants is generally reduced, which can delay and alleviate drought stress. In addition, studies have shown that aerosols have different effects on different corn varieties, and the negative effects on summer corn are greater than those on spring corn. In the future, researchers ought to concentrate on mitigating the adverse impact of pollutants on crop yields. This research investigates the multifaceted impact of air pollution on crop productivity. It explores the harmful effects of high ozone levels on sensitive crops, highlighting the urgent need for ozone mitigation strategies in the face of climate change.

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