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# Threat to future global food security from climate change and ozone air pollution

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## Main Text (including First Paragraph)

**Future food production is highly vulnerable to both climate change and air pollution with implications for global food security [1, 2, 3, 4]. Climate change adaptation and ozone regulation have been identified as important strategies to safeguard food production [5, 6], but little is known about how climate and ozone pollution interact to affect agriculture, nor the relative effectiveness of these two strategies for different crops and regions. Here we present an integrated analysis of the individual and combined effects of 2000-to-2050 climate change and ozone trends on the production of four major crops (wheat, rice, maize and soybean) worldwide based on historical observations and model projections, specifically accounting for ozone-temperature co-variation. The projections exclude the effect of rising $CO_2$, which has complex and potentially offsetting impacts on global food supply [7, 8, 9, 10]. We show that warming reduces global crop production by >10% by 2050 with a potential to substantially worsen global malnutrition in all scenarios considered. Ozone trends either exacerbate or offset a substantial fraction of climate impacts depending on the scenario, suggesting the importance of air quality management in agricultural planning. Furthermore, we find that depending on region some crops are primarily sensitive to either ozone (e.g., wheat) or heat (e.g., maize) only, providing a measure of relative benefits of climate adaptation vs. ozone regulation for food security in different regions.**

Global demand for food is expected to increase by at least 50% from 2010 to 2050 mainly as a result of population growth and a shift toward a more “westernized” diet in developing regions [11]. Assuming that agricultural production is able to meet the growing demand through a combination of economic growth and agricultural advancements, undernourishment rates in developing countries are projected to decline substantially [11]. Future production is, however, sensitive to both climate change and air pollution.

Temperature extremes are highly damaging to various major crops [1, 2, 5]. Surface ozone, formed via the photochemistry of precursor gases mainly arising from human activities, is phytotoxic and detrimental to crop yields [4, 12, 13]. Climate adaptation and ozone regulation have thus been identified as important measures to tackle food insecurity, but their relative benefits for different crops and regions remain largely uncertain.

In this study, we quantify the individual and combined effects of 2000-to-2050 mean temperature and ozone pollution trends on the global production of wheat, rice, maize and soybean and then on undernourishment rates in developing countries as a necessary input to policy formulation for food security. Fig. 1 illustrates a roadmap for our methodology and summarizes our results. First, we use the Community Earth System Model (CESM) to simulate present-day (2000) and derive future (2050) projections of hourly temperature and ozone concentration consistent with the representative concentration pathways (RCPs) represented in the IPCC Fifth Assessment Report (AR5) [14, 15]. Our future ozone projections not only follow trends in anthropogenic emissions of precursor gases but also include the effects of climate and land use changes; these confounding factors are known to significantly impact future ozone projections [16, 17] but are not considered in previous crop impact studies. We consider two scenarios: RCP4.5, representing an intermediate pathway with a global reduction in surface ozone owing to pollution control measures worldwide (except in South Asia) [14]; and RCP8.5, representing a more "pessimistic", energy-intensive pathway with a worldwide increase in ozone except in the US and Japan (Supplementary Fig. 1) [18]. The two scenarios represent a range of policy options regarding ozone regulation. Both scenarios project a global increase in surface temperature (Supplementary Fig. 1), with similar effects on crop production as discussed below. Previous historical crop-temperature impact analyses [5, 19] suggest a substantial potential for crop-level adaptation to avoid losses from warming, but they do not consider the concurrent impacts of changing ozone levels that may offset the benefits of adaptation [12]. We therefore exclude adaptation in our projections, and focus on the potential of ozone regulation to combat the warming impacts. Other environmental factors such as water scarcity and land degradation may influence future food production but are outside the scope of this study.

From the CESM-simulated results we derive various metrics to parameterize the influence of climate change and ozone pollution on crop production: growing degree days (GDD) and killing degree days (KDD) for climate, and different ozone exposure indices for ozone (see Methods). Changes in production due to climate and ozone trends for each CESM grid cell and each crop, $\Delta P$, is represented as a function of current production, $P$, by

