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Dynamics of soil available phosphorus and its impact factors under simulated climate change in typical farmland of Taihu Lake region, China

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Abstract Global climate change affects the availability of soil nutrients, thereby influencing crop productivity. This research was conducted to investigate the effects of elevated CO_2, elevated temperature, and the interaction of the elevated CO_2 and temperature on the soil available phosphorus (P) of a paddy–wheat rotation in the Taihu Lake region, China. Winter wheat (*Triticum aestivum* L.) was cultivated during the study period from 2011 to 2014 at two CO_2 levels (350 $\mu L \cdot L^{-1}$ ambient and 500 $\mu L \cdot L^{-1}$ elevated by 150 $\mu L \cdot L^{-1}$) and two temperatures (ambient and 2 °C above the ambient). Soil available P content increased at the first season and decreased at the last season during the three wheat growing seasons. Soil available P content showed seasonal variation, whereas dynamic changes were not significant within each growing season. Soil available P content had no obvious trends under different treatments. But for the elevated temperature, CO_2, and their combination treatments, soil available P content decreased in a long time period. During the period of wheat ripening stage, significant positive correlations were found between soil available P content and saturated hydraulic conductivity (Ks) and organic matter, but significant negative correlations with soil clay content and pH value; the correlation coefficients were 0.9400 ($p < 0.01$), 0.9942 ($p < 0.01$), −0.9383 ($p < 0.01$), and −0.6403 ($p < 0.05$), respectively. Therefore, Ks, organic matter, soil clay, and pH were the major impact factors on soil available P content. These results can provide a basis for predicting the trend of soil available P variation, as well as guidance for managing the soil nutrients and best fertilization practices in the future climate change scenario.

Keywords Climate change · Elevated CO_2 · Elevated temperature · Available phosphorus · Winter wheat

Introduction

The earth is undergoing an obvious climate change over the last decade; the main feature of climate change is climate warming, which is consistent with the global warming trend. Climate change has aroused wide concern among governments and the scientific community. The Chinese annual mean temperature has increased by 1.1 °C over the last 50 years, and it is expected to increase by 1.5 ~ 2.1 °C by 2020 (Ding et al. 2007). Global mean temperatures have risen approximately 0.74 °C and are projected to increase between 1.4 and 5.8 °C by the end of this century (IPCC 2007). During the past century, human activities have substantially added to the amount of

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greenhouse gases in the atmosphere by burning fossil fuels to power our cars, factories, utilities, and appliances. These added gases are primarily carbon dioxide and methane, which enhance the natural greenhouse effect, and likely contribute to the increased global average temperature. Climate change mainly caused by the elevated CO_2 and temperature will not only seriously influence global economic, social, and political activities, but also create a series of severe environmental problems. Climate change has resulted in increased intensity and frequency of extreme weather events. Increased temperature can also reduce the wheat growing period and crop production (Morison and Lawlor 1999). The increasing temperature has resulted in a positive feedback of carbon emissions caused by greater soil heterotrophic respiration and enhanced mineralization of soil organic matter (Le-Quere 2007; Bond-Lamberty and Thomson 2010). Elevated atmospheric CO_2 and temperature have great potential to affect plant photosynthesis, thereby influencing soil nutrients (Ainsworth and Long 2005; Kimball et al. 2002). In the case of agriculture, changes in temperature, precipitation, wind speed, and atmospheric CO_2 have significant impacts on crop productivity. Thus, there is an urgent need to identify factors impacting the fate of available phosphorus (P) in order to determine soil available P dynamics.

Nitrogen, phosphorus, and potassium in soils are the most common macronutrients for maintaining soil fertility and promoting plant growth under natural conditions. Information on soil P composition is important for agricultural ecosystems, especially because P is always the major growth-limiting nutrient when nitrogen (N) is sufficient (Jouany et al. 2011). One unique characteristic of P is its low availability due to slow diffusion and high fixation in soils (Shen et al. 2011). Soil parent material, physical and chemical properties, and fertilization practices are the main impact factors for soil P availability. Increasing synthetic chemical fertilizer loading directly affects ecosystems through alterations in primary production. Phosphorus fertilizer is commonly applied to paddy soil in excess of the amount that crops actually require. Of the applied phosphorus, only 15–30 % is taken up by the crops, and the rest is accumulated in surface soils (FAO 2006). Some studies have reported that elevated CO_2 and temperature have led to an increased decomposition rate of soil organic carbon (Kirschbaum 2000; Davidson and Janssens 2006). As a result, these biological processes have released more available P for plants to use.

