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Impacts of Surface Ozone Pollution on Crop Productivity: Evidence from Winter Wheat in China

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Abstract

The impact of surface ozone pollution on the yield of winter wheat is empirically estimated by considering socio-economic and climatic determinants. This research is the first to use an economic framework to estimate the ozone impact, and a unique county-level panel is employed to examine the impact of the increase of surface ozone concentration on the productivity of winter wheat. In general, the increment of surface ozone concentration during the ozone-sensitive period of winter wheat is found harmful to its yield, and the damage to China's grain supply and economic values are non-negligible. This study also confirms that other stress conditions, such as drought and air particles, can potentially mitigate the adverse effect of surface ozone exposure on the yield of winter wheat.

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1. Introduction

The Chinese government has given considerable attention on several factors that can threaten food security, such as agricultural land loss as a result of urbanization and climate change. However, yield losses driven by air pollution have not been realized. A set of air pollutants, specifically particles, and ozone, have been identified to potentially affect grain crops. Surface ozone had been recognized during the last century as an air pollutant that can adversely affect the growth of crops and induce significant yield losses in developed countries (Wahid *et al.* 1995; Benton *et al.* 2000; Fuhrer and Booker 2003; Ashmore 2005; Feng and Kobayashi 2009). China may have experienced the same effects of surface ozone pollution. According to the limited data obtained, the most industrialized areas in China, namely, Beijing-Tianjin region and Yangtze River Delta, have experienced more than 10 per cent of hourly mean of surface ozone concentrations exceeded the threshold of 60 ppb that damage crop growth. The maximum readings for Beijing-Tianjin and Sheshan, near Shanghai, are 170 and 196 ppb, respectively (Wang *et al.* 2007). According to a previous report, surface ozone concentrations in rural areas are evidently higher than those of urban areas (Wang *et al.* 2007), which implies that crops are more likely to be damaged by high ozone concentrations. Meanwhile, tolerance to ozone concentrations differs among various crops and wheat is seemingly one of the most sensitive ones (Jin *et al.* 2001; Wang *et al.* 2005). Avnery *et al.* (2011) predicted that wheat production loss from surface ozone pollution in China will be the second highest loss in the world by 2030. Therefore, measuring the relationship between the elevated surface ozone concentration and wheat yield is particularly important for future environmental policy formulation and food security in China.

The number of studies that measure the effects of surface ozone concentration on wheat productivity in China is limited. Overall, the adverse effects of elevated surface ozone concentration on crop yields have been well documented such as Heagle (1989), Ashmore (2005), and Feng *et al.* (2008). Regarding the effect of surface ozone on wheat production in China, the only available studies are those that discussed on wheat biophysical dose–response functions, such as Chameides *et al.* (1999), Wang *et al.* (2005), and Tang *et al.* (2013). These studies had similarly concluded that the yield of wheat is reduced by the high level of surface ozone concentration. Meanwhile, the economic assessment of agricultural impact of surface ozone pollution has received increased attention in the 1980s in the U.S. and Europe from researchers such as Kopp *et al.* (1985) and Adams *et al.* (1986). However, China has lagged immensely in this field.

The present paper analyzes winter wheat productivity in China by considering a comprehensive econometric estimation of wheat yield response to elevated surface ozone concentrations as a contribution to the literature. To date, the methods of assessing wheat yield losses driven by surface ozone pollution are compatible with other crops and could be classified under biological methods and economic models. A remarkable review about these two types of approaches is found in the study by Spash (1997). In laboratory or field experimentation conditions, using dose–response functions is the main biological approach to derive the influence of ozone concentrations on plants. The parameters derived from the dose–response functions are directly extended to predict crop yield losses in a specific region or nation (Chameides *et al.* 1994; Tilman *et al.* 2002). A few studies implemented economic programming models to estimate the effects of surface ozone pollution on total agricultural supply without estimating the impact of ozone exposure on yields. Instead, they used the adverse effect values of surface ozone pollution from laboratory studies or simulation models as inputs for agricultural sector models. Subsequently, future agricultural supplies and costs to reduce surface ozone concentration to preferred levels are simulated (Howitt *et al.* 1984; Adams *et al.* 1985; Adams *et al.* 1986; Adams *et al.* 1989). Technologically, all economic changes are triggered by the reductions of crop yields caused by surface ozone pollution. The advantage of these studies is the simplification of the analysis by the explicit expression between ozone concentrations and crop yields.

The use of the econometric method to estimate the effect of surface ozone exposure on crop yields is extremely limited in the literature. Regression methods have potential advantages in considering both surface ozone concentration and socio-economic factors. However, this type of research is thin. From the knowledge of the authors, Rowe and Chestnut (1985) are the only ones to use this type of method to measure the impacts of ozone concentrations on California crops. Besides the effect of surface ozone on crop yields, the estimation also considered both weather and economic determinants that are also important for crop growth and have been identified as part of the ozone impact.

Technically, studies on dose–response functions may overestimate the surface ozone shocks to agricultural sector. Most economic studies that adopt biological and programming models use dose–response functions. However, these studies encounter several methodological challenges that are driven by the inconsistency between extremely restricted laboratory requirements and various practical conditions. Quantifying the direct effect of ozone on crop yields in experiments is important to understand surface ozone pollution on agriculture. However, this step is only an initial action and is not considered to be complete. Regarding economic rationality of farmers, they may apply adaptive responses, such as adjusting management techniques and inputs to offset the adverse effect of surface ozone pollution. For example, much research has found that the decrease of growing conditions of crops, such as irrigation, could reduce ozone susceptibility (Wittig *et al.* 2007; Feng *et al.* 2008). Besides the adaptive responses of farmers, the use of dose–response functions cannot easily capture the interactions between ozone and other factors such as climate change, CO_2, and SO_2. In addition, according to Spash (1997), cultural and input variations among regions render dose–response functions derived from one area as inappropriate for other areas. Therefore, applying unique or limited dose–response functions for the prediction of future crop losses in a large country, such as China, would generate unacceptable bias. Thus, region- and crop-specific dose–response functions are strongly desired for an accurate estimation.

This paper uses econometric method and incorporates atmospheric, socio-economic, and biophysical information to identify the effect of surface ozone exposure on winter wheat yield. In the estimation, ozone exposure is found to have a significantly adverse effect on the yield of winter wheat, especially during the ozone-sensitive period. The interactions between ozone exposure and stress conditions, such as drought and air particles, are also examined. The study confirms that drought and particle pollution can mitigate the loss of winter wheat yield.

