Effects of elevated CO\textsubscript{2} concentration on bulbil germination and early seedling growth in Chinese yam under different air temperatures

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ABSTRACT
The present study investigated the effects of elevated carbon dioxide concentration ([CO\textsubscript{2}]) and air temperature on the germination of seed bulbils and the seedling vigour of two Chinese yam lines. Plants were grown under two [CO\textsubscript{2}] levels, ambient and elevated (ambient + 200 \textmu mol mol\textsuperscript{-1}), and two mean air temperature regimes, 22.2 °C (ambient + 1.4 °C) and 25.6 °C (ambient + 5.2 °C). Elevated [CO\textsubscript{2}] did not affect bulbil germination under both air temperature regimes. During the early growth stage, the dry weight (DW) of leaves, vines, shoots, roots, belowground parts (roots + tubers) and whole plants were higher under elevated [CO\textsubscript{2}] than ambient [CO\textsubscript{2}] for both lines under the low- and high-temperature regimes. The values of vigour indexes (index I = germination % × seedling length and index II = germination % × seedling DW) were also higher under elevated [CO\textsubscript{2}] than ambient [CO\textsubscript{2}] for both lines. These results indicated that Chinese yam seedlings respond positively to elevated [CO\textsubscript{2}] during the early growth stage. The above:belowground DW ratios were lower under elevated [CO\textsubscript{2}] than ambient [CO\textsubscript{2}] in seedlings with very small new tubers for both yam lines, indicating that elevated [CO\textsubscript{2}] strongly affected the root growth in the early growth stage. The DWs of post-treatment seed bulbils were higher in the elevated [CO\textsubscript{2}] under both air temperature regimes. The results showed that Chinese yam used a smaller amount of the reserves in seed bulbils under elevated [CO\textsubscript{2}] than under ambient [CO\textsubscript{2}].

1. Introduction

Yam (Dioscorea spp.) tubers contain high levels of carbohydrates and minerals in their tissues (Bhandari et al., 2003) and are an important staple food for millions of people in tropical and sub-tropical regions. Among the various yam species, Chinese yam (Dioscorea opposita Thunb.) is widely cultivated in Japan, China, Korea and Taiwan and is one of the most important root and tuber crops in the northern prefectures of Japan, such as Aomori and Hokkaido.

Atmospheric carbon dioxide concentration ([CO\textsubscript{2}]) has increased from 300 to 402 \textmu mol mol\textsuperscript{-1} (National Oceanic & Atmospheric Administration-Earth System Research Laboratory, 2016) and is likely to continue increasing for the foreseeable future (Intergovernmental Panel on Climate Change, 2013). Associated with this [CO\textsubscript{2}] increase, the globally averaged surface temperature is predicted to rise 0.3–1.7 °C by 2081–2100 in comparison with 1986–2005 under low greenhouse gas emission scenarios and 2.6–4.8 °C under high-emission scenarios (Intergovernmental Panel on Climate Change, 2013) as a result of global warming. [CO\textsubscript{2}] and air temperature are key variables affecting plant growth, development and function.

Seed germination and seedling vigour play an important role in agriculture production and influence final yield in terms of plant population density. Although many studies have been conducted on the effects of elevated [CO\textsubscript{2}] on cereal crops such as rice (Cheng et al., 2009; Roy et al., 2012; Shimono et al., 2009), wheat (Nonhebel, 1993; Valizadeh et al., 2014) and sorghum (Prasad et al., 2006; Wall et al., 2001); grain legumes such as soybean (Kumagai & Sameshima, 2014; Tacarindua et al., 2013) and peanut (Newman et al., 2005); and root and tuber crops such as potato (Chen & Setter, 2012; Craigon et al., 2002; Katny et al., 2005) and cassava (Fernandez et al., 2002; Gleadow et al., 2009), few studies have considered seed quality in terms of seed germination and early seedling vigour under elevated [CO\textsubscript{2}]. In previous studies, seed germination in response to elevated [CO\textsubscript{2}] has been reported to decrease in crops like, Arabidopsis thaliana (Andalo et al., 1996), chickpea (Saha et al., 2015), soybean, pea, sunflower, pumpkin (Ziska & Bunce, 1993), to
show no change in C₃ grassland (Thurig et al., 2003), red kidney bean (Thomas et al., 2009), rice (Chen et al., 2015) and Pinus taeda (Way et al., 2010) or to increase in Plantago lanceolate (Wulff & Alexander, 1985), Amaranthus hybridus L. and Chenopodium album L. (Ziska & Bunce, 1993), Hypochaeris radicata and Leontodon saxatilis (Edwards et al., 2001).

