LETTER

Damages of surface ozone: evidence from agricultural sector in China

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Abstract

This study measures the damages that surface ozone pollution causes within the Chinese agricultural sector under 2014 conditions. It also analyzes the agricultural benefits of ozone reductions. The analysis is done using a partial equilibrium model of China’s agricultural sector. Results indicate that there are substantial, spatially differentiated damages that are greatest in ozone-sensitive crop growing areas with higher ozone concentrations. The estimated damage to China’s agricultural sector range is between CNY 1.6 trillion and 2.2 trillion, which for comparison is about one fifth of 2014 agricultural revenue. When considering concentration reduction we find a 30% ozone reduction yields CNY 678 billion in sectoral benefits. These benefits largely fall to consumers with producers losing as the production gains lead to lower prices.

1. Introduction

Surface ozone, produced when pollutants react chemically in sunlight, damages agricultural yields by slowing photosynthesis and growth (Adams 1983, Avnery et al 2011, Emberson et al 2009, Heck et al 1982). Regionally across China some agricultural areas exhibit high, likely damaging ozone levels, but not much is known on associated crop losses. This paper reports on a study that estimates regional crop losses and economic damages within the Chinese agricultural sector. Additionally we explore the benefits of reduced ozone levels.

US studies have examined agricultural benefits of reducing ozone concentrations (Adams et al 1982, Adams et al 1985, Kopp and Krupnick 1987). These studies estimate average crop damages. Muller and Mendelsohn (2007) argue that estimation of marginal values would be better as they can be compared with marginal abatement costs. Here we estimate a curve that traces out agricultural benefits gained as ozone concentrations are reduced.

In this study, we follow the suggestion by Just et al (2005) and estimate marginal crop production losses and their value with a mathematical programming model linked to a function that gives crop yield effects of ozone concentrations. In the analysis that model is subjected to systematically varying ozone concentration levels.

2. Methodology and data

The framework we used involves several components as overviewed in figure 1. First, we selected ozone dose response functions that gave crop yield as a function of ozone concentrations. Second, we built and calibrated a Chinese agriculture sector, mathematical programming model. Third, we altered regional yields in CASM to reflect alternative ozone concentrations and solved generating marginal damage estimates. Fourth we estimated an ozone damage summary function. Fifth, benefits of ozone control in agricultural sector were estimated.
2.1. Ozone dose response functions

To estimate the crop yield effects of alternative ozone levels, we adopted ‘dose response’ functions from the international literature as studies have not been widely done in China. The functions used are those arising from the Mills et al (2007) literature review which have been used in a number of other studies (i.e. see Chuwah et al (2015), Tang et al 2013). A full list of the functions used appears in appendix A available at stacks.iop.org/ERL/13/034019/mmedia. Chuwah et al (2015) argues such functions will likely provide conservative estimates as Aunan et al (2000) and Emberson et al (2009) found that some Asian grown crop varieties such as wheat and rice are more sensitive than European and North American crops.

Different crops have widely different responses to ozone due to genetics and timing of development stages relative to concentration levels (Feng et al 2008). For example, grain crop sensitivity is highest during flowering and seed maturity (Lee et al 1988). Over all, wheat has been found to be one of the most ozone-sensitive grain crops (see Mills et al (2007)). To use those functions we needed to express ozone levels using the three-month aggregate measure $AOT40$ and we formed that as discussed in appendix B.

2.2. China agricultural sector model

Next we developed a multiple-region, multiple-commodity price endogenous, partial equilibrium Chinese agricultural sector model (CASM). CASM is a bottom–up, mathematical program that depicts monthly agricultural production across China. CASM reflects national markets and regional resources. It also reflects the fact that as production quantities change so do commodity prices incorporating product demand curves. The basic structure of the model follows the approach discussed in McCarl and Spreen (1980). The model maximizes consumers’ and producers’ surplus subject to limited resource constraints as well as demand and supply balances. This process incorporates explicit product demand and import supply curves, as well as factor supply curves, and results in an endogenous determination of commodity and factor market price, simultaneously with the determination of land allocation and production levels. The consumers’ and producers’ surplus maximization yields first order conditions that characterize a perfectly competitive equilibrium. Appendix C discusses CASM in detail.

CASM depicts production in 365 Chinese sub-regions at the prefecture level\(^6\). Each sub-region

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\(^6\) Prefecture level city is a level of administrative division in China that covers agricultural regions.
possesses differing land and labor endowments along with varying cropping and livestock possibilities and budgets. Collectively this depicts heterogeneous regional production possibilities and resource endowments. Cropping patterns are chosen by sub-regional representative farm models that depict profit maximizing farmers under perfect competition mimicking the local technical and economic environment.

CASM is an aggregate representation of the Chinese agricultural sector representing millions of farms and needs to adequately represent production possibilities and reactions. To do this we calibrate the model to observed production and consumption data for 2014 employing the positive mathematical programming (PMP) approach developed by (Howitt 1995). That alters the production costs in an effort to replicate observed cropping patterns and numbers of livestock. In particular, we add a quadratic term to production cost and calibrate the model with that term so it nearly replicates observed production levels.

