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China's clean air and climate policies help improve farmers' incomes and reduce socioeconomic inequity via mitigating ozone pollution

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Abstract. Ozone pollution imposes substantial but uneven agricultural and socioeconomic burdens across China. Using bias-corrected ozone fields from an integrated atmospheric modeling and machine learning framework, we estimate that in 2015, ozone-induced losses of wheat, rice, and maize totaled USD 59 billion, with 82% of damages concentrated in net food-producing regions, imposing losses equivalent to 9–37% of local farmers' annual income. These revenue reductions deepened existing inequalities, widening the vertical income gap between farmers and non-farmers within food-producing regions by 2,438 CNY and the horizontal gap between farmers across different regions by 1,096 CNY. By 2060, coordinated clean air and climate policies could halve these losses, reducing the vertical gap to 1,437 CNY and the horizontal to 313 CNY. Our findings reveal that ozone not only

threatens food security but also amplifies structural socioeconomic inequity, while integrated clean air-climate strategies can deliver co-benefits for agriculture, rural livelihoods, and social equity.

Main

Several hundred million tons of crops are annually lost in China due to ozone pollution[1]. Rapid economic growth in China, often hailed internationally as a "miracle of economic growth", has driven massive increases in the emissions of ozone precursor gases, making China a global hotspot for ozone pollution[2]. As the world's largest grain producer, China contributed to approximately 18%, 27% and 23% of global wheat, rice and maize production in 2021[3]. The overlap of major crop-growing areas, industrial zones, and ozone hotspots has resulted in particularly substantial crop production losses (CPLs) in China[1,4–6]. Between 2014 and 2018, ozone cut annual yields of wheat, rice and maize by 33%, 23% and 9%, respectively, resulting in estimated annual economic losses (ELs) of US$63 billion[1].

In recent years, beyond its direct environmental consequences, air pollution has increasingly been recognized as a critical dimension of social inequity, with its health burdens unevenly distributed and closely linked to geographical and income disparities and group identities[7,8]. It has been less clear if such disparities and inequity are also manifested in the agricultural burdens of air pollution. In China, regional disparities in CPLs closely mirror regional agricultural outputs[6,9], which are themselves embedded within the broader national food system guided by strategic agricultural policies. In 2003, China designated 13 major net food-producing regions across its 31 administrative units to address population–resource imbalances and safeguard national food security[10]. By concentrating resources and investments in these net food-producing areas, China has achieved stable increases in grain production over the past decade and reached 95% self-sufficiency in grain supply, a cornerstone of its food security strategy[11]. However, this concentration of production has also made these regions disproportionately exposed to ozone-induced crop yield reductions. As a result, the very areas that sustain national self-sufficiency in staple grains now face heightened agricultural risks that translate to greater economic vulnerability for local farmers.

Current discussion of air pollution-related environmental injustice has largely centered on its health impacts[7,10,12], while few have examined the inequity associated with ozone-induced CPLs. Without addressing this explicitly, the disproportionate costs borne by vulnerable groups in the pursuit of

overall benefits may continue to be overlooked. Meanwhile, China's ongoing environmental and climate policy reforms are expected to deliver substantial air quality improvements[13,14], but their potential agricultural and socioeconomic co-benefits have rarely been examined in terms of equity, limiting our ability to fully understand how integrated policies can simultaneously enhance food security and promote environmental justice.

This study has two main objectives: first, to reveal previously unrecognized socioeconomic inequity arising from ozone-induced CPLs by examining how economic burdens are unevenly distributed across regions and further impose differential impacts on local farmers; second, to explore the potential agricultural and socioeconomic co-benefits of future air quality and climate policies in light of such inequity. To this end, we used a hybrid approach combining a chemical transport model with machine learning-enabled bias correction to simulate hourly ozone concentrations for present-day (2015) and future (2060) scenarios under China's clean air and climate policies (**Methods**). To our knowledge, this is the first study to explicitly link ozone pollution to socioeconomic inequity within the national food system, thereby adding an important dimension to the larger issue of pollution-related environmental injustice. Our work offers key insights to inform clean air and climate actions from an integrated air quality–food security–social equity nexus.

Results

Spatiotemporal evolution of grain production

The spatial distribution of food output often reflects the interplay of economic, social, political and environmental forces. In populous countries like China, food security has long been treated as a matter of strategic national importance, with agricultural policies playing a critical role in shaping the production pattern. Over the past two decades, these policy-driven structural transformations have not only increased overall production but also accentuated regional differentiation trends (**Fig. 1**). Between 2005 and 2020, China's grain production increased from 417.4 Mt to 606.8 Mt, with an annual growth rate of +13.3 Mt yr^{-1} (**Fig. 1e**). However, this aggregate growth masked widening regional disparities: per capita production rose from 0.40 to 0.61 tons in net food-producing regions but declined from 0.12 to 0.08 tons in net food-consuming regions. The Gini index for total grain production increased from

0.44 in 2005 to 0.50 in 2020 (**Fig. 1f**), highlighting an increasingly uneven spatial distribution of output, with production gains concentrated in specific regions.