In the case of Chinese yam, aerial bulbils, a vegetative organ, are used for yam production. Walck et al. (2010) reported that, in nature, bulbil germination is controlled through dispersal and ambient temperatures. Our previous report (Thinh et al., 2017) was the first to show a positive response of growth and photosynthesis to elevated [CO₂] in Chinese yam at the intermediary vegetative stage. However, no attempts have been made to examine the effects of elevated [CO₂] on germination of seed bulbil and growth during the early seedling stage in Chinese yam to date. Under future climate change scenarios, it is likely that plants will be exposed to a combination of both higher [CO₂] and air temperature (Rosenzweig & Hillel, 1998). Therefore, understanding the effects of elevated [CO₂] and air temperature on bulbil germination and seedling vigour will be important for seedling establishment and sustainable production of Chinese yam in the future.

In this study, we hypothesized that elevated [CO₂] may positively affect seed bulbil vigour, including bulbil germination rate and seedling growth characteristics. To test this hypothesis, two Chinese yam lines, which are both current dominant lines in northern part of Japan, were grown under two [CO₂] conditions (ambient and elevated) under different air temperatures. To our knowledge, this is the first temperature-gradient chamber study that investigated bulbil germination and seedling growth in responses of Chinese yam to elevated [CO₂].

2. Materials and methods

2.1. Plant materials

We used two Chinese yam lines: Enshikei 6 and Shojikei, which are widely cultivated in northern Japan, to confirm the response to elevated [CO₂] and air temperature in Chinese yam. The seed bulbils of both Chinese yam lines were harvested in October 2015. After collection, the bulbils were covered with newspaper and placed into a carton box at 4 °C until use (from October 2015 to May 2016). For the experiments, seed bulbils of uniform size from each line were selected. The average fresh weight per bulbil was 1.01 ± 0.13 g for Enshikei 6 and 1.83 ± 0.25 g for Shojikei. The selected seed bulbils were then sterilized in 0.5% (v/v) sodium hypochlorite solution for 5 min and then thoroughly washed with water. Directly after sterilization, the seed bulbils were sown in plastic pots on 4 June 2016 and then placed immediately in the temperature-gradient chambers for treatment until 9 July 2016.

2.2. Temperature-gradient chambers and treatments

The experiments were conducted in temperature-gradient chambers at the Tohoku Agricultural Research Center, NARO (39°74′N, 141°13′E) in Morioka, Japan. [CO₂] and air temperature were controlled separately in each temperature-gradient chamber. Two temperature-gradient chambers were used under two [CO₂] conditions: ambient and elevated (ambient [CO₂] + 200 μmol mol⁻¹).

Each chamber was a naturally sunlit greenhouse (6 m wide × 30 m long × 3 m high) with an air inlet at one end and exhaust fans at the other end. The air in the temperature-gradient chamber flowed continuously from the inlet to the exhaust fans. The temperature gradient inside the chamber was continuously maintained along the longitudinal axis by cooling the air with an air conditioner at the inlet end, warming the air by solar radiation or through supplemental heat input (a heater and air ducts) at the outlet end or a combination of solar radiation and supplemental heat.