After calibration, CASM results on commodity production and prices closely match the 2014 observed data (table 1). The consequent model results all fall within 5% of the actual 2014 observations. We also ran the 2014 calibrated CASM under 2013 conditions and found it closely replicated data for that year (see appendix D). This led us to conclude that CASM was suitable for further analysis.

2.3. Estimation of changes in damages
CASM was first applied to compute baseline welfare at 2014 ozone levels. In order to estimate damages under alternative ozone levels, we adjust the CASM crop yields using the percentage change from the dose response function between the baseline ozone level and an alternative. We then compute the change in welfare between the baseline and the alternative. The model assumes farmers do not change technology for any crop although the CASM solution will allow them to switch crops, as well as adjust planted area.

CASM is run under a range of increasing or declining ozone levels. In doing this we first select a baseline ozone level then use the dose response functions to construct regional crop yield estimates. The baseline ozone levels are varied from −20 ppm to +10 ppm relative to 2014 levels in 1 ppm increments and the resultant yields are estimated. Then, we compute the percent change in yield under alternative ozone levels by adding 1 ppm to the baseline ozone. Subsequently, the yield estimates are imposed within CASM, which is then solved yielding results on welfare, production, prices, and consumption. Finally, we compute the change in welfare under this alternative ozone level by subtracting the ozone change-impacted welfare from the baseline welfare.

We keep repeating the above steps until we have formed marginal damage estimates for each alternative ozone level and do this for each of 365 sub-regions. This procedure generates an ozone dependent schedule of regional marginal damage estimates and producer reactions. The multi region design yields spatially differentiated estimates allowing identification of the most impacted regions.

Table 1. Comparison between observed and CASM-generated results for commodity prices and total production levels.

| Commodities       | Production level in terms of planted area in 1000 ha or livestock numbers in 1000 head | Price (CNY kg⁻¹) |
|--------------------|------------------------------------------------------------------------------------------|------------------|
|                    | Observed   | Model   | % Deviation | Observed | Model | % Deviation |
| Rice               | 28826.2    | 29599.0 | 2.6         | 2.0      | 2.1   | 3.7         |
| Wheat              | 26810.5    | 28132.4 | 4.7         | 1.6      | 1.7   | 3.0         |
| Maize              | 41171.1    | 43035.3 | 4.3         | 1.6      | 1.7   | 3.6         |
| Soybean            | 6216.9     | 6300.4  | 1.3         | 3.5      | 3.5   | 1.6         |
| Peanut             | 4619.0     | 4563.6  | −1.2        | 6.0      | 6.0   | −0.7        |
| Rapseseed          | 7632.3     | 7538.4  | −1.2        | 3.5      | 3.5   | −0.7        |
| Cotton             | 4097.4     | 4216.6  | 2.8         | 10.6     | 10.9  | 2.7         |
| Tobacco            | 1461.9     | 1506.0  | 2.9         | 15.3     | 15.9  | 3.6         |
| Sugarcane          | 1756.5     | 1756.5  | 0.0         | 0.4      | 0.4   | 0.0         |
| Sugarbeet          | 117.1      | 117.0   | −0.1        | 0.4      | 0.4   | 0.1         |
| Potato             | 9399.6     | 9543.1  | 1.5         | 0.9      | 0.9   | 1.5         |
| Fiber crops        | 83.0       | 82.2    | −0.9        | 6.8      | 7.0   | 2.2         |
| Other grain crops  | 3019.5     | 3156.4  | 4.3         | 5.7      | 6.0   | 4.8         |
| Vegetable and cucurbits | 21842.5   | 22815.2 | 0.0         | 1.4      | 1.4   | 0.1         |
| Other beans        | 1390.2     | 1354.1  | −2.7        | 3.2      | 3.2   | −0.6        |
| Other oil crops    | 1536.6     | 1553.4  | −0.2        | 6.0      | 6.0   | 0.0         |
| Hen                | 16556.0    | 16535.3 | −0.1        | 5.8      | 5.9   | 0.7         |
| Broiler            | 120740.0   | 118852.8| −1.6        | 12.7     | 12.7  | 0.6         |
| Cattle             | 47608.3    | 47425.5 | −0.4        | 48.2     | 48.3  | 0.2         |
| Cow                | 6587.3     | 6590.4  | 0.0         | 2.7      | 2.7   | 0.4         |
| Hog                | 697894.7   | 698895.8| 0.1         | 16.0     | 16.1  | 0.4         |
| Sheep              | 270995.1   | 270119.9| −0.3        | 52.1     | 52.2  | 0.3         |

Notes: Livestock price information is for their main products that are eggs, chicken meat, beef, milk, port and mutton for hen, broiler, cattle, cow, hog and sheep, respectively. Other grain crops include oat, barley, sorghum. Other beans include all dried beans except soybean. Other oil crops include sunflower and sesame.