The rest of the paper is organized as follows. Section 2 describes the production of winter wheat in China. Section 3 introduces the theoretical framework and estimation strategies.

Sections 4, 5, and 6 present the data used for estimation, the empirical results, and the conclusion, respectively.

2. Winter wheat production in China

Wheat is one of the two primary food crops in China. In 2012, wheat sown areas account for 45 per cent of grain crop (rice and wheat) planting areas, and the total output comprises 37 per cent of domestic grain production. As the central government of China always regards food security as a primary concern for agriculture, the self-sufficiency rate of wheat is more than 97 per cent. On the other hand, the world market cannot sufficiently provide if China would tremendously increase its wheat import to feed a large population. The total global export of wheat in 2011 was only 14 per cent of the domestic wheat production in China (FAO, 2014). Hence, relying on the world market to satisfy the demand of wheat in China is not feasible. The quantity of domestic wheat supply is of critical importance for the goal of food self-sufficiency in China and the world food market.

Winter wheat is widely planted and contributes to the main output of wheat in China. Diverse climatic regions in China create wheat varieties across the country, such as spring wheat and winter wheat that are defined according to the planting season. Seven provinces in northeast China have spring wheat production, but the sown areas in these regions only accounts for 10 per cent of the total wheat planting areas. Winter wheat is planted in the rest of the regions in China and is the main variety in the entire country. Although the total wheat planting area experienced a decrease before 2003 (Figure 1), a set of policies for agriculture, such as elimination of agricultural tax and grain subsidy, stabilized the wheat production. Regarding the yield for different varieties of wheat, the yield of winter wheat is higher than spring wheat by an average of 25 per cent. In general, the yearly output of winter wheat accounts for 94 per cent of the total domestic wheat supply.

The overlap between ozone-sensitive period and warm season with high level of ozone concentration is likely to decrease the yield of winter wheat. Slaughter et al. (1989) observed that the ozone-sensitive stage for winter wheat is the period of anthesis and grain-filling during warm season. In China, winter wheat is typically sown in late winter and is harvested in May or June with slight differences over the regions. For example, winter wheat planted near Yangtze River has to be harvested before early June, and the one near Yellow River must be harvested before July. Hence, the ozone-sensitive period of winter wheat in China is generally in May. Meanwhile, much research has observed that, generally, the surface ozone concentration level between April and June reaches the yearly maximum (Zhao et al. 2010; Wang et al. 2011). Therefore, the seasonal variability of surface ozone is highly believed to harm the productivity of winter wheat.

3. Methods

3.1. Conceptual framework

The biological nature of agricultural production or the time lags involved between planting and harvesting is viewed as a two-stage process (Houck and Gallagher 1976; Yu *et al.* 2012). In the first stage, cropping acreage decisions of farmers are viewed as a function of expected input and output prices, government policies, and other non-economic considerations such as climate conditions, air pollutants, and soil types. In the second stage, after a crop is planted, farmers can decide the amount of inputs for the crop production based on varying conditions such as market and weather. During the crop growing season, farmers may substantially modify their production practices by adjusting input quality and quantity or other adaptive activities. This paper follows this two-stage feature of agricultural production.

As suggested by Houck and Gallagher (1976), the production function for wheat can be written as

$$Q = f_1(I, L; O, W, T, D), \tag{1}$$

where output of wheat (Q) is a function of input vector (I) and land area (L) at given surface ozone concentration level (O), weather condition (W), technology changes (T), and regional dummy variables accounting for other effects (D) such as local soil characteristics. Based on the profit maximization goal in the production theory, wheat output can be rewritten as

$$(2) \qquad Q = f_2\left(\frac{P^W}{P^I}, L_0; O, W, T, D\right),$$

where, given land area (L_0) that has been first decided, the optimal levels of inputs for profit maximization are a function of the ratio between wheat price P^W and input price P^I.

Therefore, the wheat yield function can be expressed from Equation (2) as

$$(3) \qquad Y = \frac{Q}{L_0} = f_3\left(\frac{P^W}{P^I}, L_0; O, W, T, D\right).$$

The yield function (3) for wheat production is the basis for the empirical identification of the effect of surface ozone concentration on the yield. The yield function has at least two advantages. First, the function does not explicitly represent the relation between inputs and yield because the information about myriad practices to farmers is not available in a county level. Given that the optimal input use is a function of input and output prices, the ratio between input and output prices would capture the same information as directly using the amount of inputs. The relation between yield Y and P^W/P^I is expected to be positive. The input and output price ratios have also been used in other studies, such as those by Dixon *et al.* (1994) and Segerson and Dixon (1999). In addition, at county level, an increase in area L_0 is assumed to result in yield decrease. This assumption is believed to be reasonable because an aggregate representative farmer is known to first use the land with comparative advantage for a specific crop, and then the productivity of the incremental land becomes less than that of the first used land. For example, along with the increase of wheat price, marginal land may be incorporated to wheat production, which can reduce the average yield of wheat. Hence, the relation between Y and L_0 will be negative.

3.2 Empirical strategy

In the empirical estimation, the key variables used in Equation (3) are elaborately incorporated. To identify the effect of surface ozone on the winter wheat yield, county level observations in China in 2006, 2008, and 2010 are used to estimate the empirical model as follows.

$$(4) \qquad Y_{i,t} = \beta_0 + \frac{P^I_{i,t-1}}{P^W_{i,t-1}}\beta_1 + L_{i,t}\beta_2 + O_{i,t}\beta_3 + W_{i,t}\beta_4 + T_t\beta_5 + D_i\beta_6 + \varepsilon_{i,t},$$

where $Y_{i,t}$ denotes the wheat yield in county i and year t, and βs are parameters to be estimated. Expected output and input prices ($P^W_{i,t-1}$ and $P^I_{i,t-1}$) are substituted by actual prices in the previous year. As an input vector, from the limited input price information, fertilizer and labor are chosen as the major inputs for wheat production. Furthermore, other inputs such as pesticide, herbicide, machinery service, and seeds are assumed to be in fixed proportions to planting areas. $L_{i,t}$ is the wheat planting area in county i in year t, and the earlier assumption that $L_{i,t}$ is determined before yield $Y_{i,t}$. T_t represents the hybrid effects such as technology trend and uncontrolled annual shocks. $\varepsilon_{i,t}$ is a random error term. County dummy variable D_i is also used for region-specific characteristics such as soil quality and location.