In each temperature-gradient chamber, two treatment plots were set along an air temperature gradient. The first plot had a mean air temperature of 22.2 ± 1.7 °C (1.4 °C higher than the temperature outside the chamber; hereafter outside temperature) and the second plot had a mean air temperature of 25.6 ± 1.7 °C (5.2 °C higher than the outside temperature). Thus, we were able to test Chinese yam germination and seedling growth at ambient [CO₂] and elevated [CO₂] under two different air temperature regimes. The average daytime [CO₂] over the treatment period was 406 ± 9 μmol mol⁻¹ in the ambient [CO₂] chamber and 603 ± 22 μmol mol⁻¹ in the elevated [CO₂] chamber. Air temperature and [CO₂] were measured at 5-s intervals and averaged every 1 min, 30 min and 24 h by a datalogger (CR 1000; Campbell Sci. Inc., Logan, UT, USA).

Both Enshikei 6 and Shojikei were treated in the same manner in the temperature-gradient chambers as follows: three seed bulbils were sown in each plastic pot (180 mm width × 150 mm height × 130 mm bottom diameter) filled with commercial soil (containing 320 mg L⁻¹ of nitrogen [N], 210 mg L⁻¹ phosphorus [P₂O₅], and 300 mg L⁻¹ of potassium [K₂O]). Five pots were placed in a tray and seven trays were used for each treatment. The trays were rotated at 7-d intervals to minimize the effects of environmental differences. The four treatments were abbreviated as follows:

(1) AA: ambient [CO₂] (406 μmol mol⁻¹) and approximately ambient air temperature (1.4 °C above the outside temperature)
(2) EA: elevated [CO₂] (603 μmol mol⁻¹) and approximately ambient air temperature (1.4 °C above the outside temperature)
2.3. Bulbil germination percentage

The seed bulbil germination percentage was determined as follows: in each treatment, Chinese yam bulbils were divided into seven groups (trays) each with 15 seed bulbils for each Chinese yam line (105 seed bulbils per line). Germination of the bulbils was recorded at 7, 14, 21, 28, 35 days after sowing (DAS). When the bulbil sprouted and emerged above the soil surface, it was considered to have germinated. The number of germinated bulbils in each group and treatment were recorded separately during the monitoring period. The germination percentage was calculated using the following formula:

\[
\text{Germination percentage} = \frac{S}{T} \times 100,
\]

where \(S\) is the number of germinated bulbils and \(T\) is the total number of bulbils.

2.4. Sampling and measuring seedling growth parameters

The seedlings of the two Chinese yam lines were sampled at 35 DAS. The number of leaves on each plant was counted and then the vine and root lengths were measured using a ruler. After carefully washing the soil from the roots with running water, we separately sampled the leaves, vines, roots, seed bulbils and tubers of individual plants in each treatment. Leaf area was immediately measured using an automatic leaf area metre (AAM-9; Hayashi Denko Co. Ltd., Tokyo, Japan). Finally, all samples were dried at 80°C for 4 d to a constant weight. Dry weight (DW) was measured using an electronic scale (GX 3000; A&D Co., Ltd., Tokyo, Japan). Seedling vigour was calculated as follows Abdul-Baki and Anderson (1973) as:

- **Vigour index I** = Germination % \times seedling length (shoot + root)
- **Vigour index II** = Germination % \times seedling DW (shoot + root + tuber)

Thirty individual seedlings (in 10 plastic pots) per treatment were randomly selected to measure each growth parameter.

2.5. Statistical analysis

To test the significance of differences related to \([\text{CO}_2]\) levels, air temperature conditions, Chinese yam lines and their interactions, we applied three-way analysis of variance (ANOVA) to the following data: bulbil germination percentage, leaf number, vine length, root length, leaf area, leaf DW, vine DW, tuber DW, root DW, shoot DW and total DW; and two-way ANOVA to above:belowground DW ratio and seed bulbil DW. When ANOVA produced a significant result, we performed a Tukey–Kramer’s test for significant differences between means. All statistical analyses were performed with SPSS statistical software (SPSS ver. 24.0; IBM Corp, New York, NY, USA).
At first observation (7 DAS), no bulbil germination was observed in any of the plants. The proportion of germinated seedlings increased quickly: at 14 DAS, germination ranged from 32.2–51.1% for Enshikei 6 and 14.4%–35.6% for Shojikei; at 21 DAS, germination ranged from 78.9–93.4% for Enshikei 6 and 76.6–90.0% for Shojikei; and at 28 DAS germination ranged from 97.8–100% for both lines. At each observation, there was no significant difference between AA and EA or between AH and EH in either line according to a Tukey–Kramer’s test (Table 1).

