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# Climate extremes and ozone pollution: a growing threat to China's food security

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**Abstract.** Ensuring global food security requires a sound understanding of climate and environmental controls on crop productivity. The majority of existing assessments have focused on physical climate variables (i.e., mean temperature and precipitation), but less on the increasing climate extremes (e.g., drought) and their interactions with increasing levels of tropospheric ozone (O<sub>3</sub>). Here we quantify the combined impacts of drought and O<sub>3</sub> on China's crop yield using a comprehensive, process-based agricultural ecosystem model in conjunction with observational data. Our results indicate that climate change/variability and O<sub>3</sub> together led to an annual mean reduction of crop yield by 10.0% or 55 million tons per year at the national level during 1981–2010. Crop yield shows a growing threat from severe episodic droughts and increasing O<sub>3</sub> concentrations since 2000, with the largest crop yield losses occurring in northern China, causing serious concerns in food supply security in China. Our results imply that reducing tropospheric O<sub>3</sub> levels is critical for securing crop production in coping with increasing frequency and severity of extreme climate events such as droughts. Improving air quality should be a core component of climate adaptation strategies.

**Key words:** *China food security; climate change; crop yield; drought; tropospheric ozone (O<sub>3</sub>).*

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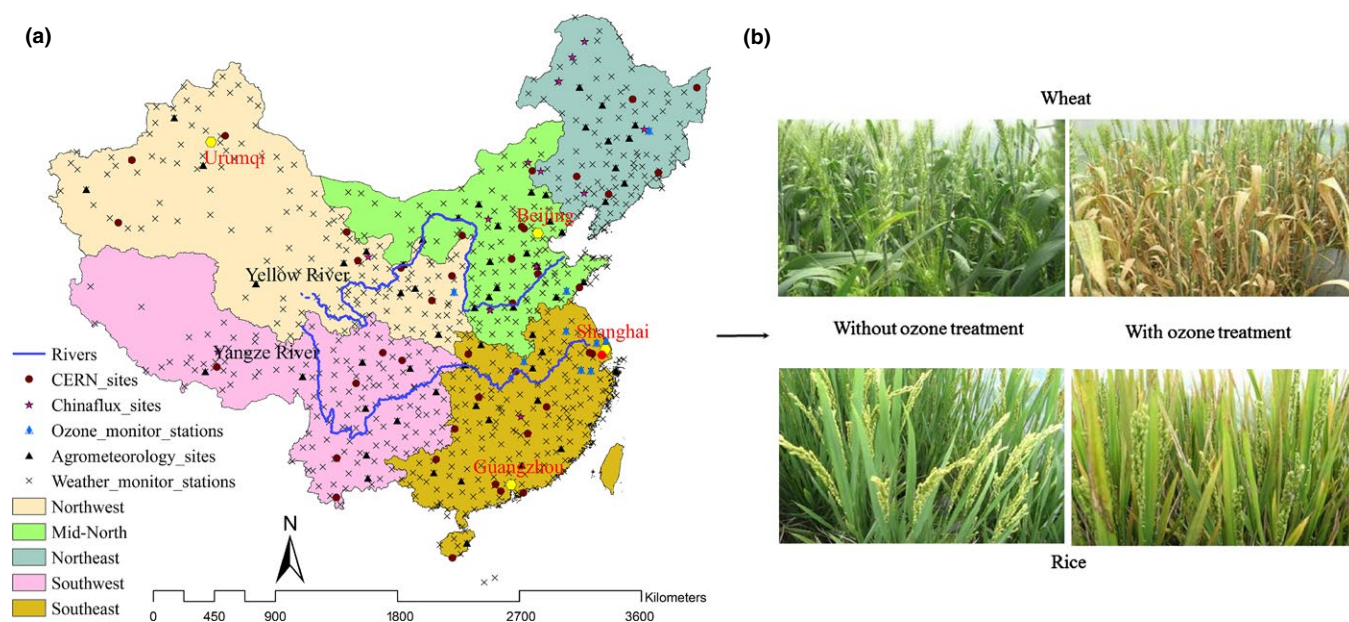
## Introduction

As the world's most populous country and second largest economy, China has been challenged to feed around 20% of the world's population with less than 7% of world's arable land. A recent report from the National Agriculture Database indicates that crop yield in China has continuously increased since 2004 thanks to intensive agriculture that involves irrigation, fertilizer application and crop genetic improvement (NBS 2013). Over the last three decades, however, China's agroecosystems have been experiencing a

complex set of multiple environmental stresses (Tian et al. 2011), which are threatening China's food supply security. Therefore, how to simultaneously achieve China's food security and environmental sustainability has been a grand challenge facing the Chinese people as well as the world (Lu et al. 2015). To reduce the increasing pressure on food security, China began to prioritize large-scale agricultural investments in Africa, Australia, and Latin America (Gale et al. 2014). China has become a major maize importer since 2009, and the world's leading soybean importer with approximately 80% of domestic soybean consumption directly coming from imports according to the Food and Agricultural Organization of the United Nations Statistical Database. However, given that China has