$$\Delta P = gP\left(\gamma_c \gamma_p - 1\right) \tag{1}$$

where $g$ is the production growth factor accounting for technology-driven yield improvements and cropland area changes; $\gamma_c$ and $\gamma_p$ are scaling factors capturing the effects of climate change and ozone pollution, respectively, based on observed relationships of crop yields with agro-climatic and ozone exposure metrics. The individual climate (or pollution) effect is represented by $\Delta P$ but omitting the other factor $\gamma_p$ (or $\gamma_c$) in equation (1). The growth factor $g$ for 2050 is based on estimates from Food and Agriculture Organization (FAO) [11]. Crop-ozone responses are based on an ensemble of statistical relationships represented in the literature. For crop-temperature responses, we develop a constrained linear regression model to quantify the sensitivities of relative crop yield to GDD and KDD for different regions worldwide based on historical observations from 1960 to 2000 (see Methods). The correlations with other climate variables such as precipitation are partially encapsulated in these agro-climatic variables (Supplementary Methods). In general, for each crop we find strong but spatially varying responses to both GDD and KDD, likely due to cultivar differences. We observe globally a strong trend of increasing sensitivity to excess heat from warmer to colder regions (in terms of growing season temperature) for wheat, maize and soybean, reflecting a spatial gradation of heat tolerance and local climate adaptability (Supplementary Fig. 5). The observed sensitivity for US maize is generally consistent with Butler and Huybers [5].

Ozone formation is strongly correlated with temperature [16], so the observed crop-temperature relationships may arise in part from ozone damage at high temperature instead of warming per se. Previous studies [1, 5, 19] typically do not consider this confounding effect. We specifically correct for ozone-temperature co-variation (see Methods), and find that on average, 24%, 9.8% and 46% of the observed sensitivity to KDD for wheat, maize and soybean, respectively, arise from higher ozone associated with high KDD (inconclusive for rice). We use the corrected sensitivity to estimate future crop-temperature responses.

Figs. 1a through 1f represent the individual and combined effects of climate change and ozone pollution on total crop production for both the RCP4.5 and RCP8.5 scenarios, expressed as the sum of $\Delta P$ per unit harvested area multiplied by the equivalent food energy for all four crops (Supplementary Table 2). We find that the effects of ozone pollution on crop production are highly dependent on the scenario. On a global scale, more severe ozone pollution expected for RCP8.5 leads to substantial crop damage (except in the US and South Korea) reducing global total crop production by 3.6% (Fig. 1d), but aggressive pollution control worldwide expected for RCP4.5 leads to substantial gains in many regions (except South Asia) with an overall 3.1% increase in global production (Fig. 1a). In contrast, the effects of climate change (Figs. 1b and 1e) are similar across the two scenarios, both with an overall reduction in global production by 11% caused primarily by more extreme temperatures associated with higher KDD. We see that ozone pollution control as represented in RCP4.5 has the potential to partially offset the negative impact of climate change, leading to a smaller combined decrease of 9.0%, compared with RCP8.5 where ozone pollution and climate change combine to reduce global crop production by 15%. We further evaluate how such combined changes may shift the current (2000) distribution of per capita food consumption in developing countries, leading to a change in the rate of undernourishment as a proxy for the potential societal impacts (see Methods). We use the current undernourishment rate of 18% as the baseline for estimation, and do not account for agricultural advances, land use change and international politics, which is beyond the scope of this study. For RCP8.5, more serious ozone pollution worldwide and climate change combine to increase undernourishment rate in developing countries by 49% (from a rate of 18% to 27%). For RCP4.5, undernourishment rate increases by only 27% because ozone regulation partially offsets the warming effect, suggesting the importance of air quality management in devising strategies for food security.

Fig. 1c shows that though ozone regulation may be able to offset some of the warming impacts on agriculture on a global scale, the effects vary greatly across regions for different crops. To devise the best measures to guard regional agriculture, the relative effects of warming vs. ozone pollution for individual crops are needed. Fig. 2 shows by regions the projected combined effects of and relative contributions from warming and ozone trends using current production as baseline, with uncertainty ranges quantified using a Monte Carlo approach from the variability of statistical parameters embedded in $\gamma_c$ and $\gamma_p$ (Supplementary Methods). Wheat in all major producing regions is mostly sensitive to ozone policy, with the ozone effect generally much higher than temperature effect. Ozone regulation as represented in RCP4.5 has the potential to completely reverse the warming impact and lead to substantial gain in wheat production in the US and China. In South Asia where ozone pollution is projected to worsen in both scenarios, wheat production is reduced by up to 40%. Wheat in South America is more sensitive to temperature likely because of the relatively small ozone changes projected there (Supplementary Fig. 1). We find that rice and maize production in China is mostly sensitive to ozone pollution. In contrast, maize in major producing regions including the US, Europe and South America, as well as soybean in South America, are mostly sensitive to temperature. In both scenarios, maize and soybean production in these regions is projected to decrease by 20-50% due to higher and more frequent extreme temperatures, regardless of ozone trends. For maize, climate adaptation may have the potential to reduce such losses by more than half in temperate regions [5], but may not be effective in tropical regions [19]. The projection for soybean in the largest producer, the US, is uncertain for both scenarios, due to the similar contribution (in magnitude) but opposite effect (in sign) from warming and ozone reduction.