### 3. Results

#### 3.1. Effects of elevated CO$_2$ concentration and air temperature on bulbil germination

According to the ANOVA results (Table 1), no significant effects of elevated [CO$_2$] on bulbil germination were detected over the whole germination period. However, significant effects of air temperature on the germination were observed at 14 DAS, 28 DAS and at 35 DAS. Significant differences between the Chinese yam lines in terms of the effect of [CO$_2$] on germination were observed only at 14 DAS; after this point, no significant differences were observed. There were no interactions among [CO$_2$], air temperature and line except for [CO$_2$] $\times$ air temperature interaction at 14 DAS.

At first observation (7 DAS), no bulbil germination was observed in any of the plants. The proportion of germinated seedlings increased quickly: at 14 DAS, germination ranged from 32.2–51.1% for Enshikei 6 and 14.4%–35.6% for Shojikei; at 21 DAS, germination ranged from 78.9–93.4% for Enshikei 6 and 76.6–90.0% for Shojikei; and at 28 DAS germination ranged from 97.8–100% for both lines. At each observation, there was no significant difference between AA and EA or between AH and EH in either line according to a Tukey–Kramer’s test (Table 1).
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3.2. Effects of elevated CO2 concentration and air temperature on seedling growth

According to the ANOVA results, elevated [CO2], air temperature and line had significant effects on leaf number, leaf area, shoot length and root length for both Enshikei 6 and Shojikei (Table 2). However, no interactions among [CO2], air temperature and yam line were detected for any of these parameters except for air temperature × line on leaf area.

According to a Tukey–Kramer’s test, for Enshikei 6, leaf number, leaf area and root length were significantly higher in EH than in AA and shoot length was greater in EA and EH than in AA and AH, respectively. For Shojikei, shoot length was also greater in EA and EH than in AA and AH, respectively. Although no significant differences were observed, there was an increasing trend in number of leaves and leaf area from AA to EA for both Enshikei 6 and Shojikei, and from AH to EH for Shojikei. The root length of Shojikei was also longer, but not significantly, in EH than in AH (Table 2).

3.3. Effects of elevated CO2 concentration and air temperature on seedling dry weight

According to the ANOVA results (Table 3), elevated [CO2] and air temperature significantly affected the final DW of leaves, vines, shoots, roots, tubers, belowground parts and total plant DW in both lines. There were also significant differences in final DWs according to yam line for all growth parameters except for tuber DW. There were interactions between [CO2] and air temperature for root DW and belowground DW and between air temperature and line for leaf DW and shoot DW.

A Tukey–Kramer’s test showed that, for both yam lines, leaf, vine, shoot, root and belowground DW were significantly higher in EA and EH than in AA and AH, respectively. Tuber DW was also higher in EH than in AH for Enshikei 6. Consequently, total plant DW was noticeably higher in EA and EH than in AA and AH, respectively, for both Chinese yam lines (Table 3).

3.4. Effects of elevated CO2 concentration on above: belowground dry weight

According to the ANOVA results, elevated [CO2] significantly affected the ratio of aboveground (shoot) to belowground (root and tuber) DW in both Enshikei 6 and Shojikei, while air temperature affected the above:belowground DW ratio only in Enshikei 6 (Figure 1). No interactions between [CO2] and air temperature on the ratio in either line were found. According to a Tukey–Kramer’s test, both Enshikei 6 and Shojikei had significantly lower above:belowground DW ratios in EA and EH than in AA and AH, respectively (Figure 1).

