



**Full Length Article**

## Comprehensive Evaluation on the Tolerance of Eight Crop Species to CO<sub>2</sub> Leakage from Geological Storage

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### Abstract

Carbon dioxide capture and storage (CCS) is considered as the most promising and potential technology of reduction in CO<sub>2</sub> emission. However, the risk of CO<sub>2</sub> 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<sub>2</sub> concentration and quantitative evaluation of crop tolerance to CO<sub>2</sub>. In this paper, the impacts of ultra-high CO<sub>2</sub> on the plant height, maximum root length, leaf number, net photosynthetic rate, transpiration rate, stomatal conductance, intercellular CO<sub>2</sub> concentration, fresh and dry biomass of eight typical crops were simulated using CO<sub>2</sub> artificial climate chamber. A comprehensive evaluation method on the crop tolerance to CO<sub>2</sub> was established based on principal component analysis (PCA) and fuzzy comprehensive evaluation method (FCE) and the tolerance of eight typical crops to CO<sub>2</sub> 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<sub>2</sub> concentration and the maximum growth indicators of C<sub>3</sub> crops was at 10 mmol·mol<sup>-1</sup> and that of C<sub>4</sub> crops was at 20 mmol·mol<sup>-1</sup>. When the CO<sub>2</sub> concentration continued to increase, the growth of C<sub>3</sub> and C<sub>4</sub> crops were inhibited in varying degrees, in which the inhibition for C<sub>3</sub> crops was higher. The relative tolerance of crops to CO<sub>2</sub> was as follows: sorghum > scorpion > millet > corn > mung bean > soybean > potato > buckwheat and C<sub>4</sub> crops were more tolerant to CO<sub>2</sub> than C<sub>3</sub> crops. The priority crops for CO<sub>2</sub> leakage of the CCS project area was recommended in Loess Plateau of China. © 2019 Friends Science Publishers

**Keywords:** CCS; CO<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> leakage through injection wells, abandoned wells or ineffective confining layers (Metz and Davidson, 2008). Once CO<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> concentration which is much higher than doubling CO<sub>2</sub> 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<sub>2</sub> leakage phenomenon in the project area. Current researches on the impact of CO<sub>2</sub> leakage on plants or crops are mostly focused on the field or indoor simulation of CO<sub>2</sub> leakage and on-site investigation or research of other CO<sub>2</sub> 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<sub>2</sub> leakage point, and gradually recovered from 6 meters away. Pfanz *et al.* (2007) found that the increase of CO<sub>2</sub> concentration at volcanic eruption led to a decrease in photosynthesis of 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<sub>2</sub> 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<sub>2</sub> leakage in different laboratory scenarios. Many studies pointed out that the difference in response of various plants to CO<sub>2</sub> 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<sub>3</sub> 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<sub>4</sub> plants is a process that CO<sub>2</sub> is converted to C<sub>4</sub> acid under the action of PEPC carboxylase firstly and the C<sub>4</sub> acid is converted to CO<sub>2</sub> again by decarboxylation reaction in mesophyll cells through Hatch-Slack pathway, and the converted CO<sub>2</sub> 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<sub>2</sub> concentration, photosynthesis of C<sub>3</sub> and C<sub>4</sub> plants is significantly different due to their photosynthesis sites and participating enzymes, and C<sub>4</sub> plants are considered to be superior to C<sub>3</sub> crops in assimilation efficiency of CO<sub>2</sub> and more tolerant for the stress of low CO<sub>2</sub> concentration, drought and other factors (Cerling *et al.*, 1993, 1998; Koch *et al.*, 2004). Whether there is a difference in the tolerance of C<sub>3</sub> and C<sub>4</sub> plants to ultra-high concentrations of CO<sub>2</sub> is still a problem worth studying.