Climate change adaptation by, for example, selecting more heat-tolerant cultivars traditionally grown in warmer regions, has been proposed to reduce heat-related losses under warming for at least certain crops [5, 19]. Our results show that while this may be effective for maize and soybean for major producing regions due to their strong sensitivity to temperature (except China for both crops and US for soybean), adaptation may be less effective than reducing ozone damage for other crops (most notably wheat) and regions where ozone sensitivity dominates. Another modulating factor is future elevated atmospheric $CO_2$, which stimulates photosynthesis while reducing stomatal conductance and thus the flux-based risk of ozone damage [7, 8, 9]. Evidence suggests, however, that elevated $CO_2$ reduces zinc, iron and protein content in $C_3$ crops [10], and may therefore only alleviate warming and ozone impacts on total food calorie production but not the broader nutritional outcome. Furthermore, rising $CO_2$ may neither prevent accelerated senescence from elevated ozone nor improve yield [8, 20], and ozone exposure may alter crop responses to rising $CO_2$ [21, 22, 23].

It has been suggested that careful crop management such as selecting ozone-resistant cultivars can bring substantial gain in wheat production [6]. Such potential is not explored in this study and warrants further investigation for ozone-sensitive crops. However, considering the challenge of implementing such a strategy, the questionable efficacy of other crop management practices [24], as well as the public health co-benefit of ozone control, ozone regulation may prove to be a practical and preferable alternative to help secure global food production in addition to climate adaptation, depending on the crop of concern. This highlights the need for greater collaboration between farmers, agricultural policy makers and air quality managers to achieve coordinated goals concerning public health and food security.

## Methods

We use the Community Earth System Model (CESM) to simulate present-day and project future surface ozone and climate in 2050. Our configuration employs coupled atmosphere and land components but fixed data ocean and cryosphere consistent with current and future climates, at a latitude-by-longitude resolution of 1.9°×2.5°. Anthropogenic emissions of greenhouse gases and ozone precursors follow the RCP4.5 and RCP8.5 scenarios represented in IPCC AR5. See Supplementary Methods for details of these simulations, data sources, and definitions of various metrics used below.

The influence of ozone pollution on crop production is parameterized using the statistical relationships of relative yield for various crops with four ozone exposure indices (AOT40, SUM06, W126, and M7 or M12):

$$\frac{Y}{Y_0} = f(M) \tag{2}$$

where $Y$ is the yield, $Y_0$ is the maximum potential yield with zero ozone exposure, $M$ is any one of the four ozone exposure metrics, and $f(M)$ represents a function of $M$. We use the exact forms of $f(M)$ obtained from an ensemble of statistical studies in the literature (Supplementary Table 1). The scaling factor, $\gamma_p$, for pollution effect in equation (1) is then

$$\gamma_p = \frac{f(M_{2050})}{f(M_{2000})} \tag{3}$$

where $M_{2000}$ and $M_{2050}$ refer to $M$ evaluated in year 2000 and 2050, respectively.

The influence of climate change on crop production is parameterized using statistical relationships of crop yield with growing degree day (GDD), which is the summation (over the growing season) of daily mean temperature in excess of a minimum temperature threshold, essentially capturing the beneficial effect of warmth; and killing degree day (KDD) [5], which is the summation of daily maximum temperature in excess of an optimal growth temperature and captures the adverse effect of temperature extremes. A rise in both the mean temperature and frequency of temperature extremes can increase KDD. We find relationships for each 1.9°×2.5° grid cell and each crop using a multiple linear regression model on 1961-2010 annual crop yield and meteorological data

