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Full Length Article

Comprehensive Evaluation on the Tolerance of Eight Crop Species to CO_2 Leakage from Geological Storage

Lu Xue[1,2], Junjie Ma[1,3*], Jiangli Wu[1], Chenyang Zhao[1], Haodong Liu[1], Dan Liu[1] and Jinfeng Ma[3]
[1]*College of Urban and Environmental Sciences, Northwest University, Xi'an 710127, China*
[2]*College of Life Science, Yulin University, Yulin 719000, China*
[3]*National & Local Joint Engineering Research Center of Carbon Capture and Storage Technology, Northwest University, Xi'an 710127, China*
[*]For correspondence: xdhgvip@163.com

Abstract

Carbon dioxide capture and storage (CCS) is considered as the most promising and potential technology of reduction in CO_2 emission. However, the risk of CO_2 leakage resulting from geological storage projects has a significant impact on the surroundings, especially on the associated farmland ecosystem. As the basis for agricultural production decision-making in the CCS project area, it is very important to carry out in-depth research on the response of crops to high CO_2 concentration and quantitative evaluation of crop tolerance to CO_2. In this paper, the impacts of ultra-high CO_2 on the plant height, maximum root length, leaf number, net photosynthetic rate, transpiration rate, stomatal conductance, intercellular CO_2 concentration, fresh and dry biomass of eight typical crops were simulated using CO_2 artificial climate chamber. A comprehensive evaluation method on the crop tolerance to CO_2 was established based on principal component analysis (PCA) and fuzzy comprehensive evaluation method (FCE) and the tolerance of eight typical crops to CO_2 in the Loess Plateau of China was evaluated. The results indicated that the growth of eight crops was promoted in a certain range of CO_2 concentration and the maximum growth indicators of C_3 crops was at 10 mmol·mol^{-1} and that of C_4 crops was at 20 mmol·mol^{-1}. When the CO_2 concentration continued to increase, the growth of C_3 and C_4 crops were inhibited in varying degrees, in which the inhibition for C_3 crops was higher. The relative tolerance of crops to CO_2 was as follows: sorghum > broomcorn millet > foxtail millet > maize > mung bean > soybean > potatoes > buckwheat and C_4 crops were more tolerant to CO_2 than C_3 crops. The priority crops for CO_2 leakage of the CCS project area was recommended in Loess Plateau of China. © 2019 Friends Science Publishers

Keywords: CCS; CO_2 leakage; Crop tolerance; Photosynthetic pathways; Farmland

Introduction

As a key part of clean energy technology, carbon dioxide capture and storage (CCS) provides a sustainable path to reduce greenhouse-gas emissions and ensures energy security (GCCSI, 2018). It injects CO_2 captured from the emission sources of industry or related energy industries into stable geological structures such as oil and gas reservoirs, deep saltwater layers and unexploited coal seams to reduce CO_2 emissions and its sequestration from the atmosphere permanently (IPCC, 2005; Christensen, 2007; Leung *et al.*, 2014). However, in terms of the current CCS development, there are still risks of CO_2 leakage through injection wells, abandoned wells or ineffective confining layers (Metz and Davidson, 2008). Once CO_2 leakage occurs, it will have a significant impact on water and soil environment, growth and development of plants and animals, as well as on human security (Zwaan and Gerlagh, 2009; Blackford *et al.*, 2013).

Previous studies about climate change impact mostly focused on the effects of doubling CO_2 concentration on typical plants (Cure and Acock, 1986; Kimball *et al.*, 1993; Wang *et al.*, 1995; Yang *et al.*, 1997; Rogers *et al.*, 1999). With the development of CCS technology, the studies of impact on typical plants or crops in ultra-high CO_2 concentration which is much higher than doubling CO_2 concentration have become an important field of CCS environmental risk research (Stenhouse *et al.*, 2009a, b). Due to the short construction time, small quantity and small storage scale of the actual CCS project, there is no obvious CO_2 leakage phenomenon in the project area. Current researches on the impact of CO_2 leakage on plants or crops are mostly focused on the field or indoor simulation of CO_2 leakage and on-site investigation or research of other CO_2 leakage points. Beaubien *et al.* (2008) and Krüger *et al.* (2009) found that the vegetation coverage was significantly affected within 6 meters around the natural CO_2 leakage point, and gradually recovered from 6 meters away. Pfanz *et al.* (2007) found that the increase of CO_2 concentration at volcanic eruption led to a decrease in photosynthesis of

