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The influence of ozone pollution on CO_2, CH_4, and N_2O emissions from a Chinese subtropical rice–wheat rotation system under free-air O_3 exposure

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ABSTRACT

A better understanding of the effects of ozone (O_3) on greenhouse gas (GHG) emissions in rotational rice (*Oryza sativa* L.)–wheat (*Triticum aestivum* L.) systems is essential for reducing potential GHG emissions in agroecosystems due to the projected increase in O_3 concentrations. Rice and wheat were rotationally grown in a free-air O_3 enrichment platform, and crop production and N_2O, CH_4, and CO_2 emissions from the soils were investigated as well as the global warming potential (GWP) of the GHGs. Exposure to elevated O_3 (50% greater than ambient O_3) slightly reduced the total biomass of wheat and significantly decreased that of rice, significantly decreased the root to total biomass ratio of wheat and slightly increased that of rice. Elevated O_3 significantly increased the CO_2 emission but did not influence the CH_4 and N_2O emissions in the rice–soil system; however, elevated O_3 did not influence the CO_2 emission, significantly increased the CH_4 emission, and significantly reduced N_2O emissions in the root-free soil during the rice season. Elevated O_3 increased the CO_2 emission and decreased the CH_4 and N_2O emissions in the wheat–soil system and root-free soil during the wheat season, although the decrease in N_2O emission in the wheat–soil system was not significant. The effects of elevated O_3 on GHGs emissions and biomass accumulation were related to crop species, plant coverage, and GHG type. Elevated O_3 significantly increased the GWP in the rice–soil system and the GWP per unit of rice yield; however, it did not change the GWP in the wheat–soil system or in the root-free soil during the wheat–rice growing period, nor did it change the GWP per unit of wheat yield. Considering the decreases in wheat and rice dry matter, reducing CO_2 emissions and planting O_3-tolerant crop cultivars during future elevated O_3 scenarios, especially during the rice-growing season, should be a primary focus of the research aimed at reducing the GWP and increasing the soil C and N sequestration of rotational rice–wheat cropping systems.

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1. Introduction

Ozone (O_3) is a highly reactive and oxidative pollutant. Anthropogenic activity has increased the concentration of tropospheric O_3 (Vingarzan, 2004). Tropospheric O_3 has strongly increased in East Asia since the 1990s (Schnadt Poberaj et al., 2009; IPCC, 2013) and is still rising (Stevenson et al., 2013). The Yangtze River Delta of China, one of the most important rice–wheat production regions, is under an increasingly serious threat of O_3 pollution (Shao et al., 2006). As levels of tropospheric O_3 > 40 ppb would cause visible leaf injury, plant damage, and a reduction in crop and forest productions (Sitch et al., 2007; Zhang et al., 2010), the effect of elevated tropospheric O_3 on terrestrial ecosystems is a concern to global scientists and the public (Ashmore, 2005; Fiscus et al., 2005; Fuhrer, 2009). Many O_3 exposure experiments (using closed chambers, open-top chambers, or free-air O_3 enrichment systems (O_3FACE)) have elucidated the responses of various ecosystems to elevated O_3 (Manning, 2005; Wang et al., 2007; Kou et al., 2014).

Elevated O_3 has been demonstrated to decrease net photosynthesis (Nie et al., 1993) via oxidative damage to cell membranes and chloroplasts (Karberg et al., 2005) and consequently reduces dry matter accumulation (Nouch et al., 1991; Kobayashi and Okada, 1995; Maggs and Ashmore, 1998; Feng et al., 2008; Shi et al., 2009) and alters its allocation belowground (Fiscus et al., 2005; McCrady and Andersen, 2000; Kanerva et al., 2006; Jones et al., 2009;

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Kou et al., 2012). Andersen (2003) hypothesized that elevated O_3 would influence soil–root respiration and microbial activity by altering plants' belowground processes. Numerous studies have demonstrated that elevated O_3 influences soil microbial activity and communities (Sami et al., 2008; Chen et al., 2010). The changes of soil–root respiration and soil microbiological processes might influence the carbon (C) and nitrogen (N) cycles in soils (Islam et al., 2000; Larson et al., 2002), thereby affecting the emissions of GHGs such as dioxide carbon (CO_2), methane (CH_4), and nitrous oxide (N_2O) from plant–soil systems (Lu and Conrad, 2005). However, the results from previous studies on the effect of elevated O_3 on GHG emissions are inconsistent (e.g., CO_2 and CH_4) and few (e.g., N_2O). The increase (Scagel and Andersen, 1997; Kasurinen et al., 2004), no change (Tingey et al., 2006; Zheng et al., 2011), and the decrease (Kanerva et al., 2006; King et al., 2001; Hu et al., 2011) in soil CO_2 emissions in response to elevated O_3 levels were observed. Similarly, promotive (Niemi et al., 2002; Mörsky et al., 2008) and inhibitory (Mörsky et al., 2008; Bhatia et al., 2011; Zheng et al., 2011) effects of elevated O_3 on CH_4 emission were measured. Only one study regarding the effect of elevated O_3 on soil N_2O emissions was reported by Bhatia et al. (2011). This study reported a decrease in the cumulative seasonal N_2O emissions from rice paddies in response to elevated O_3. The limited existing knowledge on the effects of elevated O_3 on the emissions of GHGs from soils restricts the understanding of the influence of future elevated tropospheric O_3 levels on soil C and N cycling.