$$\ln\frac{Y}{Y_m} = \beta_0 + \beta_{\mathrm{GDD}}\left(\mathrm{GDD} - \mathrm{GDD}_m\right) + \beta_{\mathrm{KDD}}\left(\mathrm{KDD} - \mathrm{KDD}_m\right) \tag{4}$$

where $Y$ is the annual crop yield from FAOSTAT, GDD and KDD are annual values calculated from NCEP/NCAR Reanalysis 1 meteorological data, $m$ denotes 5-year moving averages for detrending the data, and $\beta_{\mathrm{GDD}}$ and $\beta_{\mathrm{KDD}}$ are the observed sensitivities of crop yield to GDD and KDD. Equation (4) is constrained such that $\beta_{\mathrm{GDD}} \geq 0$ and $\beta_{\mathrm{KDD}} \leq 0$, which helps separate between the beneficial effect of warmth and adverse effect of temperature extremes, and remove collinearity when GDD and KDD are too strongly correlated. Historical data for 1961-2010 are available from FAOSTAT only at national level, so we derive finer resolution (1.9°×2.5°) historical maps of crop yield by applying a data fusion technique on the fine resolution map of crop yield for year 2000 [25]. Since the observed sensitivities $\beta_{\mathrm{GDD}}$ and $\beta_{\mathrm{KDD}}$ may arise in part from ozone damage at high GDD and KDD instead of warming per se, we estimate the true sensitivities, $\tilde{\beta}_{\mathrm{GDD}}$ and $\tilde{\beta}_{\mathrm{KDD}}$, as

$$\beta_D = \tilde{\beta}_D + \frac{\partial \ln Y}{\partial M}\frac{\mathrm{d}M}{\mathrm{d}D} \tag{5}$$

where $\partial \ln Y/\partial M$ is the sensitivity of crop yield to ozone exposure estimated as

$$\frac{\partial \ln Y}{\partial M} = \frac{f'(M)}{f(M)} \tag{6}$$

$f'(M)$ being the first derivative of $f(M)$ in equation (2) with respect to $M$; $D$ is either of the two agro-climatic variables GDD and KDD, and $\mathrm{d}M/\mathrm{d}D$ is the observed sensitivities of ozone exposure indices to GDD or KDD estimated from simple linear regression using 1993-2010 hourly ozone observations in the US and Europe. The scaling factor, $\gamma_c$, for climate effect is

$$\gamma_c = \exp\left(\tilde{\beta}_{\mathrm{GDD}}\Delta\mathrm{GDD} + \tilde{\beta}_{\mathrm{KDD}}\Delta\mathrm{KDD}\right) \tag{7}$$

where ΔGDD and ΔKDD are 2000-to-2050 average changes in GDD and KDD. We refer to Supplementary Methods for further technical details of statistical models, and Supplementary Figs. 3-5 for maps of $\beta_D$ and the spatial correlation between $\tilde{\beta}_{\mathrm{KDD}}$ and growing season temperature.

Globally averaged values for production growth factor $g$ in equation (1) for year 2050 are 1.46, 1.37, 1.95 and 2.35 for wheat, rice, maize and soybean, respectively [11]. Following FAO methodology [26] (Supplementary Methods), the distribution of per capita food consumption or dietary energy supply (DES) (kcal/person/day) for the population in developing countries can be modeled as a lognormal distribution $f(x)$ ($x$ representing DES) with parameters related to the actual arithmetic mean DES ($x_m$). Undernourishment rate ($r_u$) is defined to be the fraction of population with a DES below the minimum dietary energy requirement (MDER). Any change in $x_m$ can result in a shift in the distribution $f(x)$ and affect $r_u$ as in Fig. 1g. The change in mean DES ($\Delta x_m$) is estimated by

$$\Delta x_m = \frac{ab\Delta E}{\left(365\ \mathrm{d\ a^{-1}}\right)N} \tag{8}$$

where $\Delta E$ is the change in total global crop production (Fig. 1 and Supplementary Table 5) in terms of food equivalent energy (kcal $\mathrm{a^{-1}}$), $a$ is the fraction of global crop production consumed by developing countries [27], $b$ is the fraction consumed as food (as opposed to nonfood use) [27], and $N$ is total population in developing countries. The analysis assumes that: 1) population has flexible dietary habits; 2) there is little barrier for international trade. Violation of these assumptions would likely further increase $r_u$.

