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_3). Here we quantify the combined impacts of drought and O_3 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_3 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_3 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_3 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_3).*

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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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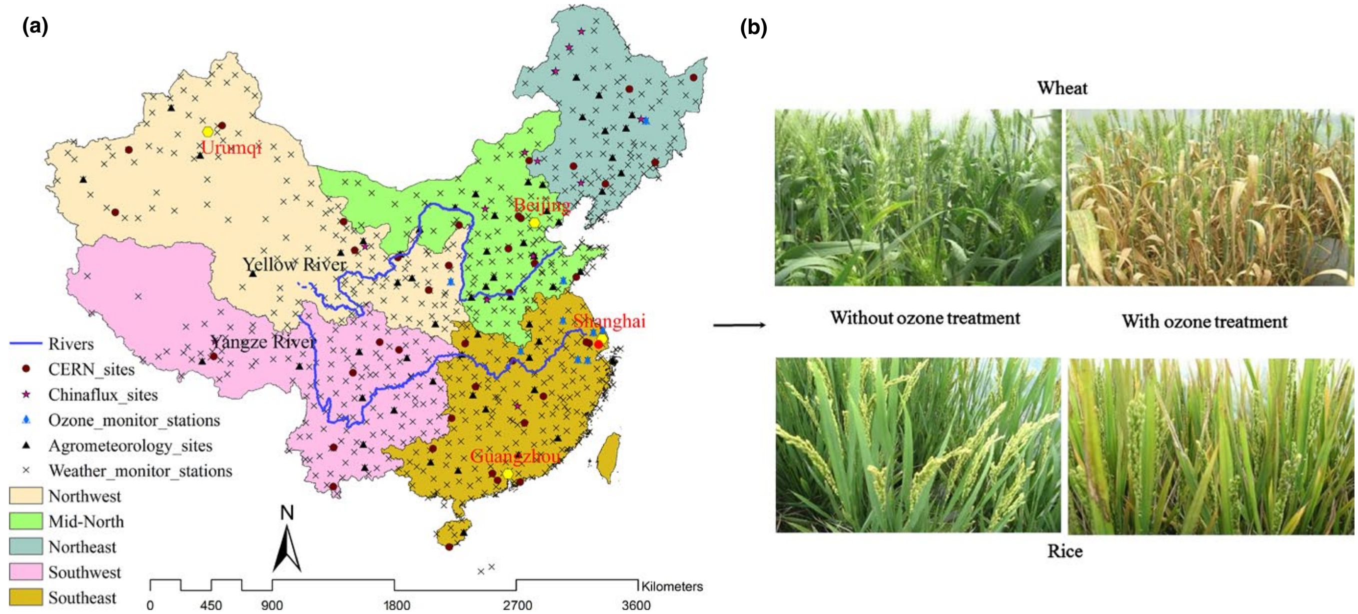

Fig. 1. (a) Data sources for model calibration and evaluation, and input data development: (1) the stars and circles are ChinaFlux and CERN (Chinese Ecosystem Research Network) sites, respectively; (2) the black triangles are agrometeorology sites; (3) the blue triangles are available ozone (O_3) monitoring 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°53′ N, 121°18′ E, Jiaxing, 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_3 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_2, 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_3 stresses (Cramer 2006). To better assess crop production in response to historical climate and O_3, 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_3, atmospheric CO_2, land-cover/land-use change (LCLUC), and land management practices (harvest, rotation, technology improvement, etc.). The input data show that O_3 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_3, 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_3 concentrations were characterized by using the O_3 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_3 risk assessment (UNECE 2010). To investigate the potential impacts of increasing O_3 levels on crop yield, we implemented additional simulations under "what if" scenarios by using different O_3 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_3 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_3, atmospheric CO_2, 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_3, in which all drivers are the same as Experiment II except that O_3 is excluded during 1981–2010; (4) Experiment IV: *Drought only*, in which only the climate changes while O_3 is excluded and all other drivers remain unchanged after 1980; and (5) Experiment V: *Drought with* O_3, in which both climate and O_3 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_3 *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_3 for the historical period 1981–2010.