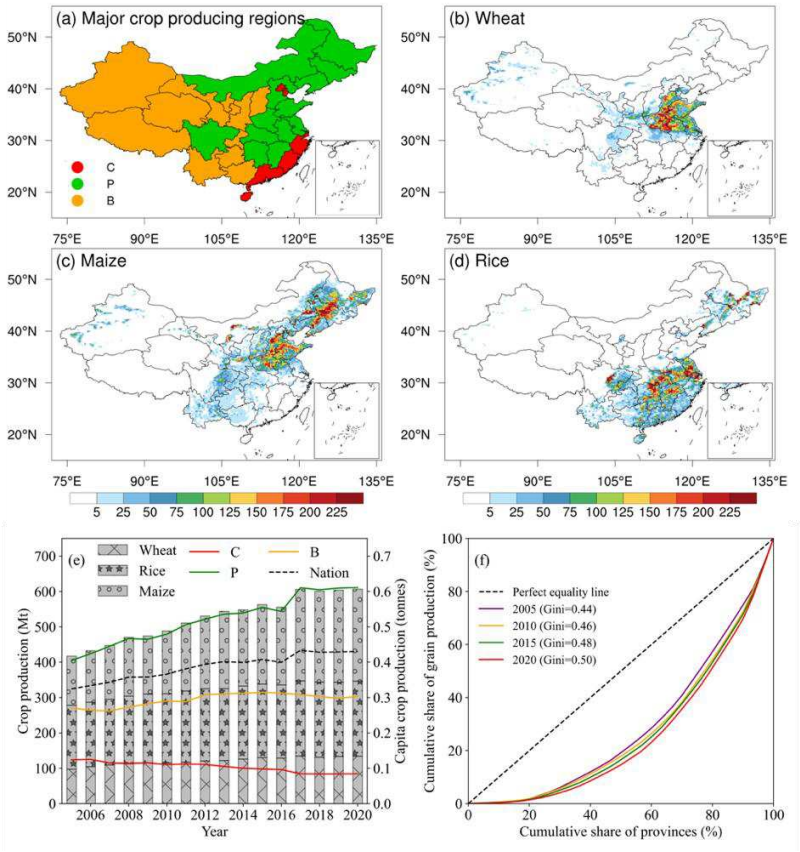


Fig. 1: Spatiotemporal evolution of crop production in China from 2005 to 2020. a, Current food production pattern according to the Ministry of Agriculture and Rural Affairs of the People's Republic of China, including 13 net food-producing areas (P), 11 net food-balanced areas (B) and 7 net food-consuming areas (C). **c-d**, Spatial distribution map of wheat (b), maize (c), and rice (d) production (in thousand metric tons per 0.25°×0.25° grid cell) in 2015. **e**, National crop production (Mt; bar plot) for three major crops and per capita total grain production in different food functional regions (line plot) from 2005 to 2020. **f**, Lorenz curve and Gini coefficient for national grain production between 2005 and 2020, with results for specific crops presented in **Fig. S1**. Detailed provincial production data for the three major crops and their food functional types can be found in **Table S1**.

By 2020, producing regions supplied nearly 80% of national grain output. Notably, these agricultural hubs largely overlap with industrialized areas characterized by high precursor emissions (**Fig. S2**). Given the co-evolution of increasingly concentrated food production and overlapping industrial

activities, it raises the very question of how ozone pollution may impose disproportionate economic burdens on food-producing regions.

Uneven ozone-related economic burdens across regions

In 2015, ozone-induced RYLs reached 28.3% for wheat, 21.0% for rice, and 7.8% for maize (**Fig. S4**), translating into CPLs of 133 Mt yr^{-1} and economic costs of 59.0 billion USD (**Fig. S5**). These losses are highly skewed, as evidenced by a high Gini coefficient of 0.55 (**Fig. 2a; Table S2**): food-producing regions, despite already falling below the national GDP per capita in nine of thirteen cases, bore 81.7% of the total burden, which is equivalent to 0.3–1.7% of their GDP, whereas food-consuming regions never exceeded 0.1% (**Fig. 2b–d**).