7 CASM covers 16 major field crops including rice, wheat, maize, soybean, peanut, rapseseed, cotton, tobacco, sugarcane, sugar beet, potato, fiber crops, vegetable and cucurbits, other grain crops include oat, barley, sorghum, other beans including all dried beans except soybean, and other oil crops include sunflower and sesame.
Given the marginal damages estimates over the range of ozone exposure levels, we estimate a summary function approach (Griffin 1977, Preckel and Hertel 1988) that summarize regional and national damages. Considering the heavy computation burden, we first develop regional estimates of marginal damages at $i = 1, \ldots, N$, for 30 added ozone concentration baseline levels. Second, the functional form used is

$$\text{MD}_{ri}(O_{ri}) = f(O_{ri} | \hat{\beta}_r) + \epsilon_{ri},$$ (1)

where $\text{MD}_{ri}(O_{ri})$ represents the $i$th observed marginal damage observation under ozone concentration level ($O_{ri}$) in sub-region $r$. The functional form $f(\cdot)$ is a polynomial. The residual term $\epsilon_{ri}$ depicts the remaining residuals that are minimized. Finally, we integrate the area below the marginal curve to compute the total damages.

Aside from calculating the aggregate damage relationship using marginal information in each sub-region, this study computes provincial marginal damages then constructs a national agricultural damage summary function. This method first uses the CASM estimates at the 365 sub-region level to form sub-regional marginal damages. Second, we construct provincial level results by adding up the result at each ppm level across all sub-regions falling into each of 31 Chinese provinces/municipalities. Third, we estimate a national summary function as above to compute the total damage functions by province. Even though this method does not represent the degree to which sub-regional marginal damages differ, the setting is consistent with China’s environmental governance strategy.

Finally, given the summary function estimates we investigate provincial differences in damages and benefits from concentration reductions. The estimates allow the identification of the most damaged areas and may help identify potential provinces in which to pursue ozone control policy.

Additionally, we perform sensitivity experiments simultaneously reducing all sub-regional ozone concentrations by 15%, 30%, and 45%.

2.4. Information sources for CASM specification

CASM models production of 16 primary field crops and 6 livestock types. Crop and livestock production budgets as well as farm gate prices were obtained from the Data Compilation of China Agricultural Product Cost and Revenue. The agricultural commodity trade data were from USDA. The data on crop planting and harvest time were obtained from both the USDA report on Major World Crop Areas and Climatic Profiles and agronomists’ suggestions, if needed. The cost of storage for major commodities were from Chen (2007). Labor supply elasticities were from Feng and Zhang (2012). The demand elasticity data for primary products were adopted from Zhang (2004). All of the prices are deflated to 2000 CNY.

Ozone exposure information were obtained from the 2014 hourly observations by the China National Environmental Monitoring Center, which provides observations for 1412 stations located in 338 prefectures (figure 2). To develop AOT40 measures for each sub-region an inverse distance weighted method was applied to interpolate the ozone data to a 1 kilometer grid which was then averaged to the prefecture level.

Normally, high concentrations of ozone precursors accompanied by stable tropospheric air, high temperature, low humidity, and intense radiation are likely to generate severe surface ozone pollution. However, the photochemical reaction process is complicated. For example, the urban NO$_x$ emissions react with ozone to generate NO$_2$. Moreover, ozone precursors emitted from urban areas are transported to rural areas through wind and often concentrations are large in rural areas. Wang et al (2007) has found evidence to show that surface ozone concentrations in Chinese rural areas are higher than those in urban areas. Therefore, we probably underestimate rural ozone concentrations since most of air quality monitoring stations are in urban areas.

3. Results

3.1. Surface ozone damages

To select the appropriate functional form for the summary functions (1), we use the shape suggested by an examination of figure 3. That figure shows that marginal damages increase at an increasing rate as surface ozone concentrations increase. Thus, the form

$$\text{MD}_{ri}(O_{ri}) = \hat{\beta}_0 + \hat{\beta}_1 O_{ri} + \hat{\beta}_2 O_{ri}^2 + \epsilon_{ri},$$

was used. The resultant narrow 95% confidence interval and the high levels of $R^2$ (around 0.99) indicate that summary functions effectively represent the CASM marginal damages.

Figure 4 illustrates spatial differences in the damage estimates from the summary functions. Significant disparities arose across seven major regions. For example, marginal damage in East China is more than four times greater than the damages in Northeast China. The economic value of ozone reductions are largest where exposures are high and the region has significant crop production (Westenbarger and Frisvold 1995). The regional differences arise due to crop mix, land area farmed, and ozone levels (see figure 2). Agricultural areas in East China exhibit high ozone concentrations while also growing sensitive crops like wheat and vegetables, for example contributing over 38% of domestic wheat supply. On the other hand, Northeast China that only contributes 0.39% of domestic wheat supply faces relatively smaller impact. In Northeast China and South China, the ozone concentrations are lower plus rice and maize (a less ozone-sensitive

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8 Detailed regression results are available upon request.
crop) account for more than 40% of the planted areas in both regions. These heterogeneous damages suggest spatially differentiated ozone pollution control policies might be attractive although lateral transport of ozone between regions should be considered.