We designed four hypothetical simulation scenarios to investigate potential responses of crop yield to alterations in O_3 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_3 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

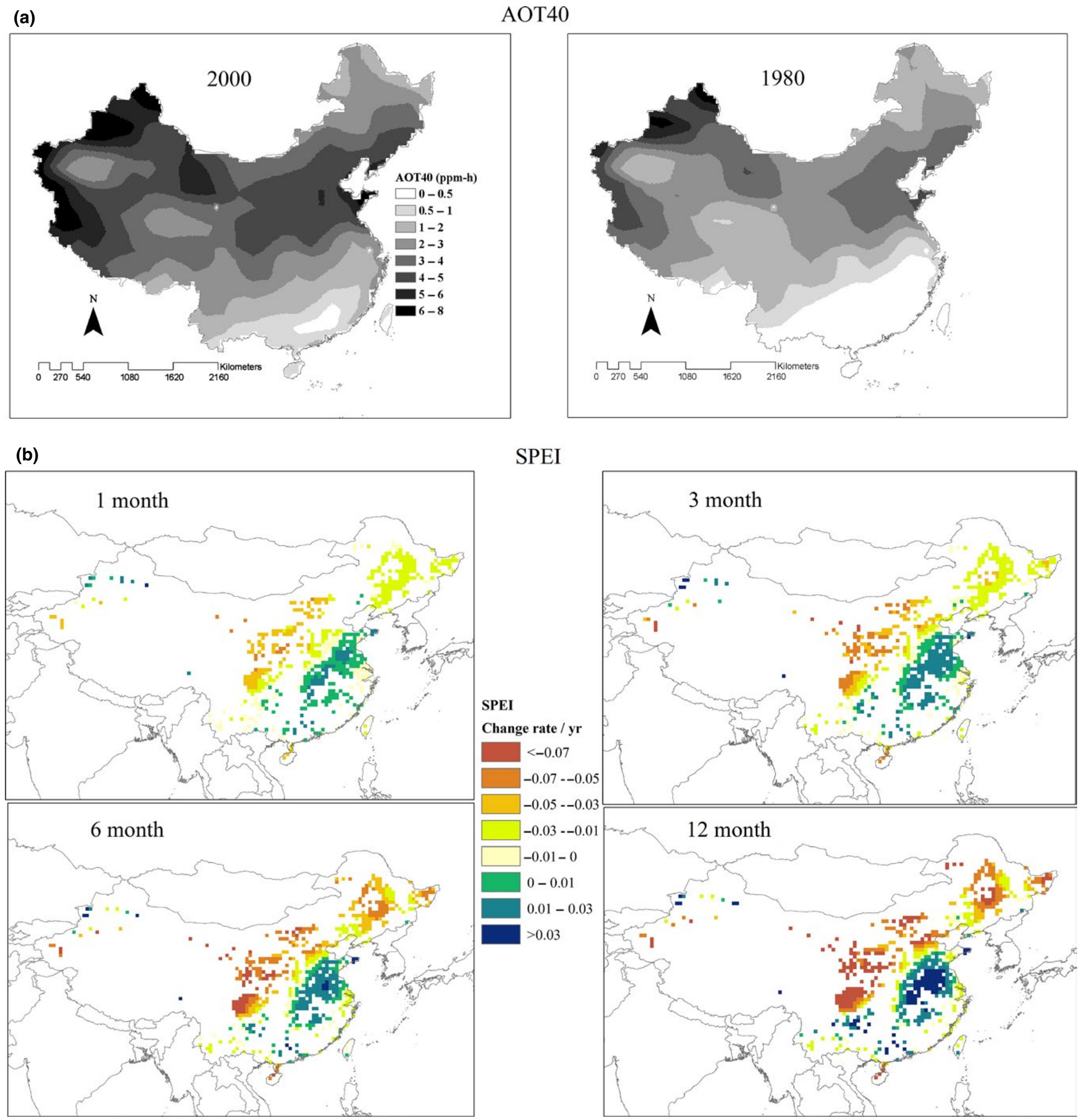

Fig. 2. Changes in spatial patterns of ozone index and drought index: (a) ozone index AOT40 (accumulated O_3 exposure over a threshold of 40 parts per billion) and (b) changing trends of 1-, 3-, 6-, and 12-month SPEI (the Standardized Precipitation Evapotranspiration Index) during 1981–2010 (per year).

