Surface Ozone Change in China from 2010 to 2017 and its Impact on Crop Yield

by

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Executive Summary

Ambient Ozone ($O_3$) exposure is considered to impose negative impacts on plants and crops. In this study, we tracked the surface $O_3$ in China from 2010 to 2017 and performed a comprehensive estimation on the crop yield losses attribute to surface $O_3$. Spatial and temporal distribution of relative yield loss and crop production loss was calculated using AOT40 metrics (hourly ozone concentration over a threshold of 0.04 ppm h over the growing season), and further the associated economic loss was estimated incorporating the crop purchase price. Relative yield and production loss of Wheat, Early and Late Rice, North and South Maize, and Soybean, are evaluated in this project.

In the first part of this paper, I provided some background information on tropospheric ozone and its concentration change in China. I simply analyzed China’s emission control policy and presented some literature review on ozone-induced crop production loss.

In the methodology part, I introduced the dataset and major matrixes adopted in this research. In the research, AOT40 was adopted as the metric to assess ozone concentration while the Relative Yield rate was calculated based on the ozone-expose functions associated to AOT40 levels during the crops growing season. Incorporating crop production data with relative yield loss, I further calculated the Crop production loss and associated economic loss.

Our results show that from 2010 to 2017, national average AOT40 level ranges from 44 ppm h in 2010 to 71 ppm h in 2014. By using concentration response function and calculating the crops relative yields, including wheat, rice, maize and soybean from surface ozone, we found that average $O_3$ induced crop yield loss were around 44.67 million Mt, 44.74 million Mt, 7.41 million Mt, and 0.38 million Mt individually, inducing average economic loss of $15.76Billion, $20.33Billion, $0.58 Billion, and $0.29Billion accordingly.

As most previous researches focus on the ozone trend only instead of its effect on crop production loss, and studies exploring the influence of ozone concentration on crop yield are mostly at the global level, or developed regions which might cover up the regional differentiation within the country, this project conducted a comprehensive analysis ozone-induce crop yield loss and the agricultural costs of four major crops in China. Our results provided quantitative estimation on crop yield loss and its economic cost from ambient ozone concentration and improved the understanding of crop and spatial sensitivity to ozone impact.

This project makes several key points and recommendations:
From 2010 to 2017, O₃ concertation in China reveals to increase under stringent emission control policy, which could be attributed to the imbalanced policy control on ozone precursors (policy control preference on NOₓ). Also, efficiently control on particulate matters (PM2.5 and PM10) might boost photolysis rates during the formation of ozone. Crop Production Loss for all four major crops have increased and hotspots are observed in major crop production areas (the North China Plain for Wheat & Maize, the Yangtze Plain for Rice, the Northeast China Plain for Soybean). Economics loss increased with CPL and Crop Purchase Price. For Maize, Soybean, and Wheat, the purchase price varies and peaks in year 2014 and 2015. The peak of crop price matched to the peak of CPL and exaggerated economic losses induced by ozone concentration change.

Abstract
Ambient Ozone (O₃) exposure is considered to impose negative impacts on plants and crops. In this study, we performed a comprehensive estimation on the crop yield losses attribute to surface O₃ in China from 2010 to 2017 applying the model predicted ambient ozone concertation across China. Spatial and temporal distribution of relative yield loss and crop production loss was calculated using AOT40 metrics (hourly ozone concentration over a threshold of 0.04 ppm h over the growing season). Our results show that from 2010 to 2017, national average AOT40 level ranges from 44 ppm h in 2010 to 71 ppm h in 2014. By using concentration response function, we then calculated the crops relative yields, including wheat, rice, maize and soybean from surface ozone, and found that average O₃ induced crop yield loss were around 44.67 million Mt, 44.74 million Mt, 7.41 million Mt, and 0.38 million Mt individually, inducing average economic loss of $15.76 Billion, $20.33 Billion, $0.58 Billion, and $0.29 Billion accordingly. Our results provided quantitative estimation on crop yield loss and its economic cost from ambient ozone concentration and improved the understanding of crop and spatial sensitivity to ozone impact.

