



Article

Effects of Carbon-Based Fertilizer on Maize Root Morphology, Root Bleeding Rate and Components in Northeast China

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Abstract: Maize (*Zea mays* L.) is the largest grain crop in Heilongjiang Province. Carbon-based fertilizer is a mixed fertilizer produced by adding a certain proportion of chemical fertilizer with biochar as the loading substrate. In this study, the effects of carbon-based fertilizer on the rhizosphere soil microenvironment and maize root system were discussed. Two maize varieties, Xianyu 335 and Jingke 968, were selected and six treatments were set as follows, including no fertilization (CK1), conventional fertilizer (CK2) and the amount of carbon-based fertilizer, which were 3 t/hm², 3.75 t/hm², 4.5 t/hm² and 5.25 t/hm², respectively. The results showed that carbon-based fertilizer increased the total root length, root volume, root area and root tip number of maize, and the root length, root volume, root area and root tip number of 4.5 t treatment performed better at all stages, which was significantly higher than that of chemical fertilizer. On 16 August (early filling stage), most of the root color changed from milky white to dark brown, the root clarity decreased, the number of roots decreased, the root volume significantly decreased and the root began to age, while the number and volume of roots treated with the carbon-based fertilizer remained stable, the root color was milky white, the morphological structure was clear and there was basically no aging. The carbon-based fertilizer treatment significantly increased the root biomass of 0–15 cm above the plant, 15–30 cm and 30–45 cm between the plants and 0–15 cm between the ridges, forming a wide and deep high-yield root system. The carbon-based fertilizer significantly increased the bleeding rate. On 8 July (jointing stage), Xianyu 335 and Jingke 968 reached the maximum value at the 3 t and 3.75 t treatments, respectively. The carbon-based fertilizer treatment had no significant effect on the amino acid content, but significantly increased the amino acid transport rate on 8 July (jointing stage) and 16 August (early filling stage). The transport rate of inorganic phosphorus gradually decreased with the advancement of the growth process. On 8 July (jointing stage), the ammonium nitrogen content and transport rate of the two varieties reached the maximum value at the treatment of 4.5 t and 3.75 t, which was significantly higher than the treatment of chemical fertilizer and no fertilizer, and showed a gradual downward trend with the advancement of the growth process. The soluble sugar content was relatively low in the early stage and increased rapidly on 4 September (waxy ripening stage). Both varieties reached the maximum value at 4.5 t treatment, and the transport rate reached the maximum value at 3.75 t treatment, which was significantly higher than that of the chemical fertilizer treatment. In conclusion, the carbon-based fertilizer significantly increased the yield of maize, and the yield of maize under the 4.5 t treatment reached the maximum, which was 15.02% and 18.24% higher than that of the chemical fertilizer treatment, respectively.

Keywords: carbon-based fertilizer; root morphology; root bleeding; transfer rate

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1. Introduction

A root is a direct consumer of soil resources and an important contributor to yield [1]. It is not only the main nutrient organ for maize to absorb water and fertilizer, but also

an important organ for synthesizing and transforming hormones, amino acids and other active substances [1,2]. As early as the 1930s, Weaver pointed out that “to understand crop production scientifically, it is necessary to comprehensively understand the growth and development of crop roots, root group distribution, root absorption of water and nutrient activity and root changes in different environments” [1–3]. The input of a large number of chemical fertilizers has led to a rapid increase in China’s grain output but, at the same time, caused a great waste of resources and environmental pollution [4]. In order to repair soil barriers, improve the productivity of cultivated land and crops, and promote the sustainable development of agriculture, biochar has been applied to agricultural production [4–6]. In order to improve the effectiveness of fertilizer and improve the soil nutrient environment, predecessors have done a lot of research and formed a series of new fertilization technologies, such as “reducing the amount of fertilizer and applying organic fertilizer” [7], “nitrogen fertilizer backward” [8] and “water and fertilizer integration” [9]. These technologies can effectively improve the soil nutrient environment and increase the yield of maize, but most of them are directly studying the relationship between nutrients and the growth and yield of aboveground parts. Moreover, due to the difficulties in the field research of maize roots, few studies have been conducted to analyze the response mechanism of roots to the soil environment and the relationship between the root’s physiological function and yield.