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timothy grass. Amonette *et al.* (2010), Lakkaraju *et al.* (2010) and Zhou *et al.* (2013) observed that plant growth withered or even plant died in the central area of CO_2 leakage source using artificial simulation platform. Pierce and Sjögersten (2009) and Patil *et al.* (2010) found that the growth of winter bean was significantly inhibited and its biomass reduced remarkably compared to pasture grass through artificial simulation platform experiments. In addition, Tian (2013), Wu *et al.* (2014) and Deng *et al.* (2017) showed that the root length and biomass of wheat, alfalfa and pea decreased more severely than that of maize by simulating CO_2 leakage in different laboratory scenarios. Many studies pointed out that the difference in response of various plants to CO_2 maybe due to different photosynthesis pathways (Beaubien *et al.*, 2008; Krüger *et al.*, 2009; West *et al.*, 2009; Xue *et al.*, 2014).

It is well known that the photosynthesis of C_3 plants is the conversion of carbon dioxide into organic matter by the Calvin cycle under the action of Rubisco enzyme in mesophyll cells. However, the photosynthesis of C_4 plants is a process that CO_2 is converted to C_4 acid under the action of PEPC carboxylase firstly and the C_4 acid is converted to CO_2 again by decarboxylation reaction in mesophyll cells through Hatch-Slack pathway, and the converted CO_2 is entered to the vascular bundle sheath cells and synthesized to organic matter through the Calvin cycle (Hatch and Slack, 1966; Rosie, 1973, Sayre *et al.*, 1979; Hatch, 1987; Weiner *et al.*, 1988). Under normal CO_2 concentration, photosynthesis of C_3 and C_4 plants is significantly different due to their photosynthesis sites and participating enzymes, and C_4 plants are considered to be superior to C_3 crops in assimilation efficiency of CO_2 and more tolerant for the stress of low CO_2 concentration, drought and other factors (Cerling *et al.*, 1993, 1998; Koch *et al.*, 2004). Whether there is a difference in the tolerance of C_3 and C_4 plants to ultra-high concentrations of CO_2 is still a problem worth studying.

In this paper, the simulation experiment of eight typical C_3 and C_4 crops in Loess Plateau of China was carried out to understand the impact of ultra-high CO_2 concentration on the crops. Meanwhile, the evaluation method of crop tolerance to CO_2 was established on the basis of principal component analysis (PCA) and fuzzy comprehensive evaluation method (FCE) to assess the eight typical crops for tolerance to CO_2. The main purpose of this paper is to systematically understand the response and quantitative evaluate the tolerance of crops to CO_2, so as to provide a reference for the agricultural production of CCS project area in the Loess Plateau of China.

Materials and Methods

Plants and Soil Characteristics

The seeds of eight typical crops (includes four C_3 crops and four C_4 crops) were provided by the Agricultural Technology Extension Station of Jingbian County, Shaanxi Province of China. Species of tested crops are shown in Table 1. The experimental soil was sampled from the surface soil of 0–20 cm on farmland in the CO_2 injection test area of the CCS testing project (E108°17'–109°27', N36°58'–38°03') in Jingbian County. The type of experimental soil is sandy loam comprising sand (79.3%), silt (12.95%) and clay (7.75%). The pH is 7.8, the organic matter is 0.31%, and the available N, P, K of experimental soil is 30.02, 1.19 and 46.40 $mg \cdot kg^{-1}$, respectively.

Experimental Methods

Experimental design and procedures: In this experiment, a CO_2 artificial climate chamber (RXZ-500C-CO_2, Ningbo, China) was used to simulate the ultra-high CO_2 environment of CO_2 leakage from CCS (Fig. 1).

The PID control system (Proportion, Integral and Derivative Control System, PIDCS) was used to collect and control CO_2 in the artificial climate chamber, and ensure the CO_2 concentration to meet and maintain the experimental requirements. The temperature, relative humidity, illumination and CO_2 concentration of the CO_2 artificial climate chamber ranged from 0 to 50℃, from 30 to 95%, from 0 to 22 KLux, and from 380 to 100000 $\mu mol \cdot mol^{-1}$ respectively. All parameters are multi-stage adjustable according to the experimental needs.