Current global-circulation models predict that atmospheric CO_2 will reach to 550 $\mu L \bullet L^{-1}$ in the middle of this century (IPCC 2001). In 2002, the CO_2 was up to 373 $\mu L \bullet L^{-1}$ (Keeling and Whorf 2003). It is estimated that the atmospheric CO_2 increased by 1.5 $\mu L \bullet L^{-1} y^{-1}$, leading to the elevation of average global temperature of ≈2–3.5 °C (IPCC 2001). However, there are limited studies on the combined effects of elevated CO_2 and temperature on plant growth. In this study, based on the temperature-free air carbon dioxide enrichment (T-FACE) platform under rice–wheat rotation in the Taihu Lake area, winter wheat (*Triticum aestivum* L.) was planted at two levels of CO_2 (350 $\mu L \bullet L^{-1}$ ambient CO_2 and elevated CO_2 approximately enriched to 500 $\mu L \bullet L^{-1}$) and two temperature levels (ambient and ambient plus 2 °C). Soil available P content was determined throughout three entire wheat growing seasons (2011–2012, 2012–2013, and 2013–2014). The objective of this study was to analyze the long-term effects of successive elevated CO_2 and temperature on the dynamics and availability of soil P under field conditions and to provide scientific evidence for better fertilizer management.

Materials and methods

Site description

The field experiment was carried out at the Changshu Experimental Station in Jiangsu Province, China (31°30′ N, 120°33′ E). This experiment station is located at the key area of food production, with a subtropical monsoon climate. Total annual day length is over 2000 h; annual average temperature is 16 °C. The annual average precipitation is 1100–1200 mm, and the annual number of frost-free days is more than 230 days. The experimental field had not been subjected to any substantial agronomic changes in the past 50 years. Local farmers used conventional tillage with rice–wheat rotation which includes a rice crop from July to October and winter wheat from November to June. The soil texture is loamy. Major soil properties are listed in Table 1.

Experimental design

The experimental design included two CO_2 levels: ambient CO_2 (AC) and elevated CO_2, with CO_2 approximately 500 $\mu L \bullet L^{-1}$ (EC); and two temperatures: ambient temperature (AT) and elevated temperature, with 2 °C above the ambient (ET). Together, the four treatments in this study were: CK (AC + AT), C (EC + AT), T

Table 1 The physical–chemical properties of the topsoil layer at the study field in Jiangsu Province, China (0–14 cm)

Organic matter ($g \cdot kg^{-1}$)	Total N ($g \cdot kg^{-1}$)	Total P ($g \cdot kg^{-1}$)	Ks ($cm \cdot s^{-1} \cdot 10^{-4}$)	Bulk density ($g \cdot cm^{-3}$)	pH	Bulk density porosity (%)	Texture/%		
							Sand	Silt	Clay
43.03	1.9	1.4	7.04	1.21	7.01	54.34	33.8	38.6	27.6

(AC + ET), and CT (EC + ET). Each treatment was replicated three times in a complete randomized design.

The T-FACE system consisted of 12 octagonal rings (Ø 8 m, 45 m^2). For the elevated CO_2 treatments, the algorithm controlled CO_2 in accordance with wind-direction and wind-speed signals.

Liquid CO_2 was stored in an insulated tank with 20,000-kg capacity and vaporized through an electric heat exchanger. To obtain gaseous CO_2 at 750 kPa, vaporized CO_2 was regulated through a gas regulator and released into each elevated CO_2 treatment via PVC pipes. Pure and pressurized CO_2 was delivered at the center of the T-FACE treatments 50 cm above the crop canopy 24 $h \cdot d^{-1}$, and the CO_2 was maintained constantly at 500 $\mu L \bullet L^{-1}$ by a computer control. The ambient rings were set at minimum 90 m apart to minimize the possibility of overlapping flow of CO_2. Details of the T-FACE system and its performance were described by Zhang et al. (2013). For the elevated temperature treatments, an infrared sensor was used to monitor the temperature above the wheat plants' canopy. The temperature was kept at 2 °C higher than the ambient by using infrared lamps, controlled by a computer (Fig. 1).