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**Fig. 1.** (a) Data sources for model calibration and evaluation, and input data development: (1) the stars and circles are ChinaFlux and CERN (Chinese Ecosystem Research Network) sites, respectively; (2) the black triangles are agrometeorology sites; (3) the blue triangles are available ozone ( $O_3$ ) monitoring stations for evaluating model  $O_3$  inputs; (4) the "x" are weather stations (more than 730) and (5) red solid circles show the location of field experiments of  $O_3$  pollution impacts on wheat and rice ( $31^{\circ}53' N$ ,  $121^{\circ}18' E$ , Jiaying, Zhejiang, China); (b) Pictures taken from field experiments, showing wheat and rice growth without ozone impacts (left top and bottom) and with ozone impacts (right top and bottom).

become the world's largest producer and consumer of agricultural products, the capacity of domestic crop production is of critical importance for China's food security as well as the global food market. Therefore, quantifying environmental and climate limits to crop productivity is a critical step to assess China's food supply capacity. Direct evidence from a large network of field experiments and observations (Fig. 1.) indicates that China has experienced increasing droughts (Qiu 2010) and elevated tropospheric  $O_3$  concentrations in recent decades (Felzer et al. 2005, Feng et al. 2014), which are threatening the capacity of crop production in China (Tian et al. 2011, Ren et al. 2012) (Fig. S3). Nevertheless, a quantitatively integrated assessment of drought and  $O_3$  impacts on crop production at the national level has not been thoroughly conducted.

The overall goal of this study was to assess the impacts of climate change/variability and increasing  $O_3$  concentrations on the yields of major crops (maize, rice, wheat, soybean, and others) across China during 1981–2010. We conducted this study with a process-based ecosystem model, the agricultural module of the Dynamic Land Ecosystem Model (DLEM-Ag) (Ren et al. 2011, 2012, Tian et al. 2011, 2012). The simulations were driven by spatially explicit, multiple environmental factors including climate change, tropospheric  $O_3$ , atmospheric  $CO_2$ , nitrogen deposition, and land-use and land-cover change. In addition to five factorial simulation experiments for assessing crop yield

responses to climate change, drought and increasing  $O_3$  during 1981–2010, six additional experiments were used to determine how crop production would respond to different levels of reduction or increase in  $O_3$  levels under either normal climate or drought conditions.

## Method and Data

### Model description

To achieve our goal of this study, we used an integrated approach that combined agricultural ecosystem modeling with ground and satellite observations. The Dynamic Land Ecosystem Model (DLEM) (Tian et al. 2010) has been widely used and well documented in studies highlighting the contribution of multiple environmental changes to terrestrial carbon (C), nitrogen (N), and water cycles in typical regions across the globe; and the model performance has been validated in China, USA, Asia, and North America (Tian et al. 2010, Ren et al. 2011, 2012, Chen et al. 2012, Liu et al. 2012, Lu et al. 2012, Xu et al. 2012, Zhang et al. 2012, Tao et al. 2013, Pan et al. 2015). The DLEM agricultural module (DLEM-Ag) has been developed to simulate the interactive effects of agronomic practices, land management, and multiple natural environmental factors on crop growth and biogeochemical (C, N,  $H_2O$ ) cycles in agriculture ecosystems (Ren et al. 2011, 2012, Tian et al. 2012). In particular, the agricultural

module has the capability to address the mechanisms of direct and indirect O<sub>3</sub> effects on photosynthesis, stomatal conductance, C/N allocation, etc. This module also accounts for changes in water use efficiency as influenced by changing climate, atmospheric CO<sub>2</sub>, nitrogen deposition, fertilizer/irrigation, and land use. Model representation of those processes is essential for improving our understanding of crop growth and production in response to drought and O<sub>3</sub> stresses (Cramer 2006). To better assess crop production in response to historical climate and O<sub>3</sub>, we have tested the DLEM-Ag against a large amount of available observations from this region. To reduce uncertainty in simulated results, we also used fine-resolution data sets of regional environmental monitoring to determine parameter values or improve forcing data. For example, remote sensing products and field observations have been applied to identify crop phenology and cropping systems (Fig. 1). The modeled results of crop production were compared with regional survey data and site-level observations (see Appendix S1: Figs. S2 and S3). Results show that DLEM-Ag captures both the trend and magnitude of regional responses of crop production to global environmental changes.