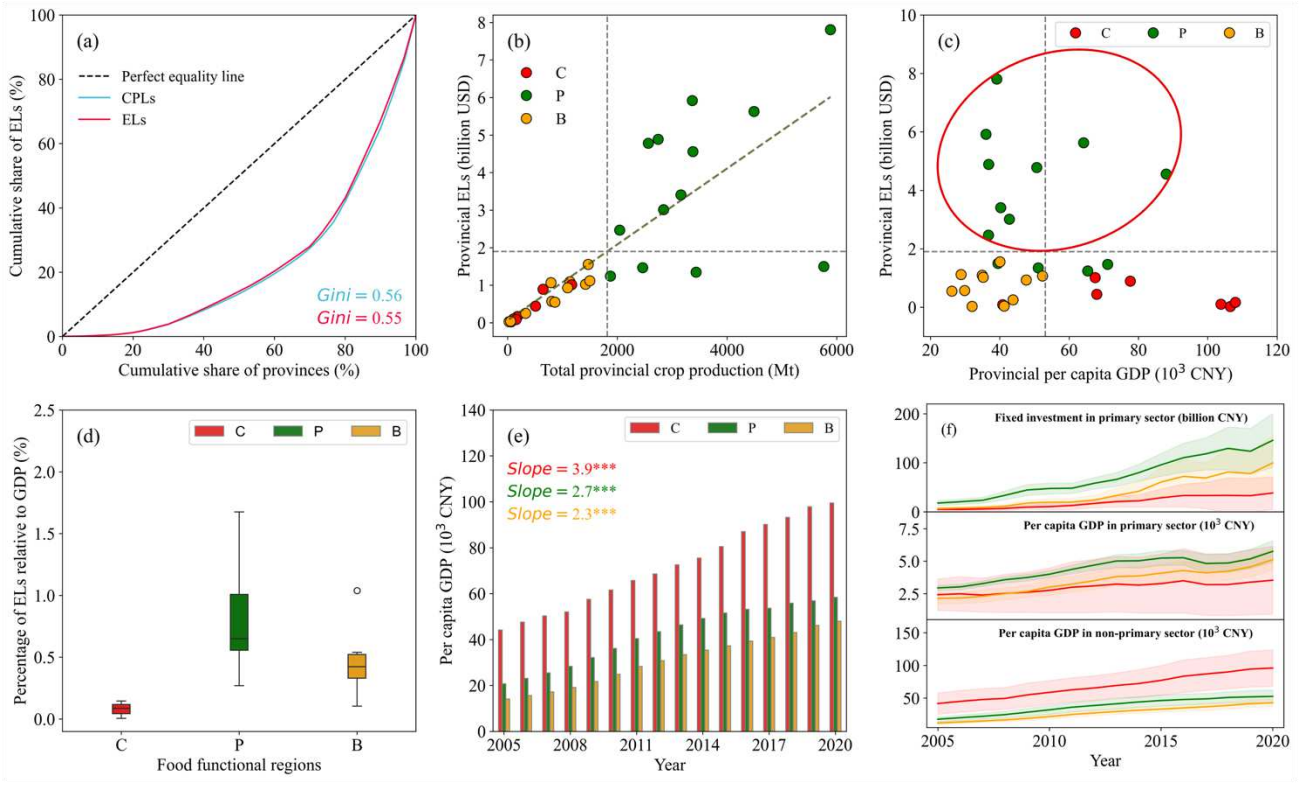


Fig. 2: Spatial disparities in ozone-induced crop production losses (CPLs) across China's food functional regions in 2015. a, Lorenz curve and Gini coefficient for present-day CPLs and associated ELs, and the results for individual crop are provided in **Fig. S3**. **b,** Relationships between provincial total grain production (including wheat, maize and rice) and ELs with the dotted line representing the mean value. **c**, Relationships between provincial per capita GDP and ELs with the dotted line representing the mean value. **d**, Boxplot of provincial ELs across different food functional regions. **e**, Per capita GDP in different food functional regions during 2014-2020. **f**, Fixed investments in primary

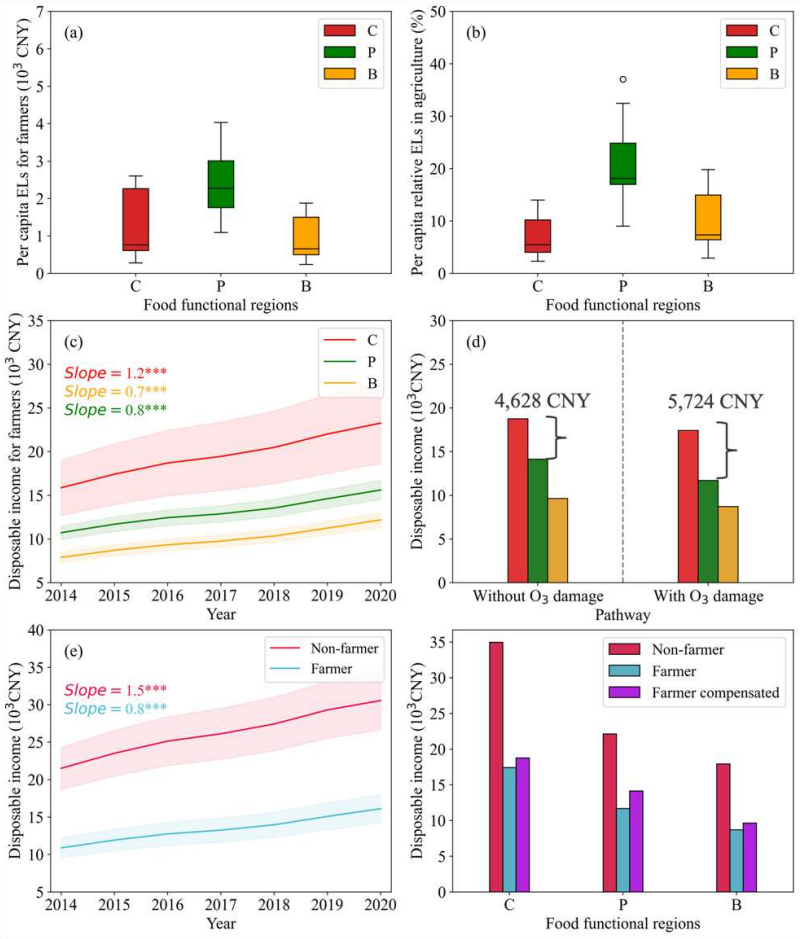
sector, per capita GDP in primary sector and non-primary sectors across different food functional regions from 2005 to 2020, with shading shows the 95% confidence intervals based on all provinces within each food functional region type. The box extends from the lower (Q1) to upper (Q3) quartile values of the data, with a line at the median, and the whiskers extend from the edges of box to show the range of the data. Significance values for two-tailed Student's *t*-test are as follows: * ($p < 0.1$), ** ($p < 0.05$), and *** ($p < 0.01$). For trend analysis, all economic-related indicators from the National Bureau of Statistics of China (NBSC) were adjusted to the 2015 general price level using the GDP deflator.