Table 2 presents monetary ozone damage estimates. Total country wide agricultural damages of 2014 ozone concentrations are estimated at CNY 1.9 trillion, or approximately 0.8% of total sectoral associated welfare, and 19% of total agricultural revenue.
Table 2. National estimates of agricultural damages caused by 2014 ozone concentrations.

| Scenario                  | Gross damage (Billion Yuan) | 95% confidence interval |
|---------------------------|----------------------------|-------------------------|
|                           | Estimate                   | Fraction of base        | Lower bound* (Billion Yuan) | Fraction of base | Upper bound (Billion Yuan) | Fraction of base |
| Subregional marginal damage | 1934.05                   | 0.82                    | 1629.77                    | 0.69             | 2238.32                    | 0.94             |
| Provincial marginal damage | 1558.98                   | 0.66                    | 1419.71                    | 0.60             | 1698.25                    | 0.72             |
| Linear marginal damage     | 2165.06                   | 0.91                    | –                          | –                | –                          | –                |

* The lower bound and upper bound of the gross damage is computed based on the 95% confidence intervals of the coefficients in quadratic form of equation (1).

Table 2 also shows the 95% confidence interval for welfare indicating total damages fall between CNY 1.6 and 2.2 trillion, a welfare loss of no more than 1%.

Table 2 row 2 reports an alternative national damage estimate formed by adding up provincial marginal damages. Notably, this value (CNY 1.559 trillion) is smaller than the summary function results estimated directly over the data set. The difference could be explained by the fact region are weighted equally in adding up the national summary function but not in the estimation. Additionally there are more minimally affected sub-regions than those greatly affected. Thus, simple average damage estimates are somewhat lower.

The third row of table 2 presents aggregate damages constructed following procedures in Muller and Mendelsohn (2007). Namely we multiply the marginal damage at a concentration level in 2014 by the estimated total tons of annual ozone emissions, divided by 2 yielding an estimate of the area below a linear marginal damage line. Figure 3 has shown the concavity of marginal damage curves. Therefore, Muller and Mendelsohn’s (2007) method is likely to overestimate the aggregate damages. Thus, the total damage on the basis of linear assumption is CNY 2.2 trillion, which is approximately 24% more than the measures based on the quadratic summary function. This finding confirms that marginal damages are increasing at an increasing rate along the range of surface ozone exposures from figure 3.

We compute the change in total damages of a change in concentrations by subtracting the welfare under the exposure of ozone pollution in 2014 from the one with an alternative level of ozone exposure. By using this direct gross damage measurement, the actual total damage is CNY 1.9 trillion, indicating that our marginal-damage method has minor 1.8% difference. The gap can be attributed to the summary function approach. However, this method is a significant improvement over the piecewise linear marginal damage assumption suggested by Muller and Mendelsohn (2007), which has a measurement error about 14%.

We also compare our damage estimates with results from other relevant studies. Since those studies are agronomic in nature, we only compare crop output losses. Table 3 summarizes the comparison and shows a large difference among the studies. The gap can be attributed to the differing assumptions on ozone concentration and dose response functions (Feng et al 2015). Our results show that our 2014 wheat and...
soybean losses have reached the levels estimated for 2020 by Wang and Mauzerall (2004). There are two reasons for the larger output losses in our estimates. First, surface ozone exposures in 2014 are much greater than the levels assumed in previous studies. With the rapid industrialization of China, the average daily growing season AOT40 has increased from 558 ppb in 2013 to 621 ppb in 2015, a level which is almost six times the standard defined in the European Union Ambient Air Quality Directive (EEA 2017). Comparing with the assumed AOT40 (15 ppm) that would occur by 2020 in the Tang et al. (2013), East China ozone exposure measured over 90 days (May–July) in 2014 was 62% more than the Tang et al. (2013)’s assumption. In addition, CASM optimally alters crop mix which alters output losses. When land is shifted out of wheat and soybean, this raises total output decreases relative to other studies.

### 3.2. Benefits of surface ozone control

Now we turn attention to the value of ozone concentration reductions. Table 4 shows CASM estimated benefits of systematic reductions from baseline 2014 surface ozone levels. Here we find an ozone reduction of 15% eliminates 19% of the damages while a 30% reduction lowers damages by 35% and a 45% reduction eliminates 50%. This shows diminishing marginal benefits to ozone control and is a result consistent with the findings in Adams et al. (1982).

We also examined the income distribution implications of ozone control. Here we found consumers benefit from ozone control but producers are damaged which is a finding contrary to the results in Adams et al. (1982) and Adams et al. (1989). However we note this is a common finding in the literature (e.g. see Adams et al. (1990) and Reilly et al. (2003)). Given an inelastic demand curve (which is common in agriculture), prices for farm production will fall when reduced ozone concentrations increase production, and the revenue losses from lower prices often offset productivity gains. In addition, because lower-income consumers tend to spend a larger income share on food they are likely to be the major beneficiaries of surface ozone control.