3.5. Effects of elevated CO2 concentration and air temperature on early seedling vigour

Elevated [CO2], high air temperature and yam line significantly affected vigour index I and vigour index II for...
higher values in EA and EH than in AA and AH, respectively. For Shojikei, vigour index II values were higher in EA and EH than in AA and AH, respectively; in contrast, the values of vigour index I were clearly higher in EH than in AH, but not significantly higher in EA than in AA (Table 4).

3.6. Effects of elevated CO₂ concentration on planted seed bulbil dry weight

According to the ANOVA results (Figure 2), elevated [CO₂] significantly affected seed bulbil DW for both Enshikei 6 and Shojikei, but no effect of air temperature was observed. There were significant interactions between [CO₂] and air temperature for Enshikei 6, but not for Shojikei. As indicated in Figure 2, seed bulbil DW for Enshikei 6 was significantly higher in EH than in AH and somewhat higher in EA than AA, though the difference was not significant. Seed bulbil DW for Shojikei was significantly higher in EA and EH than in AA and AH, respectively.

4. Discussion

Understanding the influence of elevated [CO₂] on germination is important for the seed production industry under present and future climate conditions. However, the number of studies on the direct effects of elevated [CO₂] on seed germination has been limited, with only 9 studies involving 29 species and 37 observations performed by 2014 (Marty & BassiriRad, 2014). The response of seed germination to [CO₂] in previous studies has varied depending on the plant species studied. Andalo et al. (1996) reported

Table 4. Effects of elevated CO₂ concentration on seedling vigour under different air temperatures.

| Chinese yam lines | Treatments | Vigour index I | Vigour index II |
|------------------|------------|---------------|---------------|
| Enshikei 6       | AA 22.2°C† | 6918.8 a      | 88.5 a        |
|                  | EA 22.2°C† | 8004.2 b      | 103.2 b       |
|                  | AH 25.6°C† | 9904.2 c      | 132.0 c       |
|                  | EH 25.6°C† | 11,397.6 d    | 165.0 d       |
| Shojikei         | AA 22.2°C† | 8281.9 a      | 105.8 a       |
|                  | EA 22.2°C† | 9426.6 ab     | 139.2 b       |
|                  | AH 25.6°C† | 10,590.5 b    | 146.4 b       |
|                  | EH 25.6°C† | 12,159.5 c    | 180.6 c       |

ANOVA

| CO₂ (C)      | *** | *** |
|--------------|-----|-----|
| Temperature (T) | *** | *** |
| Line (L)     | ns  | ns  |
| C × T        | *   | ns  |
| C × L        | ns  | ns  |
| T × L        | ns  | ns  |
| C × T × L    | ns  | ns  |

Notes: Vigour index I: germination % × seedling length (shoot + root), vigour index II: germination % × seedling DW (shoot + root + tuber). Different letters indicate significant differences at the 5% level (Tukey–Kramer’s test). AA: ambient [CO₂] (406 μmol mol⁻¹) and approximately ambient air temperature (1.4 °C above the outside temperature), EA: elevated [CO₂] (603 μmol mol⁻¹) and approximately ambient air temperature (1.4 °C above the outside temperature), AH: ambient [CO₂] (406 μmol mol⁻¹) and high air temperature (5.2 °C above the outside temperature), EH: elevated [CO₂] (603 μmol mol⁻¹) and high air temperature (5.2 °C above the outside temperature). †mean air temperature. ***p < 0.001; ns, not significant.

Figure 2. Effects of elevated CO₂ concentration on seed bulbil dry weight under different air temperatures.

