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An economic assessment of the health effects and crop yield losses caused by air pollution in mainland China

Weijie Miao[1], Xin Huang[2], Yu Song[1,*]

1. *State Key Joint Laboratory of Environmental Simulation and Pollution Control, Department of Environmental Science, Peking University, Beijing 100871, China. E-mail: miaoweijie@pku.edu.cn*
2. *Institute for Climate and Global Change Research, School of Atmospheric Sciences, Nanjing University, Nanjing 210093, China*

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ABSTRACT

Air pollution is severe in China, and pollutants such as $PM_{2.5}$ and surface O_3 may cause major damage to human health and crops, respectively. Few studies have considered the health effects of $PM_{2.5}$ or the loss of crop yields due to surface O_3 using model-simulated air pollution data in China. We used gridded outputs from the WRF-Chem model, high resolution population data, and crop yield data to evaluate the effects on human health and crop yield in mainland China. Our results showed that outdoor $PM_{2.5}$ pollution was responsible for 1.70–1.99 million cases of all-cause mortality in 2006. The economic costs of these health effects were estimated to be 151.1–176.9 billion USD, of which 90% were attributed to mortality. The estimated crop yield losses for wheat, rice, maize, and soybean were approximately 9, 4.6, 0.44, and 0.34 million tons, respectively, resulting in economic losses of 3.4 billion USD. The total economic losses due to ambient air pollution were estimated to be 154.5–180.3 billion USD, accounting for approximately 5.7%–6.6% of the total GDP of China in 2006. Our results show that both population health and staple crop yields in China have been significantly affected by exposure to air pollution. Measures should be taken to reduce emissions, improve air quality, and mitigate the economic loss.

Introduction

Epidemiologic studies and field experiments have consistently demonstrated that air pollution has adverse impacts on human health and crop yield and quality. Among the various atmospheric pollutants, fine particulate matter ($PM_{2.5}$, particulate matter with an aerodynamic diameter less than or equal to 2.5 μm) has received the most attention in recent years because it is more toxic than coarser PM_{10} (particulate matter with an aerodynamic diameter less than or equal to 10 μm) (Pope, 2000; Pope and Dockery, 2006; Pope et al., 2009; Samet et al., 2000). Surface O_3 is now regarded as the most harmful air pollutant to crops due to its photosynthetic toxicity and extensive distribution in the world's main agricultural areas (North America, Europe, and East Asia) (Fuhrer, 2003; Fuhrer and Booker, 2003; Heck et al., 1982, 1984a, 1984b).

Numerous studies have been conducted to quantify the health impact (Chen et al., 2013; Kan et al., 2004; Lim et al., 2012; Zhang et al., 2007) and crop yield loss (Avnery et al., 2011; Tang et al., 2013; Van Dingenen et al., 2009; Wang and Mauzerall, 2004) caused by air pollution. These assessments have linked the science to policy making, rendering it possible to quantify the effect that public policies have on the health of the population and agriculture, and assisting with the allocation of resources to deal with the problem.

* *Corresponding author*. E-mail: songyu@pku.edu.cn (Yu Song).

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With the rapid growth of the economy and urbanization, fossil fuel consumption has continued to increase, along with the concentrations of tropospheric aerosols and O_3 and will likely rise further in east Asia, particularly China, in the near future (Akimoto, 2003; Chan and Yao, 2008; Horowitz, 2006; Xu et al., 2008).

Previous health impact assessment (HIA) studies have relied mainly on surface monitoring data. Kan and Chen (2004) and Zhang et al. (2007) used monitoring data and epidemiological concentration–response (C–R) functions to evaluate the health effects of PM_{10} in Shanghai and Beijing, with reported losses of 1.03% and 6.55% of local gross domestic product (GDP), respectively. The World Bank (2007) estimated that 352,000 premature deaths were related to PM_{10} exposure among an urban population of 520 million based on air pollution monitoring data. These monitoring data-based studies have indicated that air pollution in China consistently causes health damage to the urban population. However, there are demands for new technologies to better identify the temporal and spatial distribution of air pollution, as monitoring stations are often distributed unevenly.