This uneven burden is embedded within broader socioeconomic disparities. Between 2005 and 2020, per capita GDP in net food-consuming regions grew faster than in net food-producing regions, widening the gap from 23,500 to 41,100 CNY **(Fig. 2e)**. This divergence is closely tied to the inherent opportunity costs borne by net food-producing regions[15–17]. Food-consuming regions, by prioritizing trade, can strategically reallocate resources toward high-value industries, thereby fueling economic growth without the imperative of crop self-sufficiency. In contrast, net food-producing regions are constrained by systematic obligations to secure crop supply, locking capital into the inherently low-return agricultural sector (**Fig. 2f**). First, as a primary commodity, grain has inelastic and limited demand, meaning that production increases do not translate into proportional revenue growth. Second, the sector typically exhibits a low return-to-input ratio, as labor- and land-intensive production generates relatively small profits. Third, agricultural income is exposed to high price volatility, due to seasonal variations, climate shocks, and market fluctuations. Consequently, higher production often imposes heavier fiscal burdens on food-producing regions, constraining their fiscal and development capacity. Such economic predicament has been reported and summarized by the Ministry of Agriculture and Rural Affairs of the People's Republic of China: "the more they produce, the heavier the burden; the greater the contribution, the greater the obligations" [18]. Our findings show that ozone-related CPLs intensify this structural imbalance, embedding an additional layer of inequity within China's food system.

Ozone-related socioeconomic inequity borne by farmers

At the household level, ozone-induced losses affect farmers across all regions, including net food-consuming regions where agriculture coexists with the industrial and service sectors. Importantly, the resulting financial burden is shaped not only by ozone exposure but also local farmers' income levels. We thus examined both the absolute losses and relative losses associated with local farmers' annual income levels, which offer a more accurate assessment of their economic resilience.

In 2015, ozone-induced CPLs ranged from 1,092−4,029 CNY per farmer in net food-producing regions, 283−2,603 CNY in net food-consuming regions, and 241−1,876 CNY in net food-balanced regions (**Fig. 3a**). In food-consuming regions, losses are smaller in absolute terms compared with those in food-producing regions, and the effects are further cushioned by higher incomes, limiting it to 2.4–14.0% of farmers' annual income (**Fig. 3b**). By contrast, farmers in food-producing regions face the highest absolute losses, driven by both the large production volumes and higher ozone exposure associated with more intensive anthropogenic emissions (**Fig. S2 and S6**). Coupled with the lower baseline incomes, these farmers have a more limited capacity to absorb such shocks. As a result, farmers in net food-producing regions are disproportionately vulnerable to ozone-related income shocks, with CPLs accounting for 9.0–37.1% of their annual income.



157

158 **Fig. 3: Economic impacts of ozone-induced CPLs on farmers' income and the resulting inequity**
159 **within and across food functional regions. a-b**, Absolute ELs (a; 10^3 CNY) and relative ELs (b; %)
160 suffered by per farmer in different food functional regions. **c**, Farmers' annual disposable income (10^3
161 CNY) across food functional regions from 2014 to 2020. **d,** Farmers' annual disposable income (10^3
162 CNY) across food functional regions with and without ozone damage impacts. **e**, National per capita
163 annual disposable income (10^3 CNY) for farmers and non-farmers between 2014 and 2020. **f**,
164 Differences in disposable income (10^3 CNY) between non-farmers and farmers with and without
165 impacts from ozone damage. Without available income data for specific groups (such as wheat or
166 maize cultivation), the disposable income of rural residents was used to represent farmers' income
167 levels as a general rural resident, assuming that only farmers within rural areas are affected by these
168 losses. Shading shows the 95% confidence intervals based on all provinces.

169 Notably, the income divides between farmers in food-consuming regions and those elsewhere steadily
170 widened between 2014 and 2020 (**Fig. 3c**), reflecting an increasing disparity in both economic
171 resilience and the capacity to withstand environmental shocks. This divergence is rooted in the

composition of farmers' incomes. Net food-producing regions are typically characterized by concentrated agricultural activity and limited industrial diversification, with a high share of income derived from crop farming (net operating income). In contrast, net food-consuming regions are more economically diversified, allowing farmers to benefit more from a broader range of employment opportunities and higher non-operating incomes, resulting in higher overall incomes (**Fig. S7**). These structural differences not only shape farmers' capacity to absorb losses but also underpin the disproportionate burden of ozone-induced losses on those most dependent on agriculture.

Overall, ozone-related losses exacerbated the pre-existing income inequalities. The horizontal income gap between farmers in net food-consuming and net food-producing regions, increasing it from an expected 4,628 to 5,724 CNY (**Fig. 3d**). Simultaneously, vertical disparities between farmers and non-farmers intensify (**Fig. 3e**), with gaps widening from 7,986 to 10,424 CNY in net food-producing regions, 16,183 to 17,525 CNY in net food-consuming regions, and 8,289 to 9029 CNY in net food-balanced regions (**Fig. 3f)**. The particularly striking vertical disparity underscores the structural disadvantage of farmers within the broader economy. These findings indicate that ozone pollution acts as an amplifier of existing income inequities, reinforcing both regional and rural–urban disparities within China's food systems.