Notes: Different letters indicate significant differences at the 5% level (Tukey–Kramer’s test). Bars show mean ± SE (n = 30), AA: ambient [CO₂] (406 μmol mol⁻¹) and approximately ambient air temperature (1.4 °C above the outside temperature), EA: elevated [CO₂] (603 μmol mol⁻¹) and approximately ambient air temperature (1.4 °C above the outside temperature), AH: ambient [CO₂] (406 μmol mol⁻¹) and high air temperature (5.2 °C above the outside temperature), EH: elevated [CO₂] (603 μmol mol⁻¹) and high air temperature (5.2 °C above the outside temperature). †mean air temperature. *p < 0.05; ***p < 0.001; ns, not significant.
that elevated $\text{CO}_2$ decreased seed germination rate in *Arabidopsis thaliana*. Ziska and Bunce (1993) stated that the germination rates of plants including soybean, pea, sunflower and pumpkin were reduced under enriched $\text{CO}_2$ conditions. Saha et al. (2015) also concluded that chickpea germination rate decreased by 45–47% under elevated $\text{CO}_2$. In contrast, Wulf and Alexander (1985) showed that high $\text{CO}_2$ increased the germination rate of *Plantago lanceolata*. Ziska and Bunce (1993) also found that elevated $\text{CO}_2$ increased germination in *Amaranthus hybridus* L. and *Chenopodium album* L. In contrast with these results, recently Thomas et al. (2009) demonstrated that elevated $\text{CO}_2$ did not affect germination of red kidney bean seeds under two different temperature conditions. Chen et al. (2015) also examined the responses of two rice cultivars to elevated $\text{CO}_2$ and reported that no clear effects on rice germination were found. The present study indicated that elevated $\text{CO}_2$ did not affect the bulbl germination rates of either Chinese yam line, though air temperature affected final germination percentage. However, there were no interactions between $\text{CO}_2$ and air temperature during the germination period except at 14 DAS.

Many previous studies have been published regarding the effects of elevated $\text{CO}_2$ on the growth of C$_3$ plants. In these studies, increased $\text{CO}_2$ reportedly led to increases in dry matter production in many major food crops, including rice (Baker et al., 1992; Cheng et al., 2009; Roy et al., 2012; Shimono et al., 2008; Ziska et al., 1997), potato (Aien et al., 2014; Chen & Setter, 2012; Conn & Cochran, 2006; Craigon et al., 2002; Miglietta et al., 1998) and cassava (Cruz et al., 2014; Imai et al., 1984; Rosenthal et al., 2012). In our previous study (Thinh et al., 2017), we reported that Chinese yam showed a positive response to elevated $\text{CO}_2$ as its photosynthesis rate and plant DW increased with $\text{CO}_2$ enrichment at the intermediary vegetative stage. The current study results showed that leaf number, leaf area and root length were higher with elevated $\text{CO}_2$ than ambient $\text{CO}_2$ under the high-temperature regimes for Enshikei 6 seedlings. Shoot length was also higher with elevated $\text{CO}_2$ than ambient $\text{CO}_2$ under both the approximately ambient- and high-temperature regimes for both Enshikei 6 and Shojikei seedlings. In addition, leaf, vine, shoot, root, belowground DW and total plant DW were significantly higher with elevated $\text{CO}_2$ than ambient $\text{CO}_2$ under both air temperature regimes (Tables 2 and 3). The ANOVA results also showed significant effects of elevated $\text{CO}_2$ and air temperature on both Chinese yam lines, but no interactions between the two factors. These results indicate that Chinese yam seedlings respond positively to elevated $\text{CO}_2$ at the early seedling stage in this study.