We also find that not all provinces benefit from ozone control (table 5). Most regions gain from ozone reductions from 2014 baseline ozone levels. However in Guangxi and Hainan under a 30% reduction the producers’ loss exceeds the consumers’ gain. This is likely due to local soil quality and weather conditions, plus the fact that rice is the dominant crop in these two regions and the consumer group is generally smaller. Given a surface ozone reduction, the substitution between rice and other profitable crops is limited causing losses of farmers in these two regions to exceed the gains of their relatively smaller number of local consumers. Clearly there will be differential regional effects of ozone control policy.

### 3.3. Impacts on domestic grain production

Food security is an important concern and thus we investigate food production impacts (table 6). Generally we find a concentration decrease alters production of rice, wheat, and maize. Specifically, a 45% reduction generates an additional 92 million tons of grain or about 17% above 2014 supply. Wheat accounts for more than 86% of the increase, and maize 13%. Rice production decreases slightly under a 15% reduction but increases under larger ones.

Grain output changes are not spatially uniform (table 7). Hebei, Henan, Jiangsu, and Shandong

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**Table 3. Comparisons of output loss estimates caused by ozone exposure by crop, source and year.**

| Country | Source | Year 1 | Year 2 | Losses 1 | Losses 2 |
|---------|--------|--------|--------|----------|----------|
| Wheat   | Aunan et al (2000) | 1990    | 2020   | 0.0–9.1  | 6.4–14.9 |
|        | Tang et al (2013)  | 2000    | 2020   | 1.1–1.5  | –        |
|        | Wang and Mauzerall (2014) | 1990 | 2020   | 0.8–13  | 3–5     |

**Table 4. Country wide estimated benefits of ozone concentration reductions.**

| Ozone reduction | Total | Producers | Consumers |
|-----------------|-------|-----------|-----------|
|                 | Welfare change (Billion CNY) | Fraction of base | Increase rates (%) | Surplus change (Billion CNY) | Fraction of base | Surplus change (Billion CNY) | Fraction of base |
| −15%            | 358.71 | 0.15      | –         | −39.41 | −0.05 | 418.12 | 0.33 |
| −30%            | 678.21 | 0.29      | 89.07     | −112.83| −0.10 | 791.04 | 0.63 |
| −45%            | 961.47 | 0.41      | 168.03    | −136.15| −0.12 | 1097.62| 0.87 |

*Note: Ecological studies (1), (2), and (3) assume crop planting areas fixed.*

*Increase rates are computed through dividing the amount of benefit increments from the first 15% ozone reduction by the gain at the first 15% ozone reduction.*

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9 Ozone was added into ambient air quality monitoring system in 2013.

10 1 ppm = 1000 ppb.
Table 5. Estimated provincial welfare effects under alternative ozone concentration reduction assumptions.

| Province | 15% Reduction | 30% Reduction | 45% Reduction |
|----------|---------------|---------------|---------------|
|          | Surplus (Billion CNY) | Fraction of base | Surplus (Billion CNY) | Fraction of base | Surplus (Billion CNY) | Fraction of base |
| Anhui    | 10.66          | 0.10          | 20.48          | 0.19          | 29.60          | 0.27          |
| Beijing  | 7.71           | 0.21          | 14.77          | 0.39          | 20.27          | 0.53          |
| Chongqing| 2.18           | 0.04          | 4.55           | 0.08          | 7.12           | 0.13          |
| Fujian   | 6.93           | 0.10          | 13.77          | 0.20          | 19.61          | 0.29          |
| Gansu    | 3.83           | 0.08          | 7.58           | 0.16          | 12.36          | 0.26          |
| Guangdong| 22.56          | 0.12          | 44.96          | 0.23          | 63.63          | 0.33          |
| Guangxi  | -3.24          | -0.04         | -5.12          | -0.06         | -5.95          | -0.07         |
| Guizhou  | 2.17           | 0.04          | 4.89           | 0.08          | 8.65           | 0.14          |
| Hainan   | -2.34          | -0.13         | -3.71          | -0.23         | -4.31          | -0.26         |
| Hebei    | 37.29          | 0.29          | 69.28          | 0.52          | 94.58          | 0.71          |
| Heilongjiang| 4.53        | 0.07          | 9.83           | 0.14          | 14.50          | 0.21          |
| Henan    | 31.20          | 0.19          | 57.53          | 0.34          | 79.80          | 0.47          |
| Hubei    | 10.31          | 0.10          | 19.79          | 0.19          | 28.55          | 0.27          |
| Hunan    | 10.49          | 0.09          | 21.13          | 0.17          | 30.24          | 0.25          |
| Jiangsu  | 27.01          | 0.19          | 51.27          | 0.36          | 70.88          | 0.50          |
| Jiangxi  | 10.42          | 0.13          | 20.72          | 0.25          | 29.24          | 0.36          |
| Jilin    | 8.73           | 0.18          | 17.20          | 0.35          | 24.38          | 0.49          |
| Liaoning | 15.95          | 0.21          | 30.69          | 0.59          | 42.52          | 0.54          |
| Neimenggu| 9.47           | 0.21          | 17.92          | 0.39          | 25.93          | 0.56          |
| Ningxia  | 1.16           | 0.10          | 2.16           | 0.18          | 3.21           | 0.27          |
| Qinghai  | 0.72           | 0.07          | 1.45           | 0.14          | 2.24           | 0.21          |
| Shaanxi  | 4.41           | 0.07          | 6.21           | 0.09          | 9.14           | 0.13          |
| Shandong | 57.47          | 0.34          | 111.26         | 0.63          | 156.76         | 0.89          |
| Shanghai | 7.11           | 0.17          | 13.70          | 0.32          | 18.89          | 0.44          |
| Shanxi   | 11.33          | 0.18          | 21.43          | 0.33          | 30.06          | 0.46          |
| Sichuan  | 11.18          | 0.08          | 22.09          | 0.15          | 32.79          | 0.22          |
| Tianjin  | 5.90           | 0.22          | 11.15          | 0.41          | 15.25          | 0.56          |
| Tibet    | 0.96           | 0.17          | 1.87           | 0.33          | 2.60           | 0.46          |
| Xinjiang | 19.67          | 0.49          | 37.03          | 0.90          | 52.07          | 1.27          |
| Yunnan   | 1.45           | 0.02          | 4.44           | 0.05          | 8.36           | 0.10          |
| Zhejiang | 14.52          | 0.15          | 27.88          | 0.28          | 38.50          | 0.39          |