Cropland is an important terrestrial ecosystem that is intensively influenced by anthropogenic activities. Among increasing concerns about global climate change, the predicted increase in tropospheric O_3 concentration is an important environmental change with crucial implications for agroecosystems. In southeastern China, the rice–wheat double-cropping rotation is the predominant agricultural system. As rice (*Oryza sativa* L.) paddies are one of the major sources of GHGs (IPCC, 2007), knowledge of the effects of elevated O_3 levels on GHG emissions from rice–wheat field soils would enable the prediction of the consequences of elevated atmospheric O_3 concentrations on soil C and N cycles. However, few elevated O_3 experiments (especially FACE experiments) have directly examined GHG emissions in rotational rice–wheat systems. The objectives of this study are to: (1) investigate the GHGs (CO_2, CH_4, N_2O) emissions from a rice–wheat rotation system in response to elevated O_3 using O_3FACE and (2) assess the effects of crops on GHG emissions and their global warming potential (GWP).

2. Materials and methods

2.1. Experimental site and soil

The field experiment was conducted at the O_3FACE experimental system (32°35′N, 119°42′E), located in Jiangdu County in China's Jiangsu Province. A rice–wheat rotation crop system has existed at this experimental site for over 50 years. The total annual sunshine and frost-free period were greater than 2100 h and 220 days, respectively. The dynamics of the daily mean rainfall and the mean temperature during the wheat–rice growth periods (March–October) in 2012 in the experimental area are shown in Fig. 1. The soil at the experimental site has a sandy–loamy texture according to the US soil classification system (Soil Survey Staff, 2003) and is classified as a Shajiang Aquic Cambiosol by the Chinese soil classification system (Cooperative Research Group on Chinese Soil Taxonomy, 2001). Soil texture is predominantly sandy, with a clay concentration of about 13.6% in the surface (Kou et al., 2014). At the start of the experiment, the plow-cultivated layer (0–15 cm) properties were as follows: pH of 7.2, 18.4 g kg^{-1} organic carbon content, and 1.16 g cm^{-3} bulk density. The nutrient status of

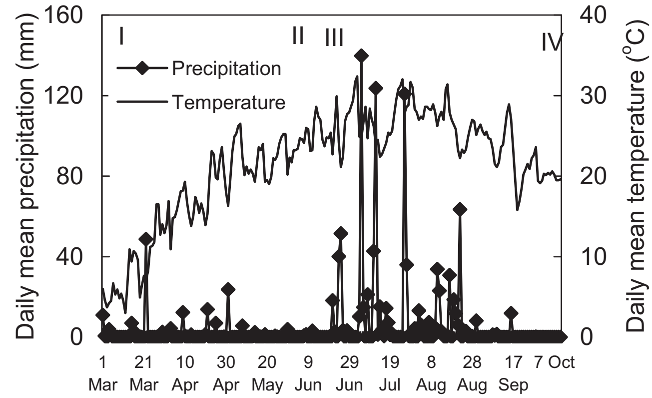

Fig. 1. The seasonal variations of daily mean precipitation and daily mean air temperature during March–October 2012 wheat and rice growing period.

the soil was as follows: 1.45 g kg^{-1} total N, 0.63 g kg^{-1} total P (as P_2O_5), 106 mg kg^{-1} available N, 33.8 mg kg^{-1} Olsen P, and 96.4 mg kg^{-1} available K.

2.2. Treatments and crop management

The O_3FACE experiment generated continuous O_3 exposure during March–November of each year since 2007 during the crop growth stage of rotational rice–wheat cropping. One rice (vs. Shanyou63, SY63) and one wheat (vs. Yangmei 15, Y15) crop were rotationally grown in the O_3FACE system every year since 2007. The O_3FACE system consisted of eight rings (14 m in diameter) with an available area of 160 m^2. Four rings with target O_3 concentrations of about 50% higher than the ambient atmosphere, which simulated future atmospheric O_3 concentration (hereinafter referred to as elevated), and four comparison rings without O_3 enrichment (hereinafter referred to as ambient) were used. Adjacent rings exceeding 70 m were buffered to avoid O_3 crossover. The O_3 exposure was continuous from the initial jointing stages (according to agronomic investigation) to harvest in the wheat growth season and after 1 week following rice transplanting to harvest in the rice growth season in 2011. Pure O_3 at 800 kPa was released towards the center of the O_3FACE rings 50 cm above the crop canopy for 7 h (09:00–16:00 Chinese Standard Time) every day. No O_3 was released on rainy days to limit acute damage to leaves. More details about the O_3FACE system can be found in Tang et al. (2011) and Kou et al. (2014).

Similar responses in shoot accumulation and grain yield of the same crop to elevated O_3 were observed from 2007–2012. The results in this study were based on GHG emissions and biomass analyses from the 2011 wheat–rice growing season. Wheat was sown on 11 November 2011 at a density of 200 plants m^{-2} and was harvested on 5 June 2012. Rice seedlings were raised in the seedbed and sown on 10 May transplanted on 10 June at 24 hills m^{-2} with 2 seedlings per hill, and harvested on 1 October 2012. Wheat and rice were planted over an area of more than 50 m^2 in each of the elevated and ambient O_3 treatment plots. The following conventional fertilizers were used: urea (46% N) as N fertilizer, superphosphate (12% P_2O_5) as P fertilizer, and potassium chloride (60% K_2O) as K fertilizer. Approximately 200 kg N ha^{-1} and 225 kg N ha^{-1} were applied to the rice and winter wheat crops, respectively. The same level (75 kg P_2O_5 ha^{-1} and 75 kg K_2O ha^{-1}) of P and K fertilizers were applied to the rice and wheat crops as base fertilizers before planting. Urea was applied at the initial and jointing stages of wheat growth with a ratio of 5:5 and at the beginning, tillering, and flowering stages of rice growth at a ratio of 3:3:4. The field management closely followed local agronomic practices including pesticide and fungicide application, irrigation,

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