## References

1. Lobell, D. B*., et al.* Prioritizing climate change adaptation needs for food security in 2030. *Science* **319**(5863)**,** 607-610 (2008).
2. Battisti, D. S. & Naylor, R. L. Historical warnings of future food insecurity with unprecedented seasonal heat. *Science* **323**(5911)**,** 240-244 (2009).
3. Avnery, S., Mauzerall, D. L., Liu, J. F. & Horowitz, L. W. Global crop yield reductions due to surface ozone exposure: 2. Year 2030 potential crop production losses and economic damage under two scenarios of O-3 pollution. *Atmos. Environ.* **45**(13)**,** 2297-2309 (2011).
4. Avnery, S., Mauzerall, D. L., Liu, J. F. & Horowitz, L. W. Global crop yield reductions due to surface ozone exposure: 1. Year 2000 crop production losses and economic damage. *Atmos. Environ.* **45**(13)**,** 2284-2296 (2011).
5. Butler, E. E. & Huybers, P. Adaptation of US maize to temperature variations. *Nature Clim. Change* **3**(1)**,** 68-72 (2013).
6. Avnery, S., Mauzerall, D. L. & Fiore, A. M. Increasing global agricultural production by reducing ozone damages via methane emission controls and ozone-resistant cultivar selection. *Global Change Biol.* **19**(4)**,** 1285-1299 (2013).
7. Ainsworth, E. A. & Rogers, A. The response of photosynthesis and stomatal conductance to rising [CO2]: mechanisms and environmental interactions. *Plant Cell Environ.* **30**(3)**,** 258-270 (2007).

8. Fiscus, E. L., Booker, F. L. & Burkey, K. O. Crop responses to ozone: uptake, modes of action, carbon assimilation and partitioning. *Plant Cell Environ.* **28**(8)**,** 997-1011 (2005).

9. Klingberg, J., Engardt, M., Uddling, J., Karlsson, P. E. & Pleijel, H. Ozone risk for vegetation in the future climate of Europe based on stomatal ozone uptake calculations. *Tellus A* **63**(1)**,** 174-187 (2011).

10. Myers, S. S.*, et al.* Increasing CO2 threatens human nutrition. *Nature* **510,** 139-142 (2014).

11. Alexandratos, N. & Bruinsma, J. World agriculture towards 2030/2050: the 2012 revision. Food and Agriculture Organization of the United Nations, Rome, Italy (2012).

12. Ainsworth, E. A., Yendrek, C. R., Sitch, S., Collins, W. J. & Emberson, L. D. The effects of tropospheric ozone on net primary productivity and implications for climate change. *Annu. Rev. Plant Biol.* **63,** 637-661 (2012).

13. Fuhrer, J. Ozone risk for crops and pastures in present and future climates. *Naturwissenschaften* **96**(2)**,** 173-194 (2009).

14. Wise, M.*, et al.* Implications of Limiting CO2 Concentrations for Land Use and Energy. *Science* **324**(5931)**,** 1183-1186 (2009).

15. Meinshausen, M.*, et al.* The RCP greenhouse gas concentrations and their extensions from 1765 to 2300. *Climatic Change* **109**(1-2)**,** 213-241 (2011).

16. Jacob, D. J. & Winner, D. A. Effect of climate change on air quality. *Atmos. Environ.* **43**(1)**,** 51-63 (2009).

17. Tai, A. P. K., Mickley, L. J., Heald, C. L. & Wu, S. Effect of CO2 inhibition on biogenic isoprene emission: Implications for air quality under 2000 to 2050 changes in climate, vegetation, and land use. *Geophys. Res. Lett.* **40,** 3479-3483 (2013).

18. Riahi, K., Grubler, A. & Nakicenovic, N. Scenarios of long-term socio-economic and environmental development under climate stabilization. *Technol. Forecast. Soc.* **74**(7)**,** 887-935 (2007).

19. Challinor, A. J*., et al.* A meta-analysis of crop yield under climate change and adaptation. *Nature Clim. Change* **4**(4)**,** 287-291 (2014).

20. Uddling, J., Teclaw, R. M., Pregitzer, K. S. & Ellsworth, D. S. Leaf and canopy conductance in aspen and aspen-birch forests under free-air enrichment of carbon dioxide and ozone. *Tree Physiol.* **29**(11)**,** 1367-1380 (2009).

21. Karnosky, D. F*., et al.* Scaling ozone responses of forest trees to the ecosystem level in a changing climate. *Plant Cell Environ.* **28**(8)**,** 965-981 (2005).