There are various factors affecting the growth and development of plant roots, which not only depend on the variety of crops but are also affected by complex environmental factors [10]. Some studies believe that the root morphology and distribution largely depend on the soil fertility level and nutrient distribution, while the morphology and configuration largely determine the ability of plants to obtain nutrients. Plants increase the root length, surface area and volume, thereby increasing the root active absorption area, thus improving the root absorption capacity and efficiency, optimizing the root morphology and promoting the formation of root morphology [11,12]. Carbon-based fertilizer is rich in nitrogen, phosphorus, potassium, sulfur, calcium, magnesium and other nutrients, which improves the level of soil nutrients and provides an important material basis for root morphogenesis and tissue development. The rich biochar and organic matter can affect the physical and chemical properties of soil, improve the permeability of soil air and water, coordinate and optimize the soil water and gas conditions and provide a good ecological environment for promoting the physiological structure and morphological development of roots. The increase in soil porosity provides more extension space for root growth [13]. Secondly, a carbon-based fertilizer has obvious heat absorption properties. After being applied to the soil, the soil temperature can be increased, the chilling injury at low temperatures can be reduced and favorable conditions for root growth and development can be provided [14]. Some studies have shown that a carbon-based fertilizer has a positive effect on root length, volume, surface area and other morphological characteristics [11–14]. The root length density (RLD) and root weight density (RWD) of the carbon-based fertilizer treatment have increased by 30% and 40%, respectively, compared with a single chemical fertilizer (CF) [15]. The root length, surface area, volume, root tip number, branching number and other root morphological indexes of spinach treated with the carbon-based fertilizer were significantly higher than those treated with a common compound fertilizer at harvest [16]. The root length, root surface area and root dry matter accumulation of ryegrass treated with the carbon-based fertilizer increased [17].

The effect of carbon-based fertilizer on crop growth is, first of all, to affect the physical and chemical properties of soil and then to affect plant growth [17,18]. The aboveground parts of sweet potato treated with carbon-based fertilizer developed earlier and faster, and the leaf area coefficient and dry matter accumulation at the growth peak were significantly higher than those of chemical fertilizer treatment, and the population declined slowly at the later stage of growth [19]. A carbon-based fertilizer can improve the activities of nitrate reductase in leaves and soluble starch synthetase in grains, improve the photosynthetic parameters of rice and improve the yield and quality of rice [20]. The new carbon-based

fertilizer prepared by using rice hull biochar and urea peroxide can release nitrogen and fix cadmium slowly at the same time, reduce the harm of Cd in the growth process of Chinese cabbage, reduce the environmental risk of Chinese cabbage and increase the accumulation of dry matter [21]. The application of a carbon-based fertilizer is more efficient and stable in promoting crop growth. The single application of biochar can promote crop growth, and the effect of the carbon-based fertilizer is more obvious [22]. The carbon-based fertilizer can increase the nitrogen absorption of maize grains, play a certain role in increasing yield, and also affect the potassium migration of plants, and increase the potassium absorption of crops [23]. The carbon-based fertilizer increased the wheat's aboveground biomass, underground biomass and N, P absorption [24]. The effect of the carbon-based fertilizer on the yield is also reflected in the distribution of nutrients, the coordination of the relationship between "source, sink and flow" in the growth process and the promotion of the transport of photosynthetic products, thus improving yield. The distribution proportion of nitrogen in each organ has a great impact on the yield. The grain yield increases with the increase of nitrogen uptake at the ear. The ratio of nitrogen uptake by rice grain and stem and leaf under the carbon-based fertilizer treatment is significantly higher than that under the chemical fertilizer treatment, and the rice ear rate and grain number per ear increased [25]. The carbon-based fertilizer is a compound fertilizer that uses biochar to load organic fertilizer and nitrogen, phosphorus and potassium fertilizer. It can play a dual role in improving the soil environment and continuously supplying crop nutrients. Through studying the changes in the rhizosphere microenvironment and root morphological and physiological characteristics after treatment with the carbon-based fertilizer, as well as the relationship between them and the yield, this experiment revealed the mechanism of action of the carbon-based fertilizer on maize root growth and the soil environment, providing a theoretical basis and technical reference for the rational application of the carbon-based fertilizer, ensuring the robust growth of maize roots and improving maize yield in the future.