### Input data description

We used different sources of data from remote sensing, field observations, and statistical surveys to develop spatially explicit historical data sets for characterizing major environmental changes across the country and then assessing how such changes have affected crop growth and productivity through simulations using the DLEM-Ag (Tian et al. 2011, Ren et al. 2012). These time-series historical gridded data (10 km × 10 km) include climate change, tropospheric O<sub>3</sub>, atmospheric CO<sub>2</sub>, land-cover/land-use change (LCLUC), and land management practices (harvest, rotation, technology improvement, etc.). The input data show that O<sub>3</sub> concentration significantly increased over the entire China and that an increasing trend of drought occurred in the agricultural areas of the Mid-North, Northeast, and Southwest regions over the past three decades (Fig. 2). Additional details on these input data sets can be found in our published work (Tian et al. 2011, Ren et al. 2012; also see Fig. S3).

We examined the effects of climate change, elevated O<sub>3</sub>, and their interaction on crop production in this study. The climate effects account for seasonal and inter-annual variability and 30-year change trends during 1981–2010. The levels and trends of O<sub>3</sub> concentrations were characterized by using the O<sub>3</sub> exposure index AOT40 (Ren et al. 2007) (Figs. 2a, 3a; Appendix S1: and S3), which was calculated as the sum of the hourly exceedance above 40 ppb, for daylight hours (8 am – 8 pm) during the assumed growing season according to the methodology for O<sub>3</sub> risk assessment (UNECE 2010). To investigate the potential impacts

of increasing O<sub>3</sub> levels on crop yield, we implemented additional simulations under “what if” scenarios by using different O<sub>3</sub> levels (assumed AOT40 values) as described in *Model implementation and experiment design*.

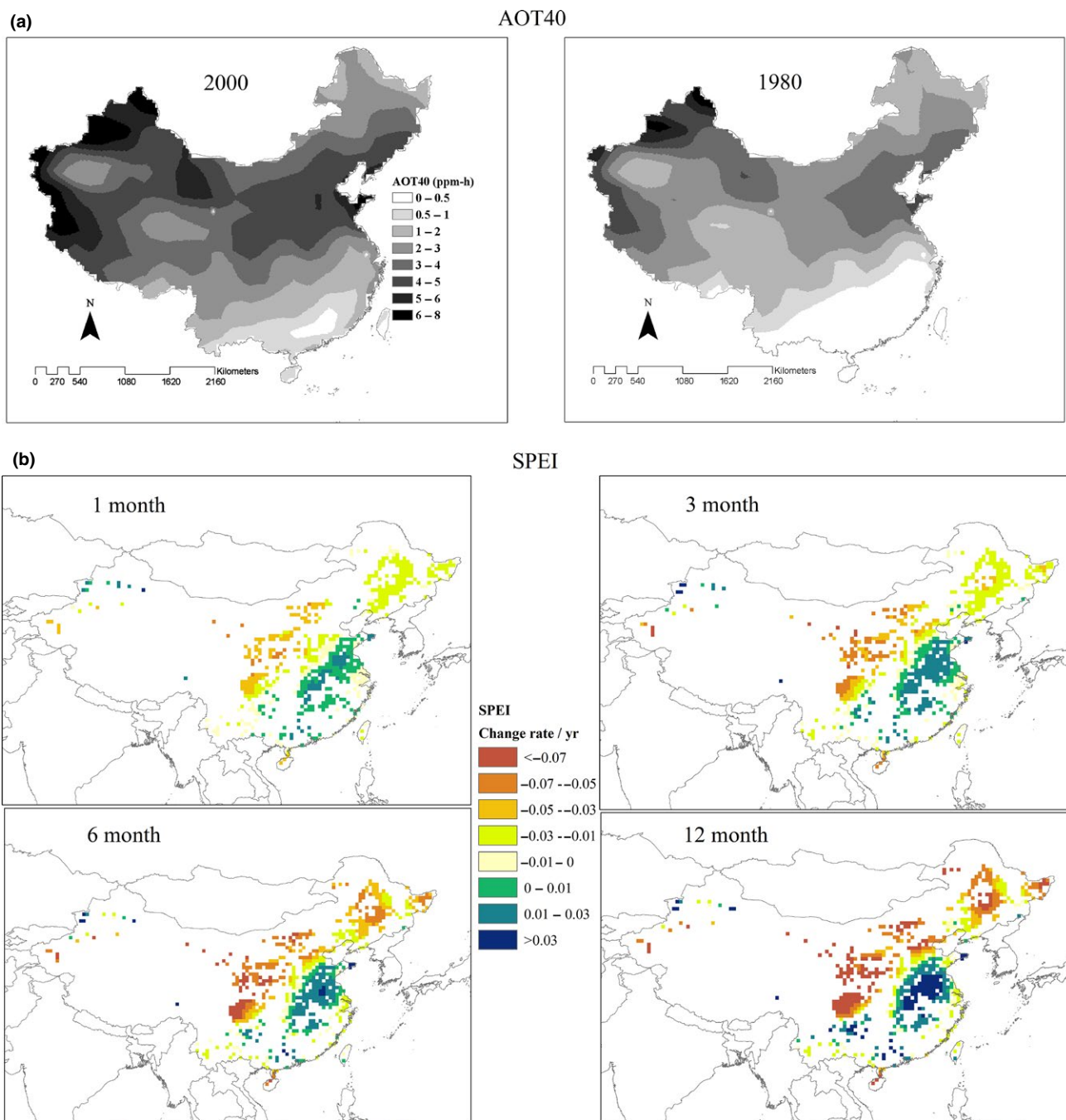
We applied the newly developed drought index, the Standardized Precipitation Evapotranspiration Index (SPEI) to identify drought years (Vicente-Serrano et al. 2010). The SPEI is based on monthly (or weekly) climatic water balance, i.e., the difference between precipitation and evapotranspiration with a log-logistic probability distribution function fitted to adjust the value. The SPEI combines the sensitivity of the Palmer drought severity index (PDSI) to changes in evaporation demand (caused by temperature fluctuations and trends) with the simplicity of calculation and multitemporal nature of the Standard Precipitation Index (SPI). We analyzed SPEI data to identify drought years and drought seasons in China during 1981–2010 (Figs. 2b, 3a; Appendix S1: Figs S3 and S4).