In the experiment, 8–10 pots and 4–5 plants/pots of each crop were cultivated to 2–3 leaves stage in the condition of no entrancing CO_2 gas in the CO_2 artificial climate chamber. 6 pots and 1–3 plants/pots of healthy crops were selected and cultivated with watering and fertilizing regularly for 30 days under the controlled CO_2 concentration. Five CO_2 concentrations of the CO_2 artificial climate chamber were set to 380 $\mu mol \cdot mol^{-1}$ (the control group), 10, 20, 40, and 80 $mmol \cdot mol^{-1}$, respectively. The other conditions of the CO_2 artificial climate chamber were set with the temperature of 25℃, RH of 75% and illumination of 22 KLux at daytime of 12 h, and with the temperature of 20℃, RH of 75% and illumination of 4.4 KLux at nighttime of 12 h, respectively.

Growth measurement indicators: Nine growth indicators including plant height, leaf number, maximum root length, fresh and dry biomass, net photosynthetic rate (*Pn*), transpiration rate (*E*), stomatal conductance (*gs*) and intercellular CO_2 concentration (*Ci*) were determined in which *Pn*, *E*, *gs*, *Ci* were measured by LI-6400X photosynthesis analyzer (Nebraska, USA).

Evaluation for Crop Tolerance to CO_2

According to Shelford's law of tolerance, the adaptation of organisms to their ecological factors have the limit of

Table 1: Species of tested corps

Photosynthetic pathway	Species	Cultivar
C_3	Mung bean (*Vigna radiata* L. Wilczek)	Local Jingbian
	Soyabean (*Glycine max* L.Merrill)	Qindou No. 8
	Buckwheat (*Fagopyrum esculentum.* Moench)	Yuqiao No. 4
	Potatoes (*Solanum tuberosum*)	Favorita
C_4	Maize (*Zea mays* L.)	Ximeng No. 6
	Sorghum (*Sorghum bicolor* L. Moench)	Jinza No. 12
	Foxtail millet (*Setaria italica* L. Beauv)	Jingu No. 29
	Broomcorn millet (*Panicum miliaceum* L.)	Neimi No. 5

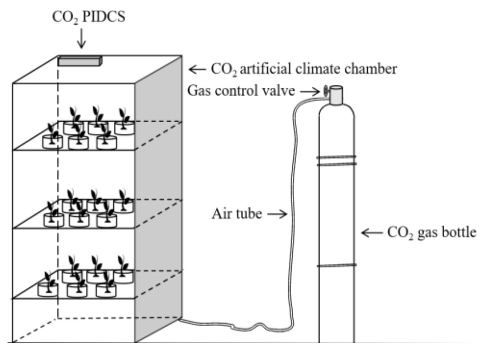

Fig. 1: CO_2 artificial climate chamber

minimum and/or maximum, and the range from the minimum to the maximum is called the biological tolerance range (Shelford, 1911a, 1911b, 1931). Shelford answered the question of biological tolerance range, but there still is difference of the optimal range and the adaptive range within the range and the measurement of ecological factor tolerance within the adaptive range needs to be further refined. On the basis of mechanism that CO_2 have effects of fertilization and inhibition on crops, the concept of crop tolerance coefficient to CO_2 is introduced to express the tolerance of crops to high CO_2 concentration compared to normal atmospheric CO_2 concentration.

The tolerance of crops is referred to the growth and development of crops which can be measured by morphological indicators, physiological indicators, biomass indicators and other indicators. As there is a certain degree of independence or complementarity between single indicators of plant, the tolerance between single indicators and the tolerance between single indicators and comprehensive indicators of crops are different, therefore, based on the tolerance coefficient of single indicator, the PCA and FCE are used to construct a comprehensive evaluation method of crop tolerance to CO_2, so as to comprehensively calculate the tolerance coefficient of different crops, in which the PCA is used to identify and eliminate the correlation between single indicators, and the FCE is used to comprehensively calculate from single indicators to comprehensive indicators. The details are as follows:

Tolerance coefficient of single indicator: The tolerance coefficient of single indicator was calculated as follows (Luo *et al.*, 2013):

$$x_i = \frac{\overline{V_i}}{V_{CK}}, (i = 1,2\ldots m) \quad (1)$$

Where i refers to i-th single indicator, m is the number of single indicators, $\overline{V}_i$ refers to an average value under different treatments of single indicator, and V_{CK} refers to the measured value under the control treatment.