2. Materials and Methods

2.1. Experimental Design

We started the preliminary experiment in 2018 and achieved good experimental results. In 2019, we modified and improved the plan based on the 2018 experiment and achieved good application results for the carbon-based fertilizer, and achieved good application data. The tested variety, Xianyu 335, was selected by Tieling Xianfeng Seed Research Co., Ltd. and Jingke 968 by the Maize Research Center of Beijing Academy of Agricultural and Forestry Sciences. The two varieties selected above were planted on a large scale in the main maize production area of Heilongjiang Province, and the suitable planting density and growth period of the two varieties were the same. Moreover, the Jingke 968 maize variety is performing better and better in Heilongjiang. The Xianyu 335 maize variety is a conventional high-yield maize variety in Heilongjiang. The planting density is 82,500 plants per hectare. The carbon-based fertilizer was provided by Heilongjiang Wuchang Runnong Science and Technology Co., Ltd. Its nutrient content is 45.6% of organic matter, 4% of nitrogen (N), 3% of phosphorus (P_2O_5), 3% of potassium (K_2O) and a pH of 7.5. The test was conducted in the Xiangyang Demonstration Base of Northeast Agricultural University in 2019. The area has a temperate continental climate, rich in light and heat resources and moderate rainfall. The test soil is chernozem, with a loose texture and basic soil fertility: organic matter 28.21 g/kg, total nitrogen 1.8 g/kg, alkali-hydrolyzable nitrogen 105.84 mg/kg, available phosphorus 47.32 mg/kg, available potassium 166.15 mg/kg and a pH of 6.82. The daily mean values of the weather variables at the experimental site during the six months of the maize growing season in 2019 were listed: average temperature (22.8 °C), precipitation (452.3 mm) and sunshine hours (1386 h). The experiment adopted a completely random design and a total of 6 treatments were set up; namely, non-fertilization treatment (CK1), conventional fertilization treatment (CK2): nitrogen (N) 180kg/hm², phosphorus (P_2O_5) 90kg/hm² and potassium (K_2O) 90kg/hm²; and four carbon-based

fertilizer treatments: 3 t/hm², 3.75 t/hm², 4.5 t/hm² and 5.25 t/hm². For the chemical fertilizer treatment, N 120 kg/hm², P₂O₅ 90 kg/hm² and K₂O 90 kg/hm² were applied as the base fertilizer before sowing, N 60 kg/hm² was applied at the jointing stage and a carbon-based fertilizer was applied at one time. After ridging, a mechanical furrow was opened on the ridge, the carbon-based fertilizer was applied and then the ridge was closed. The plot has 8 ridges at 0.65 m wide, 7 m long and an area of about 36.4 m². Each treatment was repeated three times and arranged randomly. The experiment was sown on 28 April and the sampling analysis was conducted on 8 July (jointing stage), 28 July (tasseling stage), 16 August (early filling stage), 4 September (waxy ripening stage) and 26 September (full ripening stage).

2.2. Data Collection

2.2.1. Dynamic Monitoring of Root Growth

Before sowing, install the CI-600 root monitoring system and install a transparent plexiglass root canal with a diameter of 7 cm and a length of 200 cm in each plot. The included angle between the root canal and the ground is 30 degrees. The upper part is about 20 cm above the ground and wrapped with black film and tape to prevent sunlight from entering the pipe and affecting the growth of roots near the micro-root pipe. At the same time, a top cover was installed at the pipe mouth to prevent rainwater and dust from entering the pipe. The images were scanned and collected by the CI-600 scanner on 8 July, 28 July, 16 August and 4 September, respectively. The collected images were analyzed by WinRHIZOTron for the root length, root surface area, root volume, root tip number, etc.

2.2.2. Determination of Root Dry Matter

On 16 August, Jingke 968 was selected for fertilization treatment. The soil columns were taken out at the plant growth point (on the plant), 1/2 between the two-plant spacing (1/2 between the plants) and 1/4 between the two ridges (1/4 between the ridges) with a root drill with a diameter of 7 cm. The soil columns were taken every 15 cm as a layer and a total of five layers were taken. The soil columns were put into a net bag and washed clean and the maize roots were selected. The maize roots were killed at 105 °C, dried at 80 °C to a constant weight and weighed [26].

2.2.3. Collection and Measurement of Root Bleeding

The bleeding fluid was collected by the volume method, which involved cutting off about 4 cm of the ground in the stem base, putting on a rubber tube, binding it tightly with a rubber band, taking off the rubber tube after 10 h, weighing the collected bleeding fluid and calculating the flow (g/h). The content of the ammonium nitrogen in the bleeding fluid was determined by a flow analyzer, the content of the inorganic phosphorus was determined by indophenol blue colorimetry, the content of the soluble sugar was determined by the anthrone method and the content of amino acid was determined by ninhydrin colorimetry [27].

