Atmospheric Environment 142 (2016) 93–103

Contents lists available at ScienceDirect

Atmospheric Environment

journal homepage: www.elsevier.com/locate/atmosenv

Evaluation of the chronic effects of ozone on biomass loss of winter wheat based on ozone flux-response relationship with dynamical flux thresholds

Rongjun Wu [a, b, c, *], Youfei Zheng [a, c], Chengda Hu [c]

[a] Jiangsu Collaborative Innovation Center of Atmospheric Environment and Equipment Technology (CICAEET), Nanjing University of Information Science & Technology, Nanjing, 210044, China
[b] Jiangsu Key Laboratory of Agricultural Meteorology, Nanjing University of Information Science and Technology, Nanjing, 210044, China
[c] College of Applied Meteorology, Nanjing University of Information Science & Technology, Nanjing, 210044, China

HIGHLIGHTS

- Adaptation ability for ozone damage on wheat is attribute to photosynthesis ability.
- A dynamical ozone flux thresholds based on the gross photosynthesis is proposed.
- Assessing ozone damage effect on wheat based on variable flux thresholds.

ARTICLE INFO

Article history:
Received 23 February 2016
Received in revised form
25 June 2016
Accepted 10 July 2016
Available online 11 July 2016

Keywords:
Ozone
Winter wheat
Dry matter weight
Uptake flux
Gross photosynthesis rate

ABSTRACT

To evaluate the chronic negative effects of elevated ozone concentration on winter wheat in China, a parameterized Jarvis-type multiplicative stomatal conductance model with data collected from open-top chamber experiments on field grown wheat during four growing seasons in 2008–2011, were utilized to derive relationships between relative biomass and absorbed ozone phytotoxic dose (*POD*). The work introduced a variable flux threshold expressed as a function of gross photosynthesis rate (*A*), considered the detoxification ability for ozone damage on winter wheat, varying with time of day and growth stages of winter wheat. The results showed the linear relationships with the highest coefficient of determination ($R^2 = 0.8029$) and intercept closer to 1 (value 1.0018) were obtained, between the POD_Y above a varied flux threshold *Y* and relative dry matter loss of wheat, compared with other fixed flux thresholds. The results demonstrated that the flux response relationship accounting for the photosynthetic ability can be used with confidence to assess and predict the damage effects of ozone on yields loss of crops across China.

1. Introduction

Surface ozone is regarded as one of the most phytotoxic air pollutants. Some studies have pointed out that global average of surface ozone concentrations will increase by 20–25%, and it has been forecasted to reach to 75 nL·L^{-1} in 2100 (Vingarzan, 2004; Sitch et al., 2007). In Europe and North America, past trends in surface ozone have been mostly revealed strong increases (Gilge et al., 2010). In Asia, concentrations of tropospheric ozone have been increasing along with positive trends in the emission of its precursors, and this trend is expected to continue in the near future (Xu et al., 2015). High concentrations of ozone have been observed in many areas in China (Wang et al., 2007; Lin et al., 2008). Meanwhile, Transport of air pollutants and ozone precursors in particular from heavily polluted areas could bring high ozone levels in surrounding areas, and ozone concentrations above 140 nL L^{-1} have been once observed in rural sites in Yangtze Delta region (Cheung and Wang, 2001; Zhou, 2004).

The surface ozone damages the agricultural crops through dry deposition, inducing negative effects on the growth, productivity and quality of crops in the Europe, Australia, America and Asia (Ashmore, 2005; Feng et al., 2008; Feng et al., 2009, 2012; Mills

* Corresponding author. No.219 Ningliu Road, Nanjing City, Jiangsu Province, 210044, China.
E-mail address: wurj@nuist.edu.cn (R. Wu).

http://dx.doi.org/10.1016/j.atmosenv.2016.07.025
1352-2310/

et al., 2011b). The negative effects of ozone on wheat (Wang et al., 2007; Feng and Kobayashi, 2009), soybean (Morgan et al., 2003) and rice (Ainsworth, 2008; Shi et al., 2009) have been studied comprehensively and will threaten global food security (Tai et al., 2014). The effect of ozone on above-ground biomass (−9%) and grain yield (−14%) of wheat loss over Europe was found (Pleijel et al., 2014). Global crop production losses were estimated to be US $ 11–18 billion (Avnery et al., 2011). Meanwhile, yield losses of wheat in China and India reached 6.4–14.9% and 8.2–22.3%, respectively (Tang et al., 2013). Estimated reductions of global yields ranged 4.5–6.3% for maize, 10.6–15.6% and 12.1–16.4% for wheat and soybean (Avnery et al., 2011). Therefore, routinely evaluating current effects of ozone on wheat in China region is needed.

