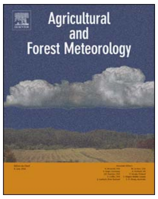
Agricultural and Forest Meteorology 250–251 (2018) 202–208

Contents lists available at ScienceDirect

Agricultural and Forest Meteorology

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



Changes in nutrient uptake and utilization by rice under simulated climate change conditions: A 2-year experiment in a paddy field

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ARTICLE INFO

Keywords:
Free-air CO_2 enrichment (FACE)
Elevated air temperature
Climate change
Nutrient dynamic
Southeast China

ABSTRACT

Global climate change with elevated atmospheric CO_2 concentration and temperature has been known impacting plant photosynthesis and grain yield in agroecosystems. However, how nutrient uptake and utilization by rice change under climate change stresses has been poorly addressed. An open-air field experiment was conducted to investigate the impacts of factorial combinations of CO_2 enrichment (up to 500 ppm) and canopy warming (+2 °C) on nutrient concentration (PNC), accumulation (PNA) and utilization efficiency (NUE) for two cropping years in a paddy from southeast China. Plant samples of aboveground biomass were collected across the growing stages and grain yield measured at harvest. Compared to ambient condition, CO_2 enrichment more or less decreased PNC of N, P and K, but unchanged PNA of N and P while increased aboveground biomass. In contrast, warming increased PNC of N, P and K respectively by 7.4%, 11.0% and 13.4% at the ripening stage, but decreased PNA of N, P and K respectively by 18.6%, 22.6% and 10.8% in 2013. Whereas, concurrent CO_2 enrichment and warming unchanged PNC but slightly decreased PNA of N and K in both years. In addition, CO_2 enrichment unchanged the apparent NUE, but increased NUE of N and K under concurrent warming in both years. Therefore, canopy warming may have impacted the rice response in NUE to CO_2 enrichment as the change in PNA with concurrent CO_2 enrichment and warming was in a similar trend to that with warming alone. Our findings suggest that nutrient uptake and utilization by rice are more impacted by warming compared with CO_2 enrichment under the simulated climate change conditions. Therefore, simulated climate change experiments should be conducted regarding how simultaneous atmospheric CO_2 enrichment and warming influences plant traits and functions in rice paddy, to provide a better understanding of agricultural production changes and sustainable nutrient management under future climate change.

1. Introduction

The global atmospheric carbon dioxide (CO_2) concentration has increased by 40% since the pre-industrial time and surface temperature has increased by 0.85 °C during 1880–2012, resulting from the anthropogenic greenhouse gas emissions from land use change and fossil fuel combustion (IPCC, 2013). These characteristics of climate change have exerted both direct effects on crop growth and production (Wang et al., 2016a; Wheeler and von Braun, 2013) and indirect effects on plant nutrient uptake and utilization (Cheng et al., 2010; Lam et al., 2012a). Elevated atmospheric CO_2 concentration generally increases crop yield through enhanced photosynthesis (Horie et al., 2000; Kim et al., 2003; Mitchell et al., 1993; Sakai et al., 2006), while warming reduces dry matter accumulation via increased plant respiration and accelerated phenological development (Bhattacharyya et al., 2014; Dong et al., 2011; Wheeler et al., 2000). While nutrient balance and utilization are known central to the impact of climate change on crop production (Fuhrer, 2003; Lam et al., 2012b; Wheeler and von Braun, 2013), the response of crop in agroecosystems to concurrent CO_2 enrichment and warming has not yet been sufficiently addressed.