To express the effect of ozone exposure on winter wheat, three widely applied approaches are used to represent the relationship between surface ozone concentration and wheat yields.

$$M7(\text{ppbh}) = \frac{1}{n}\sum_{i=1}^{n} C^i_{O_3}$$

$$M12(\text{ppbh}) = \frac{1}{n}\sum_{i=1}^{n} C^i_{O_3}$$

$$SUM06(\text{ppb}) = \sum_{i=1}^{n}\left(C^i_{O_3} - 60\right) \quad \text{for } C^i_{O_3} \geq 60 \text{ ppb}$$

M7 and M12 are the average values of the hourly mean ozone concentration ($C_{O_3}^i$) during daylight hours (ppb per hour), 9:00 to16:00 and 8:00 to 20:00, respectively. SUM06 (also denoted 24-hr SUM06) is calculated as the sum of the differences between the hourly mean ozone concentration and 60 ppb when $C_{O_3}^i > 60$. n is the number of hours in the target growing season. In this paper, the growing season is defined similarly to that by Van Dingenen *et al.* (2009). It is calculated using accumulated daily mean temperature and occurs when an accumulated temperature sum of 1075 ºC is reached after the first frost-free day. However, the start of the ozone-sensitive period is days before the mid-anthesis at 270 ºC, and the end of the period is days after the start date at 970 ºC. To have an identical accumulation period length for all regions, the wheat growing season is reduced to three-month (92 days) period preceding the end date, as suggested by Van Dingenen *et al.* (2009) for comparison. Each of these measures is a different characterization of the ambient ozone condition that may affect wheat. M7 and M12 are average hourly measures, and SUM06 is a threshold measure. All these methods assume the linear relationship between crop yields and ozone concentrations. Hence, linear and quadratic forms of the measurement of surface ozone in the wheat yield estimation are separately used for robustness check.

Regarding the weather impacts on wheat yield, the method by Schlenker *et al.* (2006) that utilizes growing degree days (GDD) is followed to represent the relationship between weather and wheat yield. GDD is defined as the sum of degrees above a baseline and below the upper threshold during the growing season. Although the appropriate temperature threshold is debatable, the suggestion by Ritchie and NeSmith (1991) is followed to set the lower threshold temperature of 8 ºC and the upper threshold of 32 ºC. In addition, the quadratic form of the GDD between 8 and 32 ºC is selected to capture the effects of nonlinear temperature on winter wheat yield. As suggested by Ritchie and NeSmith (1991), accumulated degrees for winter wheat when exposed to the temperature that is higher than 34 ºC represent the potential harm of temperature on the yield.

Accumulated precipitation in the growing season covers another part of the weather impact on the winter wheat. The growing season has been defined from the first frost-free day to the day with accumulated temperature sum of 1075 ºC. According to the agronomic literature, a plateau is present after water reached a high threshold. Hence, a quadratic form of the precipitation is included to represent this nonlinear relationship.

Besides separately using temperature and precipitation to identify the weather impacts on the yield of winter wheat, both temperature and precipitation could be combined to construct aridity index to represent the crop–weather relation. Four potential aridity indices are used following Paltasingh *et al.* (2012) .

$$A_1 = \frac{R}{1.07^H}$$

$$A_2 = \frac{R}{H}$$

$$A_3 = \frac{R}{H + 10}$$

$$A_4 = \frac{R}{0.1\,H}$$

where $A_j, \forall\, j = 1, \dots, 4$, is various aridity indices defined according to sound agronomic and meteorological concepts. R and H represent average precipitation and mean temperature, respectively, during the winter wheat growing season, which essentially normalize rainfall with respect to temperature. Therefore, a low aridity index indicates high possibility of drought. For example, when A_1 is below 20, drought is implied, and when the value falls below 10, desert-like drought is indicated.

The definitions of aridity index can be used to reflect the interactions between drought and ozone effect on wheat yield. Feng *et al.* (2008) had substantially reviewed the impacts of intense drought on the adverse effect of ozone on wheat yield, but their conclusions on the relationship between ozone and drought remained mixed. The decrease of foliar gas exchange because of drought stress is considered to have less ozone-induced yield loss (Heagle 1989; Feng *et al.* 2008). However, in some studies, no clear interactions are observed between ozone and water stress (Temple 1986; Fangmeier *et al.* 1994). Hence, the current study adds an interaction term to model (4), between ozone exposure and drought index[1], to identify the possible mitigation effect of water stress. This setting has policy meaning because farmers can reduce irrigation to adapt to the elevated ozone concentration.

We also incorporate interaction terms between air particle pollution and ozone concentration in the estimation. Particles in growing season can reduce plant photosynthesis and respiration that decrease crop productivity (Farmer 1993; Hirano *et al.* 1995; Glenn *et al.* 2001). Hence, air pollution data must be added to the estimation (Wang *et al.* 2011). This setting is also for robustness examination.

4. Data

4.1 Economic variables

County-specific winter wheat yield and sown areas are collected from the database of the Institute of Agricultural Information at the Chinese Academy of Agricultural Sciences. First, a total of 19 provinces are chosen as the main winter wheat production area, accounting for 92 per cent of the nationwide winter wheat planting areas in the last decade. These provinces include Beijing, Tianjin, Heibei, Shanxi, Shannxi, Shanghai, Jiangsu, Anhui, Fujian, Jiangxi, Shandong, Henan, Hubei, Hunan, Guangdong, Guangxi, Chongqing, Sichuan, and Yunnan. However, not all the winter wheat planting counties in these 19 provinces are used for the estimation because of the lack of simulated ozone data. Among the winter wheat production areas, a total of 750 counties are used as sample, which accounts for 73 per cent of the planting areas in the selected provinces. The sample is considered to be adequate to represent the winter wheat production in the country. Summary statistics for the wheat production are shown in Table 1.

Provincial wheat production data including wheat, wage, and fertilizer prices are obtained from the data compilation of the China Agricultural Product Cost and Revenue. This type of information is used to fill the deficiency of county-specific data.

4.2 Weather

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[1] We define drought if $A_1 < 20$, and vice versa.

