

# Plant-soil hydraulic interaction under biochar treatment in future elevated atmospheric CO<sub>2</sub> condition

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**ABSTRACT:** The concentration of atmospheric CO<sub>2</sub> is rising obviously, which is predicted to reach to 1000 ppm at the end of 21 century. Some studies have investigated how CO<sub>2</sub> enrichment influences the matric suction of vegetated soil. However, how coupled elevated CO<sub>2</sub> and treatment of biochar, a commonly used carbon-negative soil amendment, affects the plant-soil hydraulic interaction is not well understood. Therefore, the aim of this study is to investigate the effects of CO<sub>2</sub> enrichment on plant-soil hydraulic interaction under biochar treatment. A series of pot tests were conducted in a plant room (i.e., 400 ppm of ambient CO<sub>2</sub>) and a future CO<sub>2</sub> condition chamber (i.e., 1000 ppm of elevated CO<sub>2</sub>). Plants (*Pseudostellaria heterophylla*) were grown for 4 months in lateritic soil amended with biochar (peanut shell) at dosages of 0, 3% and 5% (by mass). Each condition has twenty-one seedlings in three replicated pots. During plant growth period, plant properties such as shoot height, leaf area and stomata conductance were measured to evaluate plant growth. Root properties, including root length and root length density, were analysed at harvest. Soil matric suction and moisture in the root zone were monitored using tensiometer and moisture sensor to assess water retention in vegetated soil. The transpiration rate of plants and the total transpiration-induced water loss were also determined. This study revealed the plant-soil hydraulic interaction under coupled future elevated CO<sub>2</sub> condition and biochar amendment. The findings could provide a foundation for recommendations aimed at enhancing soil-plant ecosystems in the context of eco-geotechnics.

**KEYWORDS:** biochar, CO<sub>2</sub> enrichment, future climate, hydraulic interaction, vegetated soil.

## 1 INTRODUCTION

The continuous rise in atmospheric carbon dioxide (CO<sub>2</sub>) concentrations, driven primarily by fossil fuel combustion, deforestation, and industrial activities, is a defining feature of anthropogenic climate change. Projections indicate that CO<sub>2</sub> levels could arrive approximately 1000 ppm by 2100 (Taub, 2010), profoundly impacting global ecosystems, agricultural productivity, and hydrological cycles. Based on previous studies, CO<sub>2</sub> is a critical factor influencing plant growth and properties, as it serves as the primary carbon source for photosynthesis (Prior et al. 2011). Elevated CO<sub>2</sub> levels can enhance photosynthetic rates, leading to increased biomass production and improved water-use efficiency in many plant species (De Kauwe et al. 2013). However, excessive CO<sub>2</sub> may also alter plant physiology, reducing nitrogen content and protein synthesis, which can negatively affect nutritional quality (Hu et al. 2001). Additionally, long-term exposure to high CO<sub>2</sub> can modify leaf morphology, root development, and secondary metabolite production, impacting plant resilience to environmental stresses. While CO<sub>2</sub> enrichment boosts plant productivity, its effects vary among species and growing conditions, highlighting the complex relationship between atmospheric CO<sub>2</sub> and plant properties.

CO<sub>2</sub> significantly influences plant-soil hydraulic interactions by altering plant water uptake, root physiology, and soil moisture dynamics. Elevated CO<sub>2</sub> levels enhance photosynthetic efficiency, often leading to reduced stomatal conductance and lower transpiration rates, which can decrease overall water demand (Ng et al. 2019). However, increased plant growth under high CO<sub>2</sub> may also expand root systems, modifying water extraction patterns and soil hydraulic properties (Wang & Ni 2024). Additionally, CO<sub>2</sub>-induced changes in rhizodeposition and microbial activity can affect soil structure and water retention (Ng et al. 2023). These interactions create a feedback loop where shifts in plant water use and soil hydrology influence nutrient availability and ecosystem resilience. Understanding these dynamics is crucial for predicting how rising atmospheric CO<sub>2</sub> concentrations will

impact water utilisation and plant productivity in changing climates.