Principal component analysis: According to the calculation method of the correlation coefficient, the correlation coefficients between each single indicator were calculated, and the correlation coefficient matrix of all indicators was obtained. When there were significant or extremely significant correlations between the single indicators in the correlation coefficient matrix, the PCA was used to convert the original correlation indicators into independent indicators. The formula is as follows (Yu, 1993):

$$Z_j = \sum_{i=1}^{m} b_{ij}x_i, (i = 1,2\ldots m, j = 1,2\ldots n, n \leqslant m) \quad (2)$$

Where Z_j is the value of j-th principal component indicator; b_{ij} is the Eigen vector of i-th indicator to j-th principal component, and n is the number of principal component.

The Eigen value (λ_j), variance contribution (P_j), and cumulative variance contribution ($\sum P_j$) for each principal component were calculated. Generally, the number of principal components extracted is required to satisfy $\sum P_j > 0.85$.

Comprehensive tolerance coefficient: According to FCE, the comprehensive tolerance coefficient (D_k) of each crop to CO_2 was calculated using the following formula (Xie and Liu, 2013):

$$D_k = \sum_{j=1}^{n} \mu_{(Z_{jk})} * W_j, (j = 1,2\ldots n) \quad (3)$$

$$\mu_{(Z_{jk})} = \frac{Z_{jk} - Z_{min}}{Z_{max} - Z_{min}} \quad (4)$$

$$W_j = \frac{P_j}{\sum_{j=1}^{n} P_j} \quad (5)$$

Where Z_{jk} is Z_j value of k-th crop, Z_{max} and Z_{min} represent the maximum and minimum values of j-th principal component of all crops respectively, W_j is the weight value of j-th principal component, and $\mu_{(Z_{jk})}$ is the membership function value of Z_{jk} for comprehensive tolerance in formula 3–5.

Statistics Analysis

Microsoft Office Excel 2010 and origin 8.5 were used for data statistics. SPSS 22.0 was used for significance analysis, correlation analysis and principal component analysis.

Result

Impacts of Ultra-high CO_2 on Growth and Development of Crops

Morphological indicators: The impacts of ultra-high CO_2 on plant height, maximum root length and leaf number of eight crops were shown in Fig. 2. Different CO_2 concentration had significant effects on plant height (Fig. 2a) and maximum root length (Fig. 2b) of the eight crops ($P < 0.05$), but had no significant effect on the number of leaves (Fig. 2c), especially the C_4 crop. Although plant height and maximum root length of C_3 crops were increased at CO_2 concentration of 10 mmol·mol^{-1} compared to CK group, significantly inhibited when CO_2 concentration increased to 20, 40, 80 mmol·mol^{-1}. The plant height and longest root length of C_4 crops were promoted at CO_2 concentration of 10 and 20 mmol·mol^{-1}, while inhibited when CO_2 concentration increased to 40 and 80 mmol·mol^{-1}.

Physiological indicators: Gas exchange is often used to reflect the physiological characteristics of plants, which usually involves four indicators; net photosynthetic rate (*Pn*), transpiration rate (*E*), stomatal conductance (*gs*) and intercellular CO_2 concentration (*Ci*). The photosynthesis of C_3 and C_4 crops showed different trends with the increase of CO_2 concentration, which were explained by the examples of mung bean of the C_3 plant and maize of the C_4 plant (Fig. 3). The *Pn*, *E* and *gs* of mung bean and maize had significant differences at CO_2 concentration of 10, 20, 40, 80 mmol·mol^{-1} compared to CK group. The *Pn*, *E* and *gs* of mung bean reached the maximum when CO_2 concentration was 10 mmol·mol^{-1}, while those of maize reached the maximum when CO_2 concentration was 20 mmol·mol^{-1}. As the concentration of CO_2 continues increased, the *Pn*, *E* and *gs* of mung bean and maize gradually decreased, and the decrease in mung bean was greater than that of maize. In addition, the *Ci* of mung bean and maize showed an increasing trend with the increase of CO_2 concentration. At different CO_2 concentration, the difference of *Ci* in mung bean was slightly larger than that in maize.