The above:belowground ratio depends upon the allocation of photosynthates (Rogers et al., 1996). Many studies have reported that elevated $\text{CO}_2$ stimulates the growth of both shoots and roots (Conn & Cochran, 2006; Pilumwong et al., 2007; Usuda & Shimogawara, 1998; Ziska et al., 1997). However, the allocation of biomass to shoots and roots in crops under elevated $\text{CO}_2$ may be different from that under ambient $\text{CO}_2$ under certain conditions. Variability in the above:belowground DW ratios found in different studies may result from differences in plant species, development age and other experimental conditions (Rogers et al., 1996). Harmens et al. (2000) reported that elevated $\text{CO}_2$ altered patterns of the allocation of biomass in *Dactylis glomerata* L., plants only transiently during the early stage of growth. Baxter et al. (1997) showed that elevated $\text{CO}_2$ increased the root:shoot ratio in *Poa alpina var. vivipara* L. under high concentrations of nitrogen and phosphorous but not under low concentrations. Some previous studies found that elevated $\text{CO}_2$ increased the allocation of biomass in the tubers and roots of crops such as potatoes (Aien et al., 2014; Chen & Setter, 2012; Conn & Cochran, 2006; Craigon et al., 2002; Miglietta et al., 1998) and radish (Usuda & Shimogawara, 1998). In a previous study (Thinh et al., 2017), we also reported that leaf photosynthetic rate responded to elevated $\text{CO}_2$ more readily in Chinese yam than in rice because yam has a higher sink capacity than rice at the vegetative stage. In this study, elevated $\text{CO}_2$ and air temperature significantly affected aboveground DW and belowground DW in both yam lines (Table 3), and both DWs were significantly higher with elevated $\text{CO}_2$ than ambient $\text{CO}_2$ under both the approximately ambient- and high-temperature regimes. The above:belowground DW ratios were clearly higher under ambient $\text{CO}_2$ than elevated $\text{CO}_2$ under both the air temperature regimes in seedlings with very small new tubers of both Chinese yam lines (Figure 1). These results indicate that elevated $\text{CO}_2$ affected the belowground portion of the plants, particularly the roots, making them stronger from the early stage of growth.

Seedling vigour is one of the most important criteria for determining seed quality and is related to crop growth and yield (Ellis, 1992). Previous studies on dry bean (Sanhewa et al., 1996) and red kidney bean (Thomas et al., 2009) showed no effects of elevated $\text{CO}_2$ on early seedling vigour. In contrast, Saha et al. (2015) reported that rising atmospheric $\text{CO}_2$ significantly decreased the seedling vigour of chickpea plants (vigour indexes I and II) owing to 45–47% reductions in germination, although root and shoot lengths and seedling biomass exhibited negligible changes. In the case of Chinese yam, shoot length and seedling DW were significantly higher under elevated $\text{CO}_2$ than ambient $\text{CO}_2$ (Tables 2 and 3). The values of vigour index I and II were clearly higher with elevated $\text{CO}_2$ (Table 2). The vigour values we obtained for Chinese yam were 10 and 30 times higher for vigour indexes I and II,
In the current study, we also found that elevated [CO 2] reported that high [CO2] increased the size of consistent with those of Wulff and Alexander (1985), who not affect seedling growth in this study. Our results were for treatment. That is, we can assume that dormancy did not affect seedling growth in this study. Our results were consistent with those of Wulff and Alexander (1985), who reported that high [CO 2] increased the size of Plantago lanceolata L. seedlings.

Bulbils are a means of vegetative reproduction and dispersal for many plants (Walck et al., 2010) including Chinese yam. Okagami (1986) found that bulbils and seeds were similar in terms of their dormancy and germination characteristics. Seed reserves have important effects on early seedling growth and physiology after germination (Kennedy et al., 2004). The major reserves stored within the seed bulbils are mobilized after germination, providing nutrients to support early seedling growth. In a previous study, we found that the net photosynthesis rate of Chinese yam at the vegetative stage was higher under elevated than ambient [CO2]. Consequently, yam plant DW was also higher with elevated [CO2] (Thinh et al., 2017).

In the current study, we also found that elevated [CO2] positively affects Chinese yam growth at the early stage. However, plant growth is the result of contributions from both seed bulbils (specially, the stored reserves) and the photosynthetic process (photosynthates). The results in Figure 2 demonstrate that the DWs of post-treatment seed bulbils were significantly higher with elevated [CO2] than ambient [CO2] under both air temperature regimes. This indicates that Chinese yam seedlings used less reserve from seed bulbils under elevated [CO2] than under ambient [CO2] conditions. Therefore, elevated [CO2] is a positive resource for seedling growth in the yams.

In the future, climatic conditions will be changed with increasing [CO2] and air temperature atmospheric. The data in this study will provide important information for the agricultural management strategies, breeding and genenic improvements required to sustain Chinese yam productivity under future climate change.

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Disclosure statement
The authors have no conflict of interest to declare.

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