22. Loya, W. M., Pregitzer, K. S., Karberg, N. J., King, J. S. & Giardina, C. P. Reduction of soil carbon formation by tropospheric ozone under increased carbon dioxide levels. *Nature* **425**(6959)**,** 705-707 (2003).

23. Sitch, S., Cox, P. M., Collins, W. J. & Huntingford, C. Indirect radiative forcing of climate change through ozone effects on the land-carbon sink. *Nature* **448**(7155)**,** 791-U794 (2007).

24. Teixeira, E*., et al.* Limited potential of crop management for mitigating surface ozone impacts on global food supply. *Atmos. Environ.* **45**(15)**,** 2569-2576 (2011).

25. Monfreda, C., Ramankutty, N. & Foley, J. A. Farming the planet: 2. Geographic distribution of crop areas, yields, physiological types, and net primary production in the year 2000. *Global Biogeochem. Cy.* **22**(1)**,** GB1022 (2008).

26. FAO. FAO Methodology for the Measurement of Food Deprivation: Updating the minimum dietary energy requirements. Food and Agriculture Organization of the United Nations, Rome, Italy (2008).

27. FAO, WFP & IFAD. The State of Food Insecurity in the World 2012: Economic growth is necessary but not sufficient to accelerate reduction of hunger and malnutrition. Food and Agriculture Organization of the United Nations, Rome, Italy (2012).

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## Author Contributions

A.P.K.T. conceived the strategies, developed the analytical tools and statistical models, processed and analyzed the data, and wrote the paper.

M.V.M. conducted the Community Earth System Model simulations, and provided the future ozone and climate projections.

C.L.H. supervised the project and writing of the paper.

## Declaration of Competing Financial Interests

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**MANUSCRIPT NUMBER: NCLIM-14030307B**