In this paper, the simulation experiment of eight typical C<sub>3</sub> and C<sub>4</sub> crops in Loess Plateau of China was carried out to understand the impact of ultra-high CO<sub>2</sub> concentration on the crops. Meanwhile, the evaluation method of crop tolerance to CO<sub>2</sub> 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<sub>2</sub>. The main purpose of this paper is to systematically understand the response and quantitatively evaluate the tolerance of crops to CO<sub>2</sub>, 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<sub>3</sub> crops and four C<sub>4</sub> 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<sub>2</sub> 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·kg<sup>-1</sup>, respectively.

### Experimental Methods

**Experimental design and procedures:** In this experiment, a CO<sub>2</sub> artificial climate chamber (RXZ-500C-CO<sub>2</sub>, Ningbo, China) was used to simulate the ultra-high CO<sub>2</sub> environment of CO<sub>2</sub> leakage from CCS (Fig. 1).

The PID control system (Proportion, Integral and Derivative Control System, PIDCS) was used to collect and control CO<sub>2</sub> in the artificial climate chamber, and ensure the CO<sub>2</sub> concentration to meet and maintain the experimental requirements. The temperature, relative humidity, illumination and CO<sub>2</sub> concentration of the CO<sub>2</sub> artificial climate chamber ranged from 0 to 50°C, from 30 to 95%, from 0 to 22 KLux, and from 380 to 100000 μmol·mol<sup>-1</sup> 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<sub>2</sub> gas in the CO<sub>2</sub> 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<sub>2</sub> concentration. Five CO<sub>2</sub> concentrations of the CO<sub>2</sub> artificial climate chamber were set to 380 μmol·mol<sup>-1</sup> (the control group), 10, 20, 40, and 80 mmol·mol<sup>-1</sup>, respectively. The other conditions of the CO<sub>2</sub> artificial climate chamber were set with the temperature of 25°C, RH of 75% and illumination of 22 KLux at daytime of 12 h, and with the temperature of 20°C, RH of 75% and illumination of 4.4 KLux at nighttime of 12 h, respectively.

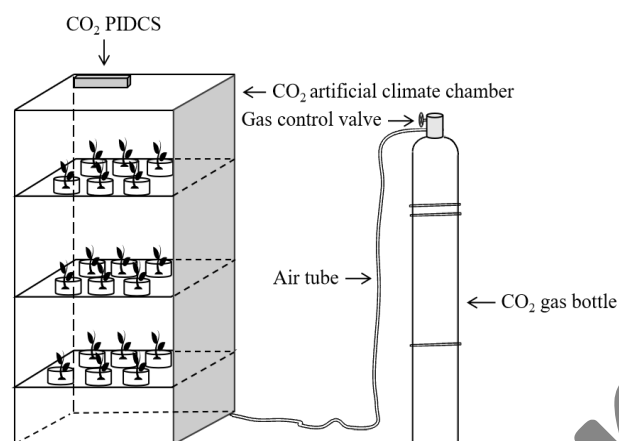
**Growth measurement indicators:** Nine growth indicators including plant height, leaf number, maximum root length, fresh and dry biomass, net photosynthetic rate (*P<sub>n</sub>*), transpiration rate (*A*), stomatal conductance (*g<sub>s</sub>*) and intercellular CO<sub>2</sub> concentration (*C<sub>i</sub>*) were determined in which *P<sub>n</sub>*, *A*, *g<sub>s</sub>*, *C<sub>i</sub>* were measured by LI-6400X photosynthesis analyzer (Nebraska, USA).