1. Introduction
Tropospheric ozone, as a secondary pollutant of high concerned, is a type of air pollution that could hurt both human and vegetation health (Van Dingenen et al., 2009; Booker et al., 2009; Brauer et al., 2013). Since the 19th century, rapid industrialization and urbanization have elevated the background O₃ concentration of the Norther Hemisphere significantly (The Royal Society, 2008). In the past few decades, the strong linkage between fossil fuel usage and economic growth
boosted emissions of ozone precursors in China (Aunan et al., 2000). The rapidly increase of ozone concentrations in China has been leading to emerging concerns (Lu et al., 2018, 2020). As a greenhouse gas that is not directly emitted by human activities, tropospheric ozone is mainly generated from photochemical oxidation of volatile organic compounds (VOC), carbon monoxide or methane and of NOx in the presence of sunlight (Atkinson, 2000; Lu et al., 2018). The core of ozone concentration control is to limit the emission of these two groups of precursors. Since 2010, due to the severe fine particulate matter (PM$_{2.5}$) pollution in China, the Chinese government commenced to adopt stringent emission and pollution monitoring and control policy (Zhang et al., 2016). In recent years, the ambient air pollution monitor records indicate that while the PM$_{2.5}$ and NOx pollution are controlled efficiently, the ozone concentration in China still reveals a tendency of increasing (Wang et al., 2019; Li et al., 2018 & 2019; Lu et al., 2020). Studies on observational emission data in eastern China also indicate that, from 2012 to 2016, NOx emission in this region has decreased over 25% (Wang et al., 2019). Conversely, from 2010 to 2017, anthropogenic emission of VOC was estimated to have increased by 11% due to the lack of effective emission control measurements (Zheng et al., 2018).

As indicated in many biological and ecological studies, high ozone concentration can seriously damage vegetation and substantially impair crop yield, which also derives tremendous economic costs and threat to food security (Krupa et al., 1998; Mills et al., 2007; Lin et al., 2018). Based on different filed-based concetration-response matrix, for year 2000, ambient ozone exposure induced crop yield to reduce by 3.9%-15% for wheat, 2.2% -5.5% for maize, and 8.5%-14.0% for soybeans, with global crop production loss of 79 -121 million metric tons (Avnery et al., 2012; Tang et al., 2013). For Eastern Asia, in 2000, ozone-induced maize reduction is around 3.8%, wheat yield reduction averages around 17%, and soybean reduction as high as 21% (Van Dingenen et al., 2009; Avnery et al., 2012; Tang et al., 2013; Mills et al, 2018). Throughout China specifically, by 2020, AOT40-based maize production was projected to be decreased by around 7.2%, wheat (for winter and spring wheat) production loss was estimated to be 13.4%- 29.3%, soybean reduction to be around 18%-21% (Aunan et al., 2000; Tang et at., 2013; Feng et al., 2015).

At present, most researches focus on the ozone trend only instead of its effect on crop production loss. Studies exploring the influence of ozone concentration on crop yield are mostly at the global level, or developed regions while assessment still maintains on country level which might cover up the regional differentiation within the country (Zhao et al. 2017; Rosenzweig et al. 2014). This
The project is going to focus on the ozone-exposure impact analysis in China to assess the crop yield losses and the integrated economic costs. The study aims to present a comprehensive analysis on ozone-induce crop yield loss and the agricultural costs from ozone pollution. Such analysis is expected to provide scientific support to policy-makers for their decision making.

2. Materials and Methods:

2.1 Dataset

The hourly ozone concentration adopted in this paper covered the whole terrestrial region of China were simulated by using a state-of-the-art global chemistry model (CAM_Chem) and regridded to 0.5 degree by 0.5 degree. The anthropogenic emissions in China from 2010 to 2017 are from Multi-resolution Emission Inventory (MEIC) which were developed by Tsinghua University in China. The emissions outside China are from Community Emissions Data System (CEDS) which were prepared by the Pacific Northwest National Lab (PNNL) for the Coupled Model Intercomparison Project Phase 6 (CMIP6) experiments. Hourly surface ozone dataset was saved from 2010 to 2017 from the model simulation.

Comparison dataset used in this project includes hourly ozone concentration of China from 2010 to 2017, which were downloaded from National Environmental Monitoring Center (CNEMC) Network (http://106.37.208.233:20035/). It collects at least 100 million environmental monitoring data from 1497 established air quality monitoring stations annually for national environmental quality assessment.

Crop production data for Wheat, Rice, Maize and Soybean, is developed by Dingenen et al. (2009) from USDA national and regional production numbers and Agro-Ecological Zones suitability index. It contains global crop production data in 1000 t with distribution of 1 degree × 1 degree. Crop production was held to be consistent from 2010 to 2017.