Biochar, a carbon-rich material produced through the pyrolysis of biomass, has gained attention as a sustainable soil amendment with multiple environmental and agricultural benefits (Ng et al. 2022b). Its highly porous structure and large surface area enhance soil water retention, nutrient availability, and microbial activity, improving overall soil health (Wang et al. 2024). Additionally, biochar can sequester carbon, reducing greenhouse gas emissions while also mitigating soil contamination through adsorption (Vaccari et al. 2011). Studies suggest that its application enhances plant growth by optimizing soil physicochemical properties and promoting root development. Given its abundance as an agricultural byproduct, peanut shell biochar presents an eco-friendly solution for waste recycling, soil remediation, and sustainable farming practices (Ng et al. 2022a, b). Previous studies have explored the combined effects of biochar and CO<sub>2</sub> enrichment. When biochar is applied, CO<sub>2</sub> enrichment enhances the plant growth benefits of biochar, resulting in the highest biomass (Ng et al. 2022a). Biochar and CO<sub>2</sub> promote the development of soil microbes that are beneficial for plant growth (Ng et al. 2023). However, there are few studies on the combined effects of biochar treatment and elevated CO<sub>2</sub> on plant-soil hydraulic interactions.

This study aims to investigate the plant-soil hydraulic interaction under biochar treatment in future elevated atmospheric CO<sub>2</sub> condition. The characteristics of biochar are assessed. Plant root development and soil water retention are analyzed. Additionally, plant transpiration rates and water loss are measured. The findings of this study provide valuable insights into optimizing soil management practices to enhance plant growth and water efficiency in changing climate.

## 2 METHODOLOGY

### 2.1 Soil and biochar preparation

The soil used in this study was laterite, sourced from a field site in Bijie, Guizhou province, China. Before utilization, it was sieved through a 4.75 mm mesh. The soil comprised 98% of particles ranging from 0.075 to 4.75 mm and 2% of particles smaller than 0.075 mm. According to the classification specified in ASTM D2487-11 (2011), the soil was classified as poorly graded sand (SP). The biochar examined in this research was produced from peanut shells at a pyrolysis temperature of 500 °C and was commercially provided by Sanli New Energy Co., Ltd. in Shangqiu, Henan province, China. The pH of the biochar was measured at 6.98, with a total organic carbon content of 20.66%.

### 2.2 Set-up of plant growth experiment

Cylindrical pots with a diameter of 240 mm and a height of 160 mm were prepared, each featuring six drainage holes at the bottom. The lateritic soil was amended with 0% (control), 3%, and 5% peanut shell biochar. Seedlings of *Pseudostellaria heterophylla* were sourced from Changhao-jinhuang Traditional Chinese Medicine Co. Ltd. in Guizhou province, China. The seedlings were planted at a depth of 60 mm with a horizontal spacing of 60 mm, with seven seedlings placed in each pot. The pots containing 0%, 3%, and 5% biochar in a CO<sub>2</sub>-controlled chamber (1000 ppm CO<sub>2</sub>) were labeled as E0, EB3, and EB5, respectively. The pots with 0%, 3%, and 5% biochar dosages in a plant room (400 ppm CO<sub>2</sub>) were labeled as Control, B3, and B5. Each condition included three replicate pots, totaling 21 seedlings. During the four-month growth period, each pot was irrigated every eight days to maintain approximately 40% soil water content, which is optimal for plant growth.