Biomass indicators: Biomass indicators are usually measured by fresh and dry biomass. The impacts of ultra-high CO_2 concentration on fresh and dry biomass of eight crops were shown in Fig. 4. Different CO_2 levels had significant effects on fresh and dry biomass of eight crops ($P < 0.05$), and there were the same trends with that of plant height and maximum root length. However, the impacts of ultra-high CO_2 on fresh and dry biomass of C_3 and C_4 crops were different. The impact of ultra-high CO_2 concentration on dry biomass of C_3 crops was greater than that of fresh biomass, while it was opposite for C_4 crops ($P < 0.05$).

Assessment of Crop Tolerance to CO_2

Tolerance coefficient of single indicator: The tolerance coefficient of single indicator for each crop was calculated

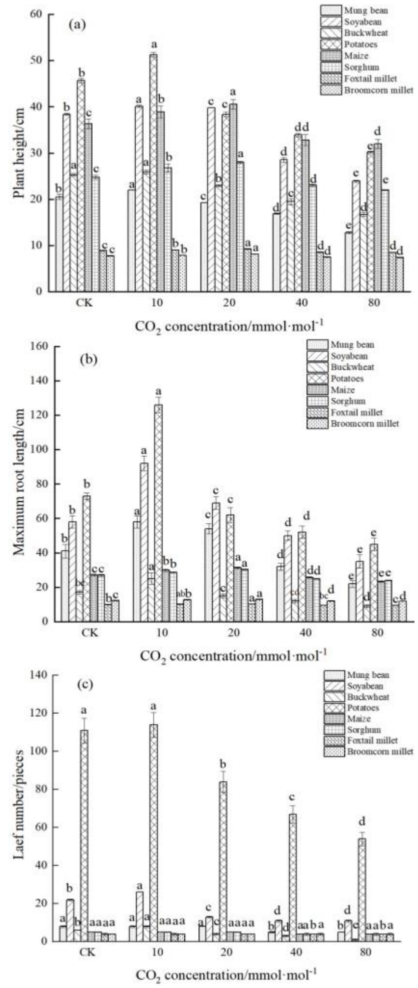

Fig. 2: Impacts of different CO_2 concentration on plant height (a), maximum root length (b) and leaf number (c) of eight crops

using formula (1) given in Table 2. It can be seen that the differences of tolerance coefficients in *Pn*, *E*, and *gs* were greater than that in plant height, leaf number, longest root length, fresh biomass, dry biomass and *Ci*, and the tolerance coefficient in *Ci* was all greater than 1.

Principal component analysis: Through the correlation analysis of the tolerance coefficient of single indicators, the correlation coefficient matrix of each indicator can be obtained as shown in Table 3. It can be seen that the tolerance coefficient of plant height, leaf number, fresh biomass, dry biomass, net photosynthetic rate and stomatal conductance were extremely significantly correlated, the tolerance coefficient of maximum root length, leaf number, net photosynthetic rate and transpiration rate were significant correlated, and while the tolerance coefficient of intercellular CO_2 concentration was not related to that of the other indicators.

The Eigen values (λ_i), variance contributions (P_j), and cumulative variance contributions (ΣP_j) of each principal component were obtained by the PCA as shown in Table 4.

Table 2: The tolerance coefficient of each indicator to CO_2 for eight crops (x_i)