The earliest impact assessments of ozone on the crops were based on the relationship between ozone concentration and crop yields (Heck and Adams, 1983). The concentration-based critical levels of ozone for crops were defined using AOT40 (concentration accumulated over a threshold ozone concentration of 40 ppb) index (Fuhrer et al., 1997). The index AOT40 has been utilized widely to evaluate the risk of damage on crops, but several important limitations and uncertainties have been recognized (UNECE, 2004). Particularly, the real impacts of ozone primarily depend on the amount of ozone reaching the spots of damage within the leaf through the stomata (Musselman et al., 2006). Therefore, the cumulative uptake flux of ozone through the stomata and associated response functions of climate variables such as light intensity, radiation, temperature, soil water potential and vapor pressure deficit (VPD), can be utilized to quantify the impacts (Mills et al., 2011a). Based on the algorithm by Jarvis (1976), a multiplicative model of stomatal conductance response to environmental conditions was developed for wheat and potato (Danielsson et al., 2003; Pleijel et al., 2007). Based on the multiplicative models of stomatal conductance with improved parameterization, stomatal uptake flux of ozone can be calculated and used widely to derive relationships between yield loss for crops in Europe (Emberson et al., 2000a, 2000b; Danielsson et al., 2003; Pleijel et al., 2004, 2007; Grünhage et al., 2012; González-Fernández et al., 2013), North America (Massman et al., 2000), and eastern Asia (Oue et al., 2008, 2011; Feng et al., 2012; Tang et al., 2013; Yamaguchi et al., 2014). The accumulative ozone uptake flux has stronger relationships with yields reduction for crops compared with AOT_{40} index, because the ozone flux through the stomata is strongly dependent on climatic conditions (Pleijel et al., 2007). Meanwhile, the assessment approach using flux-based critical level, rather than ozone concentration-based index, could evidently provide an improved estimate of ozone damage risk to crops (Emberson et al., 2000b).

Once the stomatal uptake flux of ozone has been calculated, the negative effects of ozone in crops can be predicted by applying flux-response relationships obtained as regression between phytotoxic dose (POD) above threshold Y (POD_Y) and yield reduction of crops in different sites on the same or similar species (Mills et al., 2011b). In this context, POD_Y has been a standardized term, denoting the accumulated stomatal flux over a specified time interval above a flux threshold of Y nmol m-2·PLA s^{-1}. Y represents a detoxification threshold, and means that the ozone uptake flux above this threshold may lead to reduction of dry matter weight and yield of crops (Musselman et al., 2006). Actually, a fraction of ozone entering the leaves through the stomata will be scavenged by extra cellular antioxidants such as ascorbate present in the cell wall of plant, consequently, the plant tissue possesses certain adaptation and detoxification ability for ozone damage (Barnes et al., 2002). A certain level of ozone through stomata will not reduce photosynthesis of crops (Weinstein et al., 1998; Massman, 2004). Prior researches based on field experiments by open top chamber (OTC), showed that relationships between the calculated POD_Y and relative yield loss is most significantly correlated when Y value is 6 nmol m^{-2} PLA s^{-1} (UNECE, 2004; Harmens et al., 2007; Pleijel et al., 2007). Meanwhile, Feng et al. (2012) found that the ozone uptake threshold of 12 nmol m^{-2} s^{-1} could be the most reasonable for the wheat flux-response relationship in subtropical China.

However, there are some significant difference for the adaptation and detoxification capacity of ozone, among different crop species, developmental stages and environmental factors(Plöchl et al., 2000). Meanwhile, the flux threshold of ozone was most likely to be an indirect function of the gross photosynthesis rate, varying with time of day and season(Massman, 2004). Therefore, the adaptation and detoxification ability of crops for ozone damage likely are greater during the morning to noon hours because photosynthesis is then maximal (Massman et al., 2000). In addition, the flux threshold reached the maximum value during flowing to grain-filling stages, then gradually deceased (Massman, 2004). However, numerous yield loss and risk assessment of ozone damage on plants utilized one constant as uptake threshold of ozone and did not consider those variations (Emberson et al., 2000a; Pleijel et al., 2000, 2007; Danielsson et al., 2003; Feng et al., 2012).

Therefore, the objective of the present research is to develop one new varying flux threshold of Y according to the functional relationship with gross photosynthesis rate for winter wheat in Eastern China. Furthermore, accumulated stomatal ozone uptake flux POD_Y will be calculated based on different threshold and changed critical level of ozone damage. Meanwhile, the most reasonable and significant flux-response relationship between POD_Y and relative yield loss of winter wheat will be proposed. The research will apply the flux-based approach using the multiplicative model of stomatal conductance and uptake flux model (Emberson et al., 2000b; Pleijel et al., 2007) and data from a four-year field experiment using open-top chambers where winter wheat was fumigated with elevated ozone. The stress effects of elevated ozone on the crops biomass and yields across Eastern China and Yangtze Delta region, at present and in the future are also comprehensively evaluated.

2. Materials and methods

2.1. Field experiments by OTC

The field experiments were conducted with open-top chambers (OTC) at an agro-meteorological experiment station located in the campus of Nanjing University of Information Science and Technology (NUIST) (32°14′N, 118°42′E) in Jiangsu province of China. The station is in the subtropical moist monsoon climate zone, with an annual average temperature of 15.3 °C, and rainfall of 1106.5 mm.

The open-top chamber construction details were described in Zheng et al. (2010). For each treatment, two chamber replications, for a total of six chambers were used. All OTCs were ventilated with non-filtered air (NFA). From the green-up stage of winter wheat, ozone was injected into the ventilating ductwork of the six chambers, with ozone treatments randomly assigned to chambers, to achieve three targeted daytime(7 h/d) treatments: NFA, 100 nL $L^{-1}O_3$ (NF100, 96–108 nL L^{-1}) and 150 nL $L^{-1}O_3$ (NF150, 145–160 nL L^{-1}). Ozone was generated from oxygen by electric discharge and supplied to ozone chambers following dilution in a stream of clean compressed air. Ozone levels were logged and controlled using a feedback regulation system based around a motorized voltage regulator. When winter wheat grow to green-up period, ozone was injected into the OTCs by blower. The beginning of green-up was 7 Mar, 18 Feb, 1 Mar and 3 Mar, in 2008, 2009, 2010 and 2011, respectively. Once the rainy day, the fumigation of ozone