Impacts of future air quality and climate policies

Air quality enhancements are considered as a critical strategy for bolstering China's food security[19,20]. We showed that, for equivalent ozone control outcomes, net food-producing regions could reduce more CPLs, potentially leading to greater economic benefits (**Fig. 4a**). This indicates that, beyond environmental gains, controlling ozone pollution can also alleviate environmental injustice, which is an aspect often overlooked in previous assessments. In this context, we evaluated prospective agricultural and socioeconomic benefits under future clean air and climate policies.

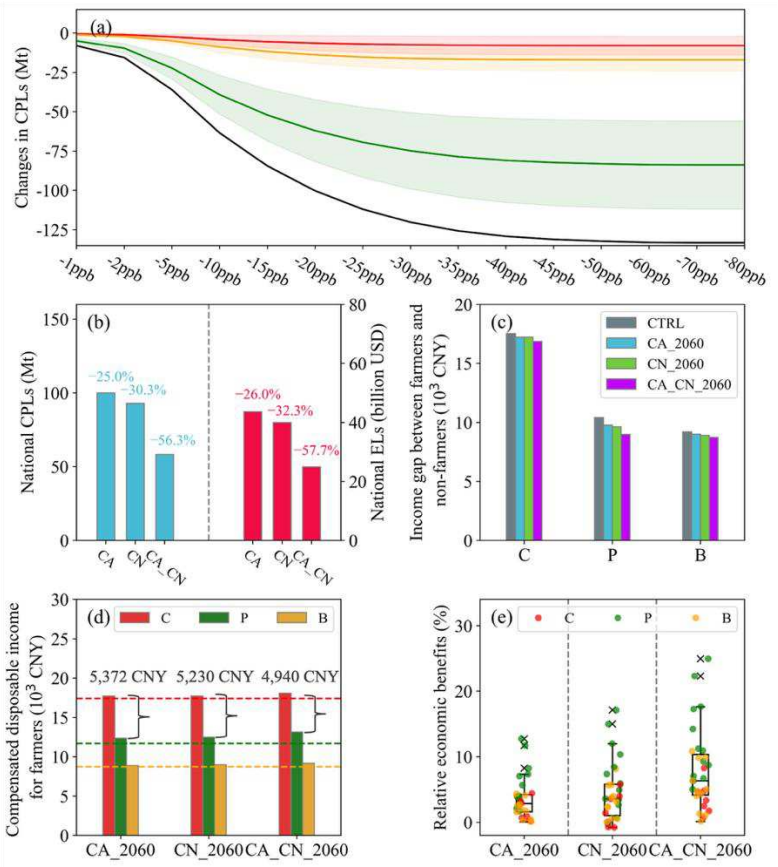


Fig. 4: Co-benefits of ozone control in reducing crop losses, mitigating economic impacts, and alleviating related inequity. Three scenarios (2015–2060) were evaluated to quantify the individual and combined effects of clean air (CA) and carbon neutrality (CN) policies: CA_2060, CN_2060, and CA_CN_2060. a, Changes in national and provincial ozone-induced total CPLs (Mt) for three major crops under various ozone control outcomes, with regional CPLs multiplied by 10 for better illustration. **b**, National ozone-induced CPLs and associated ELs under different policy scenarios. Provincial CPLs for the three major crops under different scenarios are presented in **Tables S3–S5**, with corresponding ELs detailed in **Table S6**. **c**, Farmers' disposable income (10^3 CNY) compensated by saved ELs under different policy scenarios, with the dotted line representing the actual income level in 2015. **d**, differences in disposable income (10^3 CNY) between farmers and non-farmers across food functional region under present-day and different mitigation pathways. **e**, Economic benefits for farmers in relation to their income levels under different policy scenarios (%). Farmers are defined here as individuals specifically engaged in crop farming. We used disposable income—which encompasses all sources of earnings and living expenses—to provide a more accurate measure of their economic well-being.

Different policy scenarios are projected to reduce national CPLs by 25.0%−56.3% and related ELs by 26.0%−57.7% by 2060 (**Fig. 4b**). These interventions could narrow the vertical income gap from 10,424 to 8,986–9,774 CNY in net food-producing regions, from 17,515 to 16,860–17,216 CNY in net food-consuming regions, and from 9,209 to 8,728–9,008 CNY in net food-balanced regions (**Fig. 4c)**. Because food-producing regions stand to gain most from ozone mitigation (**Fig. S8**), horizontal disparities among farmers are also expected to contract, with the gap between food-producing and food-consuming regions narrowing to 5,372 CNY under CA_2060, 5,230 CNY under CN_2060, and 4,940 CNY under the integrated CA_CN_2060 scenario (**Fig. 4d**).

Rural households, as the most economically vulnerable group, face outsized impacts from even minor income fluctuations. Although ozone mitigation contributes little to reducing the broader socioeconomic disparities, it could markedly improve famers' financial well-being, boosting their income by up to 25.0% (**Fig. 4e**). In the short term, these gains help rural households overcome binding income constraints, secure essential consumption, and provide a buffer against external shocks. Over the long term, they can facilitate investments in productive assets and strengthen economic resilience, thereby potentially helping rural households break the self-reinforcing poverty trap of low-return agriculture. Our findings highlight that, beyond directly mitigating crop losses, clean air and climate policies can also strengthen national food security at the socioeconomic level by improving rural livelihoods and economic resilience.