Soil sampling and analysis

During every growth period (seeding, wintering, jointing, and ripening) of winter wheat, combined soil samples were collected from the top 0–14 cm in the area between rows in every plot. Soil samples were air dried, and any visible extraneous materials (e.g., residues, roots, and stones) were separated before the sample was ground to pass through a 2-mm sieve and weighed.

Soil bulk density was determined from core samples (stainless steel cylinders with a volume of 100 cm^3) taken from every horizon at every sampling point. The Ks was measured according to the constant-head method. Soil texture was determined by pipette method, and sodium hexametaphosphate as the dispersing agent after the removal of organic matter using hydrogen peroxide and heat treatment (ISSCAS 1978). Soil pH was determined by pH electrode in 5:1 water to soil ratio slurry. Soil organic matter was determined by the Walkley–Black dichromate oxidation procedure (Nelson and Sommers 1982). Soil available P was extracted with 0.5 M $NaHCO_3$ and analyzed using a UV–visible spectrophotometer (Brookes et al. 1982).

Statistical analysis

All data were expressed as the arithmetic mean value ± standard deviation. The repeated measurements analysis of variance was conducted to analyze the effects of elevated CO_2 and temperature on dynamic changes of soil available P over time. The changes in soil available P under the four different treatments were examined using the multiple comparisons–LSD method at a significance level of $p < 0.05$. Pearson's correlation coefficients were calculated to determine the relationship between the variables. All statistical analyses were carried out using SPSS20.0 software for Windows.

Results

The dynamics of soil available P content in the wheat growing season 2011–2012

Phosphorus can be strongly adsorbed by soil particles, so it becomes nearly immobile in soils. It is

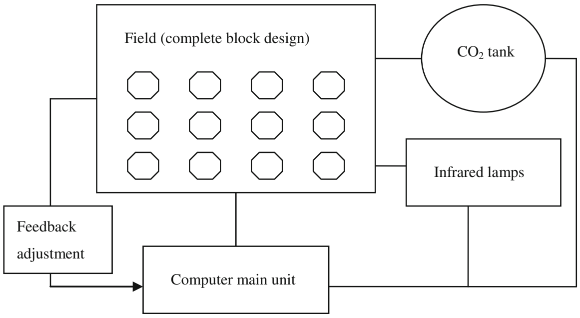


Fig. 1 Schematic demonstration of the T-FACE system

important to quantify the seasonal variation of available P in the surface soil layer because surface run-off can remove some of the P in the topsoil. The effects of CO_2, temperature, and time on soil available P in the topsoil layer are shown in Table 2. During the whole wheat growth period in 2011–2012, soil available P content was significantly affected by CO_2 and temperature (Fig. 2; $p < 0.05$). No significant interaction effect of elevated CO_2 and temperature on soil available P content was observed. Soil available P content did not change from jointing stage to ripening stage. During seeding stage to wintering stage, elevated CO_2, elevated temperature, and the interaction between the elevated CO_2 and temperature significantly decreased the soil available P content. For example, in the seeding stage, soil available P content in C, T, and CT rings was decreased by 3.91, 2.44, and 1.92 $mg \cdot kg^{-1}$, respectively. In the wintering stage, soil available P content in C, T, and CT rings was decreased by 2.24, 4.30, and 5.15 $mg \cdot kg^{-1}$, respectively. Soil available P content in C and T rings was 3.91 and 1.69 $mg \cdot kg^{-1}$ higher than that in CK rings in the jointing stage. In the ripening stage, soil available P content in CK rings was 4.03 $mg \cdot kg^{-1}$ lower than that of C rings, while it was 2.20 $mg \cdot kg^{-1}$ higher than CT rings. Soil available P content in T rings was close to that in CK rings in the jointing and ripening stages.