Species	Height	Leaf number	Maximum root length	Fresh biomass	Dry biomass	*Pn*	*E*	*gs*	*Ci*
Mung bean	0.8659	0.8125	1.0122	0.8940	0.8841	0.7904	0.8575	0.9108	1.1206
Soyabean	0.8613	0.6932	0.9044	0.8892	0.8884	0.4609	1.0858	0.8576	1.1077
Buckwheat	0.8399	0.6667	0.8971	0.8842	0.8479	0.5257	0.7799	0.4391	1.1087
Potatoes	0.8414	0.7185	0.9760	0.9255	0.8770	0.4553	1.0944	0.6116	1.1425
Maize	0.9926	0.9000	1.0125	0.9835	0.9755	1.1481	1.2275	1.0737	1.1537
Sorghum	1.0063	0.9000	0.9996	0.9776	1.0005	1.0970	1.1741	1.1444	1.2337
Foxtail millet	0.9966	1.0000	1.0020	0.9946	0.9943	1.2274	1.2078	1.2287	1.1048
Broomcorn millet	0.9948	1.0000	1.0042	1.0188	1.0254	1.1045	1.2610	1.2778	1.0840

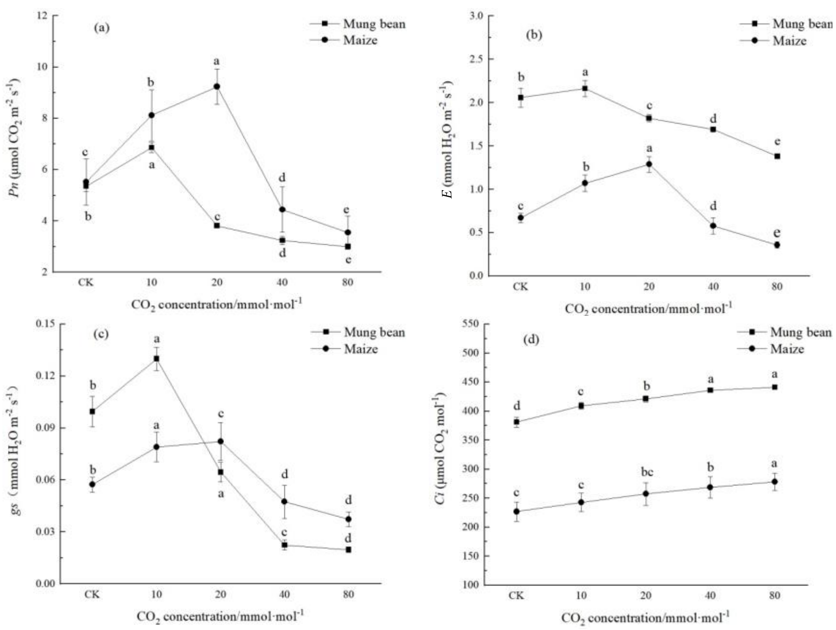

Fig. 3: Impacts of different CO_2 concentration on *Pn* (a), *E* (b), *gs* (c) and *Ci* (d) of mung bean and maize

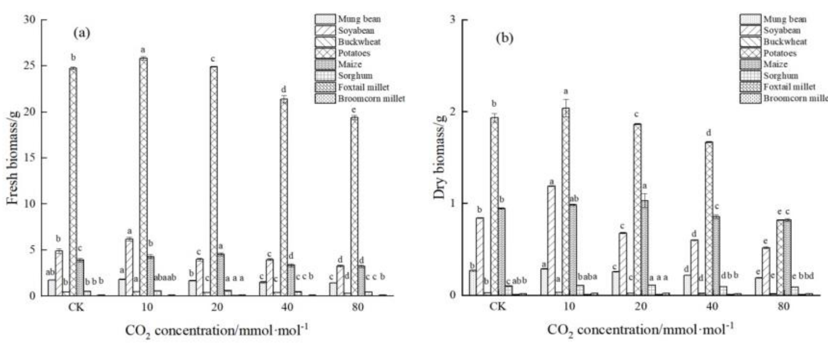

Fig. 4: Impacts of different CO_2 concentration on fresh (a) and dry (b) biomass of eight crops

It can be seen that the cumulative variance contribution of the first three principal components has reached 92.24%, which can reflect the information of the tolerance coefficients of the nine single indicators. The Eigen vector of the single indicator to the first three principal components is shown in Table 5.

Comprehensive evaluation of crop tolerance to CO_2: Z_1, Z_2 and Z_3 of each crop were calculated according to Table 5 and formula (2). The membership degree ($\mu_{(Z_{jk})}$) of each principal component to the comprehensive tolerance coefficient of each crop were calculated by formula (4), the weight values of each principal component were calculated by formula (5) and the comprehensive tolerance coefficient (D) of each crop were finally calculated according to formula (3) as shown in Table 6.