Discussion

We present the first integrated assessment explicitly linking ozone-induced CPLs to socioeconomic inequity within China's food systems and evaluate the potential agricultural and social co-benefits of coordinated clean air and climate policies. Ozone pollution not only reduces staple crop yields but also deepens structural economic disadvantages for farmers in food-producing regions. These uneven burdens exacerbate pre-existing income disparities, increasing the gap by 2,438 CNY between farmers and non-farmers within food-producing regions and by 1,096 CNY between farmers in food-producing and food-consuming regions. By 2060, synergistic clean air and climate policies are expected to halve CPLs and reduce the ozone-attributable widening gap to 1,437 CNY vertically and 314 CNY

horizontally. Our findings reframe ozone not only as an environmental stressor but also as a driver of inequity, embedding crop losses into deeper structural income divides.

Ozone-related inequity is rooted in longstanding, policy-driven spatial patterns of food production embedded within China's broader industrial landscape. Historically, these patterns have prioritized staple grain self-sufficiency to safeguard national food security. Yet the growing mismatch between production and consumption regions has raised enduring sustainability concerns[21–23]. Previous studies have highlighted this challenge from an environmental perspective, documenting how intensive fertilizer use, soil degradation, and heavy chemical inputs have strained fragile agricultural systems[24–26]. Here, we add a socioeconomic dimension, tracing how ozone-induced crop losses deepen pre-existing structural disadvantages. Agriculture-dependent regions face persistently low returns alongside rising input and labor costs, locking them into poverty traps. Farmers, already disadvantaged relative to urban residents, bear the costs of ozone damage while not equitably sharing in the economic benefits of industrial expansion that drives emissions. Interregional trade patterns further redistribute these burdens across provinces, concentrating strain on food-producing regions. Together, these dynamics reinforce both rural–urban and interprovincial income gaps. Rising opportunity costs, manifested as low regional returns and lagging farm wages relative to urban alternatives, threaten labor retention in agriculture. If this divide reaches a tipping point, labor flight from agriculture could undermine food security despite adequate land and technology[e.g., 27].

China's reliance on domestic staple crops underscores the centrality of national food security in the face of intensifying environmental and socioeconomic pressures. Over the past decade, $PM_{2.5}$ concentrations have declined substantially[28], but ozone, particularly during the warm growing season, remains a critical threat to agricultural production. Escalating geopolitical instability and trade tensions have magnified the risks of global food insecurity, amplifying China's dependence on domestic harvests. In 2024, for instance, China's grain imports fell by 29.6% compared with the previous year (from USD 16.2 to 11.4 billion, 2015 values). Strikingly, ozone-induced CPLs alone were equivalent to 364% of the value of these imports, underscoring the centrality of ozone mitigation for national food security. As China embarks on its 15th Five-Year Plan (2026–2030), its current and future policy trajectory oriented toward more sustainable development and officially termed "New Productive

Forces" offers an opportunity to confront these challenges. Coordinated clean air and climate policies can simultaneously curb ozone pollution, secure harvests, and reduce socioeconomic inequity, directly advancing SDGs 1 (No Poverty) and 10 (Reduced Inequalities). Beyond protecting yields, these interventions deliver environmental, economic, and social co-benefits that are essential for sustaining the food systems over the long term (**Fig. 5**). Reframing ozone control as both an environmental necessity and a pathway to social equity positions air quality management as a critical aspect of China's broader sustainable development agenda.