The weather data are obtained from the China Meteorological Data Sharing Service System, which provides the daily minimum, maximum, and average temperatures as well as precipitation recorded in 825 weather stations in China in 2006, 2008 and 2010. However, the distribution of weather stations is not exactly consistent with county territory, that is, a few counties may have more than one station or may have none. Hence, the spatial interpolation method based on the *observed climatic information is used to generate weather data for each county.*

4.3 Ozone

Yearly measurements of surface ozone are extremely limited in China. Ideally, actual monitored data for agricultural regions should be used for the estimation. Unfortunately, such complete data do not exist in China, even for developed urban areas. Only sparse and discontinuous monitoring data before 2000 are available, which are mostly project-driven observations. No long-term ozone monitoring data are found from established observation sites (Wang *et al.* 2007). Instead, simulated surface ozone data can be found in existing studies (Aunan *et al.* 2000; Fishman *et al.* 2010; Avnery *et al.* 2011; Wang *et al.* 2011). As emphasized by meteorologists, simulated model results are in a fairly close correspondence between predicted and observed ozone levels. In the present paper, the Community Multi-scale Air Quality (CMAQ) model (Byun and Schere 2006) of the US Environmental Protection Agency is used to simulate hourly ozone concentration for each county. CMAQ simultaneously treats multiple pollutants from local to continental scales and includes comprehensive physics and chemical processes, such as gas and aqueous chemical transformation, aerosol chemistry and dynamics, deposition, and photolysis. In this study, CMAQ is run in a horizontal resolution of 36 x 36 km and a vertical structure of 15 sigma layers, with gas-phase chemistry mechanism and aerosol module of CB05 and AERO4, respectively. The simulation region covers the main terrestrial zone of China. The field measurement data from Hongkong in the Pearl River Delta and Nanjing in the Yangtze River Delta in 2008 are used to validate the simulation results. The ozone-sensitive period of winter wheat is mostly between March and May. Thus, Figure 2 illustrates the similar pattern between simulated data and the observed ozone information although some observations are missed in Nanjing.

The county-level simulated ozone concentration data are the main concern for the biased estimation. In the canonical errors-in-variables (EIV) models, observed surface ozone data are denoted by $O = O^* + \eta$, where O is the measurement for the latent variable of ozone concentration O^* with measurement error η. To simplify notations, the subscripts for all the variables in the above expression are removed. η is assumed to have zero as mean, variance σ_η, and is independent of O^*, which means that the errors are only introduced by the measuring device and the simulation model calibrations. The observed magnitudes do not depend on the value being measured. If the measurement errors are not considered, the estimation will obtain an attenuation bias, i.e., $\beta_3^* = \lambda\,\beta_3$. $\lambda = \frac{1}{1+\sigma_\eta^2/\sigma_{O^*}^2}$ is also called reliability ratio and is less than 1, β_3^* and β_3 are the true effect of surface ozone on yield and the coefficient of simulated surface ozone on yield, respectively. Hence, addressing the measurement error variance is the critical step for the unbiased estimation. Given that hourly simulated surface ozone concentration data are simultaneously generated, $\sigma_\eta^2/\sigma_{O^*}^2$ is assumed to be constant over time in various regions. Surface ozone data of Hongkong and Nanjing in 2008 are then used to estimate the variance ratio and applied in the remaining steps. After integrating the observed and simulated surface ozone concentration data of the two cities during the research period, the reliability ratio is estimated as 0.96.

4.4 Air particle

With the absence of county-level data, the present study uses the city-level air quality data. Air pollution index (API) measured urban area air qualities in China before 2013. With API only measuring SO_2, NO_x, and particulate matter, the values over 100 and 200 therefore represent mild and moderate pollution, respectively. Typically, API is measured based on daily primary pollutant, and 95 per cent of daily API is calculated on the basis of particles. Therefore, the API value is believed to generally show daily particle level.

5. Results

5.1 Empirical results

Regression results for various specifications are shown in Table 2. From specifications (1) to (4), more explanatory variables are controlled to identify the impact of ozone exposure. Among the four models, ozone concentration measured by M7 has significantly negative effects on the yield of winter wheat. Given that specification (1) does not control county-specific effects, the sign for wheat planting areas contradicts the expectation of this study. Specification (3) rules out time and county-fixed effects, and all the signs for the covariates are found to have expected signs. In addition, the R-squared in specifications (2) and (3) have impressive improvements of 0.9. This result implies higher explanatory power of the estimation. Specification (4) is the preferred estimation because this specification considers both economic covariates and weather variables, including temperature and precipitation. The results show that one unit increase of ozone exposure measured by M7 corresponds to a decrease in winter wheat yield by 0.68 per cent, which is significant at 1 per cent level. Specification (5) incorporates M7 squared to capture the nonlinear relationship between the yield of winter wheat and ozone exposure, and the coefficient is found to be negative.

Table 3 presents the results of different ozone exposure measures proposed in the literature. Specifications (1), (3), and (5) incorporate M7, M12, and SUM06, respectively, to measure the effects of ozone exposures on winter wheat. These measurements are calculated during the winter wheat ozone-sensitive periods. The coefficients for the various scenarios are close and significant at 1 per cent level. Van Dingenen *et al.* (2009) suggested using an identical accumulation period length (three months) for all regions in comparing different ozone exposure approaches. Thus, specifications (2), (4), and (6) also measure ozone exposure using M7, M12, and SUM06, respectively, but are not limited to ozone-sensitive periods. However, no significantly negative effects of ozone on the wheat yield are found. Therefore, we confirm that wheat is only sensitive to ozone pollution during specific periods (Slaughter *et al.* 1989), and addressing the exact time is important for the identification of ozone effect. In the unreported specifications that include squared M12 or SUM06, surface ozone also has significantly adverse effect on the wheat yield.

For the ozone measurement error, Table 4 demonstrates the attenuation of coefficients by the variable measurement errors. By comparing the results in Table 4 with those in Table 3, the estimated negative effects of ozone pollution are found less than those indicated in Table 3. Hence, the effect of surface ozone exposure on wheat yield is underestimated if the measurement errors are ignored.