### Evaluation for Crop Tolerance to CO<sub>2</sub>

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

**Table 1:** Species of tested corps

Photosynthetic pathway	Species	Cultivar
C <sub>3</sub>	Mung bean ( <i>Vigna radiata</i> L. Wilczek)	Local Jingbian
	Soyabean ( <i>Glycine max</i> L.Merrill)	Qindou No. 8
	Buckwheat ( <i>Fagopyrum esculentum</i> . Moench)	Yujiao No. 4
	Potatoes ( <i>Solanum tuberosum</i> )	Favorita
C <sub>4</sub>	Maize ( <i>Zea mays</i> L.)	Ximeng No. 6
	Sorghum ( <i>Sorghum bicolor</i> L. Moench)	Jinza No. 12
	Foxtail millet ( <i>Setaria italica</i> L. Beauv)	Jingu No. 29
	Broomcorn millet ( <i>Panicum miliaceum</i> L.)	Neimi No. 5


**Fig. 1:** CO<sub>2</sub> artificial climate chamber

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<sub>2</sub> have effects of fertilization and inhibition on crops, the concept of crop tolerance coefficient to CO<sub>2</sub> is introduced to express the tolerance of crops to high CO<sub>2</sub> concentration compared to normal atmospheric CO<sub>2</sub> 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<sub>2</sub>, 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):

$$x_i = \frac{\bar{V}_i}{V_{CK}}, (i = 1, 2, \dots, m) \quad (1)$$

Where  $i$  refers to  $i$ -th single indicator,  $m$  is the number of single indicators,  $\bar{V}_i$  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):

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

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 ( $\lambda_j$ ), 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<sub>2</sub> was calculated using the following formula (Xie and Liu, 2013):

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

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

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

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<sub>2</sub> on Growth and Development of Crops

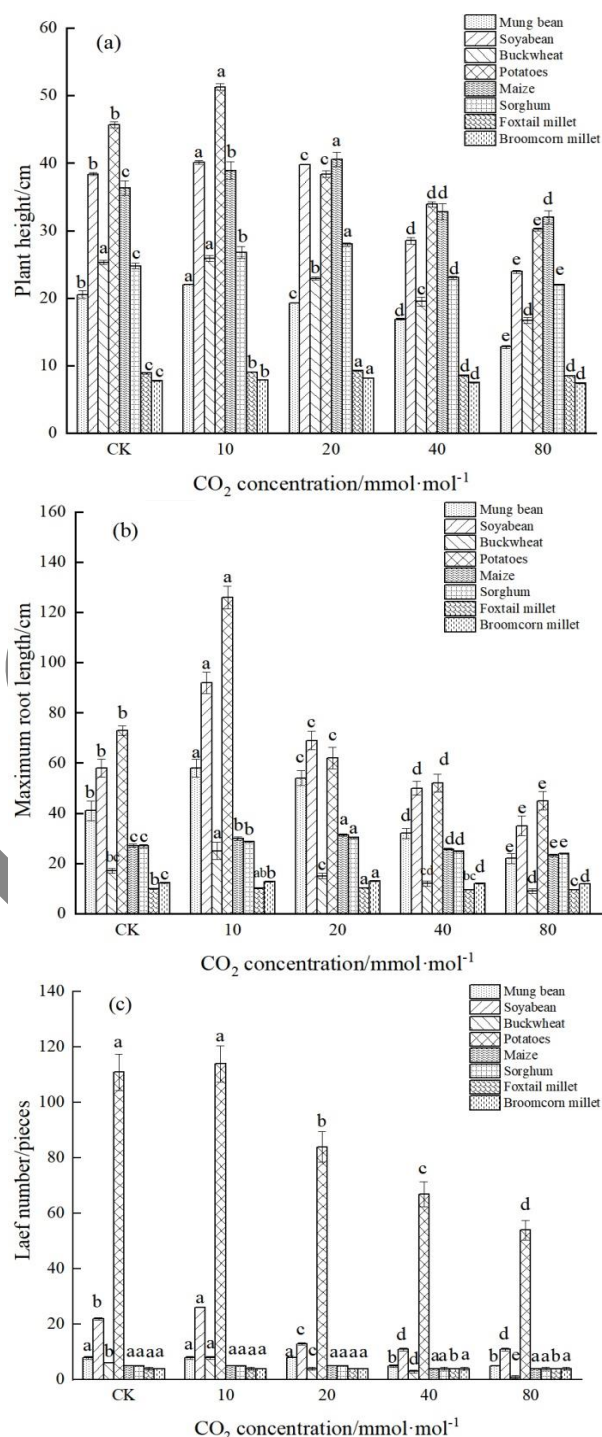
**Morphological indicators:** The impacts of ultra-high CO<sub>2</sub> on plant height, maximum root length and leaf number of eight crops were shown in Fig. 2. Different CO<sub>2</sub> concentration had significant effects on plant height (Fig. 2a) and maximum root length (Fig. 2b) of the eight crops ( $P < 0.05$ ), but had no significant effect on the number of leaves (Fig. 2c), especially the C<sub>4</sub> crop. Although plant height and maximum root length of C<sub>3</sub> crops were increased at CO<sub>2</sub> concentration of 10 mmol·mol<sup>-1</sup> compared to CK group, significantly inhibited when CO<sub>2</sub> concentration increased to 20, 40, 80 mmol·mol<sup>-1</sup>. The plant height and longest root length of C<sub>4</sub> crops were promoted at CO<sub>2</sub> concentration of 10 and 20 mmol·mol<sup>-1</sup>, while inhibited when CO<sub>2</sub> concentration increased to 40 and 80 mmol·mol<sup>-1</sup>.