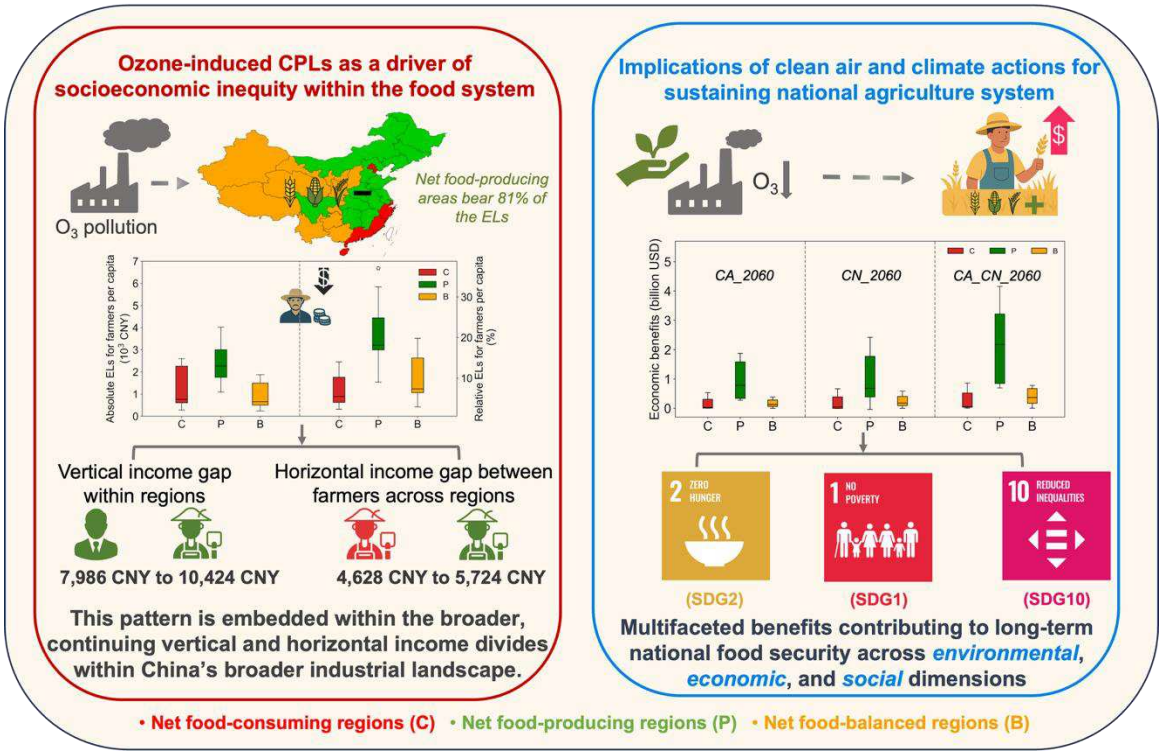


Fig. 5: Ozone impacts and policy co-benefits for sustainable agriculture in China. Conceptual diagram illustrating how ozone-induced crop losses drive socioeconomic inequity in the food system (left), and how China's clean air and climate policies support the long-term sustainability of agricultural systems through broad environmental, economic, and social benefits (right).

Two key assumptions were made in our analysis. First, we assumed ozone-induced losses do not affect farmers' input costs and market prices for crops. Quantifying such price effects is challenging due to the lack of controlled comparisons and limited available data. Moreover, despite annual variations in ozone impacts, total grain production in recent years has remained relatively stable, supporting the assumption that these losses are unlikely to have substantially affected crop prices through the supply-

demand balance. Second, due to data limitations, farmers within each province were treated as a homogeneous group without distinguishing between specific crops (e.g., wheat versus maize). Future studies should incorporate sector-specific data to better understand how ozone impacts vary across crops and whether it may drive the shifting of cultivation choices among farmers. Uncertainties in RYL estimates also persist. Compared with Feng et al.[1] and Wang et al.[6], our maize and wheat CPL estimates align closely, while our rice estimates are higher than Wang et al.[6] but consistent to Feng et al.[1]. This discrepancy largely reflects our inclusion of high-yielding hybrid rice cultivars, which Feng et al.[1] report to be substantially more sensitive to ozone exposure. Overall, our estimates fall within the middle of the uncertainty range reported in previous studies.

Although this study is focused on China, its findings carry broader resonance for the Global South. Across low- and middle-income regions, environmental stressors such as air pollution, climate extremes, and resource constraints exert disproportionate pressure on agricultural communities. Similar to China, smallholder farmers in these contexts often face the heaviest productivity losses while possessing limited adaptive capacity. By contrast, high-income and industrialized regions can offset such impacts through technological innovations and strong institutional support. Extending similar analyses to other countries and agroecological contexts will be critical to identifying where ozone pollution most acutely threatens both food security and equity, and to designing policies that secure equitable agricultural livelihoods under escalating environmental pressures.

Despite remaining uncertainties, this study provides the first evidence revealing ozone pollution as a structural driver of inequity via the food systems. By reframing ozone as both an environmental and socioeconomic challenge, it establishes a new foundation for integrated policy design. Addressing this inequity requires not only synergistic clean air and climate policies but also spatially rational agricultural planning. Unlocking production potential in resource-abundant, non-producing regions, coupled with compensation schemes for food-producing areas, could help rebalance burdens while ensuring food security. Moreover, targeted economic measures to support local farmers are essential to prevent agricultural communities from being left behind in China's development trajectory. Ultimately, future efforts must be guided by the principle of "leaving no one behind," ensuring that

these actions advance not only environmental sustainability but also fairness, resilience, and equity within the national food system.

Methods

Simulations of surface ozone concentrations

In this study, we adopted a hybrid modeling approach, as used in Mao et al.[5], combining the machine learning (ML) algorithm LightGBM and chemical transport model (CTM) GEOS-Chem High Performance (GCHP) to generate ozone concentrations for the present-day baseline simulation ([CTRL]), representative of conditions in 2015. The hybrid approach consists of the following steps. First, GCHP was run at a relatively coarse resolution (2.0° × 2.5°) to simulate ozone concentrations. The LightGBM model was then trained to correct biases in the GCHP output and to downscale the simulated ozone fields to a finer resolution (0.25° × 0.25°) by integrating multiple high-resolution observational and environmental datasets. By taking advantage of the unprecedented ability of ML to integrate model simulations with vast amounts of Earth system data, this hybrid approach has two key advantages: (1) it effectively reduces the biases in CTM output, whereby the biases could arise from multiple sources (e.g., incomplete model physics, and numerical errors); (2) it enhances the resolution of CTM-simulated ozone with substantial lower computational costs. The flowchart illustrating the hybrid approach, along with model validation results, is presented in **Fig. S9** and **Fig. S10**, with required input datasets listed in **Table S7**. Detailed descriptions of the LightGBM and GCHP models are provided in the **Supplementary Material**.

Alongside the baseline simulation, three mitigation scenarios—[CA_2060], [CN_2060], and [CA_CN_2060] were conducted to quantify the individual and combined effects of clean air (CA) and carbon neutrality (CN) policies by 2060. As systematic model biases in GCHP are expected to be largely consistent across scenarios, they are unlikely to affect the interpretation of relative differences between present-day and future conditions. Therefore, bias-corrected ozone concentrations for each mitigation scenario were derived using the formulation: $[EXPR_{corrected}] = [EXPR] - [CTRL] + [CTRL_{corrected}]$. This approach preserves the modeled scenario-driven ozone changes while anchoring them to the bias-corrected present-day baseline. Detailed descriptions of all GCHP simulations are provided in **Table S8**.