Table 2 Analysis of the effects of CO_2, temperature, and time on soil available P in topsoil layer (0–14 cm)

Factors	The growing season 2011–2012	The growing season 2012–2013	The growing season 2013–2014
CO_2	0.047*	0.089 ns	0.000**
T	0.049*	0.000**	0.000**
Time	0.129 ns	0.000**	0.000**
$CO_2 \times T$	0.285 ns	0.434 ns	0.006**
$CO_2 \times$ time	0.158 ns	0.346 ns	0.901 ns
T × time	0.559 ns	0.928 ns	0.003**
$CO_2 \times T \times$ time	0.726 ns	0.022*	0.926 ns

Note: Numbers are shown as p values. *ns* means the difference is not significant. *One asterisk* and *two asterisks* indicate significant difference at $p < 0.05$ and $p < 0.01$, respectively. *CO_2* means elevated CO_2, *T* means elevated temperature, and *time* means the four different growth periods of winter wheat

The dynamics of soil available P content in the wheat growing season 2012–2013

In the course of the whole wheat growth period 2012–2013, time and $CO_2 \times T \times$ time significantly affected soil available P content with $p < 0.01$ and $p < 0.05$, respectively (Table 2). In general, soil available P content was high relative to 2011–2012. The highest concentration of soil available P in the CK treatment was 54.71 $mg \cdot kg^{-1}$ in the wintering stage (Fig. 3). Compared with CK, soil available P content of C, T, and CT rings in the seeding stage was reduced by 7.78, 13.05, and 14.21 $mg \cdot kg^{-1}$, respectively. In the wintering stage, soil available P content in C, T, and CT rings was decreased by 12.01, 15.78, and 12.22 $mg \cdot kg^{-1}$, respectively. In the ripening stage, soil available P content in C, T, and CT rings was decreased by 4.67, 11.10, and 15.29 $mg \cdot kg^{-1}$, respectively. However, soil available P content in C rings was higher than that in CK rings in the jointing stage.

The dynamic changes of soil available P content in the wheat growing season 2013–2014

During winter wheat growth in 2013–2014, soil available P was significantly affected by CO_2, temperature, and time, as well as $CO_2 \times T$, T × time ($p < 0.01$) (Table 2). The soil available P content was higher than in the first year, but lower than in the second year. This difference is due to fluctuating climate conditions in the three years. Soil available P content of the four different treatments (CK, C, T, and CT) ranged from 34.95 to 42.20 $mg \cdot kg^{-1}$, 26.41 to 33.15 $mg \cdot kg^{-1}$, 22.46 to 32.52 $mg \cdot kg^{-1}$, and 19.67 to 33.23 $mg \cdot kg^{-1}$, respectively (Fig. 4). During the jointing stage, a substantial amount of soil available P was taken up by wheat; however, the residual available P was still a significant amount, not decreased as expected (Fig. 4). Increased CO_2 can promote soil organic P mineralization, increasing soil P availability. In comparison with 2011–2012, the variation of available P content was not the same in the growing period of 2012–2013. After the jointing stage, increased temperature will promote land surface evaporation and plant transpiration, while the increased atmospheric water vapor may lead to more intense and longer-lasting precipitation (Trenberth et al. 2003; Sheffield and Wood 2008). In the seeding, wintering and jointing stages, all the three treatments resulted in a reduction of available P content, resulting in available P content in the order: CK>C>T>CT. Meanwhile, soil available P

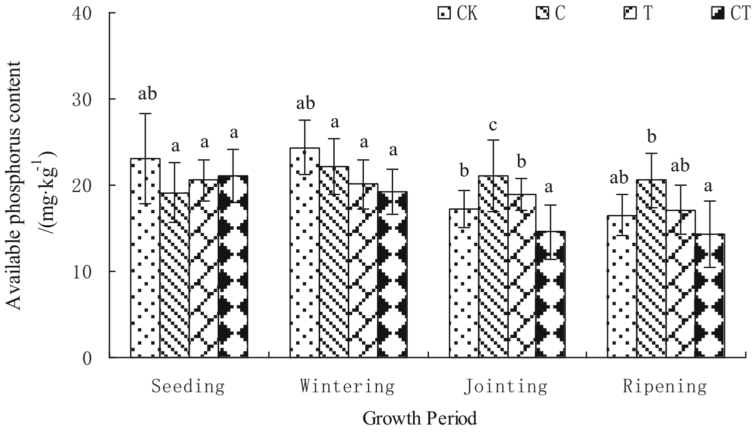


Fig. 2 The relationship of growth periods with available phosphorus in 2011–2012

content in CK rings was higher than in the other rings in the ripening stage (Fig. 4).