Rice (*Oryza sativa*) is one of the most important staple crops for more than half of the world population (Nagai and Makino, 2009). About one quarter of the croplands of China are cultivated for rice production, accounting for about 20% to the world total rice area (Frolking et al., 2002). Rice grain production could be enhanced by 11–19% under atmospheric CO_2 enrichment (Long et al., 2006), which could be potentially negated by concurrent warming (Wang et al., 2016a). Such a change could be partly attributed to changes in nutrient

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Abbreviations: PNC, plant nutrient concentration; PNA, plant nutrient accumulation; NUE, nutrient utilization efficiency

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https://doi.org/10.1016/j.agrformet.2017.12.254
Received 9 August 2016; Received in revised form 19 April 2017; Accepted 17 December 2017

dynamics in the soil and plant system. Furthermore, soil food web (Okada et al., 2014) and nitrification processes (Hu et al., 2016) were more impacted by elevated temperature compared with elevated CO_2 concentration. So far, it remains unclear whether the impacts of warming outweigh the effects of elevated CO_2 concentration on nutrient uptake and utilization in rice production.

Uptake and utilization of nitrogen (N), phosphorus (P) and potassium (K), as the major essential plant nutrients, are recognized as the most important abiotic factors for crop physiological function and production capacity. Changes in concentrations, uptake and utilization efficiency of these nutrients in agroecosystems have been addressed using experiments with atmospheric CO_2 enrichment or warming alone (Bloom et al., 2010; Jin et al., 2012; Li et al., 2015; Ma et al., 2007; Nam et al., 2013; Roy et al., 2012). A decrease in plant nutrient concentration (PNC) under elevated CO_2 was generally attributed to an increase in biomass, the so-called dilution effect (Conroy, 1992; Gifford et al., 2000; Pang et al., 2006; Yang et al., 2007). Despite a reduction in PNC, plant nutrient accumulation (PNA) was increased under elevated CO_2 as a function of the increase in biomass (Pang et al., 2006; Roy et al., 2012). Moreover, a change in transpiration under CO_2 enrichment or warming could modify the nutrient transfer by water transported from belowground (Jauregui et al., 2015; McGrath and Lobell, 2013; Wang et al., 2018). As shown in a recent study with winter wheat, warming significantly increased PNC of micronutrients, and stimulated their translocation from root to shoot (Wang et al., 2016b). In contrast, Pregitzer and King (2005) reported that warming decreased PNC of N in root and shoot of rice. To date, the effect of climate change (CO_2 enrichment and warming) on nutrient uptake by rice is not well understood.

The main objective of this study was to examine the changes in PNC, PNA and nutrient utilization efficiency (NUE) of N, P and K in a rice paddy field under simulated climate change conditions. We hypothesize that CO_2 enrichment may decrease PNC but increase PNA and NUE, while warming could increase PNC decrease NUE, mainly due to the changes in biomass production; We also hypothesize that concurrent CO_2 enrichment and warming may overall increase PNC but decrease NUE, potentially due to the stronger negative effect by warming on biomass production. We aim to provide knowledge for improving nutrient management in agriculture tackling future climate change.

2. Materials and methods

2.1. Site description

This study was conducted with a simulated climate change system in an experimental station of the Institute of Resource, Ecosystem and Environment of Agriculture (IREEA), Nanjing Agricultural University. This system was built on a rice farm in Kangbo Village (31°30′N, 120°33′E), Guli Township, Changshu Municipality Jiangsu Province, China. The soil is a typical rice paddy soil classified as Gleyic Stagnic Anthrosol formed on clayey lacustrine deposit. The topsoil has a pH (H_2O) of 7.0, soil organic carbon of 19.2 g kg^{-1}, total N of 1.3 g kg^{-1}, total P of 0.9 g kg^{-1}, total K of 15.0 g kg^{-1}, and the bulk density is 1.2 g cm^{-3}. The soil texture is clayey loam with 33.8% sand, 38.6% silt and 27.6% clay. The minimum, maximum and mean temperature over the whole rice growing season were 23.7 °C, 31.3 °C and 27.0 °C in 2013, and 21.2 °C, 28.1 °C and 24.2 °C in 2014, respectively. The total rainfall over the rice growing season were 567 mm and 804 mm respectively in 2013 and 2014.