Table 6. Estimated effects of ozone concentration reductions on national grain production.

| Ozone reduction assumption | Grain supply (Million ton) | Fraction of base | Rice (Million ton) | Fraction of base | Wheat (Million ton) | Fraction of base | Maize (Million ton) | Fraction of base |
|---------------------------|---------------------------|------------------|-------------------|------------------|--------------------|------------------|--------------------|------------------|
| −15%                      | 29.57                     | 5.39             | −0.50             | −0.24            | 25.16              | 19.94            | 4.91               | 2.28             |
| −30%                      | 57.63                     | 10.51            | 0.26              | 0.13             | 48.44              | 38.39            | 8.93               | 4.13             |
| −45%                      | 91.83                     | 16.75            | 0.97              | 0.47             | 78.86              | 62.50            | 12.00              | 5.56             |

3.4. Discussion on surface ozone control policy in China

This study finds substantial agricultural benefits arise from ozone control along with lower food prices that would benefit consumers particularly the poor. The welfare estimates would need to be compared with the control policy costs although we do not attempt that here. But this comparison would not tell the whole story as the estimates omit health and other benefits. China has begun to control ozone by regulating its precursors imposing regionally specific emission fees. Based on recent provincial ozone precursor regulations, VOC emission charges vary from 1.26 CNY kg⁻¹ to 40 CNY kg⁻¹, and NOₓ fees from 1.26 CNY kg⁻¹ to 10 CNY kg⁻¹. Table 8 presents estimates optimistic and pessimistic estimates of aggregate surface ozone precursor changes if current highest and lowest standards are implemented, respectively. The lower bound on the monetary gain from such actions is approximately CNY 58 billion, which accounts for 3% of gross damage. The upper bound on the gain is around...
Table 7. Estimated effects of ozone concentration reductions on provincial grain production.