### Model implementation and experiment design

Eleven simulation experiments were designed to capture both the single effects of climate and its combination effects with O<sub>3</sub> on crop yield (Table 1). For the time period 1981–2010, we designed five simulation experiments: (1) Experiment I: *All combined* simulation, which considers concurrent effects of climate, tropospheric O<sub>3</sub>, atmospheric CO<sub>2</sub>, nitrogen deposition, and land-use and land-cover change; (2) Experiment II: *All combined without climate change* simulation, in which all drivers are the same as Experiment I excepting that the 30-year mean climate (1961–1990) is used for the period 1981–2010; (3) Experiment III: *All combined without climate and O<sub>3</sub>*, in which all drivers are the same as Experiment II except that O<sub>3</sub> is excluded during 1981–2010; (4) Experiment IV: *Drought only*, in which only the climate changes while O<sub>3</sub> is excluded and all other drivers remain unchanged after 1980; and (5) Experiment V: *Drought with O<sub>3</sub>*, in which both climate and O<sub>3</sub> vary over time but other drivers remain unchanged after the year 1980. The *Climate effect* is calculated as the difference between Experiment I and Experiment II, and the *Climate+O<sub>3</sub> effect* is calculated as the difference between Experiment I and Experiment III. With this approach, we captured the relative impacts of an environmental factor (direct effects plus interactive effects of this factor with other environmental factors). Experiment IV and Experiment V are used to test the sensitivity of crop yield to drought only and drought with O<sub>3</sub> for the historical period 1981–2010.

We designed four hypothetical simulation scenarios to investigate potential responses of crop yield to alterations in O<sub>3</sub> levels, –100%, –50%, +50%, and +100% of current level of AOT40 while other factors are kept unchanged in 2005. To test the potential impacts of elevated O<sub>3</sub> and severe droughts, we designed two additional simulation experiments, which are +50% and +100% of AOT40 level in the year 2005 with a drought condition similar to the





**Fig. 2.** Changes in spatial patterns of ozone index and drought index: (a) ozone index AOT40 (accumulated O<sub>3</sub> exposure over a threshold of 40 parts per billion) and (b) changing trends of 1-, 3-, 6-, and 12-month SPEI (the Standardized Precipitation Evapotranspiration Index) during 1981–2010 (per year).

year 2000. A 100% reduction in O<sub>3</sub> indicates an ideal case, in which there is zero O<sub>3</sub> damage. The O<sub>3</sub> levels after 50% reduction are comparable to that around the beginning of economic reform in China (1978). To examine crop sensitivity to O<sub>3</sub> increase, we choose an opposite case of 100% increase in O<sub>3</sub> level, which is projected to occur in the 2060s, and a 50% increase in O<sub>3</sub> concentrations, which would occur around the late 2030s under a greenhouse gases policy case scenario (Reilly et al. 1999, Felzer et al. 2005).