**Physiological indicators:** Gas exchange is often used to reflect the physiological characteristics of plants, which usually involves four indicators; net photosynthetic rate ( $P_n$ ), transpiration rate ( $E$ ), stomatal conductance ( $g_s$ ) and intercellular CO<sub>2</sub> concentration ( $C_i$ ). The photosynthesis of C<sub>3</sub> and C<sub>4</sub> crops showed different trends with the increase of CO<sub>2</sub> concentration, which were explained by the examples of mung bean of the C<sub>3</sub> plant and maize of the C<sub>4</sub> plant (Fig. 3). The  $P_n$ ,  $E$  and  $g_s$  of mung bean and maize had significant differences at CO<sub>2</sub> concentration of 10, 20, 40, 80 mmol·mol<sup>-1</sup> compared to CK group. The  $P_n$ ,  $E$  and  $g_s$  of mung bean reached the maximum when CO<sub>2</sub> concentration was 10 mmol·mol<sup>-1</sup>, while those of maize reached the maximum when CO<sub>2</sub> concentration was 20 mmol·mol<sup>-1</sup>. As the concentration of CO<sub>2</sub> continues increased, the  $P_n$ ,  $E$  and  $g_s$  of mung bean and maize gradually decreased, and the decrease in mung bean was greater than that of maize. In addition, the  $C_i$  of mung bean and maize showed an increasing trend with the increase of CO<sub>2</sub> concentration. At different CO<sub>2</sub> concentration, the difference of  $C_i$  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<sub>2</sub> concentration on fresh and dry biomass of eight crops were shown in Fig. 4. Different CO<sub>2</sub> 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<sub>2</sub> on fresh and dry biomass of C<sub>3</sub> and C<sub>4</sub> crops were different. The impact of ultra-high CO<sub>2</sub> concentration on dry biomass of C<sub>3</sub> crops was greater than that of fresh biomass, while it was opposite for C<sub>4</sub> crops ( $P < 0.05$ ).