Discussion

Although high concentrations of organic P persist, its potential availability is particularly low and determined by the type of soil P compounds. In soils, P occurs almost entirely as organic phosphate and inorganic orthophosphate or polyphosphates. The relationships between nutrients and physical factors like temperature, CO_2, as well as light, can shift due to climate change and affect the growth of plants. When plants are exposed to the combination of elevated CO_2 and temperature, the responses are more complex. The positive effect of elevated CO_2 on soil available P content may be enhanced by temperature elevation or combined with meteorological and environmental factors. Some results can be obtained by multivariate analysis. The effects of CO_2, temperature, and time were increasingly obvious each year.

Effect of elevated CO_2 on soil available P levels

Soil available P includes all water soluble phosphorus, some forms of absorbed phosphorus, and organic P fractions. The bioavailability of P is affected by many factors, for instance, pH, organic matter, moisture content, etc. In the present study, elevated CO_2 and temperature showed significant effects on soil available P content. P acquisition by wheat was significantly enhanced under elevated CO_2 during the wheat growth period. Elevated CO_2 led to lower soil available P content than that of CK during the growing seasons.

Elevated CO_2 stimulates leaf-level photosynthesis, which leads to rapid plant growth, resulting in higher biomass production or yield (Wang et al. 2012). In the jointing and ripening stages, soil available P uptake was more rapid because the wheat and most soil microbes are active and need substantial P. At the same time, rhizosphere secretions such as organic acids, amino acids, and sugars can intensify leakage of inorganic P from soil Fe/Al complexes in a highly P-limited system (Marschner

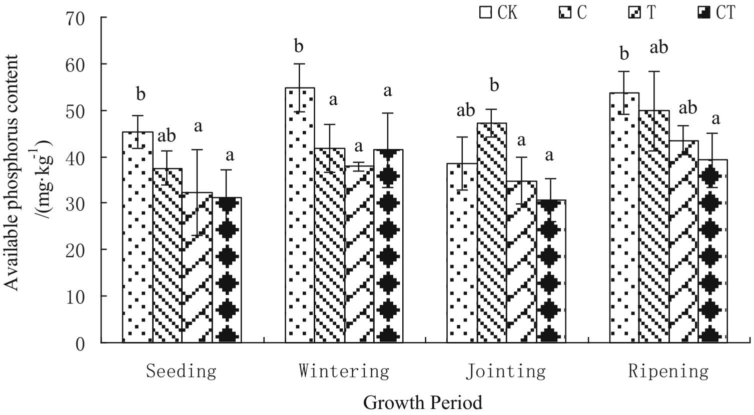
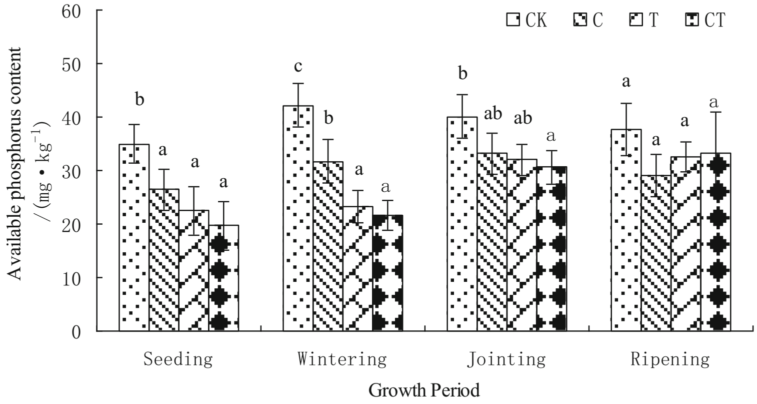


Fig. 3 The relationship of growth periods with available phosphorus in 2012–2013

Fig. 4 The relationship of growth periods with available phosphorus in 2013–2014



1995). Organic acids such as citric acid and tartaric acid can also be produced in the process of organic matter decomposition (Kupryianchyk et al. 2013). Previous rice/wheat FACE experiments conducted in China have shown that the increase in root biomass and exudates was able to increase soil P availability (Xie et al. 2002; Ma et al. 2007). Rising CO_2 is expected to increase soil temperature, which may stimulate the flux of carbon dioxide from soils, causing a positive feedback (Ise and Moorcroft 2006). These results might explain why soil extractable P increased under elevated CO_2 treatments.