## Results

### Relative contributions of climate change and tropospheric O<sub>3</sub> to crop yield variability

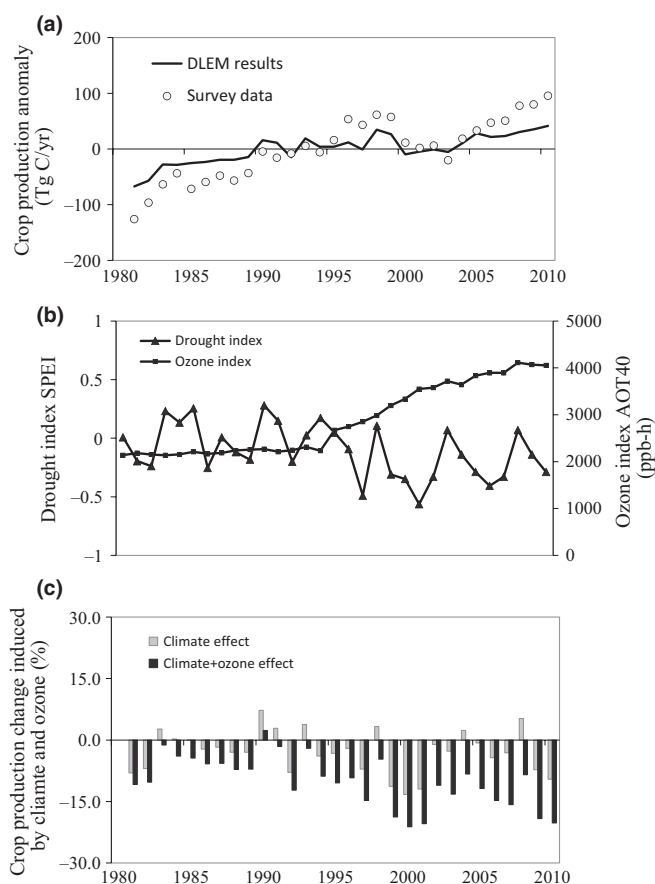
Our simulated results indicate that national crop production during 1981–2010 continuously increased as a result of the combined effects of climate, tropospheric O<sub>3</sub>, atmospheric CO<sub>2</sub>, nitrogen deposition, land-use and

land-cover change (*All combined effect*). Total crop yield continuously increase under scenarios with mean climate condition and non-O<sub>3</sub> (*Simulation2*), but show significant inter-annual variations since 1990, when considering climate variability (*Simulation1*) (Fig. 3b). This indicates that China's crop yield is highly vulnerable to climate variability and climate extremes.

To further examine the relative importance of climate variability and tropospheric O<sub>3</sub>, we quantify the *Climate+O<sub>3</sub> effect* through calculating the difference between *All combined* and *All combined without climate change and O<sub>3</sub> effect*, which demonstrates notable annual crop yield losses of  $-10.0\% \pm 6.2\%$  (mean  $\pm 1$  SD) or 55 million tons per year for the entire nation during 1981–2010, compared to the *Climate effect* experiment, in which changes in crop yield vary from  $-8.0\%$  to  $2.4\%$ . These results indicate substantial negative impacts on crop yield and the increasing risk resulting from elevated levels of O<sub>3</sub>. We found that the maximum reduction in crop yield ( $-17.5\%$ ) occurred in 2000, a year with extreme drought and relatively high O<sub>3</sub> concentrations (Fig. 3c). This finding further suggests that the comprehensive impact assessment of crop production should consider climate extreme events (e.g., droughts) and their interactive effects with concurrent environmental stressors such as tropospheric O<sub>3</sub>.

### Individual and interactive impacts of drought and tropospheric O<sub>3</sub>

Next we examined individual and combined impacts of drought and O<sub>3</sub> by excluding other factors. Based on two simulation experiments, one for drought years with O<sub>3</sub> (*Drought+O<sub>3</sub>*) and the other for drought years without O<sub>3</sub> (*Drought only*), we found that the combination of drought and O<sub>3</sub> exacerbated the effects of drought only (Fig. 4). These results indicate that the negative impacts of drought could be amplified by O<sub>3</sub> across China's cropland, in spite of the fact that O<sub>3</sub> damage is less under drought conditions due to lowered stomatal conductance. Our simulations also indicate substantial spatial variations in crop yield response to drought and O<sub>3</sub> among major cropping systems (Fig. 5). The highest reduction rate was found in the Mid-North region (MN), which has experienced more frequent droughts (Zou et al. 2005) and higher O<sub>3</sub> concentrations than other regions (Ren et al. 2007). Spring wheat was most sensitive, showing a reduction of 5.5% in extreme droughts and a reduction of 11.6% by extreme droughts with O<sub>3</sub>. We found less reduction in rice due to either drought alone or drought with O<sub>3</sub> than other crops. Southeastern China (SE), dominated by rice fields, was the least affected under the various scenarios due to fewer drought events and lower O<sub>3</sub> concentrations than other regions. Clearly, there is an important need to explore the mechanisms of interactions among climate change, O<sub>3</sub>, and other environmental factors (Long et al. 2005) in affecting crop yield across different spatial scales (Wang et al. 2007, Tao et al. 2008).



**Fig. 3.** (a) Changes in temporal patterns of the ozone pollution index AOT40 and the drought index SPEI (the Standardized Precipitation Evapotranspiration Index), calculated by the mean of multiple-scale SPEI indices (3-month, 4-month, 5-month, 6-month, 12-month, and 24-month) during 1981–2010. (b) Crop yield anomaly (Tg C/yr) derived from survey data and DLEM results of model simulation experiment (I: all combined effects). (c) Simulated effects of climate only (Climate effect) and the combination effects of climate and ozone (Climate+ozone effect) derived from simulation experiments (I: all combined effects, II: all combined without climate effect, and III: all combined without climate and O<sub>3</sub> effects). Note: all combined effects include historical changes in climate, O<sub>3</sub>, and others (land use/land cover, land management practices, CO<sub>2</sub>, and nitrogen deposition) during 1981–2010; “without climate effect” means 30-year average climate condition (1961–1990) applied in each year during the study period; “without O<sub>3</sub> effect” means O<sub>3</sub> pollution excluded.