### Assessment of Crop Tolerance to CO<sub>2</sub>

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

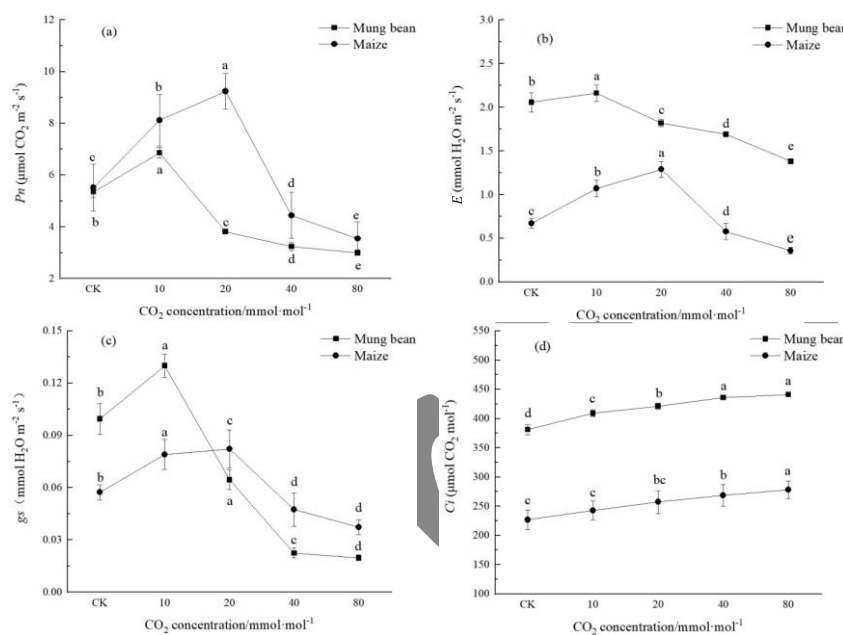


**Fig. 2:** Impacts of different CO<sub>2</sub> concentration on plant height (a), maximum root length (b) and leaf number (c) of eight crops

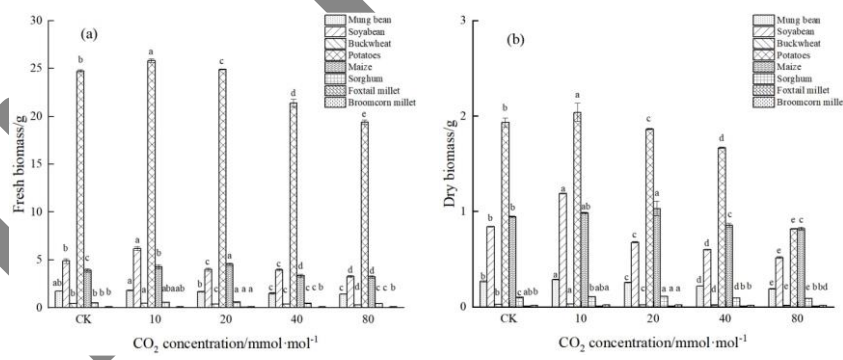
using formula (1) given in Table 2. It can be seen that the differences of tolerance coefficients in  $P_n$ ,  $A$ , and  $g_s$  were greater than that in plant height, leaf number, longest root length, fresh biomass, dry biomass and  $C_i$ , and the tolerance coefficient in  $C_i$  was all greater than 1.

**Table 2:** The tolerance coefficient of each indicator to CO<sub>2</sub> for eight crops ( $x_i$ )

Species	Height	Leaf number	Maximum root length	Fresh biomass	Dry biomass	$P_n$	$E$	$g_s$	$C_i$
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<sub>2</sub> concentration on  $P_n$  (a),  $E$  (b),  $g_s$  (c) and  $C_i$  (d) of mung bean and maize



**Fig. 4:** Impacts of different CO<sub>2</sub> concentration on fresh (a) and dry (b) biomass of eight crops

**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<sub>2</sub> concentration was not related to that of the other indicators.

The Eigen values ( $\lambda_i$ ), variance contributions ( $P_j$ ), and cumulative variance contributions ( $\Sigma P_j$ ) of each principal component were obtained by the PCA as shown in Table 4. It can be seen that the cumulative variance contribution

**Table 3:** The correlation matrix of each indicator

Indicators	Height	Leaf number	Maximum root length	Fresh biomass	Dry biomass	Pn	E	Gs
Height								
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	0.046	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:**  $\lambda_i$ ,  $P_j$  and  $\sum P_j$  of each principal component

Principal components	$\lambda_i$	$P_j/\%$	$\sum P_j/\%$
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,  $\mu$  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

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<sub>2</sub>:**  $Z_1$ ,  $Z_2$  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.