2.2 Ozone crop metrics

In order to assess the influence of ozone concentration on crop yield, many different crop-ozone matrixes are adopted to measure the chronic ozone exposure risk of vegetation (Wang and Mauzerall, 2004; Van Dingenen et al., 2009). In this project, we adopted AOT40 as the metric to
assess ozone concentration. AOT40 counts the accumulated ozone exposure concentration over the threshold of 40 ppm. AOT40 is one of the wildly adopted metrics in crop yield assessment. By counting concentration over 40ppbv, AOT40 is able to sensitively capture the influence of extremely high ozone concentration (Van Dingenen et al., 2009; Hollaway et al., 2012). In a synthesis study by Mills et al. (2007), the AOT40 has a statistically significant relationship with many crops.

\[ AOT40 = \sum_{i=1}^{n} ([O_3]_i - 0.04), \text{for } [O_3]_i \geq 0.04 \text{ ppm} \quad (1) \]

In the AOT40 function (1), \([O_3]_i\) means the hourly ozone concentration level during daylight hours (8:00am – 7:59pm, GMT+8) (Van Dingenen et al., 2009); \(n\) is the total hours of growing season which was counted as the 3-month harvest season based on the crop calendar (Lin et al. 2018), or 75 days composed by 44 days and 31 days before and after the anthesis dates (Feng et al., 2017). The ozone concentration level was simulated from the surface ozone concentration.

### 2.3 Relative Yield and Relative Yield Loss

In this project, we focused on four major crops, wheat, rice (including double Early Rice and Late Rice), maize (North and South), and soybean, to analyze their yield responses to ozone exposure. Previous filed studies provide various crop-sensitivity functions on global or regional scales. In this project, relative yield (RY) was calculated based on the exposure-response function provided by Mills et al. (2007) (Table 1), where RY is in % and AOT 40 is in ppm h.

Since the ozone-expose functions are indicated by the accumulation of ozone concentration over crops’ growing season, which is usually a period of 3 months (Dingenen et al., 2009). Growing seasons for Wheat, Rice, Maize and Soybeans are acquired from USDA Major World Crop Areas and Climate Profiles (MWCACCP), and the Food and Agriculture Organization of the United Nation (FAO) (Lin et. al, 2018). Ozone-crop matrixes for Rice and Maize are consistent for Early and Late Rice, and South and North Maize, but differentiated in growing seasons which affect accumulated AOT40 levels (Table 1).

<table>
<thead>
<tr>
<th>Crops</th>
<th>Response Function</th>
<th>Growing Season</th>
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<tbody>
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Table 1. Crop-yield and Ozone response function
<table>
<thead>
<tr>
<th>Crop</th>
<th>Relative Yield Equation</th>
<th>Growth Period</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wheat</td>
<td>( R_Y = -0.0016 \times AOT_{40} + 0.99 )</td>
<td>MAR, APR, MAY ( (AOT_{40} ≤ 40) )</td>
</tr>
<tr>
<td>Rice</td>
<td>( R_Y = -0.0039 \times AOT_{40} + 0.94 )</td>
<td>MAY, JUN, JULY (Double Early Rice), SEP, OCT, NOV (Double Late Rice)</td>
</tr>
<tr>
<td>Maize*</td>
<td>( R_Y = -0.0036 \times AOT_{40} + 1.02 )</td>
<td>JUNE, JULY, AUG. (North Maize), AUG, SEP, OCT. (South Maize)</td>
</tr>
<tr>
<td>Soybean</td>
<td>( R_Y = -0.0116 \times x + 1.120 )</td>
<td>JUNE, JULY, AUG.</td>
</tr>
</tbody>
</table>

*North maize is considered to grow in northern provinces, while South Maize are in southern provinces only.

Based on the Relative Yield, the relative yield loss (RYL) could be calculated as function (2).

\[
R_{YL_i} = 1 - R_Y_i \quad (2)
\]

### 2.4 Crop Production Losses and Associated Economics Costs

For further integrated agricultural production loss assessment, the Crop Production Losses (CPL) can be calculated and then evaluate the overall economic losses (EL) (Dingenen et al., 2009; Wang and Mauzerall, 2004; Avnery et al., 2011) (Function (3)).

\[
CPL_i = \frac{R_{YL_i}}{1 - R_{YL_i}} \times CP_i \quad (3)
\]

- \( CPL_i \): Crop Production Loss in grid \( i \), Mt

In function (3), \( CP_i \) is the actual crop production of pixel \( i \) of the same year. Through integrating the \( CPL_i \) up, the national CPL of that year can be obtained. Average Relative Crop Production Loss is further calculated based on CPL and CP to identify how much the crop production loss takes in total crop production (Function (4)). Economics loss is quantified by multiplying CPL with crops’ national market price (Function (5)).