Table 3: The correlation matrix of each indicator

Indicators	Height	Leaf number	Maximum root length	Fresh biomass	Dry biomass	*Pn*	*E*	*Gs*
Leaf number	0.919**							
Maximum root length	0.661	0.719*						
Fresh biomass	0.927**	0.924**	0.694					
Dry biomass	0.974**	0.940**	0.670	0.960**				
Pn	0.954**	0.953**	0.719*	0.873**	0.909**			
E	0.789*	0.719*	0.527	0.862**	0.847**	0.642		
gs	0.898**	0.931**	0.711*	0.837**	0.933**	0.880**	0.780*	
Ci	0.304	0046	0.275	0.137	0.210	0.209	0.176	0.104

Note: **indicate extremely significant correlation ($P<0.01$); * indicate significant correlation ($P<0.05$)

Table 4: λ_i , P_j and $\sum P_j$ of each principal component

Principal components	λ_i	P_j/%	$\sum P_j$/%
1	6.899	76.65	76.65
2	1.022	11.36	88.01
3	0.561	6.23	94.24
4	0.313	3.48	97.72
5	0.157	1.75	99.47
6	0.041	0.46	99.93
7	0.008	0.08	100.00
8	0.000	0.00	100.00
9	0.000	0.00	100.00

Table 5: The Eigen vector of the single indicator to the principal component

Indicator	b_{i1}	b_{i2}	b_{i3}
Height	0.971	0.075	0.093
Leaf number	0.968	-0.170	-0.157
Maximum root length	0.784	0.153	-0.501
Fresh biomass	0.957	-0.086	0.128
Dry biomass	0.982	-0.028	0.137
Pn	0.947	0.005	-0.189
E	0.833	-0.035	0.447
gs	0.941	-0.119	-0.014
Ci	0.226	0.970	0.075

Table 6: Z values, μ values and D values of eight crops

Species	Z_1	Z_2	Z_3	$\mu_{(Z1)}$	$\mu_{(Z2)}$	$\mu_{(Z3)}$	D value	Order
Mung bean	6.7176	0.9326	-0.0134	0.4101	0.7000	0.0000	0.4162	5
Soyabean	6.3381	0.9205	0.2230	0.2637	0.6349	1.0000	0.3598	6
Buckwheat	5.6543	0.9857	0.0796	0.0000	0.9864	0.3935	0.1459	8
Potatoes	6.2011	0.9855	0.1954	0.2109	0.9856	0.8831	0.3509	7
Maize	7.9089	0.9185	0.1065	0.8696	0.6243	0.5070	0.8148	4
Sorghum	7.9226	0.9882	0.1077	0.8749	1.0000	0.5121	0.8645	1
Foxtail millet	8.2239	0.8340	0.0708	0.9911	0.1686	0.3561	0.8479	3
Broomcorn millet	8.2470	0.8027	0.1216	1.0000	0.0000	0.5712	0.8500	2

According to the above definition of crop tolerance to CO_2, greater the D value, stronger would be the crop tolerance to CO_2. It can be seen from Table 6 that the comprehensive tolerance coefficient (D value) to CO_2 of the eight crops ranged from 0.1459 to 0.8645, wherein the D values of the C_3 crop were from 0.1459 to 0.4162, and the D values of the C_4 crop were from 0.8148 to 0.8645. The comprehensive tolerance coefficient to CO_2 of the eight typical crops in the Loess Plateau of China was: sorghum > broomcorn millet > foxtail millet > maize > mung beans > soybean > potatoes > buckwheat successively. That is to say, the tolerance of C_4 crops to CO_2 was obviously stronger than that of C_3 crops. This finding is highly consistent with the results of the actual potted plant in simulation experiment on the apparent characteristics and biomass changes of crops.

Discussion

This study mainly simulated the impacts of ultra-high CO_2 concentration from CO_2 leakage of CCS project on typical crops. It was found that the growth of crops in experiment were all promoted as the CO_2 concentration was less than 10 mmol·mol^{-1} for C_3 crops and 20 mmol·mol^{-1} for C_4 crops. At those points of CO_2 concentration, the plant height, maximum root length, biomass, *Pn*, *E* and *gs* of the eight crops were reached to the highest among the different treatments of CO_2 concentration (Fig. 2–4).