According to the above definition of crop tolerance to CO<sub>2</sub>, greater the D value, stronger would be the crop tolerance to CO<sub>2</sub>. It can be seen from Table 6 that the comprehensive tolerance coefficient (D value) to CO<sub>2</sub> of the eight crops ranged from 0.1459 to 0.8645, wherein the D values of the C<sub>3</sub> crop were from 0.1459 to 0.4162, and the D values of the C<sub>4</sub> crop were from 0.8148 to 0.8645. The comprehensive tolerance coefficient to CO<sub>2</sub> 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<sub>4</sub> crops to CO<sub>2</sub> was obviously stronger than that of C<sub>3</sub> 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<sub>2</sub> concentration from CO<sub>2</sub> leakage of CCS project on typical crops. It was found that the growth of crops in experiment were all promoted as the CO<sub>2</sub> concentration was less than 10 mmol·mol<sup>-1</sup> for C<sub>3</sub> crops and 20 mmol·mol<sup>-1</sup> for C<sub>4</sub> crops. At those points of CO<sub>2</sub> 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<sub>2</sub> concentration (Fig. 2–4).

As we know, photosynthesis of C<sub>3</sub> and C<sub>4</sub> plants immobilizes CO<sub>2</sub> using the Ribulose-1, 5-bisphosphate carboxylase (RuBisCO) in Calvin cycle (Pan, 2015). The elevation of CO<sub>2</sub> concentration within a certain range can increase the activity of RuBisCO and the binding of RuBisCO with CO<sub>2</sub>, 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<sub>2</sub> concentration was higher than 20 mmol·mol<sup>-1</sup>, the growth of C<sub>3</sub> and C<sub>4</sub> crops was inhibited in varying degrees, and the tolerance of C<sub>4</sub> crops to CO<sub>2</sub> was more stronger than that of C<sub>3</sub> 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<sub>2</sub> may cause a decrease in soil O<sub>2</sub>, 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<sub>2</sub> on crop growth and development are very complex and the tolerance of crops to CO<sub>2</sub> 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<sub>2</sub> (Donnelly *et al.*, 2016; Nan *et al.*, 2016). Based on the study of the impacts of CO<sub>2</sub> on crops, nine indicators were selected to evaluate the crop tolerance to CO<sub>2</sub> in the study. According to the measured values of indicators under normal CO<sub>2</sub> 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<sub>2</sub> can be realized (Table 6).

In addition, by studying the effects of CO<sub>2</sub> on crop nutrients, enzyme systems and other metabolic indicators, the selection range of the evaluation indicators can be expanded to more fully understand the tolerance of crops to CO<sub>2</sub>.

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<sub>2</sub> 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<sub>2</sub> concentration was used as the tolerance coefficient of the single indicator, and the "fertilization" and "inhibition" effects of CO<sub>2</sub> 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

The C<sub>3</sub> crops growth were promoted when CO<sub>2</sub> concentration was less than 10 mmol·mol<sup>-1</sup>, and C<sub>4</sub> crops growth were promoted when CO<sub>2</sub> concentration was less than 20 mmol·mol<sup>-1</sup>. When CO<sub>2</sub> concentration continues to increase, the growth of C<sub>3</sub> and C<sub>4</sub> crops were inhibited by varying degrees, in which the inhibition for C<sub>3</sub> crops were more obvious. Based on PCA and FCE, a comprehensive evaluation method of crop tolerance to CO<sub>2</sub> 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. C<sub>4</sub> crops showed stronger tolerance to CO<sub>2</sub> than that of C<sub>3</sub> crops. Therefore, when CCS projects are implemented in the Loess Plateau of China, C<sub>4</sub> crops, especially sorghum, can be used as priority crops for agricultural production, while C<sub>3</sub> crops, especially buckwheat, are expected to be indicator crops for CO<sub>2</sub> leakage.

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