| Province | Base (Million ton) | 15% Reduction | % Change | 30% Reduction | % Change | 45% Reduction | % Change |
|----------|-------------------|---------------|----------|---------------|----------|---------------|----------|
| Anhui    | 32.07             | 1.82          | 5.66     | 3.12          | 9.72     | 4.96          | 15.47    |
| Beijing  | 0.62              | 0.06          | 10.17    | 0.14          | 21.99    | 0.22          | 36.01    |
| Chongqing| 7.84              | −0.03         | −0.38    | 0.00          | −0.06    | 0.06          | 0.82     |
| Fujian   | 5.11              | 0.11          | 2.10     | 0.20          | 3.88     | 0.29          | 5.60     |
| Gansu    | 8.73              | 1.31          | 15.00    | 2.69          | 30.83    | 4.26          | 48.79    |
| Guangdong| 11.52             | −0.21         | −1.84    | −0.33         | −2.86    | −0.43         | −3.71    |
| Guangxi  | 14.12             | −0.26         | −1.86    | −0.32         | −2.24    | −0.33         | −2.36    |
| Guizhou  | 8.03              | 0.19          | 2.34     | 0.23          | 2.91     | 0.36          | 4.52     |
| Hainan   | 1.53              | −0.08         | −5.46    | −0.15         | −10.10   | −0.22         | −14.39   |
| Hebei    | 5.17              | 0.52          | 10.47    | 0.63          | 19.89    | 0.76          | 30.48    |
| Heilongjiang | 55.73   | 0.19          | 0.35     | 0.39          | 0.70     | 0.60          | 1.08     |
| Henan    | 55.13             | 6.30          | 11.42    | 11.08         | 20.10    | 16.81         | 30.49    |
| Hubei    | 24.14             | 0.92          | 3.81     | 1.69          | 6.98     | 2.56          | 10.60    |
| Hunan    | 27.93             | 0.12          | 0.44     | 0.06          | 0.23     | 0.05          | 0.17     |
| Jiangsu  | 33.31             | 2.60          | 7.81     | 5.89          | 17.69    | 9.97          | 29.93    |
| Jiangxi  | 20.08             | −0.13         | −0.63    | 0.03          | 0.14     | 0.19          | 0.97     |
| Jilin    | 33.65             | 0.35          | 1.05     | 0.66          | 1.97     | 0.99          | 2.95     |
| Liaoning | 16.47             | 0.11          | 0.64     | 0.27          | 1.63     | 0.45          | 2.70     |
| Neimenggu| 24.52             | 1.37          | 5.57     | 2.41          | 9.82     | 3.72          | 15.15    |
| Ningxia  | 3.27              | 0.23          | 6.92     | 0.43          | 13.23    | 0.72          | 21.93    |
| Qinghai  | 0.62              | 0.02          | 3.91     | 0.01          | 0.83     | 0.03          | 4.31     |
| Shaanxi  | 10.62             | 1.67          | 15.70    | 4.27          | 40.21    | 7.45          | 70.17    |
| Shandong | 42.90             | 4.49          | 10.47    | 9.53          | 22.21    | 15.74         | 36.70    |
| Shanghai | 1.09              | 0.09          | 8.39     | 0.19          | 17.46    | 0.30          | 27.93    |
| Shanxi   | 12.40             | 1.47          | 11.84    | 2.54          | 20.51    | 3.73          | 30.12    |
| Sichuan  | 27.39             | 0.66          | 2.41     | 0.88          | 3.23     | 1.43          | 5.23     |
| Tianjin  | 1.71              | 0.51          | 18.28    | 0.62          | 36.45    | 0.99          | 57.59    |
| Tibet    | 0.94              | 0.00          | 0.04     | 0.00          | 0.05     | 0.00          | 0.10     |
| Xinjiang | 13.47             | 1.31          | 9.71     | 2.28          | 16.96    | 3.41          | 25.29    |
| Yunnan   | 15.10             | 0.90          | 5.99     | 1.77          | 11.74    | 2.70          | 17.86    |
| Zhejiang | 6.53              | 0.37          | 5.62     | 0.74          | 11.29    | 1.15          | 17.65    |

Table 8. Emission charges levied on surface ozone precursors.

| Ozone precursor emission charge | Lower bound | Upper bound |
|--------------------------------|-------------|-------------|
| VOC charge standard (CNY kg⁻¹) | 1.26        | 1.26        |
| NOₓ charge standard (CNY kg⁻¹) | 40          | 10          |

Aggregate emission charge (CNY Billion) 57.58 1204.51
% of aggregate damage 3.31 69.25

a NOₓ emission is collected from industry in 2014, and VOC emission is the aggregate level from industry in 2012 due to data availability.

b Per unit VOC and NOₓ emission charge standards are from provincial emission rules in 2015.

CNY 1205 billion, which is 69% of the gross damage estimate.

Given the evolution of climate change induced by greenhouse gases will affect atmospheric dynamics and the relationship between ozone precursors and actual ozone concentrations in rural areas as discussed in Lobell and Asseng (2017), the ozone control effort may well have to be a dynamic standard rather than a fixed one.

4. Conclusions

This study has assessed the monetary and production impacts of surface level ozone on China’s agricultural sector. Findings show ozone has significant negative national impacts suppressing food production particularly for wheat. Our estimates of the range of total damages falls between CNY 1.6 trillion and CNY 2.2 trillion, which accounts for a loss in total economic welfare in the agricultural sector of approximately 1%. Thus ozone control could help in improving country level welfare and food security. We also find provincial level damages vary across the county which in turn suggests that regionally targeted policies may be appropriate. In particular, perhaps regionally specific ozone pollution standards could be used to address the most damaged areas.

We also studied the benefits and their distribution from ozone control. We found an ozone level reduction of 30% results lowers agricultural sector damages by CNY 0.7 trillion or 35% less. Consumers are the main beneficiaries of reductions, while producers lose. Those losses occur because the decreases in product prices more than offset the increase in supply. Regarding food production, wheat in traditional major
grain production provinces is strongly increased under ozone control with maize increased somewhat and rice unaffected. Furthermore, the reader should note that the damage estimates herein are conservative for several reasons. First they only cover marginal damages in the agricultural sector neglecting effects on human health and other sectors. Second, they may well arise from underestimates of ozone exposure in many rural areas in turn resulting in a lower bound. Third, the lack of China based information on crop sensitivity biases the crop losses and the corresponding damages which some argue leads to underestimates. Finally, the identification of the most damaged areas is limited by using 2014 observations because lateral transport may heavily confound the adverse effects of surface ozone. For example, regional ozone precursor production may have wide spread and differing cross regional effects due to transmission over distances under variable winds.