As we know, photosynthesis of C_3 and C_4 plants immobilizes CO_2 using the Ribulose-1, 5-bisphosphate carboxylase (Rubisco) in Calvin cycle (Pan, 2015). The elevation of CO_2 concentration within a certain range can increase the activity of Rubisco and the binding of Rubisco with CO_2, so as to improve the carboxylation rate of Rubisco and the photosynthesis rate of plants, and thereby promoting the growth of plants (Mauney *et al.*, 1978; Sharkey, 1985; Wong, 1990). When the CO_2 concentration was higher than 20 mmol·mol^{-1}, the growth of C_3 and C_4 crops was inhibited in varying degrees, and the tolerance of C_4 crops to CO_2 was more stronger than that of C_3 crops, which is consistent with the results of West *et al.* (2009), Wu *et al.* (2014) and Ji *et al.* (2018). In general, the reason of the inhibition in most crops is that high concentration of CO_2 may cause a decrease in soil O_2, or lead to the decrease of soil pH and the acidification of soil solution, which may reduce the source of plant energy and inhibit the absorption of water and mineral nutrition by root system (Beaubien *et al.*, 2008; Li *et al.*, 2009; Patil *et al.*, 2010; Zhang *et al.*, 2016).

The impacts of CO_2 on crop growth and development are very complex and the tolerance of crops to CO_2 is diverse (Krüger *et al.*, 2009; West *et al.*, 2009; Ziogou *et al.*, 2013; West *et al.*, 2015). The selection, interaction and treatment of indicators should be considered in establishment of evaluation method for the crops tolerance to CO_2 (Donnelly *et al.*, 2016; Nan *et al.*, 2016). Based on the study of the impacts of CO_2 on crops, nine indicators were selected to evaluate the crop tolerance to CO_2 in the study. According to the measured values of indicators under normal CO_2 concentration, the tolerance coefficient of each single indicator was calculated (Table 2). Nine single indicators were converted into three principal components by PCA (Table 4). On the basis of the Eigen vector of the single indicator to the principal component (Table 5), the comprehensive tolerance coefficient of eight crops was obtained by FCE. In this study, the correlation between single indicators was eliminated by PCA (Table 3). Through FCE, the comprehensive effect of the evaluation indicators of crop tolerance was refined (Table 6). By setting the weight value of evaluation indicators of crop tolerance with the variance contributions of each principal component, the subjectivity of weight value determination of evaluation indicators of crop tolerance can be avoided, and the quantitative evaluation of crop tolerance to CO_2 can be realized (Table 6).

In the determination of the tolerance coefficient of single indicators, the tolerance of indicators only with simple inhibition is easy to measure, while the tolerance of the indicators both with promotion and inhibition is more complicated. The measured values of the indicators under normal CO_2 concentration were used as the control in this study. The ratio of the average value at all concentrations to the measured values under normal CO_2 concentration was used as the tolerance coefficient of the single indicator, and the "fertilization" and "inhibition" effects of CO_2 were simply synthesized. Whether it is necessary to distinguish and how to more accurately describe the difference between the effects of "fertilization" and "inhibition" is a question that needed further consideration.

Conclusion

Growth of C_3 crops was promoted when CO_2 concentration was less than 10 mmol·mol^{-1}, and growth of C_4 crops was improved when CO_2 level was less than 20 mmol·mol^{-1}. When CO_2 concentration continues to increase, the growth of C_3 and C_4 crops was inhibited by varying degrees, in which the inhibition for C_3 crops were more obvious. Based on PCA and FCE, a comprehensive evaluation method of crop tolerance to CO_2 was established, which not only dealt with the information overlap caused by the correlation among the single indicators, but also dealt with the assignment of the weight values of each indicator in comprehensive evaluation. The C_4 crops showed stronger tolerance to CO_2 than C_3 crops. Thus, when CCS project is implemented in the Loess Plateau of China, C_4 crops, especially sorghum, can be used as priority crops for agricultural production, while C_3 crops, especially buckwheat, may be the indicator crops for CO_2 leakage.

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