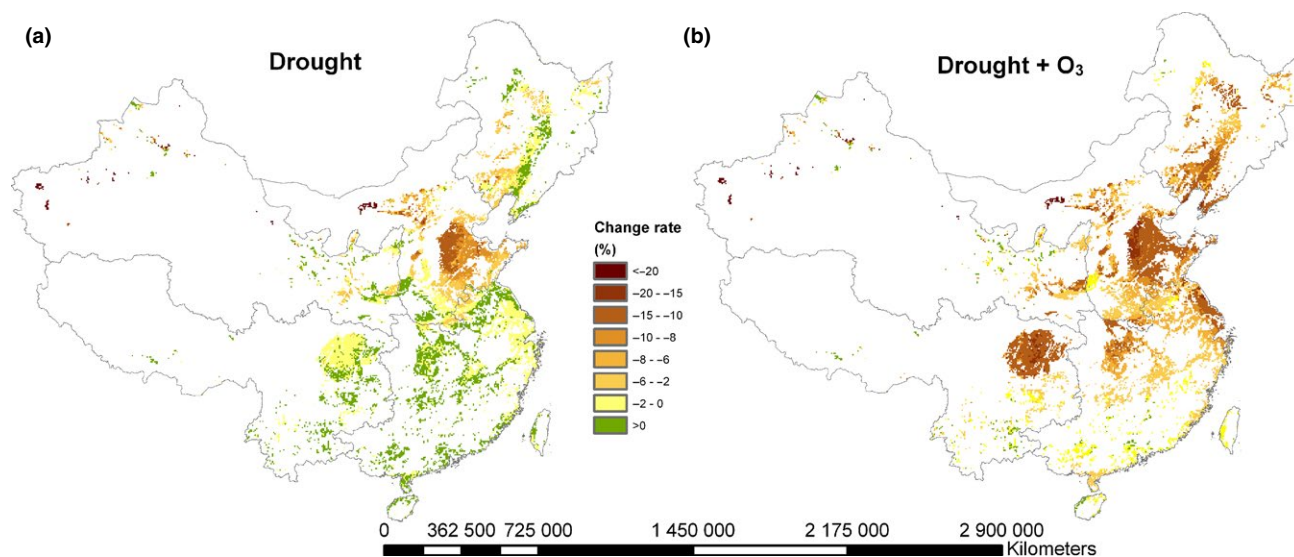
### Potential responses of crop yield to drought and tropospheric O<sub>3</sub>

To further assess potential impacts of increasing O<sub>3</sub> concentrations on China's crop yield in the future, we designed four hypothetical simulation scenarios:  $-100\%$ ,  $-50\%$ ,  $+50\%$ , and  $+100\%$  of current level of AOT40, a threshold concentration of 40 ppb O<sub>3</sub>, per hour of exposure, below which it is assumed that no plant damage will occur, while other factors were kept unchanged from 2005. Results from this sensitivity analysis (Fig. 6) suggest that China's crop yield

**Table 1.** Simulation experimental design.

	Experiments	Climate	O <sub>3</sub>	Ndep	CO <sub>2</sub>	LCLUC
1	All combined	H	H	H	H	H
2	All combined without climate change	M	H	H	H	H
3	All combined without climate change and O <sub>3</sub>	M	N	H	H	H
4	Drought only	H	N	C	C	C
5	Drought+O <sub>3</sub>	H	H	C	C	C
6	O <sub>3</sub> -100%	2005	-100%	2005	2005	2005
7	O <sub>3</sub> -50%	2005	-50%	2005	2005	2005
8	O <sub>3</sub> +50%	2005	+50%	2005	2005	2005
9	O <sub>3</sub> +100%	2005	+100%	2005	2005	2005
10	O <sub>3</sub> +100%+drought	2000	+100%	2005	2005	2005
11	O <sub>3</sub> +50%+drought	2000	+50%	2005	2005	2005

Note: H means historical period (1981–2010), C stands for no change since the year 1980, M represents a 30-yr climatic average (1961–1990), and N means no O<sub>3</sub> effects (AOT40 equals zero). LCLUC is land-cover/land-use change and Ndep stands for nitrogen deposition. We selected the year 2005 as a normal year and the year 2000 as a dry year.



**Fig. 4.** Spatial distribution of mean crop yield changes (%) in drought years (a) without O<sub>3</sub> effect (Drought) and (b) with O<sub>3</sub> effect (Drought+O<sub>3</sub>) relative to the 30-yr average. Note: drought years identified by using SPEI drought index include 1986, 1992, 1997, 1999, 2000, and 2001.