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References

Adams R M 1983 Issues in assessing the economic benefits of ambient ozone control: some examples from agriculture Environ. Int. 9 539–48
Adams R M, Crocker T D and Thanavibulchai N 1982 An economic assessment of air pollution damages to selected annual crops in southern California J. Environ. Econ. Manage. 9 42–58
Adams R M, Glycer J D, Johnson S L and McCarroll B A 1989 A reassessment of the economic effects of ozone on US agriculture J. Air Pollut. Control Assoc. 39 960–8
Adams R M, Hamilton S A and McCarroll B A 1985 An assessment of the economic effects of ozone on US agriculture J. Air Pollut. Control Assoc. 35 938–43
Adams R M, Rosenzweig C, Peart R, Ritchie J T and McCarroll B A 1990 Global climate change and US agriculture Nature 345:219
Aunan K, Berntsen T K and Seip H M 2000 Surface ozone in China and its possible impact on agricultural crop yields AMBIO: A J. Hum. Environ. 29 294–301
Averyn S, Maurer D L, Liu J and Horowitz L W 2011 Global crop yield reductions due to surface ozone exposure: 1. Year 2000 crop production losses and economic damage Atmos. Environ. 45 2284–90
Chen B 2007 Cost of food security and update of cropping mixes in China PhD dissertation Huazhong Agricultural University
Chuwah C, van Noije T, van Vuuren D P, Stehfest E and Hazeleger W 2015 Global impacts of surface ozone changes on crop yields and land use Atmos. Environ. 106 11–23
EEA (European Environment Agency) 2017 Air Quality in Europe (Copenhagen: Publications Office of the European Union)
Emerson B, BØker P, Ashmore M, Mølgaard L, Agrawal M, Atikuzzaman M, Cunderby S, Engardt M and Jamir C 2009 A comparison of North American and Asian exposure–response data for ozone effects on crop yields Atmos. Environ. 43 1945–53
Feng J and Zhang T 2012 Estimates of the elasticity of rural labor supply China Rural Econ. 10 69–82 (in Chinese)
Feng Z, Hu E, Wang X and Jiang L 2015 Ground-level O 3 pollution and its impacts on food crops in China: a review Environ. Pollut. 199 32–8
Feng Z, Kobayashi K and Ainsworth E A 2008 Impact of elevated ozone concentration on growth, physiology, and yield of wheat (tritium aestivum L.): a meta-analysis Glob. Change Biol. 14 2696–708
Griffin J M 1977 Long-run production modeling with pseudo data: electric power generation Bell J. Econ. 8 112–27
Heck W W, Taylor O, Adams R, Bingham G, Miller J, Preston E and Weinstein L 1992 Assessment of crop loss from ozone J. Air Pollut. Control Assoc. 32 353–61
Howitt R E 1995 Positive mathematical programming Am. J. Agric. Econ. 77 329–42
Just R E, Hueth D L and Schmitz A 2003 The Welfare Economics of Public Policy: A Practical Approach to Project and Policy Evaluation (Cheltenham: Edward Elgar Publishing)
Kopp R J and Krupnick A J 1987 Agricultural policy and the benefits of ozone control Am. J. Agric. Econ. 69 956–62
Lee E H, Tingey D T and Hogsett W E 1988 Evaluation of ozone exposure indices in exposure-response modeling Environ. Pollut. 53 43–62
Lobell D B and Asseng S 2017 Comparing estimates of climate change impacts from process-based and statistical crop models Environ. Res. Lett. 12 015001
McCarl B A and Spreen T H 1980 Price endogenous mathematical programming as a tool for sector analysis Am. J. Agric. Econ. 62 87–102
Mills G, Buse A, Gimeno B, Bermejo V, Holland M, Emberson L and Pleijel H 2007 A synthesis of AOT40 based response functions and critical levels of ozone for agricultural and horticultural crops Atmos. Environ. 41 2630–43
Muller N Z and Mendelsohn R 2007 Measuring the damages of air pollution in the United States J. Environ. Econ. Manage. 54 1–14
Preckel P V and Hertel T W 1988 Approximating linear programs with summary functions: pseudodata with an infinite sample Am. J. Agric. Econ. 70 397–402
Reilly J, Tubiello F, McCarl B, Abler D, Darwin R, Fuglie K, Hollinger S, Izaaralde C, Jiaapt S and Jones J 2003 US agriculture and climate change: new results Clim. Change 57 43–67
Tang H, Takigawa M, Liu G, Zhu J and Kobayashi K 2013 A projection of ozone-induced wheat production loss in China and India for the years 2000 and 2020 with exposure-based and flux-based approaches Glob. Change Biol. 19 2739–52
Wang X, Manning W, Feng Z and Zhu Y 2007 Ground-level ozone in China: distribution and effects on crop yields Environ. Pollut. 147 394–400
Wang X and Mauzerall D L 2004 Characterizing distributions of surface ozone and its impact on grain production in China, Japan and South Korea: 1990 and 2020 Atmos. Environ. 38 4383–402
Westenburger D A and Frisvold G B 1995 Air pollution and farm-level crop yields: an empirical analysis of corn and soybeans Agric. Resour. Econ. Rev. 24 156–65
Zhang Z 2004 A solution to improve the profits of agricultural sector Sci. Technol. Rev. 2 49–51