\[
ARYL_i = \frac{CPL_i}{CP_i + CPL_i} \times 100\% \quad (4)
\]

- \( ARYL_i \): Average Relative Yield Loss in grid \( i \), %

\[
EC_p = CPL_p \times Crop\ Price_p \quad (5)
\]

- \( EC_p \): Economic Cost of crop \( p \), $
- \( Crop\ Price_p \): Crop Production of crop \( p \), $/Mt
3. Results and Discussion

3.1 Temporal and Spatial Distribution of Ozone Concentration Change

Figure 1 plotted China’s annual accumulated ozone concentration over 40 ppm h (AOT40) from 2010 to 2017, which indicated that under a series stringent emission policy, total ozone emission in China was monitored to increase for few years with a graduate decrease after 2014. The annual average ozone concentration in 2014 was around 70 ppm h. The highest three annual average concentrations were identified in Xizang (91 ppm for 2014), Qinghai (83 ppm for 2014) and Tianjing (84 ppm for 2014).

The spatial distribution of annual average AOT40 (Fig S1) from 2010 to 2017 revealed a higher concentration level in the west, and lower values in the South. A hotspot was identified in Beijing-Tianjin-Hebei area with a horizontal extension to the south of Liaoning and Shanxi provinces, and a southward extension to the Shanghai-Nanjing-Hangzhou Economic Zone. Most provinces have annual mean ozone concentration level peaked in 2014. Ningxia (increased by 42.85 ppm), Gansu (increased by 41 ppm), and Tianjin (increased by 40.37 ppm) ranked top three in annual mean concentration change from 2010 to 2017.

3.2. Growing-Season Ozone Concentration for Cropland

3.2.1. Wheat

During the growing season of Wheat (March, April and May), the spatial pattern of AOT40 revealed to be higher in the Tibet Plateau and part of the Yangtze Plain while low AOT40 level was identified in the Southern such as Hainan, Guangdong and Guangxi. Part of the Xinjiang Province also reveals low in growing season ozone concentration. From 2010 to 2017, average
AOT40 level during growing season of wheat ranges from 12.98 ppm h (year 2010) to 28.28 ppm h in 2014 and has similar trend to the yearly averaged AOT40 level in Fig 1. When translate the growing season ozone concentration to RYL (Figure S2), the RYL value for 33 provinces and regions from 2010 to 2017 ranges from 10.24% (Beijing of 2011) to 59.57% (Xizang in 2012). Coherent to the spatial patterner of AOT40, higher RYL values are observed in Xizang (8-year-average RYL of 50.44%), Yunnan (42.67%), Qinghai (39.88%), Sichuan (39.44%), and Anhui (37.06%). Lowest average values are observed in Southern Provinces including Hainan (8-year-average RYL of 15.63%), Guangdong (20.56%), and Guangxi (23.52%).

3.2.2. Rice (Double Early Rice and Late Rice)
Spatial distribution of AOT40 during the growing season of Early Rice (May, June, July) shows low ozone concentrations in the southern areas including Guangxi, Guangdong, Taiwan and Hainan. Ozone concentration hotspot is identified on the North China Plain (Tianjin, Hebei, and Beijing), followed by high values in the Northeast China Plain and the Yangtze Plain. From 2010 to 2017, average AOT40 values range in 2.35 (Hainan, 2010) - 45.05 ppm h (Tianjin, 2015). Average AOT40 during growing season of Early Rice across the whole country increases from 18.73 ppm h in 2010 and peaks in 2014 at 22.57 ppm h. RYL of Early Rice also implies this spatial distribution (Figure S3) of growing season AOT40. Tianjin suffered the highest 8-year-average RYL of 21.19% (range 17.81%-23.57% from 2010 to 2017), followed by Hebei of 19.84% (18.03% - 21.17%), Beijing of 19.74% (17.76%-21.34%), Shanxi 19.30% (18.56% - 20.38%), and Liaoning 18.44% (17.02% - 19.73%). Southern regions including Hainan (8-year-average RYL of 7.46%), Taiwan (7.94%) and Guangdong (8.72%) reveal low RYL values nationally. RYLs for Early Rice reveals increasing trend from 2010 to 2017 and peaks in 2014 or 2015 for most provinces.