Effect of elevated temperature on soil available P levels

To some extent, higher temperature will alter seed germination, growth, reproduction as well as other physiological and biochemical processes in different ways (Mondoni et al. 2012). Soil temperature controls biogeochemical process such as dissolved organic carbon export, length of growing season, mineralization rates, and decomposition of soil organic matter and nutrient assimilation by plants (Haei et al. 2013; Melillo et al. 2002). The elevated temperature treatments seemed to cause a great decrease in soil available P content throughout the investigated period.

Photosynthesis is a complex process which is influenced by many factors, such as photochemical reactions, enzyme reactions, temperature, and others. On one hand, temperature can influence microbial activities and P activity, which would also promote P release (Zhang et al. 2013). On the other hand, the P-solubilizing microbes (bacteria, fungi, and actinomycetes) can convert insoluble P to soluble P, thereby improving P utilization (Wu et al. 2008). In the wheat reproductive growth stage, plants and soil microbes need abundant nutrients. Microbial activities can promote the decomposition of organic P for plant utilization. Moreover, temperature can improve enzyme activity and soil respiration. The enzymes secreted mainly by wheat roots, mycorrhizae, and bacteria are one of the most active organic compounds in soils and drive almost all the organic reactions. The increase of root secretions can promote P availability. In addition to the effect on P mineralization, elevated temperatures were reported to affect soil P composition by decreasing the amount of monoester-P (Sumann et al. 1998). A previous study regarding climate change and future wheat growing conditions revealed that dissolved organic phosphorus can be directly absorbed by wheat. Elevated temperature may reduce soil moisture content by enhancing evaporation, thus reducing soil P efficiency (Ruosteenoja et al. 2005). If available water decreases due to global warming, this could have a negative impact on crop productivity.

The relationships between soil available P and Ks, soil clay, organic matter, and pH value

Ks is a key variable in the water movement process. It determines rainfall infiltration into soil layers and into different hydrologic paths, such as groundwater recharge, lateral, subsurface runoff, and overland flow. Soil available P content was significantly correlated with Ks at wheat ripening stage (Pearson's correlation coefficient $r = 0.9400^{**}$, $n = 14$). This is due to the increased soil profile cracking during wheat growth. Soil available P content increased with the increase of Ks in the subsoil layer.

Soil organic matter is the key factor that controls the release of nutrients. Some researchers have indicated organic matter can produce hydroxyl, carbonyl, and phenolic hydroxyl species that compete for adsorption with P, reducing P adsorption (Ni et al. 1995). Soil organic matter can be decomposed to produce abundant free radicals so as to adsorb soil nutrients. Soil available P and soil organic matter at wheat ripening stage showed significant positive correlation with $r=0.9942^{**}$, $n=14$. Soil organic matter and soil porosity in the topsoil layer were higher than in the subsoil layer. Microbial activity was inhibited because of the lack of nutrients. Both CO_2 and temperature elevation increased mineralization of nutrients in the soil organic matter during wheat growth.

Clay particles have the minimum diameter and the largest specific surface among soil particles. Clay is the most active component of the solid phase in soils and a key factor in the formation of soil aggregates. In particular, it protects soil organic matter from biological degradation and regulates water and gas flows, run-off, and erosion. Clay minerals have a major role in soil aggregation, which can promote soil and water conservation and decomposition of organic matter, and also stop nutrient leaching into the subsoil. The relationship between soil available P and soil clay percentage at wheat ripening stage was significant ($r=-0.9383^{**}$, $n=14$). Soil available P content decreased with increasing clay content.

Soil pH is also an important factor for evaluating soil quality. Rhizosphere secretions increase with the increase of temperature and CO_2 under the condition of climate change. Thus, soil pH is decreased. Variation of pH can change the aggregation/cohesion behavior of soil particles by altering their surface charge properties. The effect of pH on P release is mainly shown through the P speciation in combination with other elements (Kim et al. 2003). There was a remarkable negative linear correlation between pH value and soil available P content at wheat ripening stage. The correlation coefficient was -0.6403^{*} ($n=14$).

Conclusions

Elevated CO_2, temperature, and the interaction of elevated CO_2 and temperature had a significant effect on soil available P content, this effect could become stronger over time. Elevated CO_2 and temperature can stimulate the release of P from soils, and therefore, the application of P fertilizer should be adjusted accordingly. Significant positive correlations were found between soil available P content and Ks and organic matter but significant negative correlations with soil clay and pH value during the wheat ripening stage.

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