Calculation of ozone exposure metrics

Among ozone exposure indices, AOT40 has been widely used during the last two decades due to a strong relationship with the relative yield (RY) of many crop species[1,4,29,30], which is more desirable for assessing the impacts of ozone on crops. The AOT40 (ppm-h) is defined as follows:

$$\mathrm{AOT40} = \sum_{i=1}^{n} ([\mathrm{O_3}]_i - 0.04) \quad (1)$$

where the $[\mathrm{O_3}]_i$ is the hourly mean ozone concentration (ppm) during the 12 hours of local daytime (08:00–19:59); *n* is the number of hours in the growing season defined as the 90 days prior to the start of the harvesting period according to the crop calendar. The crop calendar data in China were provided by Luo et. al[31] at a resolution of 1 km for the year 2015. To fill the gaps of urban grid cells where phenological data are missing, we upscaled the 1-km grids to 0.25° by assuming the same phenology within each of the coarser grid cells.

Estimation of crop production losses and economic costs

Crop yield responses to ozone are generally higher in Asia than in America or Europe, indicating greater sensitivity of Asian varieties [1]. To assess ozone-induced risks to crops in China, we estimated the RY of crops using the Asia-specific AOT40–RY relationships derived from field experiments in China (**Table S9**) [1]. For provinces where double-cropping rice is prevalent, values of relative yield losses (RYLs; 1 – RY) for the early and late crops were weight-averaged using the amount of the respective crops. Additionally, for rice in provinces where hybrid cultivars are widely grown, RYLs were calculated separately for hybrid and inbred types and weight-averaged to overall RYLs using the amount for the respective types. The national mean RYLs for three crops were weighted by the production quantities at each grid.

Crop production loss (CPL) is calculated by [4,30,32]:

$$\mathrm{CPL}_i = \mathrm{CP}_i \times \frac{(1 - \mathrm{RY})}{\mathrm{RY}} \quad (2)$$

where RY is the relative yield, defined as the ratio of ozone-affected yield to yield without ozone exposure, and CP is the annual crop production. Grid-level crop production for 2015 was obtained from the Global Agro-Ecological Zones (GAEZ) dataset and then scaled to match provincial values reported by the National Bureau of Statistics of China (NBSC). National production losses were

calculated by summing losses across all grid cells.

National economic loss (EL) for wheat were then calculated by multiplying the market price in each year using **Eq. (3)**:

$$\mathrm{EL} = \mathrm{CPL} \times \mathrm{Price} \quad (3)$$

where Price stands for the annual market price for each crop in China with a unit of USD Mt^{-1}. The annual crop producer prices were derived from FAOSTAT (https://www.fao.org/faostat/en/#data/PP). Producer prices represent the income received by farmers at the point of initial sale, excluding downstream additional costs such as processing, distribution, and retail margins. In 2015, producer prices were 380.0 USD for wheat, 432.4 USD for maize, and 506.7 USD for rice. As 2015 producer prices for wheat and rice were unavailable, we used the average price from 2014 and 2016, normalized to the 2015 consumer price index (CPI) from FAOSTAT. Economic losses are expressed in USD for comparability with previous studies, but for assessing impacts on farmers' incomes, values were converted to local currency using the 2015 exchange rate of 6.32 USD/CNY.

Inequality assessment

The Lorenz curve, developed by Max O. Lorenz in 1905[33], is commonly utilized in development economics to quantify income inequality within a population. It is originally presented as the cumulative share of income earned (%) on the vertical axis versus the cumulative share of people from the lowest to highest income (%) on the horizontal axis. Recently, it has been extensively applied to assess environmental injustice[10,34–36]. Here, we used the Lorenz curve to reveal the disparities in grain production, CPLs and ELs across provinces. Variables were ranked across 31 administrative regions from lowest to highest, and cumulative provincial shares (%) were plotted against cumulative shares of grain production or ELs (%).

The Gini coefficient, derived from the Lorenz curve, provides a quantitative measure of inequality. It is calculated as:

$$\mathrm{Gini} = 1 - \left| \sum_{i=1}^{N-1} (X_{i+1} - X_i)(Y_{i+1} + Y_i) \right| \quad (4)$$

where X and Y are the cumulative shares of provinces and the variable of interest (grain production or

ELs), N is the total number of provinces, and i indicates the i'th area ordered from lowest to highest grain production or ELs. The Gini coefficient is a unit-free measure and ranges from 0 to 1. The larger the Gini value, the greater the inequality. A zero value of the Gini coefficient indicates perfect equality, and conversely, a Gini coefficient of 1 suggests complete inequality. Generally, a Gini coefficient exceeding 0.5 indicates severe inequality.

Data availability

All the data used in this study are publicly available and can be downloaded from the following links. (1) Gross domestic product (GDP), disposable income, sector-specific population, and crop-specific production data at provincial scales: http://www.stats.gov.cn/sj/ndsj/. (2) Grid-cell crop calendar data: https://doi.org/10.6084/m9.figshare.8313530. (3) The proportion of the crop farming population in the primary sector: https://www.stats.gov.cn/sj/tjgb/nypcgb/qgnypcgb/202302/t20230206_1902105.html. (4) Grid-cell annual crop production data in the year 2015 were from the Global Agro-Ecological Zones (GAEZ) (https://dataverse.harvard.edu/dataset.xhtml).

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