year 2000. A 100% reduction in O_3 indicates an ideal case, in which there is zero O_3 damage. The O_3 levels after 50% reduction are comparable to that around the beginning of economic reform in China (1978). To examine crop sensitivity to O_3 increase, we choose an opposite case of 100% increase in O_3 level, which is projected to occur in the 2060s, and a 50% increase in O_3 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_3 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_3, atmospheric CO_2, 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_3 (*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_3, we quantify the *Climate+O_3 effect* through calculating the difference between *All combined* and *All combined without climate change and O_3 effect*, which demonstrates notable annual crop yield losses of −10.0% ± 6.2% (mean ± 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_3. We found that the maximum reduction in crop yield (−17.5%) occurred in 2000, a year with extreme drought and relatively high O_3 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_3.

Individual and interactive impacts of drought and tropospheric O_3

Next we examined individual and combined impacts of drought and O_3 by excluding other factors. Based on two simulation experiments, one for drought years with O_3 (*Drought+O_3*) and the other for drought years without O_3 (*Drought only*), we found that the combination of drought and O_3 exacerbated the effects of drought only (Fig. 4.). These results indicate that the negative impacts of drought could be amplified by O_3 across China's cropland, in spite of the fact that O_3 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_3 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_3 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_3. We found less reduction in rice due to either drought alone or drought with O_3 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_3 concentrations than other regions. Clearly, there is an important need to explore the mechanisms of interactions among climate change, O_3, and other environmental factors (Long et al. 2005) in affecting crop yield across different spatial scales (Wang et al. 2007, Tao et al. 2008).

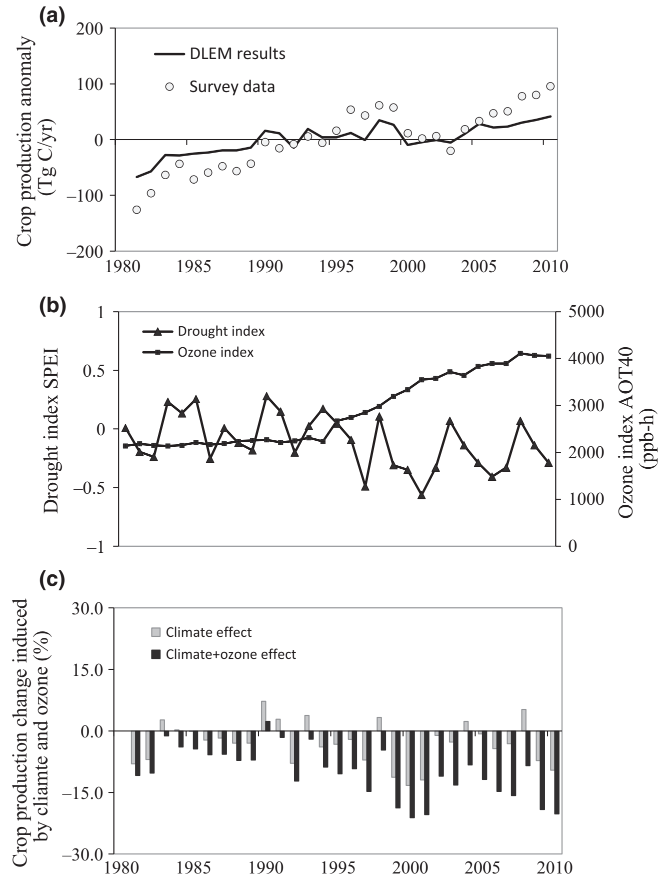

Fig. 3. (a) Changes in temporal patterns of the ozone pollution index AOT40 and the drought index SPEI (the Standardized Precipitation Evapotranspiration Index), calculated by the mean of multiple-scale SPEI indices (3-month, 4-month, 5-month, 6-month, 12-month, and 24-month) during 1981–2010. (b) Crop 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_3 effects). Note: all combined effects include historical changes in climate, O_3, and others (land use/land cover, land management practices, CO_2, 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_3 effect" means O_3 pollution excluded.