Different from the spatial distribution of Early Rice, during growing season of Late Rice (SEP, OCT, NOV), high value of ozone concentration is observed in the Tibet Plateau and few hotspots are identified in the Southeastern area. AOT40 level during this period ranges from 2.18 ppm h (Heilongjiang of 2012) to 20.18 ppm h (Xizang in 2012) which is lower than the AOT40 of Early Rice. From 2010 to 2018, the highest ozone exposure levels for Late Rice are observed in Xizang with 8-year-mean AOT40 of 17.67 ppm h, followed by Fujian, Jiangxi, Guangdong, and Anhui with average AOT40 over 12.5 ppm h.
Consistently, in RYL based on AOT40, from 2010 to 2017, areas with RYLs > 10% expand from the Tibet Plateau and southeastern China to the Central and Southwest provinces including (Qinghai, Sichuan, and Hubei). Average RYLs of each 33 provinces range from 7% to 14%. Areas in Anhui, Zhejiang and Fujian are observed to have RYLs peaks over 12.5%.

3.2.3. North Maize
Growing season average AOT40 levels for North Maize (JUNE, JULY, AUG) are observed to have similar spatial distribution pattern to the Early Rice. Hotspots of ozone concentration are identified in the North China plain. Top 5 provinces or regions with 8-year-average AOT40 are Tianjin (41.60 ppm h), Beijing (36.54 ppm h), Hebei (36.54 ppm h), Shanxi (33.82 ppm h), and Liaoning (31.92 ppm h). Southern and Western China has lower AOT40 levels during growing season of North Maize. From 2010 to 2018, North Maize suffered from increasing ozone conventions with a slight drop in 2012 and following peaks in 2014.

RYLs of North Maize show the corresponding patterns (Fig 2S). Province averaged RYLs range from 0 to 15.53%. Southern provinces with low AOT40 reveal 0 RYLs for North Maize while hotspot appears in areas of Beijing and Hebei in 2010 with RYL > 16%. Overall, areas with RYL > 8% concentrate in the North China Plain.

3.2.4. South Maize
Average AOT40 values during South Maize growing season (AUG, SEP, OCT) is lower than that for North Maize. From 2010 to 2017, province average AOT40 level ranges from 2.5 ppm h (Yunnan, 2010) to 28.27 ppm h (Tianjin, 2015) during from August to October. National averaged AOT40 value increase from 11.03 ppm h in 2010 and peaks in 2014 at 16.18 ppm h.

Based on linear ozone exposure function of AOT40, average RYL values for each province reveals similar patterns. From 2010 to 2017, national average RYL ranges from 0 to 8.18%. From 2013 to 2015, the North China Plain reveals RYL > 6% and a hotspot of RYL > 8% is observed in Tianjin in 2015.

3.2.5. Soybean
Soybean has the same growing season to the North Maize (JUNE JULY AUG) which reveals the same growing season AOT40 spatially and temporally. When the RYL is expressed by the soybean-ozone exposure matrix, high RYL values are observed in the North China plain and the Northeast China Plain where is the major producing area of Soybean. From 2010 to 2017, province mean RYL range from 0 to 44.5%. National mean RYL increase from 10.47% and reveals peaks
in 2014 at 12.96%. Hotspots of RYL > 42% was identified in Beijing-Tianjin-Hebei area (in 2010, 2011, 2014, and 2015). In 2010 this area reveals Soybean RYL over 49%.

3.3. Crop Production Loss and Average Relative Yield Loss

3.3.1 Wheat
Wheat production area in China is mainly located in the North China Plain. National Wheat production is 81.12 million Mt while based on RYL, from 2010 to 2017, yearly average national CPL is 16.10 million Mt. For provincial losses, the top five wheat production provinces, Shandong, Henan, Hebei, Jiangsu, and Anhui, where take 67.5% of national total wheat production, also show high Wheat CPL. Shandong and Henan are remarkable for the highest and 2nd highest wheat CPLs for 8 years with 8-year provincial average wheat CPL over 8.5 million Mt. These high CPL provinces also reveals relatively high RYL ranging between 12.03% to 45.17% and the average Wheat CPL maps reveal similar spatial and temporal distribution patterns to the RYL Maps of Wheat (Fig 3s). In 2014, the national CPL peaks at 61.77 million ton, causing economics loss around USD 23.29 Billion.