Model-simulated air pollution results could reproduce the evolution and distribution of pollutants with a high resolution. Several recent studies of $PM_{2.5}$ (Apte et al., 2015; Lim et al., 2012; Rohde and Muller, 2015) have used an integrated exposure-response model together with surface observed data, or a combination of surface observed data, satellite data, and chemical model results, to conclude that 1.2–1.6 million premature deaths from five major diseases per year were related to $PM_{2.5}$ in China. These results suggest that major damage to population health is caused by air pollution, with damage levels higher than previously experienced in China. However, C–R functions, population data, and thresholds still need further verification.

Surface O_3 pollution in China is considered to be high enough to affect crop yields (Chameides et al., 1999). Previous studies (Avnery et al., 2011; Tang et al., 2013; Van Dingenen et al., 2009; Wang and Mauzerall, 2004) have demonstrated that staple crop yields in China (wheat, rice, maize, and soybean) have been suffering losses due to surface O_3 in China, with relative yield losses of 5%–11% for wheat, 10%–15% for rice, 22% for maize, and 16% for soybean. However, global scale studies usually require coarse resolution crop yield data, which may overestimate or underestimate crop yield losses in China. Other studies have only focused on yield loss in one or two staple crops, which may weaken the implications of the results.

To develop new air quality standards for protecting human health and crops and to take measures to mitigate air pollution, more studies are needed to improve policy decision making. There have been no synthesized studies that have focused on both the adverse health effects of $PM_{2.5}$ and the adverse effects on crops countrywide due to surface O_3. In this study, we applied the WRF-Chem (Weather Research and Forecasting model coupled to Chemistry) model, high-resolution population data, and crop yield data, combined with a C–R function derived from a meta-analysis of epidemiological studies and field experiments to perform an integrated assessment of the economic losses resulting from the health effects and crop yield losses due to air pollution in China. The objectives of this study can be summarized as follows: (1) to estimate the health effects due to exposure to $PM_{2.5}$ in China, (2) to estimate the crop yield loss due to surface O_3, and (3) to quantify the economic losses from health effects and crop yield losses.

1. Methods and data

1.1. Air quality model

In this study, the WRF-Chem model (Grell et al., 2005) with updated surface parameters (land cover, green vegetation fraction, and leaf area index) and improved reactions (Huang et al., 2015) were used to simulate $PM_{2.5}$ and surface O_3, with a 50 km × 50 km horizontal resolution and 15 vertical levels. The simulated domain covered the whole of China and its surrounding area with 95 × 110 grid cells (Fig. S1, inner black rectangle). The model setting, meteorological parameters, and emission inputs are described in Huang et al. (2015). Simulated meteorological results and PM_{10} have been evaluated using observed data (Huang et al., 2015). The mean biases (MB) of simulated temperature at 2 m above ground level (T2) and of relative humidity at 2 m above ground level (RH2) were −0.5°C–0.7°C and less than ±4%. The root-mean-square error (RMSE) for T2 and RH2 were 1.55°C–1.8°C and 9%–11%, respectively. The normalized mean biases (NMB) for the simulation of PM_{10} were within ±30%. Generally, the model effectively reproduced the temporal and spatial variations of meteorological conditions and PM_{10} and captured the spatial pattern and seasonal cycle. A detailed comparison of the model results for $PM_{2.5}$ and surface O_3 with those of other studies is provided in Section 2.1. In this study, the annual average concentration of $PM_{2.5}$ was used to evaluate the health effects, and the hourly concentration of surface O_3 was used to calculate the exposure index for crop yield loss assessment.

The assessments of the health impacts and crop yield losses were only conducted in mainland China (Fig. S1, blue line), as population and crop yield data were not available for Hong Kong, Macao, and Taiwan.

1.2. Health endpoints and epidemiological C–R function

1.2.1. Health endpoints

Long-term exposure to $PM_{2.5}$ has been linked to many health effects, including cardiovascular and respiratory mortality and morbidity (Pope and Dockery, 2006). As recommended by the World Bank (2007), all-cause mortality was used for evaluating mortality losses. Hospital admissions for respiratory disease (RD) and cardiovascular diseases (CVD), and chronic bronchitis were selected for evaluating morbidity losses in this study.

1.2.2. Function

The shape of C–R function is critical for assessing health loss. Several forms of C–R function, such as linear, log-linear, power law, have been used in previous researches (Apte et al., 2015; Krewski et al., 2009). Linear or log-linear forms have been regarded as unreasonable in high concentration (Apte et al., 2015; Pope et al., 2011). As emphasized by Pope et al. (2015), recent evidence has suggested that the C–R function between $PM_{2.5}$ exposure and mortality risk may be supralinear across a