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Mapping ozone risks for rice in China for years 2000 and 2020 with flux-based and exposure-based doses

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HIGHLIGHTS

- Ozone flux to rice leaves was modeled with observations in free-air fumigation.
- Surface ozone concentration in China was estimated with a chemical transport model.
- Ozone risks on the flux and exposures were estimated for China in 2000 and 2020.
- Rice regions along the Yangtze River and south China had high ozone risks in 2000.
- The ozone risks will double or triple from 2000 to 2020 in the major rice regions.

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ABSTRACT

We parameterized a multiplicative model of stomatal conductance (g_{sto}) for O_3 uptake by rice leaves with the field measurements in a fully open-air ozone (O_3) fumigation experiment. The estimated g_{sto} compared well with the observed one ($r^2 = 0.79$). By using the g_{sto} model for O_3 uptake, we estimated a flux-based O_3 risk (POD_6, accumulated stomatal flux of O_3 above a threshold of 6 nmol m^{-2} s^{-1}) for rice across China in years 2000 and 2020, and compared it with the exposure-based O_3 risk (AOT40, accumulated hourly O_3 concentration above 40 ppb during daytime) for the same period. For the year 2000, both POD_6 and AOT40 indicated the middle and lower reaches of Yangtze River and the south China being at the highest O_3 risk. From the years 2000–2020, the O_3 risks are projected to double (POD_6) or triple (AOT40) in a majority of rice producing areas in the above two regions. Among three major rice cropping in the middle and lower reaches of Yangtze River, double-late rice is projected to have lower O_3 risk than double-early rice and single rice on the either O_3 risk measure in both 2000 and 2020. In south China, on the other hand, the O_3 risks for double-late rice are comparable to that for early double-rice. In this study, the O_3 risk was not measured as yield loss but as O_3 flux and O_3 exposure. The crop loss estimation would require a relationship between O_3 flux and yield loss for major rice production regions across China.

1. Introduction

China has experienced phenomenal economic growth in the past several decades, but it has resulted in a significant increase in emissions of primary ozone (O_3) precursors, e.g. NO_x, CO and VOCs (Streets and Waldhoff, 2000; Ohara et al., 2007) due to the rapid urbanization, industrialization and development of transportation. High concentrations of O_3 ($[O_3]$) have consequently been observed in many populated and industrial areas in China (Lam et al., 2005; Geng et al., 2008; Zhao et al., 2009), and neighboring agricultural regions, especially downwind regions, are often enveloped by the regional O_3 pollution (Wang et al., 2006; Zheng et al., 2010; Tang et al., 2013a). As surface $[O_3]$ is predicted to continue rising over Eastern Asia for the coming decades (Royal Society, 2008; Yamaji et al., 2008; Takigawa et al., 2009), there is an increasing concern

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about the O_3 risk for the major crops in China. Indeed, ample evidences have proved the phytotoxic effect of O_3 on various staple crops (Morgan et al., 2006; Feng and Kobayashi, 2009; Pang et al., 2009; Zhu et al., 2011).

Rice (*Oryza sativa* L.) is the most important food crop that feeds the largest proportion of the world's population (Maclean et al., 2002). Although rice was once ranked among the species moderately resistant to O_3 (Mills et al., 2007), recent studies have showed that it is as sensitive to O_3 as other major crop species (Feng and Kobayashi, 2009; Pang et al., 2009; Shi et al., 2009) especially with the cultivars from Asian region (Emberson et al., 2009; Wang et al., 2012). China is the largest rice producer in the world with an annual production of 197 million metric tons, which accounts for almost 30% of the global rice production (FAO, 2010). Assessing the risk of the increasing surface [O_3] for rice in China is thus of crucial importance for the global food security.

In China, there are three major rice cropping, i.e. single-cropping rice (SR), double-cropping early rice (DER) and double-cropping late rice (DLR) (China Agricultural Yearbook Editorial Committee, 2010). Their distinct growing seasons and strong seasonal changes in [O_3] could make a clear difference in O_3 risk between the cropping. It must also be noted that rice is grown across a wide range of latitudes and, therefore, climate. The large spatial and temporal variability in rice cropping would require consideration to biological and climatic influences on O_3 risk via the leaf stomatal flux of O_3, which better accounts for the O_3 impacts on plants than [O_3] in surrounding air (Emberson et al., 2000; Danielsson et al., 2003; Pleijel et al., 2004; Mills et al., 2011b). The flux-based POD_Y (phytotoxic O_3 dose, accumulated stomatal flux of O_3 above a threshold of Y nmol m^{-2} s^{-1}) has been recognized to be superior to the exposure-based AOT40 (accumulated hourly [O_3] over a threshold of 40 ppb during daytime) in accounting for the yield loss observed in wheat and potato (Pleijel et al., 2007; Feng et al., 2012). Maps of flux-based O_3 risk for vegetation in Europe have also shown better correspondence with the adverse effects than those with AOT40 (Hayes et al., 2007; Mills et al., 2011a). In view of the importance of rice as the staple crop and the large spatial and temporal variability of its cropping, a flux-based assessment of the increasing O_3 risk is required.