3.3.2 Early Rice and Late Rice
Major rice producing areas are in the south and east of China. National Rice production in China is 164.66 million MT. The largest amount of rice production is 19.81 million Mt in Anhui, followed by Jiangxi (19.15 million Mt), Hunan (18.36 million Mt), Hubei (16.57 million Mt), and Jiangsu (15.05 million Mt). These provinces account for over 54% of national rice production. Based on the AOT40 during Early Rice growing season, RYL for the major production area is between 10% and 20%. From 2010 to 2018, average CPL in China is 25.30 million Mt which accounts for 15% of national Rice Production. Anhui province has largest provincial CPL over 3.4 million Mt for 8 years and the highest value over 3.97 million Mt in 2012. For the top 5 major crop production provinces, ozone induced provincial CPL are over 2.2 million Mt every year. For Hebei-Tianjin-Beijing area where has high RYL during Early Rice Growing time, due to the low crop production, this area does not reveal high CPLs. Early Rice CPL peaks 2014 at 26.95 million Mt, bringing economic losses at USD 12.34 Billion. In 2016 with a significant increment of Rice purchase price, from 458 USD/Mt in 2014 to USD560/Mt, though the CPL has decreased since 2014, the associated economics loss to 2016 CPL rise to USD 13.85 Billion.
Provinces with high CPLs do not show high ARYL. For Early Rice, highest ARYL is 23.01% in Hebei in 2015. Remarkable provinces are Hebei (18%-23%), Tianjin (18% - 23%), and Shanxi (19%-21%). Those regions are not the major rice producing area. The spatial distributions for Late Rice CPL are similar to the CPL of Early Rice (Fig 5). For Late Rice, higher RYLs are observed in the south and southeast regions. Besides the top five provinces with high crop production and ozone concentration, Guangxi, Guangdong and Fujian Province also reveal relatively higher CPL for late rice. The 8-year-average Late Rice CPL is 19.44 million Mt which is less than the CPL of Early Rice. The largest provincial CPL is observed in Jiangxi Province in 2013 at 2.68 million Mt. The highest national economic loss of CPL is observed in 2013 at USD 9.23 Billion. Respectively, ARYLs for Late Rice is much lower than the ARYLs of Early Rice. Highest ARYLs are observed in Xizang for 8 years (increasing from 13.5% to 17.9%). ARYLs for major production provinces varies between 10% and 14%.

3.3.3 North Maize and South Maize
Maize production areas are mainly concentrated in the North China Plain and the Northeast China Plain. Total Maize production in China is 91.31 million Mt while 74.77 million Mt for North Mazie and 16.54 million Mt for South Maize.

For North Maize, five major production provinces are Shandong (13.73 million Mt), Hebei (12.39 million Mt), Jilin (9.87 million Mt), Henan (9.07 million Mt), and Heilongjiang (8.30 million Mt). Those five provinces produced 71% of the national North Maize production.

Based on the ozone response function, during the North Mazie growing season, high RYLs are observed in the major Maize production areas. The combination of high growing season AOT40, high RYL, and high crop production results in hotspots of CPL in the North China Plain and Northeast China plain. From 2010 to 2018, highest CPLs are all observed in Hebei province (range from 1.32 million Mt to 1.87 million Mt). In 2014, national accumulated CPL of North Maize peaks is 7.92 million Mt. The associated economic loss from ozone induced CPL is USD 0.59 Billion. Though not a major production province of North Maize, Tianjin presents relatively high ARYLs (9.6% to 14.8%). Following is the main production province, Hebei, reveals ARYLs to range between 9.6% to 13.1%. However, other major production provinces show ARYLs between 5% -10%.
Due to the lower AOT40 during South Maize growing season, RYL rates for South Maize are about half of the RYLs of North Maize. Respectively, South Maize production is much lower than the North Maize. The 8-year-average CPL of South Maize is 16.54 million Mt. Sichuan (4.82 million Mt) and Chongqing (3.01 million Mt) are the top two South Maize production provinces. Constantly, high production loss where observed in areas with high crop production. Sichuan province ranks the first for 8 years in South Maize CPLs (range between 0.13 million Mt and 0.27 million Mt). ARYLs for South Maize are all below 9%. From 2010 to 2018, economics cost from CPL ranges from USD 0.05 B to USD 0.21 B (20130).

3.3.4. Soybean
Soybean mainly grows in the North China Plain and the Northeast China Plain. Total soybean production in China is around 2.16 million Mt. Heilongjiang province takes around 50% of the national soybean production (1.11 million Mt), followed by Anhui (0.20 million Mt) and Henan (0.20 million Mt). The RYLs of major soybean production areas are between 21% and 56%, inducing high Soybean CPL in Hebei and Heilongjiang. Highest CPL of 0.16 million Mt is observed in highest Soybean production province, Heilongjiang, in 2012 bringing economic loss of USD 0.32 B. The national CPL and corresponding economic loss peaks at 0.41 million Mt (USD 0.36 Billion).