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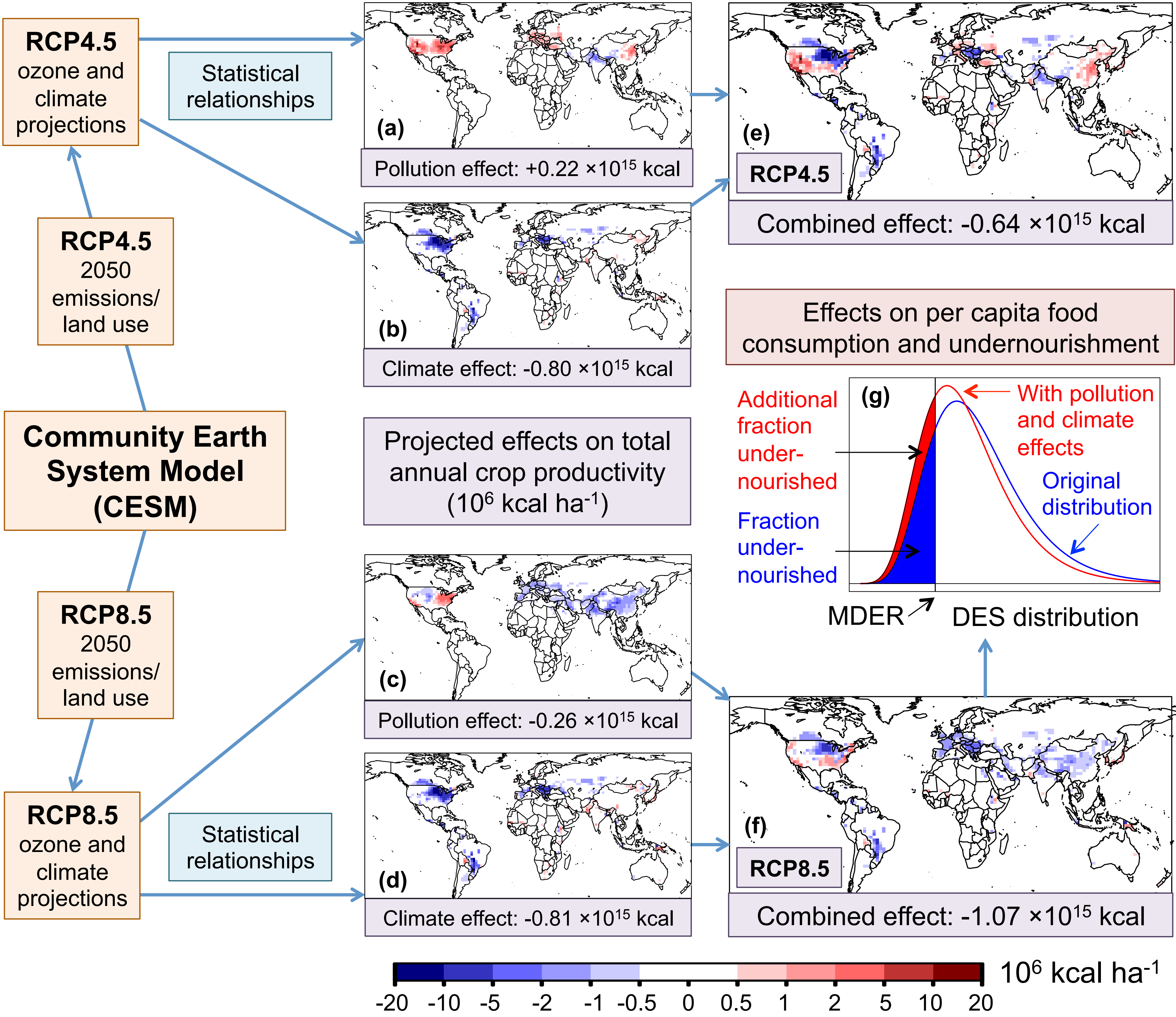
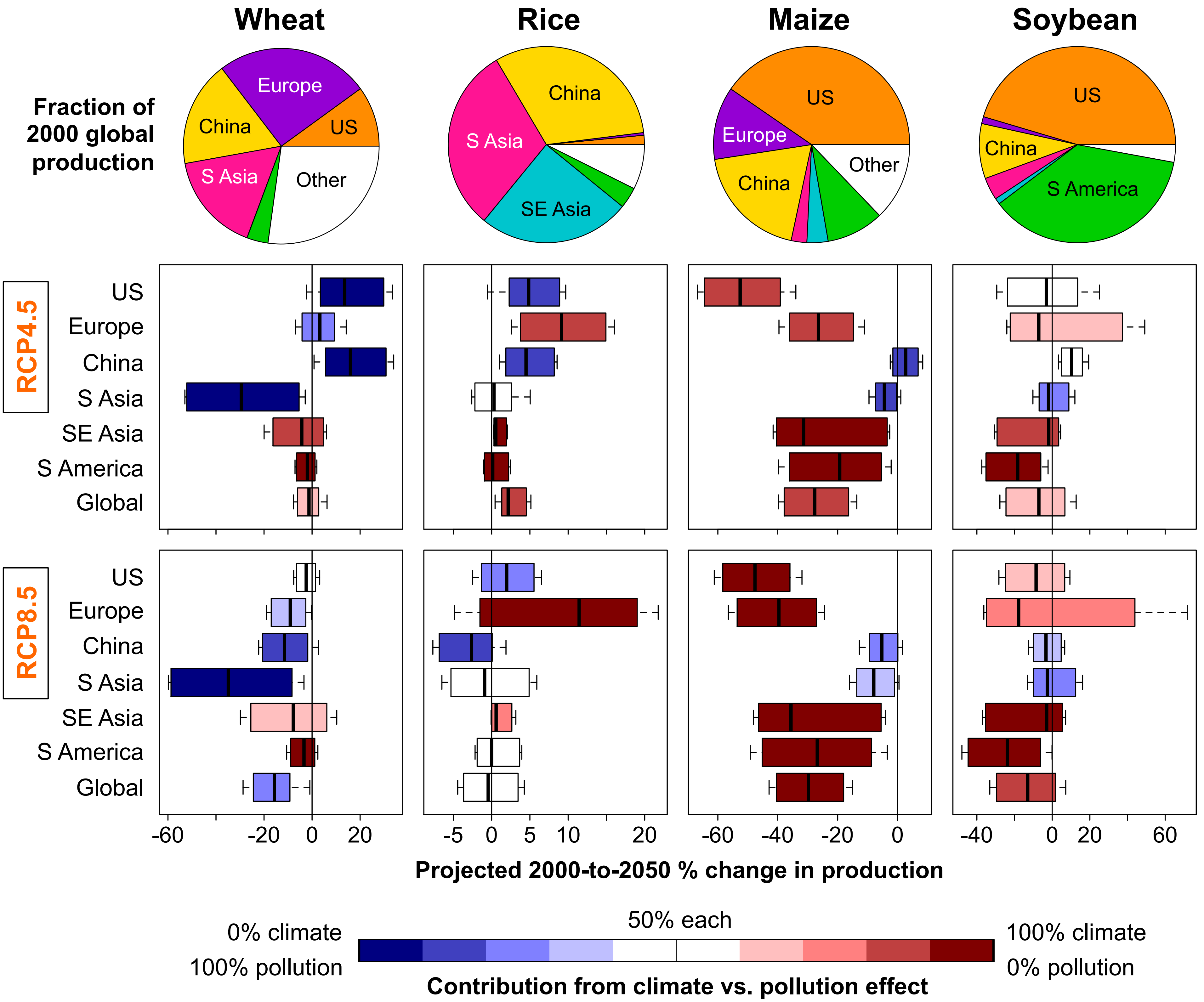
**Figure legends**