5.2 Robustness check

Two types of sensitivity checks are presented in Tables 5 and 6 to ensure that the estimated ozone effect on wheat yield is identified from other covariates, such as water stress and air pollution. Specifications (2) to (5) in Table 5 use four different aridity indices to control weather impacts on wheat yields. The coefficient for ozone exposure is found to be robust. The positive coefficients for aridity indices indicate that normalized rainfall stimulates the wheat yields regardless of the non-significance. Notably, specification (6) incorporates the interacted term between ozone concentration and drought index. The significantly positive coefficient on the interaction variable shows that drought mitigates the damage effect of ozone on the wheat yield, and this finding is consistent with the results obtained by Heagle (1989) and Feng *et al.* (2008).

Table 6 shows the interactions between ozone exposure and air particle pollution. We find that particle pollution reduces wheat yield (columns 3 and 5 in Table 6), which is consistent with the findings by Farmer (1993) and Hirano *et al.* (1995). In addition, this result is comparable with the drought discussion that the stress from air particle also mitigates the adverse effect of ozone on wheat yield from specifications (2) and (5) using interaction terms between ozone concentration and API in Table 6.

5.3 Impact of surface ozone variation

This section describes the relative contributions of the various covariates to wheat yield change from 2006 to 2010, as shown in Table 7. The coefficients used for the calculations are from baseline specification (4) in Table 2. The total yield growth of winter wheat from 2006 to 2008 was 6.53 per cent. Weather, including temperature and precipitation, evidently contribute by 20 per cent and 4 per cent, respectively. However, the increase of wheat planting areas has a negative 12 per cent impact to the yield growth during this period. The elevated surface ozone concentration results in yield decrease by 46 per cent, which is not a trivial impact to the yield.

Without factors such as technology advancement that contribute to over 122 per cent of the yield increment, the increase in wheat yield from 2006 to 2008 would not have been observed.

Meanwhile, ozone exposure was found to positively affect winter wheat yield growth from 2006 to 2010. Out of the 6.4 per cent yield growth of wheat in this period, ozone concentration change contributed to 21 per cent (Table 7). This finding seemingly contradicts the results from 2006 to 2008. Again, surface ozone concentration is not solely determined by anthropogenic emissions. Climate and other natural precursor sources also affect the concentrations (Wang *et al.* 2011). Therefore, yearly ozone concentration is not monotonously increasing. Compared with the ozone concentration level in 2006, the mean ozone level in 2008 increased by more than 10 per cent, but decreased by more than 5 per cent in 2010 (see Figure 3). Therefore, the result in column (3) is consistent with that in column (5), with consideration of the change direction of ozone (in Table 7). In other words, the results from 2006 and 2010 confirm that winter wheat can benefit from the reduction of ozone exposure.

This study also computes the economic loss of wheat driven by the increase of ozone exposure from 2006 to 2008. Using different measures of ozone concentrations (M7, M12 and SUM06) in the winter wheat ozone-sensitive season, the total output of winter wheat is reduced by 2.15 per cent, 1.35 per cent and 1.56 per cent, respectively. The corresponding economic loss is between 157 million to 254 million Yuan. This amount of economic loss exceeds 1/3 of annual direct grain subsidy budget in one of the main grain production province, Sichuan.

6. Conclusions

Given that more attention has recently been given to air pollution concerns in China, such as impacts of air quality change on public health, the impacts of surface ozone pollution on grain yields have not been realized. The potential adverse effect could be a serious threat to the goal of the central government on food security. This study provides a rigorous analysis of ozone exposure on winter wheat yield based on a unique county-specific panel. Daily weather and socio-economic variables are compiled to identify the impact of ozone exposure on winter wheat yield. This study is the first empirical county-level study that estimates the relationship between wheat yield and surface ozone.

This study finds that the increase of ozone exposure is harmful to the yield of winter wheat. By incorporating the most commonly used measurements of surface exposure, which are M7, M12, and SUM06, the increase of ozone concentration during the sensitive period is observed to consistently dampen the winter yield increase. This empirical finding supports previous biological literature about the negative effect of ozone on wheat yield. However, evidence on whether the extended period of ozone exposure can reduce the yield is not indicated. In addition, this paper confirms the potential mechanism of the interactions between stress conditions and ozone to wheat productivity. Drought and dust in the air are found to possibly mitigate the negative impact of ozone on the yield of winter wheat. Overall, the increase of ozone concentration is harmful to the winter wheat yield. In the meantime, the economic loss driven by the ozone pollution is not trivial. From the perspective of agricultural production and food security, the government has to formulate relevant environmental policies to reduce ozone precursor emissions.

This study could be improved in several ways. First, given that the data only cover three years, the effects on the adaptation behavior of farmers may not have been captured. Hence, the magnitude of the ozone impact is possibly higher than the realistic effect. A long panel is needed to accurately address the impacts of ozone exposure on the wheat yield. Second, although significant impact of ozone exposure is found, the observed ozone data are always preferred at their availability for the future research. Third, the analysis of this study did not consider the impacts of interaction effect of ozone and other air pollutants on the wheat yield. The decrease of wheat yield caused by ozone exposure is expected to be less at elevated CO_2 and SO_2 (Wang *et al.* 2005; Feng *et al.* 2008). This study obviously cannot fully identify these interactions because of the data shortage.