High ARYLs (>30%) are mainly observed in the Beijing- Tianjin-Hebei area in 2014 and 2015. The highest two ARYL is observed in Tianjin of 42% (in 2014) and 40% (in 2015). Heilongjiang, as the major soybean production province, shows low ARYLs around 9%-13%.
3.4. Economic Loss and Average Relative Yield Loss

From 2010 to 2017, Soybean has the highest crop purchase price between 677.9 USD/ton and 869.7 USD/ton, followed by Rice (296.6 USD/ton to 559.9 USD/ton), Wheat (279.5 USD/ton - 391.4 USD/ton) and Maize (252.2 USD/ton – 489.1 USD/ton). For Maize, Soybean, and Wheat, the purchase price varies and peaks in year 2014 and 2015, which is align with the peak of crop production loss, causing economics loss to peak in these years.

High Economic loss are observed in provinces with high Crop Production. For Wheat, high economic loss are observed in the major production provinces in which Henan and Shandong reveal 8-year average economics loss of 2.68 Billion USD and 2.63 Billion USD. The following provinces, Hebei, Jiangsu, and Anhui also reveal economic loss over 1 Billion USD. Economics loss for Early Rice ranges between 7.14- 13.85 Billion USD in which the major production provinces, Anhui, Jiangsu, Hubei, and Jiangxi, are identified economics loss over 1 Billion USD. Late Rice reveals similar patterns where Anhui, Jiangxi, Hunan, and Hubei show economics loss of 0.97 Billion USD, 0.96 Billion USD, 0.89 Billion USD, and 0.81 Billion USD. North Maize has much higher economic loss than the South Maize. For North Maize, the Hebei and Shandong are the top two production province while also the top two provinces experiencing average economic loss of 0.58 Billion USD and 0.46 Billion USD. As far as the South Maize, Sichuan and
Chongqing suffer from relatively high 8-year-average economics loss of 0.07 Billion USD and 0.04 Billion USD separately. As for Soybean, the provinces suffer high economic loss is Heilongjiang Province (0.1 Billion USD) which is also the largest soybean production area. From 2010 to 2017, wheat experiences the highest economic loss with 8-year-average of 15.76 Billion USD, following crops are Early Rice and Late Rice, while South Maize suffers least of 0.12 Billion USD (Figure 3).

ARYL identified how much the crop production loss takes in total crop production. Nationally, ARYL for Early Rice ranges from 12.71% to 14.07%, Late Rice range between 9.68% and 11.52%, Soybean ranges in 14.10% - 16.11%. ARYL values for both North Maize South Maize are under 10%. It is noteworthy that high ARYL values (> 40%) are observed for Wheat from 2014 – 2017. Provinces with high ARYL are more fragile in resource depletion. Even though some provinces did not rank high in CPL due to the limited producing area distribution, they are still sensitive to the ozone concentration change and express high ARYL (Figure 4).
4. Discussion

By tracking the ozone concentration from 2010 to 2017, ozone concentration in China reveals clear increase. National ozone concentration peaks in 2014 and decrease slight from 2014 to 2017. The Beijing-Tianjin-Hebei area was observed as a hotspot of ozone concentration in China. Obvious increments were observed in the North China Plain, the Northeast China Plain, and the Yangtze River Delta where are not only the most populated and important economic areas but also major crop production regions. The calculated growing-season AOT40 values of each crops reveal similar spatial distribution to the yearly AOT40 (Fig 2S).

The increment of ozone concentration under the scenario of stringent emission control could be attributed to the policy preference to NOx control. Management on O3 precursors in China was concentrated on NOx limitation while less control was implemented on VOCs (Wang et al., 2019). In the Beijing-Tianjin-Hebei Industrial Zone and the Shanghai-Nanjing-Hangzhou Economic Zone, however, VOCs’ emission was a major influential factor that induced ozone generation. Correspondingly, the efficient control on particulate matters (PM2.5 and PM10) in these regions boosted photolysis rates during the formation of ozone.