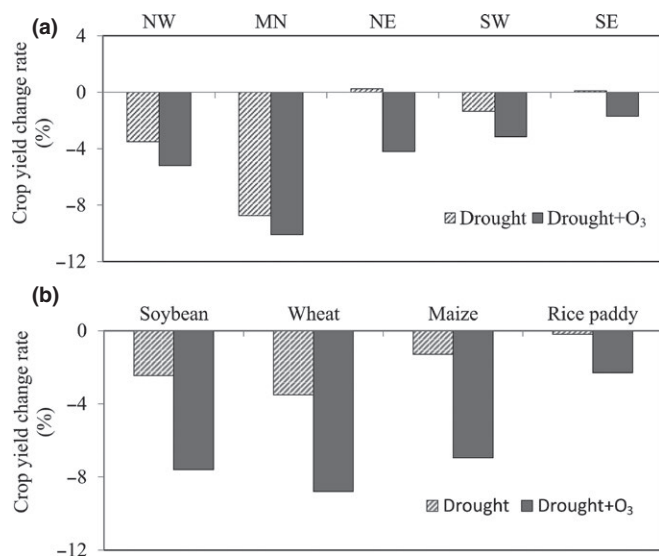
would significantly increase 5% and 10% if O<sub>3</sub> levels would be reduced by 50% and 100%, respectively. Conversely, China's crop yield would largely decrease if air quality continue to worsen, e.g., approximately 14% of crop yield would be lost if O<sub>3</sub> levels were doubled, i.e., increased by 100%, and crop yield would be reduced by 19% if doubled O<sub>3</sub> levels coincided with a drought like in the year 2000 (Fig. 6). These results imply that the nation's O<sub>3</sub> pollution level control is critical for securing crop production in coping with future frequent extreme climate conditions, e.g., droughts.

## Discussion

### The recent trend and controls of China's crop production

The simulation results derived from this study are consistent with national crop production survey data, showing a continuous increase in crop yield over recent decades (Huang et al. 2007) (Fig. 3b). Our factorial simulation experiments further indicate that this increase in crop production was primarily attributed to intensified management (e.g., fertilizer use and



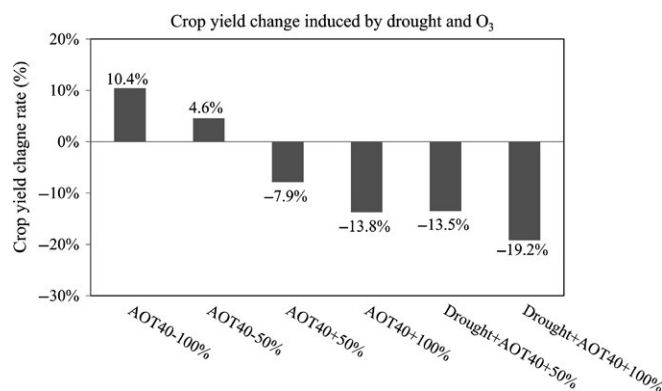


**Fig. 5.** Mean crop yield changes (%) in drought years without O<sub>3</sub> effect (Drought) and with O<sub>3</sub> effect (Drought+O<sub>3</sub>) relative to the 30-yr average in (a) five regions (Northwest: NW, Mid-North: MN, Northeast: NE, Southwest: SW, and Southeast: SE) and (b) four major crop types (soybean, wheat, maize, and rice paddy). Note: drought years identified by using SPEI drought index include 1986, 1992, 1997, 1999, 2000, and 2001.

irrigation), crop genetic improvements, and CO<sub>2</sub> fertilization effect (Ren et al. 2012, Tian et al. 2012). Further analysis indicates that precipitation was the dominant climatic variable shaping the year-to-year patterns of crop yield, while a slight increase in temperature (about 0.02°C per year) had minor impacts on national crop production in China during 1981–2010. Our results are different from a recent study which suggested that climate warming reduced the growth rate in crop yield and the climate influence was large enough to offset a significant portion of the increases in average crop yield due to technology improvement, CO<sub>2</sub> fertilization, and other factors in some countries over recent decades (Lobell et al. 2011).