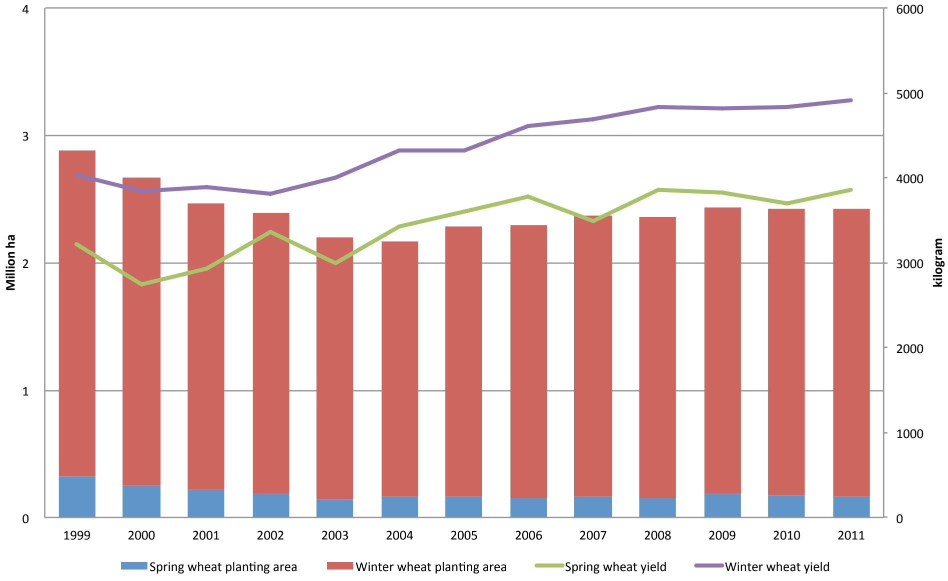

Figure 1: Sown areas and yields for spring wheat and winter wheat in China

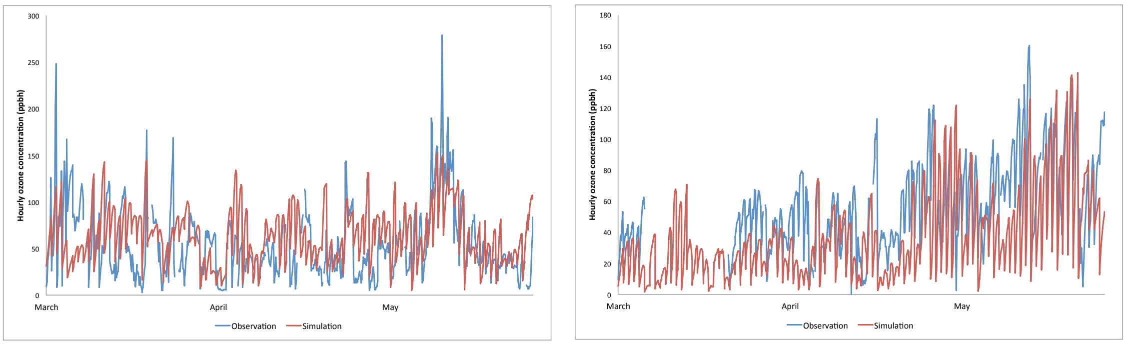

Figure 2: Comparison between observed hourly surface ozone and simulated ozone concentration in Hongkong (left) and Nanjing (right) in 2008

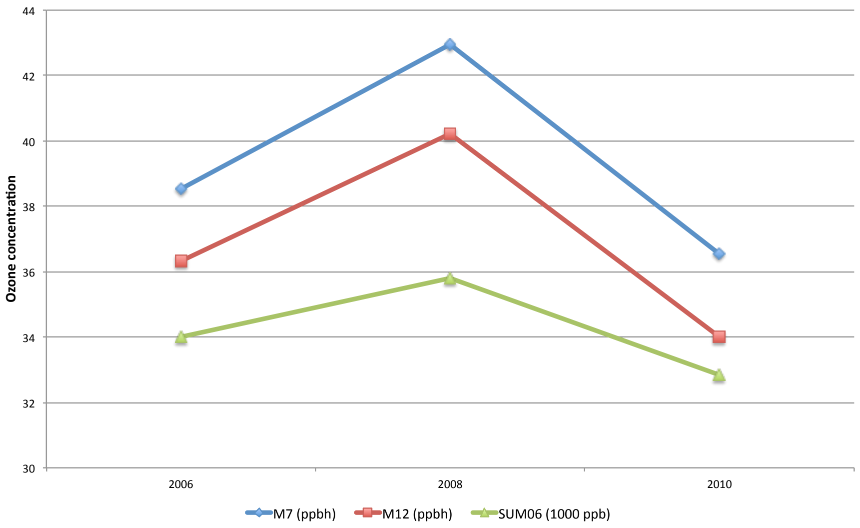

Figure 3: Various surface ozone concentration measurements (2006, 2008, and 2010)

Table 1: Summary statistics (2006, 2008, and 2010)

Variable	Mean	S.D.	Minimum	Maximum
Wheat sown area (1000 ha)	21.3875	23.2231	0.0010	221.8800
Yield (tonne/ha)	4.4657	1.6438	0.1342	9.4876
Wheat price (yuan/kg)	1.4284	0.1354	1.1260	1.7164
Wage (yuan/mu)	30.1238	9.5119	15.6064	56.5109
Fertilizer price (yuan/kg)	3.7727	0.2981	3.1071	4.3607
M7 (ppbh)	39.3708	13.1714	7.4711	94.8753
M12 (ppbh)	36.8737	14.4255	5.3005	93.4381
SUM06 (1000 ppb)	34.2312	21.5956	0	155.8464
Growing degree days (8-32°C) (1000)	1.1918	0.3091	0.02175	2.5455
Growing degree days (34°C+)	0.0014	0.0287	0	0.6000
Precipitation (meter)	0.1400	0.1191	0.0004	1.1614
Days of API more than 100	23.2984	12.5760	0	62.0233
Days of API more than 200	1.2857	1.8575	0	9.0000
Number of observations	2180			

Notes: 1 hectare = 15 mu.

Table 2: Effect of ozone on winter wheat yield (Errors-in-variables regression)

Variable	(1)	(2)	(3)	(4)	(5)
M7 (ppbh)	-0.0191***	-0.0030**	-0.0059***	-0.0068***	
	(0.0008)	(0.0014)	(0.0016)	(0.0018)	
M7 (ppbh) squared					-0.0001***
					(0.0000)
Wheat sown area	0.0056***	-0.0118***	-0.0122***	-0.0124***	-0.0124***
	(0.0004)	(0.0007)	(0.0006)	(0.0006)	(0.0006)
Ratio of wheat price and wage	0.3412	-0.9523***	0.1806	0.3470	0.4036
	(0.3413)	(0.1869)	(0.2512)	(0.2559)	(0.2581)
Ratio of wheat price and fertilizer price	0.9624***	0.4338**	0.4208	0.4327	0.4256
	(0.3079)	(0.2144)	(0.3201)	(0.3193)	(0.3189)
Growing degree days (8-32°C)				-0.6113**	-0.5574**
				(0.2619)	(0.2546)
Growing degree days (8-32°C) squared				0.1944*	0.1711
				(0.1097)	(0.1062)
Square root of growing degree days (34°C+)				0.0421	0.0394
				(0.1256)	(0.1255)
Precipitation				0.4521***	0.5263***
				(0.1643)	(0.1660)
Precipitation squared				-0.6189***	-0.6551***
				(0.1943)	(0.1954)
Year fixed effect	No	No	Yes	Yes	Yes
County fixed effect	No	Yes	Yes	Yes	Yes
Constant	1.6736***	0.5816***	0.6804***	0.6848***	0.4754**
	(0.0908)	(0.1920)	(0.2303)	(0.2451)	(0.2260)
Number of observations	2180	2180	2180	2180	2181
R^2	0.3713	0.9145	0.9172	0.9186	0.9186

Notes: Reliability ratio of the five models are all set to 0.96. Significance codes: * 10% level, ** 5% level, *** 1% level. Standard errors are in parentheses.