### 2.3 Measurements during plant growth and at harvest

The morphology of peanut shell biochar surface was analysed by scanning electron microscope (SEM). The surface functional groups of biochar were determined by a Fourier transform infrared spectroscopy (FTIR). During plant growth, soil matric suction and moisture were monitored at a depth of approximately 5–10 cm, which corresponded to the root zone. Soil matric suction was measured using a miniature-tip tensiometer (2100F, Soil Moisture Equipment Corporation). Volumetric water content (VWC) was monitored with a moisture sensor (EC5) positioned near the tensiometer. Both sensors were placed at the center of each pot. After two months of plant growth, the relationship between matric suction and VWC was utilized to plot the soil water retention curve (SWRC). To investigate the transpiration of *P. heterophylla* in pots, laminated plastic sheets were placed over the soil surface to reduce evaporation. During the drying period, the mass loss of each pot was recorded using an electronic balance every 24 hours to estimate the transpiration rate. According to Wang and Ni (2024), the amount of water consumed for photosynthesis is generally negligible in comparison to transpiration. The total water loss from the plant due to transpiration was calculated by multiplying the leaf area by the leaf transpiration rate. After harvesting of the plants, the different plant organs were carefully washed with Milli-Q water. Root length (RL) was measured using ImageJ, and root length density (RLD) was calculated by dividing the total root length by the soil volume (Ng et al. 2022a).

## 3 RESULTS AND DISCUSSION

### 3.1 Microstructure and functional group of biochar

Figure 1 shows the SEM (Scanning Electron Microscopy) images of peanut shell biochar. It reveals a highly porous structure characterized by a complex network of interconnected pores and cavities. The surface morphology displays a heterogeneous distribution of micropores formed during the pyrolysis process as volatile compounds are released and organic matter is carbonized. These pores vary in shape and size, contributing to the large surface area of peanut shell biochar and its enhanced adsorption capacity. Some study has revealed the pore volume and surface area appear to be positively correlated with the percentage of lignin and insoluble minerals in the feedstock (Zhao et al. 2014). The well-developed porous framework highlights the potential of peanut shell biochar for various environmental applications, including water retention, pollutant removal, soil microbial activity, and carbon sequestration (Ng et al. 2022b).

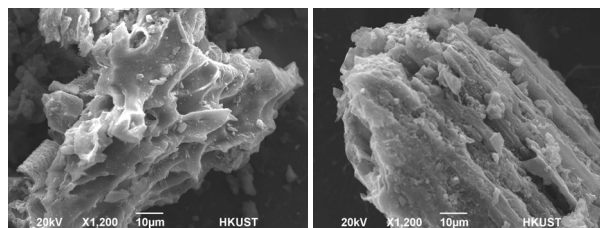


Figure 1. Scanning electron microscope (SEM) for biochar.

The FTIR analysis of peanut shell biochar in Figure 2 reveals the presence of key functional groups, including hydroxyl (-OH), carboxyl (-COOH), and phosphorus-containing (P-containing) moieties. The broad absorption band around 3400 cm<sup>-1</sup> corresponds to -OH stretching vibrations, indicating the presence of surface-bound water, alcohols, or phenols. The peak near 1700 cm<sup>-1</sup> suggests C=O stretching from -COOH groups, which enhances the cation exchange capacity and metal-binding affinity of peanut shell biochar. Additionally, the detection of P-related bands (e.g., ~1000–1100 cm<sup>-1</sup>, possibly from P=O or P-O-C stretches) indicates the retention of phosphorus from the peanut shell feedstock, which could contribute to nutrient retention in soil applications. Collectively, these functional groups enhance the efficiency of biochar as soil amendment, making it suitable for various environmental applications, such as water adsorption, soil fertility enhancement, and organic contaminant removal (Wang et al. 2024).