In response to the linear regression relationship between AOT40 and RYL, RYL in China reveals similar patterns. Wheat (RYL: 12% - 46%) and Soybean (0%< RYL <45%) have generally higher RYL values than Maize and Rice. For Early Rice and Late Rice that applied to the same ozone-response function, RYL values for Early Rice is universally higher than RYL values of Late Rice. This different also applies to North Maize and South Maize. Variation in growing season among these crops affect the accumulated AOT40 levels. The growing months for Early Rice and North
Maize are concentrated in late Spring and Summer while Late Rice and South Maize grow in the late fall. This observation confirmed the Spring and Summer ozone maximum in China (Yin et al, 2019). In our model, the national average RYL range from 24% to 41% for Wheat, 8.9% - 15% for Rice (Early and Late Rice), 2% to 5.4% for Maize (North and South), 8.9% to 10.5% for soybean. Utilizing the Chemical Transport Model CMAQ, Lin et al (2018) modeled the ozone concentration change and estimated the RYLs for multiple crops. Results show ozone induced RYLs are between 8.5% and 14% for winter wheat, 9–15.0% for rice, and 2.2–5.5% for maize (Lin et al, 2018). In the model simulation conducted by Avnery et al (2011), national RYLs of 2000 in east Asia are around 2% - 4% for Maize, 15%- 20% for Wheat, and 20 - 25% for Soybean. An open-top-chamber study in Wang et al (2012) indicated ozone-induced RYL to be around 47% and 39.4% in 2016 and 2017 for Winter Wheat. Mills et al. (2018) adopted AOT40 of 90 day to calculate Wheat RYL and estimated a 25% RYL from 2010-2012 in China. Results in our study present relatively higher RYL for Wheat while RYL for Maize and Rice are coherent to previous studies. Differences in studied years, averaged area size, and accumulation period for AOT40 might attribute to the difference in RYL. The spatial distributions of growing seasons AOT4 and RYS are aligned with previous researches (Avnery et al., 2012; Lin et al., 2018; Feng et al., 2019).

In parallel with crop production, high CPL values are observed in major crop production areas. Hotspots for Rice CPL spread out in the Yangtze Plain in Anhui, Jiangsu, Hunan, Hubei, and Jiangxi where are also highly populated and industrialized. The North China Plain is identified to be a hotspot for Wheat and Maize production. High CPL of soybean concentrated in the Northeast Plain where Heilongjiang Province is the largest production province. 5 crops except South Maize present CPL peak in 2014. Wheat shows the highest crop production loss in 15.76 Billion while South Maize, with least production, ranks bottom in economics loss (Figure 3).

From 2010 to 2017, economic losses in Wheat ranges between USD 5.93 Billion and USD 23.61 Billion, USD 7.14B – 13.04B for Early Rice, USD 5.22B – USD 10.47B for Late Rice, USD 0.32B – 0.62B for North Maize, USD 0.05 B – 0.21B for South Maize, and economic losses for Soybean is between USD 0.92B – USD 1.51B. It is remarkable that for Maize, Soybean, and Wheat, the purchase price varies and peaks in year 2014 and 2015. The peak of crop price matched to the peak of CPL and exaggerated economic losses induced by ozone concentration change.
5. Conclusion:
This paper presented a comprehensive study on the impact of ozone concentration on crop yield in China. From 2010 to 2017, O3-induce agricultural yield change of 4 major crops, Wheat, Maize, Rice, and Soybean, are assessed simultaneously. Such analysis could provide scientific support to improve decision-making on mitigate ozone impacts.
In this study, we modeled the ozone concentration change in China and revealed that from under stringent emission control policy, ozone pollution was not controlled efficiently. Since 2010, AOT40 level had been increasing and peaked in 2014. Based on the AOT40 and crop-ozone matrix, we investigated impact of O3 on 4 major crops: Wheat, Rice (Early and Late), Maize (South and North), and Soybean. Provincial average RYL ranges in 12.6–45.7% (Wheat), 7.8–19% (Early Rice), 6.8–13.9% (Late Rice), 0–15.5% (NMaize), 0–8.2% (SMaize), and 0–44% (Soybean). Accordingly, national accumulated CPL varies between 21.23–61.77 Million Mt (Wheat), 23.99–26.96 Million Mt (Early Rice), 17.65–21.43 Million Mt (Late Rice), 6.29–7.92 Million Mt (NMaize), 3.30–6.94 Million Mt (SMaize), and 3.38–4.14 Million Mt (Soybean). Respectively, from 2010 to 2017, average ozone induced economics losses for Wheat are in range of USD 5.93–23.61B, USD 7.14–13.85 B for Early Rice, USD 5.22–10.47 B for Late Rice, USD 0.31–0.62 B for NMaize, USD 0.05–0.21B for SMaize, USD 0.22–0.36 B for Soybean.
The results reveal slight overestimation of AOT40 and RYL for wheat and under estimation of RYL for Soybean. These differences may attribute to the variation of averaged scale, study years, and AOT40 accumulation period.
6. References


Supported Materials

Fig S1. AOT40
Fig S2. RYL for Wheat, Soybean, North Maize, South Maize, Early Rice, Late Rice
Figure S3. Crop Production Loss (Mt)