Table 3: Effect of ozone on winter wheat yield with different ozone exposure measures (Errors-in-variables regression)

Variable	Baseline	Alternative approach to represent ozone exposure				
	(1)	(2)	(3)	(4)	(5)	(6)
M7 (ppbh) (ozone-sensitive period)	-0.0068***					
	(0.0018)					
M7 (ppbh) (March-May)		-0.0226				
		(0.0166)				
M12 (ppbh) (ozone-sensitive period)			-0.0063***			
			(0.0017)			
M12 (ppbh) (March-May)				-0.0234		
				(0.0150)		
SUM06 (1000 ppb) (ozone-sensitive period)					-0.0070***	
					(0.0023)	
SUM06 (1000 ppb) (March-May)						-0.0018
						(0.0011)
Wheat sown area	-0.0124***	-0.0122***	-0.0124***	-0.0123***	-0.0125***	-0.0121***
	(0.0006)	(0.0006)	(0.0006)	(0.0007)	(0.0007)	(0.0006)
Ratio of wheat price and wage	0.3470	0.4733	0.3332	0.4883	0.2622	0.2192
	(0.2559)	(0.3395)	(0.2553)	(0.3252)	(0.2531)	(0.2552)
Ratio of wheat price and fertilizer price	0.4327	1.3581	0.4176	1.3887*	0.6647**	0.6715*
	(0.3193)	(0.8306)	(0.3189)	(0.7536)	(0.3378)	(0.3861)
Growing degree days (8-32°C)	-0.6113**	-0.7497	-0.5867**	-0.7369*	-0.7298**	-0.2950
	(0.2619)	(0.4555)	(0.2597)	(0.4054)	(0.2936)	(0.2465)
Growing degree days (8-32°C) squared	0.1944*	0.3353	0.1825*	0.3362	0.1702	0.0628
	(0.1097)	(0.2547)	(0.1086)	(0.2264)	(0.1114)	(0.1037)
Square root of growing degree days (34°C+)	0.0421	0.0793	0.0461	0.0943	0.0788	0.0331
	(0.1256)	(0.1337)	(0.1257)	(0.1347)	(0.1270)	(0.1267)
Precipitation	0.4521***	0.2545	0.4396***	0.2037	0.3979**	0.4120**
	(0.1643)	(0.2078)	(0.1642)	(0.2172)	(0.1643)	(0.1655)
Precipitation squared	-0.6189***	-0.5736***	-0.6032***	-0.5217***	-0.5241***	-0.5251***
	(0.1943)	(0.1968)	(0.1938)	(0.1923)	(0.1924)	(0.1939)
Year fixed effect	Yes	Yes	Yes	Yes	Yes	Yes
County fixed effect	Yes	Yes	Yes	Yes	Yes	Yes
Constant	0.6848***	1.3180*	0.6515***	1.3598*	0.7884***	0.3816*
	(0.2451)	(0.7934)	(0.2418)	(0.7207)	(0.2773)	(0.2303)
Number of observations	2180	2180	2180	2180	2180	2180
R^2	0.9186	0.9184	0.9186	0.9188	0.9187	0.9175

Notes: Reliability ratio of the six models are all set to 0.96. Significance codes: * 10% level, ** 5% level, *** 1% level. Standard errors are in parentheses.

Table 4: Effect of ozone on winter wheat yield without consideration of measurement errors

Variable	(1)	(2)	(3)
M7 (ppbh) (ozone-sensitive period)	-0.0037***		
	(0.0011)		
M12 (ppbh) (ozone-sensitive period)		-0.0033***	
		(0.0011)	
SUM06 (1000 ppb) (ozone-sensitive period)			-0.0022***
			(0.0007)
Wheat sown area	-0.0122***	-0.0122***	-0.0121***
	(0.0013)	(0.0013)	(0.0013)
Ratio of wheat price and wage	0.2627	0.2540	0.1947
	(0.2763)	(0.2758)	(0.2751)
Ratio of wheat price and fertilizer price	0.3800	0.3711	0.4256
	(0.3309)	(0.3307)	(0.3269)
Growing degree days (8-32°C)	-0.4337	-0.4175	-0.3822
	(0.2752)	(0.2744)	(0.2592)
Growing degree days (8-32°C) squared	0.1128	0.1051	0.0648
	(0.1048)	(0.1042)	(0.0973)
Square root of growing degree days (34°C+)	0.0305	0.0324	0.0360
	(0.0695)	(0.0700)	(0.0700)
Precipitation	0.4404**	0.4336**	0.4178**
	(0.1859)	(0.1866)	(0.1867)
Precipitation squared	-0.5733**	-0.5641**	-0.5212**
	(0.2633)	(0.2638)	(0.2637)
Year fixed effect	Yes	Yes	Yes
County fixed effect	Yes	Yes	Yes
Constant	0.5007***	0.4798***	0.4412***
	(0.1610)	(0.1585)	(0.1540)
Number of observations	2180	2180	2180
R^2	0.9179	0.9179	0.9176

Notes: Significance codes: * 10% level, ** 5% level, *** 1% level. Standard errors are in parentheses.