The flux-based approach relies on the ability to adequately describe the variation of leaf stomatal conductance (g_{sto}), which is determined by species-dependent maximum of g_{sto} and alterations by phenological and environmental variables. Models of stomatal O_3 uptake have been parameterized for a number of agricultural and horticultural crops, forest trees and (semi-) natural vegetation in Europe (Uddling et al., 2004; Pleijel et al., 2007; LRTAP, 2010; González-Fernández et al., 2013), and wheat in subtropical China (Feng et al., 2012). For rice, some models of stomatal O_3 flux have been developed also, but they are limited to either a model for calculating instantaneous O_3 flux without considering crop phenology (Oue et al., 2008) or that derived from a small chamber experiment under significantly altered microclimate (Tong et al., 2011). Neither of them is suitable for O_3 risk assessment at regional scales.

In this study, we aimed (1) to parameterize a g_{sto} model of O_3 flux to rice leaves by using field measurements in a fully open-air O_3 fumigation experiment; (2) to use the model to estimate the O_3 risk with rice in China; and (3) to compare the projected O_3 risks among different rice growing regions and cropping systems. In the assessment, we focused on the increase of O_3 risk from the base year (2000) to the near future (2020). Since 2000, anthropogenic emissions of O_3 precursors over China has been dramatically increasing as shown by both satellite observations and model estimations (Streets et al., 2005; Ohara et al., 2007; Zhang et al., 2007, 2012; Kurokawa et al., 2009). The resultant increase of surface [O_3] and its risk has been projected with flux-based and exposure-based approaches for wheat (Tang et al., 2013b), but, for rice, the projections of O_3 impacts have been limited to exposure-based approaches (Aunan et al., 2000; Wang and Mauzerall, 2004; Van Dingenen et al., 2009).

2. Materials and methods

2.1. Field measurements of gas exchange

Gas exchange of rice leaves was measured in ambient [O_3] (A-O_3) and elevated [O_3] (E-O_3) at a FACE-O_3 (Free-Air Concentration Enrichment system with ozone) experiment in Xiaoji town, Jiangdu county, Jiangsu province, China (119°45′ E, 32°35′ N, 5 m a.s.l.). The site is situated in the subtropical marine climatic zone with a mean annual precipitation of 1100–1200 mm, a mean annual temperature of 16 °C, a total number of annual sunshine hours >2000, and a frost-free period of >230 days. The design of the FACE-O_3 experiment and the performance of the [O_3] control in E-O_3 have been described in detail by Tang et al. (2011). In all experimental plots (four replications for each [O_3] treatment), rice was planted following common cultivation practices in the region as described in detail by Pang et al. (2009) and Shi et al. (2009).

The g_{sto} in flag leaves of two rice varieties Yangdao 6 (inbred indica cultivar, hereafter referred to as YD6) and Liangyoupeijiu (two-line hybrid cultivar, hereafter referred to as LYPJ) was measured in situ with an open gas exchange photosynthesis system (LI-6400 by LICOR, Lincoln, Nebraska, USA) in the 2008 growing season. Diurnal change of g_{sto} in flag leaves of both YD6 and LYPJ was measured five times (26 August, 6, 22 and 27 September, and 1 October) in the A-O_3 and E-O_3 plots every 120 min from 8:00 AM to 5:00 PM, Chinese Standard Time. In total, 757 leaves were measured. The g_{sto} was averaged across 3–5 replicate leaves measured in each plot in one measurement round, and was used to validate and adjust the g_{sto} model. YD6 data were used for model parameterization, whereas both YD6 and LYPJ data were used for model evaluation. This is because no difference was found in g_{sto} between YD6 and LYPJ before O_3-induced leaf senescence in late grain filling stage, when YD6 exhibited lower g_{sto} than LYPJ. This varietal difference was, nevertheless, omitted in our O_3 flux estimation, since g_{sto} had become very low at the late grain filling stage.

2.2. Parameterization of the stomatal conductance model for rice

A Jarvis-type multiplicative model (Jarvis, 1976) was adopted and parameterized to simulate the g_{sto} in this study. Model algorithm is similar to that used for wheat and other crops in previous studies (Feng et al., 2012; LRTAP, 2010), viz.

$$g_{sto} = g_{max} \times \min\left(f_{phen}, f_{O_3}\right) \times f_{light} \times \max\left(f_{min}, \left(f_{VPD} \times f_{temp}\right)\right) \quad (1)$$

where g_{sto} is the stomatal conductance to O_3 per unit projected leaf area (PLA) (mmol O_3 m^{-2} PLA s^{-1}), g_{max} is the maximum g_{sto} (mmol O_3 m^{-2} PLA s^{-1}) estimated from measurements around flowering under optimal condition for stomata opening, and f_{min} is the relative minimum g_{sto} (fraction of g_{max}). The factors f_{phen}, f_{O_3}, f_{light}, f_{VPD} and f_{temp} are the response functions expressed in relative terms (i.e. they take values between 0 and 1), representing the influences of phenology, O_3 (in terms of POD_0, accumulated hourly stomatal O_3 flux above a flux threshold of 0 nmol O_3 m^{-2} PLA s^{-1}), light (in terms of PPFD, photosynthetic photon flux density), leaf-to-air VPD (vapor pressure deficit), and air temperature, respectively. Because the paddy field was flooded with water in most of