The operational procedures of the facility were described in Wang et al. (2016a) and Liu et al. (2015). In brief, the system was designed based on two factorial combination of climate change conditions, including an atmospheric CO_2 enrichment up to 500 ppm (CE), a warming of canopy air by 2 °C (WA), and a concurrent atmospheric CO_2 enrichment and warming (CW), compared to ambient condition (CK). Each treatment plot was performed in an octagonal ring with a diameter of 8 m (a total plot area of *ca* 50 m^2) and replicated in triplicates. The treatment rings were separated by an in-between spacing of 28 m at least to avoid potential CO_2 contamination across the treatment areas. The actual average CO_2 enrichment and temperature increment were 535 ± 21 ppm and 1.8 ± 0.7 °C in 2013, and 505 ± 18 ppm and 1.6 ± 0.4 °C in 2014, respectively. The performance and maintenance of these treatments were carefully managed with a monitoring and adjusting facility throughout the rice growing period of both years.

2.2. Crop cultivation and fertilizer management

Rice was a japonica hybrid cultivar (*Oryza sativa* L. cv. Changyou No. 5) transplanted with 3 seedlings per hill and 26 hills per m^2 (15.3 cm × 25.4 cm for each hill) on 23rd June 2013 and 20th June 2014, and harvested on 29th October 2013 and 1st November 2014, respectively.

Farm management was carried out following local agronomic practices. Nitrogen was applied as urea (46% N) at 86 kg N ha^{-1} as basal fertilizer (incorporated at 10 cm depth) and at 69 kg N ha^{-1} as topdressing. A compound fertilizer of N-P_2O_5-K_2O (15-15-15, %) was applied at 375 kg ha^{-1} as topdressing after heading. Paddy rice was irrigated with the regimes of continuous flooding with drainage twice during mid-season of rice growing.

2.3. Plant sampling and analysis

Aboveground biomass (shoot plus grain) were collected at each treatment plot respectively at the jointing, heading and ripening stages in accordance with the phenological development subject to the climate change treatment. After washing with distilled water, the collected samples were oven-dried at 105 °C for 30 min and then at 70 °C until constant weight. All the plant samples were weighed and then ground to pass of 0.25 mm sieve prior to analysis. Plant samples were pretreated with H_2SO_4-H_2O_2 and the resultant mixture was heated in an electric heating plate at 550 °C for 4 h. Subsequently, the concentration of N was analyzed by the Kjeldahl digestion method (Bremner and Mulvaney, 1982). The P concentration was analyzed by spectrophotometry (TU-1810, Beijing Purkinje General Instrument Co., Ltd., China), and K concentration by flame photometer (FP6410, INESA, China).

Grain yield was measured in this study to estimate the NUE. All of the grain ears in each ring was collected in the ripening stage and weighted, and then threshed by portable thresher. Three random subsamples of grain were air-dried to measure the water content in rice grain (105 °C for 30 min, then 70 °C for 24 h).

2.4. Statistical analysis

N, P and K utilization (assimilation) efficiency represents the amount of grain produced by per unit of N, P and K up-taken by plant till harvest (Xu et al., 2012). Thus, the NUE of N, P and K could be calculated with the following equation:

$$NUE = \frac{Grain\ yield}{Nutrient\ accumulation}$$

Where, the NUE (g g^{-1}) is the grain yield (g m^{-2}) per unit of nutrient up-taken (g m^{-2}) by rice till harvest, either of N, P and K.

All data were expressed as means with standard deviation of three replicates. One-way ANOVA followed by Duncan's test was used to test the differences between treatments. The general linear mixed (GLM) model was conducted to analyze the major effects of CO_2 enrichment, warming, cropping season and their interactions on nutrient uptake and their utilization efficiency. All statistical analyses were carried out using IBM SPSS ver. 20.0. A difference was considered significant at a probability level $p < 0.05$.