Table 5: Effect of ozone on winter wheat yield with different weather variables (Errors-in-variables regression)

Variable	Baseline	Alternative approach to represent weather impacts				
	(1)	(2)	(3)	(4)	(5)	(6)
M7 (ppbh)	-0.0068***	-0.0058***	-0.0058***	-0.0058***	-0.0058***	-0.0094***
	(0.0018)	(0.0016)	(0.0016)	(0.0016)	(0.0016)	(0.0021)
M7 (ppbh) × dummy variable for drought						0.0020***
						(0.0006)
Aridity index 1 (A_1)		0.0010				
		(0.0007)				
Aridity index 2 (A_2)			0.0038			
			(0.0024)			
Aridity index 3 (A_3)				0.0103		
				(0.0075)		
Aridity index 4 (A_4)					0.0004	
					(0.0002)	
Wheat sown area	-0.0124***	-0.0122***	-0.0122***	-0.0122***	-0.0122***	-0.0122***
	(0.0006)	(0.0006)	(0.0006)	(0.0006)	(0.0006)	(0.0006)
Ratio of wheat price and wage	0.3470	0.1999	0.1839	0.1999	0.1839	0.5130**
	(0.2559)	(0.2514)	(0.2511)	(0.2515)	(0.2511)	(0.2611)
Ratio of wheat price and fertilizer price	0.4327	0.4462	0.4565	0.4461	0.4565	0.5508*
	(0.3193)	(0.3204)	(0.3206)	(0.3205)	(0.3206)	(0.3202)
Growing degree days (8-32°C)	-0.6113**					-0.8562***
	(0.2619)					(0.2765)
Growing degree days (8-32°C) squared	0.1944*					0.2854**
	(0.1097)					(0.1150)
Square root of growing degree days (34°C+)	0.0421					0.0423
	(0.1256)					(0.1249)
Precipitation	0.4521***					0.7081***
	(0.1643)					(0.1791)
Precipitation squared	-0.6189***					-0.8484***
	(0.1943)					(0.2059)
Year fixed effect	Yes	Yes	Yes	Yes	Yes	Yes
County fixed effect	Yes	Yes	Yes	Yes	Yes	Yes
Constant	0.6848***	0.6168***	0.5818**	0.6198***	0.5818**	0.7389***
	(0.2451)	(0.2347)	(0.2386)	(0.2348)	(0.2386)	(0.2461)
Number of observations	2180	2180	2180	2180	2180	2180
R^2	0.9186	0.9173	0.9174	0.9173	0.9174	0.9195

Notes: Reliability ratio of the six models are all set to 0.96. Significance codes: * 10% level, ** 5% level, *** 1% level. Standard errors are in parentheses.

Table 6: Effect of ozone on winter wheat yield--interaction with air particle pollution (Errors-in-variables regression)

Variable	Baseline	Incorporate air particles			
	(1)	(2)	(3)	(4)	(5)
M7 (ppbh)	-0.0068***	-0.0099***	-0.0269***	-0.0070***	-0.0080***
	(0.0018)	(0.0020)	(0.0048)	(0.0018)	(0.0020)
M7 (ppbh) × Days of API that is more than 100		0.0001***	0.0005***		
		(0.0000)	(0.0001)		
M7 (ppbh) × Days of API that is more than 200				0.0002**	0.0007**
				(0.0001)	(0.0003)
Days of API more than 100			-0.0169***		
			(0.0034)		
Days of API more than 200					-0.0233**
					(0.0119)
Wheat sown area	-0.0124***	-0.0126***	-0.0135***	-0.0124***	-0.0124***
	(0.0006)	(0.0006)	(0.0007)	(0.0006)	(0.0006)
Ratio of wheat price and wage	0.3470	0.4051	1.4675***	0.0328	0.5270
	(0.2559)	(0.2536)	(0.3455)	(0.2894)	(0.3891)
Ratio of wheat price and fertilizer price	0.4327	-0.4480	-1.0603***	0.2086	0.2012
	(0.3193)	(0.3513)	(0.3739)	(0.3333)	(0.3328)
Growing degree days (8-32°C)	-0.6113**	-0.9543***	-1.9336***	-0.7420***	-0.7967***
	(0.2619)	(0.2720)	(0.3713)	(0.2683)	(0.2719)
Growing degree days (8-32°C) squared	0.1944*	0.3661***	0.8128***	0.2602**	0.2835**
	(0.1097)	(0.1160)	(0.1643)	(0.1136)	(0.1153)
Square root of growing degree days (34°C+)	0.0421	-0.0406	-0.0060	0.0011	0.0141
	(0.1256)	(0.1249)	(0.1219)	(0.1267)	(0.1267)
Precipitation	0.4521***	0.4491***	0.1637	0.4457***	0.4197**
	(0.1643)	(0.1624)	(0.1673)	(0.1641)	(0.1643)
Precipitation squared	-0.6189***	-0.5978***	-0.4585**	-0.6126***	-0.5826***
	(0.1943)	(0.1920)	(0.1874)	(0.1940)	(0.1939)
Year fixed effect	Yes	Yes	Yes	Yes	Yes
County fixed effect	Yes	Yes	Yes	Yes	Yes
Constant	0.6848***	1.1025***	2.2542***	0.8000***	0.8337***
	(0.2451)	(0.2615)	(0.3940)	(0.2504)	(0.2525)
Number of observations	2180	2180	2180	2180	2180
R^2	0.9186	0.9205	0.9245	0.9189	0.9191

Notes: Reliability ratio of the five models are all set to 0.96. Significance codes: * 10% level, ** 5% level, *** 1% level. Standard errors are in parentheses.

Table 7: Accounting for winter wheat yield change

Variable	Estimated coefficient	2006-2008		2006-2010	
		Change in Explanatory varialbe (2006-2010)	Contribution to yield growth (%)	Change in Explanatory varialbe (2006-2010)	Contribution to yield growth (%)
	(1)	(2)	(3)=(1)×(2)	(4)	(5)=(1)×(4)
M7 (ppbh)	-0.68	4.41	-3.00	-2.00	1.36
			(-45.94)		(21.18)
Wheat sown area	-1.24	0.62	-0.77	1.67	-2.07
			(-11.77)		(-32.28)
Temperature			1.30		1.92
			(19.91)		(29.98)
Growing degree days (8-32°C)	-61.13	-0.02	1.22	-0.12	7.64
			(18.72)		(119.16)
Growing degree days (8-32°C) squared	19.44	0.004	0.08	-0.29	-5.72
			(1.19)		(-89.18)
Precipitation			0.29		0.84
			(4.37)		(13.17)
Precipitation	45.21	0.02	0.90	0.03	1.35
			(13.85)		(21.11)
Precipitation squared	-61.89	0.01	-0.62	0.01	-0.51
			(-9.48)		(-7.95)
Time effect	—	—	8.00	—	5.39
			(122.51)		(84.09)
Residual	—	—	0.71	—	-1.03
			(10.92)		(-16.13)
Total growth			6.53		6.41
			(100)		(100)

Notes: The estimated coefficients are taken from specification (4) in Table 2. The number in parentheses are the contributions of these variables to wheat yield growth, with total yield growth set at 100.

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