### Potential mechanisms of drought and O<sub>3</sub> impacts

One mechanism that may account for additional crop yield loss from drought combined with increasing O<sub>3</sub> concentration is the complex interactions among soil moisture, water uptake, and temperature on plant photosynthesis. In drought years, both low precipitation and high temperature contribute to the decrease in soil moisture. O<sub>3</sub> injuries to leaves reduce the rate of photosynthesis and subsequently root biomass through carbon allocation favoring aboveground biomass (Fiscus et al. 2005). The reduced root biomass then decreases the water uptake capacity in low soil moisture conditions and further predisposes the adverse influences of drought on plant productivity. Another potential mechanism is that impaired stomatal closure resulting



**Fig. 6.** Potential impacts of O<sub>3</sub> reduction and increase on China's crop yield without and with a coincidence of drought condition. Note: (a) AOT40 is accumulated O<sub>3</sub> exposure over a threshold of 40 parts per billion. (b) AOT40 +100%, AOT40 +50%, AOT40 -50%, AOT40 -100% are simulation experiments with AOT40 values increased by 100% and 50% and reduced by 50% and 100% of the current level (2005).

from elevated O<sub>3</sub> exposure may cause increases in transpiration and thus decreases in soil moisture (McLaughlin et al. 2007, Wilkinson and Davies 2009), exacerbating drought stress, especially in extreme drought conditions. Some field experiments suggest that elevated O<sub>3</sub> concentrations could reduce photosynthesis due to a reduction in stomatal conductance under high O<sub>3</sub> and a decrease in both leaf and root biomass (Wittig et al. 2007), resulting in a decrease in root water uptake under drought conditions. These effects are somewhat countered by the fact that lowered stomatal conductance under drought conditions allows for less O<sub>3</sub> uptake (Felzer et al. 2007), though recent work suggests the effect of O<sub>3</sub> on stomatal conductance is less than on photosynthesis itself (Sitch et al. 2007, Lombardozzi et al. 2012a, b).

### Uncertainties and research needs

We recognize a few caveats in this study that may cause uncertainty in this regional assessment. First, input data sets can be improved with finer resolutions at the regional level. Second, it is essential to adopt multiple O<sub>3</sub> indices in future work because one popular O<sub>3</sub> index (AOT40) applied in this study may cause the bias (Booker et al. 2009). Third, additional model calibrations/validations should be conducted according to recent work in China (Feng et al. 2015). As we look to making future evaluation and prediction on climate change in conjunction with increasing O<sub>3</sub> concentrations, we recognize the need to evaluate and incorporate crop variety improvement and other adaptation strategies farmers may adopt in the face of these environmental threats. In addition, we should be aware that other rising pollutants may significantly influence crop production and should be included in an integrated assessment of food security in China. For example, crops



have been greatly affected by heavy metals and polluted soils in many regions of China (Lu et al. 2015).

### Implications for adaptation and mitigation

Our results provide several insights for designing climate change adaptation strategies regarding food security in China and globally. Global observations and modeling studies have suggested that global warming is causing more frequent and intense droughts (Dai 2013) and worsened air pollution (Felzer et al. 2005). In particular, extreme droughts and elevated O<sub>3</sub> occurring in densely populated or major crop production regions may trigger serious regional and global food crises. To protect regional and global food security, there is an urgent need to develop practical adaptation and mitigation strategies for minimizing potential adverse impacts of climate extremes on food crop production. For example, introducing more drought-tolerant and O<sub>3</sub>-tolerant cultivars may help alleviate food shortages resulting from droughts and air pollution. Moreover, our attribution analysis based on factorial experiments shows that drought-induced reduction in crop yield could be doubled if drought occurs in regions with serious air pollution. This implies that the combined effects of climate warming and other major environmental factors, such as drought and increasing O<sub>3</sub> concentration investigated in this study, should be included in policy-making strategies to promote food security. Our further “what if” analyses suggest that the reduction in O<sub>3</sub> concentration (or improving air quality) would be an effective way to increase crop yields and also alleviate the adverse effects of droughts. Therefore, improving air quality should be a core component of climate adaptation strategies. In addition, the optimized management practices should be adopted to increase water and nitrogen-use efficiency. These practices are important for minimizing NO<sub>x</sub> emission, reducing surface O<sub>3</sub> concentration, and adapting to future climate change that may result in increased water shortage and droughts.

### Conclusions

Although previous studies have examined individual impacts of either climate change or O<sub>3</sub> pollution on crop production in China, this study has made the first attempt to quantify the possible combined effects of increasing tropospheric O<sub>3</sub> and drought on crop yield at the national level in China by using a land ecosystem model inclusive of an enhanced agricultural module driven by multiple environmental factors. We found that notably varied reductions in annual crop yield (10.0 ± 6.2%) were induced by climate change/variability and tropospheric O<sub>3</sub> together in the nation of China during 1981–2010. Crop yield loss due to an increasing threat from O<sub>3</sub> and droughts since 2000 has caused serious concerns in food supply security in China. Our

quantitative investigation of crop responses to climate and O<sub>3</sub> suggests that future climate risk assessment of crop production should consider the combination effects of climate change/extremes and air pollution. Given the projected increases in severe episodic droughts and elevated O<sub>3</sub> pollution in the future, reducing air pollution would be an efficient way to secure crop production in the face of future climate change in China. Improving air quality should be a core component of climate adaptation strategies in China.

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## Supporting Information

The Appendix is available online: <http://onlinelibrary.wiley.com/doi/10.1002/ehs2.1203/supinfo>