Potential responses of crop yield to drought and tropospheric O_3

To further assess potential impacts of increasing O_3 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_3, 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_3	Ndep	CO_2	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_3	M	N	H	H	H
4	Drought only	H	N	C	C	C
5	Drought+O_3	H	H	C	C	C
6	O_3–100%	2005	−100%	2005	2005	2005
7	O_3–50%	2005	−50%	2005	2005	2005
8	O_3+50%	2005	+50%	2005	2005	2005
9	O_3+100%	2005	+100%	2005	2005	2005
10	O_3+100%+drought	2000	+100%	2005	2005	2005
11	O_3+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_3 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.

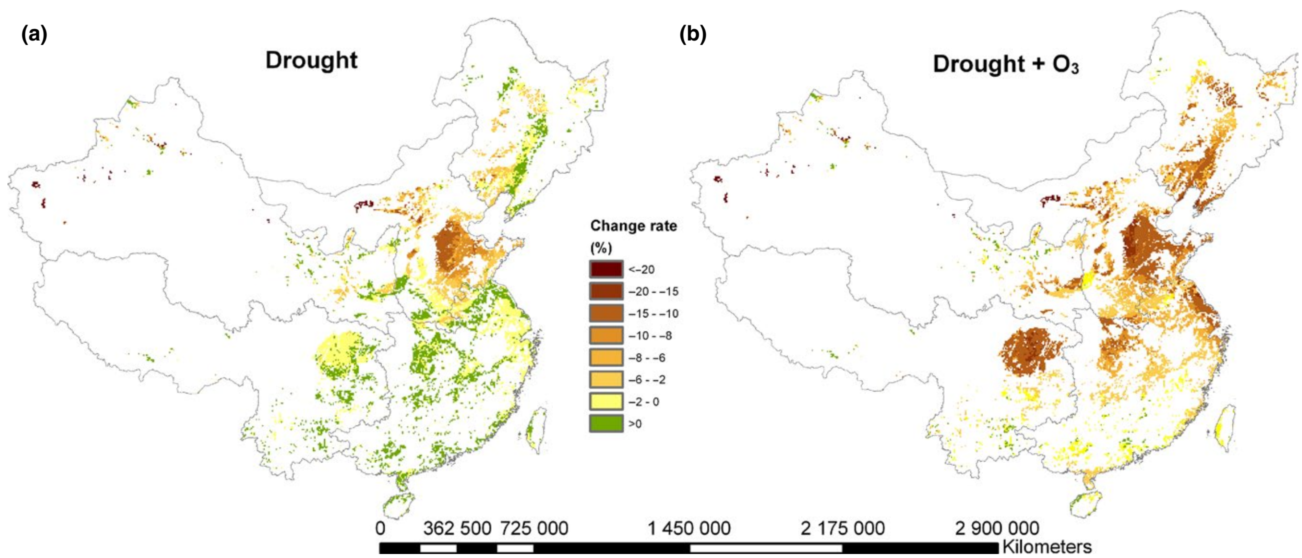

Fig. 4. Spatial distribution of mean crop yield changes (%) in drought years (a) without O_3 effect (Drought) and (b) with O_3 effect (Drought+O_3) relative to the 30-yr average. Note: drought years identified by using SPEI drought index include 1986, 1992, 1997, 1999, 2000, and 2001.

would significantly increase 5% and 10% if O_3 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_3 levels were doubled, i.e., increased by 100%, and crop yield would be reduced by 19% if doubled O_3 levels coincided with a drought like in the year 2000 (Fig. 6). These results imply that the nation's O_3 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