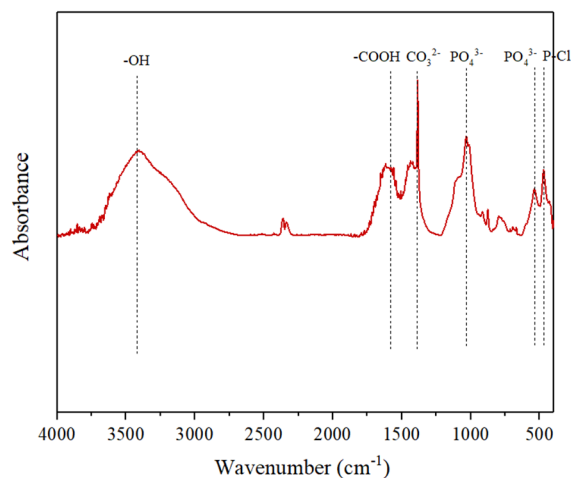


Figure 2. Fourier transform infrared spectrum (FTIR) of biochar

### 3.2 Root development and water retention of root zone soil

Figure 3 shows the root development of plants under coupled biochar and CO<sub>2</sub> enrichment. The results indicate a significant influence of biochar application and CO<sub>2</sub> concentration on root growth parameters. The largest root length was observed in the EB3 treatment, where a 3% biochar dosage was applied under elevated CO<sub>2</sub> conditions, reaching 87.3 mm. Under ambient CO<sub>2</sub> conditions, the maximum root lengths for treatments B3 and B5 showed slight decreases compared to the control, with reductions of approximately 3.6% and 4.3%, respectively. Notably, under elevated CO<sub>2</sub> conditions, the maximum root length significantly increased in treatments EB3 and EB5, with increases of 54.2% and 26.7% compared to the control. This suggests that elevated CO<sub>2</sub> enhances root growth, particularly with the addition of biochar. The root length density also exhibited interesting trends. Under ambient conditions, the root length density for treatment B3 increased by about 3.3% compared to the control, while treatment B5 showed a decrease of approximately 13.1%. In contrast, under elevated CO<sub>2</sub>, both EB3 and EB5 treatments demonstrated substantial increases in root length density, with EB3 showing an increase of 84.9% and EB5 an increase of 88.7% compared to the control. This indicates that biochar application, especially under elevated CO<sub>2</sub>, significantly enhances root length density. These findings suggest that the application of peanut shell biochar, particularly under elevated CO<sub>2</sub> conditions, can promote root growth and development, potentially enhancing plant resilience and productivity in changing environmental conditions.

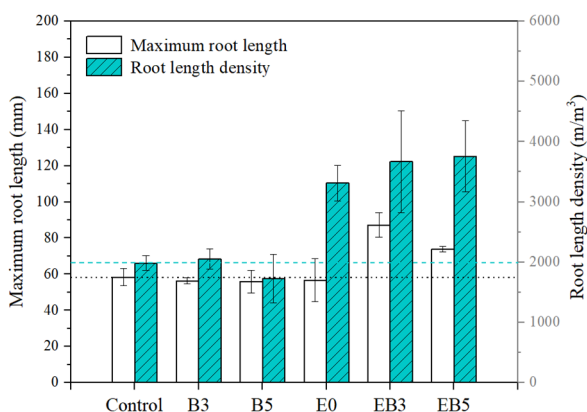


Figure 3. Maximum root length and root length density under coupled biochar and elevated CO<sub>2</sub> condition

Figure 4 illustrates the soil water retention in the root zone under the combined treatment of peanut shell biochar and elevated CO<sub>2</sub>. The measured data for each soil condition were analysed using the van Genuchten model (Van Genuchten, 1980). The addition of biochar was found to increase the saturated soil moisture content, which aligns with findings that biochar enhances soil porosity (Hardie et al. 2014). The combination of biochar and CO<sub>2</sub> enrichment resulted in higher air-entry values (AEV). Furthermore, this coupled treatment significantly increased the volumetric water content (VWC) at any given suction level, indicating an improved water-holding capacity of the soil. This enhancement may be attributed to the development of fine root growth that occupies the soil pore space in the root zone, leading to a reduction in the diameter of soil pore throats. Consequently, this results in increased suction at a given water content, as described by capillary law.