Figure 1. Methodology and results. Using Community Earth System Model (CESM), we derive future (2050) projections for ozone exposure indices and agro-climatic variables, which are used to estimate subsequent effects on total annual crop productivity based on statistical crop-ozone and crop-climate relationships. Effects are expressed as sum of $\Delta P$ in equation (1) per unit harvested area multiplied by equivalent food energy for all four major crops (wheat, rice, maize, soybean). Upper (lower) panels represents changes following 2000-to-2050 RCP4.5 (RCP8.5) anthropogenic emissions and land use scenario. Panels (a) and (c) represent effects of ozone pollution only, (b) and (d) effects of climate change only, and (e) and (f) represent combined effects. In purple boxes below panels (a)-(f) are global total effects ($\sum\Delta P\times A$ over all grid cells, where $A$ is harvested area). Here we use current production as baseline ($g = 1$) with global total of $7.09\times10^{15}$ kcal $a^{-1}$; see Supplementary Table 5 for results based on 2050 projections. Panel (g) represents shift in distribution of per capita dietary energy supply (DES) in developing countries (by 2000 definition) following 2000-to-2050 ozone and temperature changes (for RCP8.5 as an example). Shaded in color is proportion of population consuming below minimum dietary energy requirement (MDER).

Figure 2. Impacts of climate change and ozone pollution on crop production by regions and by individual crops. Top panels show the contributions to current (2000) global production from major producing countries/regions (see Supplementary Table 6 for region definitions). Middle and bottom panels show the combined effects of climate change and ozone pollution trends on crop production for major producing countries/regions (using current production as baseline). For each box plot, the two ends of box span the 67% confidence intervals, the notches span the 90% confidence intervals, and the thick line indicates mean. Color of box

indicates individual contribution to the combined effects from climate change and ozone air pollution.


RCP4.5 ozone and climate projections
Statistical relationships
RCP4.5 2050 emissions/ land use
Community Earth System Model (CESM)
RCP8.5 2050 emissions/ land use
RCP8.5 ozone and climate projections
Statistical relationships
(a)
Pollution effect: +0.22 ×10$^{15}$ kcal
(b)
Climate effect: -0.80 ×10$^{15}$ kcal
Projected effects on total annual crop productivity (10$^6$ kcal ha$^{-1}$)
(c)
Pollution effect: -0.26 ×10$^{15}$ kcal
(d)
Climate effect: -0.81 ×10$^{15}$ kcal
(e)
RCP4.5
Combined effect: -0.64 ×10$^{15}$ kcal
Effects on per capita food consumption and undernourishment
(g)
Additional fraction under-nourished
Fraction under-nourished
With pollution and climate effects
Original distribution
MDER
DES distribution
(f)
RCP8.5
Combined effect: -1.07 ×10$^{15}$ kcal
-20 -10 -5 -2 -1 -0.5 0 0.5 1 2 5 10 20
10$^6$ kcal ha$^{-1}$


Wheat
Rice
Maize
Soybean
Fraction of 2000 global production
Europe
China
US
S Asia
Other
SE Asia
S America
RCP4.5
RCP8.5
US
Europe
China
S Asia
SE Asia
S America
Global
-60
-20
0
20
-5
0
5
10
20
-60
-40
-20
0
-40
0
20
60
Projected 2000-to-2050 % change in production
0% climate
100% pollution
50% each
100% climate
0% pollution
Contribution from climate vs. pollution effect