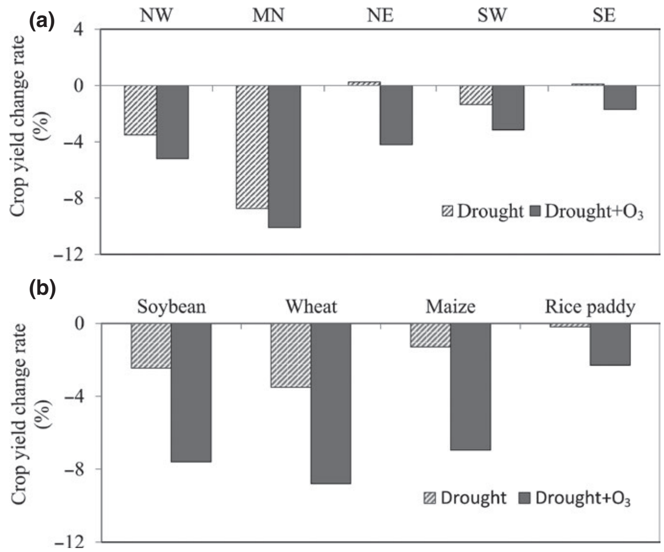

Fig. 5. Mean crop yield changes (%) in drought years without O_3 effect (Drought) and with O_3 effect (Drought+O_3) relative to the 30-yr average in (a) five regions (Northwest: NW, Mid-North: MN, Northeast: NE, Southwest: SW, and Southeast: SE) and (b) four major crop types (soybean, wheat, maize, and rice paddy). Note: drought years identified by using SPEI drought index include 1986, 1992, 1997, 1999, 2000, and 2001.

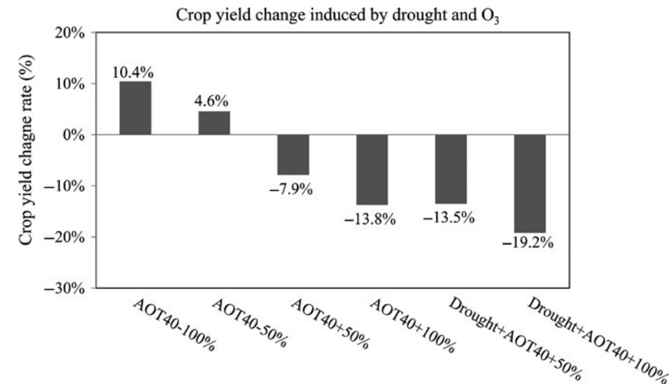

Fig. 6. Potential impacts of O_3 reduction and increase on China's crop yield without and with a coincidence of drought condition. Note: (a) AOT40 is accumulated O_3 exposure over a threshold of 40 parts per billion. (b) AOT40 +100%, AOT40 +50%, AOT40 −50%, AOT40 −100% are simulation experiments with AOT40 values increased by 100% and 50% and reduced by 50% and 100% of the current level (2005).

irrigation), crop genetic improvements, and CO_2 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_2 fertilization, and other factors in some countries over recent decades (Lobell et al. 2011).

Potential mechanisms of drought and O_3 impacts

One mechanism that may account for additional crop yield loss from drought combined with increasing O_3 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_3 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 from elevated O_3 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_3 concentrations could reduce photosynthesis due to a reduction in stomatal conductance under high O_3 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_3 uptake (Felzer et al. 2007), though recent work suggests the effect of O_3 on stomatal conductance is less than on photosynthesis itself (Sitch et al. 2007, Lombardozzi et al. 2012*a*, *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_3 indices in future work because one popular O_3 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_3 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_3 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_3-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_3 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_3 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_x emission, reducing surface O_3 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_3 pollution on crop production in China, this study has made the first attempt to quantify the possible combined effects of increasing tropospheric O_3 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_3 together in the nation of China during 1981–2010. Crop yield loss due to an increasing threat from O_3 and droughts since 2000 has caused serious concerns in food supply security in China. Our quantitative investigation of crop responses to climate and O_3 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_3 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.

Acknowledgments

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Supporting Information

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