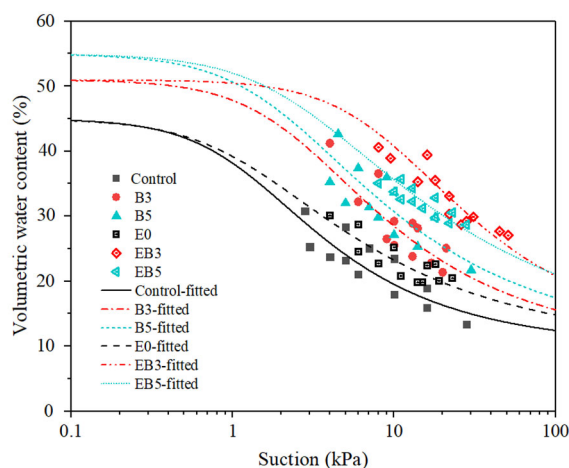


Figure 4. Soil water retention in the root zone

### 3.3 Plant transpiration and water loss

Figure 5 shows the transpiration rates and water loss by leaf transpiration under different treatments. Under ambient CO<sub>2</sub> conditions, the transpiration rates decreased with the addition of biochar. The B3 treatment exhibited a reduction of approximately 10.9% compared to the control, while the B5 treatment showed a more significant decrease of about 16.5%. This trend suggests that the presence of biochar may alter the water uptake or retention properties of the soil, affecting the transpiration process. Under elevated CO<sub>2</sub> conditions, the transpiration rates dropped significantly. The E0 treatment, which had no biochar, showed a decrease of approximately 49.6% compared to the control. The EB3 and EB5 treatments further reduced transpiration rates by 58.9% and 64.5%, respectively, compared to the control. These results indicate that elevated CO<sub>2</sub> conditions can significantly suppress transpiration, likely due to stomatal closure as a response to increased atmospheric CO<sub>2</sub> (Ng et al. 2019).

Regarding water loss by leaf transpiration, under ambient conditions, the B3 treatment resulted in an increase of approximately 121.2% compared to the control, while the B5 treatment exhibited a slight decrease of about 119.6%. In contrast, under elevated CO<sub>2</sub> conditions, water loss by leaf transpiration decreased significantly. The E0 treatment demonstrated a reduction of approximately 54.1% compared to the control. This suggests that elevated CO<sub>2</sub> substantially reduces water loss, likely due to lower transpiration rates.

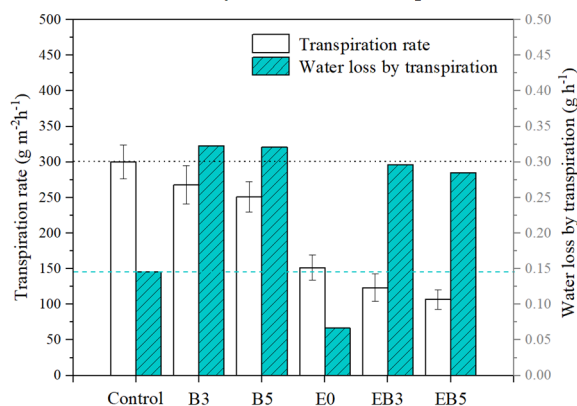


Figure 5. Transpiration rate and transpiration-induced water loss

## 4 CONCLUSIONS

This study investigates the combined effects of biochar and CO<sub>2</sub> enrichment on plant-soil hydraulic interactions. Analysis of the

microstructure and functional groups reveals a porous system with abundant oxygen-containing functional groups (e.g., -OH, -COOH) on biochar surface. The combination of biochar treatment and elevated CO<sub>2</sub> significantly increases root development indicators, including maximum root length and root length density. Root occupancy in soil pores alters pore size, enhancing water retention. CO<sub>2</sub> enrichment significantly reduces plant transpiration, and the combination of biochar and CO<sub>2</sub> results in the lowest transpiration rates. Despite CO<sub>2</sub> enrichment decreasing transpiration-induced water loss due to an enlarged leaf area, biochar plays a more dominant role in increasing total water loss through transpiration. The findings could serve as a basis for recommendations designed to improve soil-plant ecosystems within the framework of eco-geotechnics.

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