2.2.4. Determination of Yield and Yield Components

The yield of the maize was measured by the actual harvest. The ear characters, such as the number of rows per ear, the number of grains per ear, the 100-grain weight and the water content, were investigated in the laboratory, and the grain yield was calculated by 14% water content.

2.3. Statistical Analysis

We used Office 2016 software to sort out the data and draw charts, and SPSS24.0 software to analyze the data.

3. Results

3.1. Root Morphology

The maize root morphology and spatial distribution play a key role in the absorption of soil nutrients and water. It can be seen from Figure 1 that the total length, total surface area, total volume and root tip number of the root system increased first and then decreased with the progress of the growth process. The total root length was significantly higher in the treatment of the carbon-based fertilizer than that of the chemical fertilizer on 8 July, 16 August and 4 September. On 28 July, in addition to the 3 t treatment, the treatment of the carbon-based fertilizer was also higher than that of the chemical fertilizer. During the whole sampling period, the total root length of the 4.5 t treatment was the highest. The total root surface area of the 3 t treatment level was the lowest in the whole growth period. On 8 July, except for 3 t, the difference between the other treatments was small. From 28 July to 4 September, 3.75 t, 4.5 t and 5.25 t were higher than the chemical fertilizer: 23.60–26.56% higher on 28 July, 7.84–14.40% higher on 16 August and 21.39–29.33% higher on 4 September. There was no significant difference between 3.75 t, 4.5 t and 5.25 t. The total root volume in the whole growth period was the lowest in the 3 t treatment and the highest in the 4.5 t treatment. On 8 July, except for 3 t, the other treatments were less different. On 28 July, the treatment of 4.5 t and 5.25 t were higher than that of the chemical fertilizer: 12.79% and 8.65% higher, respectively. On 16 August, 3.75 t, 4.5 t and 5.25 t were higher than those of the chemical fertilizer treatment: 26.19%, 31.67% and 20.29%, respectively. On 4 September, 3.75 t, 4.5 t and 5.25 t were higher than those of the chemical fertilizer treatment, which were 16.15%, 26.31% and 17.35% higher, respectively. The number of root tips in the 4.5 t treatment was the highest in the whole growth period and the lowest in the 3 t treatment on 8 July. Other carbon-based fertilizer treatments were significantly higher than chemical fertilizers. The number of root tips of the 3.75 t, 4.5 t and 5.25 t treatments on 28 July was higher: 10.67%, 18.02% and 12.03% higher than that of the chemical fertilizer treatment, respectively. On 16 August, the treatment of the carbon-based fertilizer was higher than that of the chemical fertilizer, which was 20.51–34.96% higher, respectively. On 4 September, the treatment of the carbon-based fertilizer was higher than that of the chemical fertilizer, which was 9.54–57.51% higher, respectively. From 16 August to 4 September, the rate of decline of the 3 t treatment was the fastest. In general, at the 4.5 t treatment level, the root length, surface area, volume and the number of root tips have significant advantages (Figure 1).

As can be seen from Figure 2, on 8 July, the root system was in the initial stage of development and the root system morphology had not yet been completely completed. The roots were all milky new roots and mainly water-absorbing roots. The construction of the root morphology was basically completed on 28 July. On 16 August, the color of most of the roots treated with the chemical fertilizer changed from milky white to dark brown, which was the result of dead or weak roots, mainly due to the oxidation of phenolic compounds released by cortex cells, which reduced the root clarity, reduced the number of roots, significantly reduced the root volume and began to age. The number and volume of the roots treated with the carbon-based fertilizer remained stable, the root color was milky white, the morphological structure was clear and there was basically no aging. On 4 September, almost all of the roots treated with the chemical fertilizer turned dark brown, the definition of the fine roots decreased sharply, most of the fine roots were invisible and the root showed obvious signs of aging. The roots treated with the carbon-based fertilizer also aged significantly but, compared with the chemical fertilizer, some fine roots were still clearly visible, the root color was milky white and the clarity was high. The above results showed that the application of the carbon-based fertilizer could promote the maize root to maintain a high vitality, delay root senescence and effectively improve the nutrient absorption of the root at the later stage of growth (Figure 2).

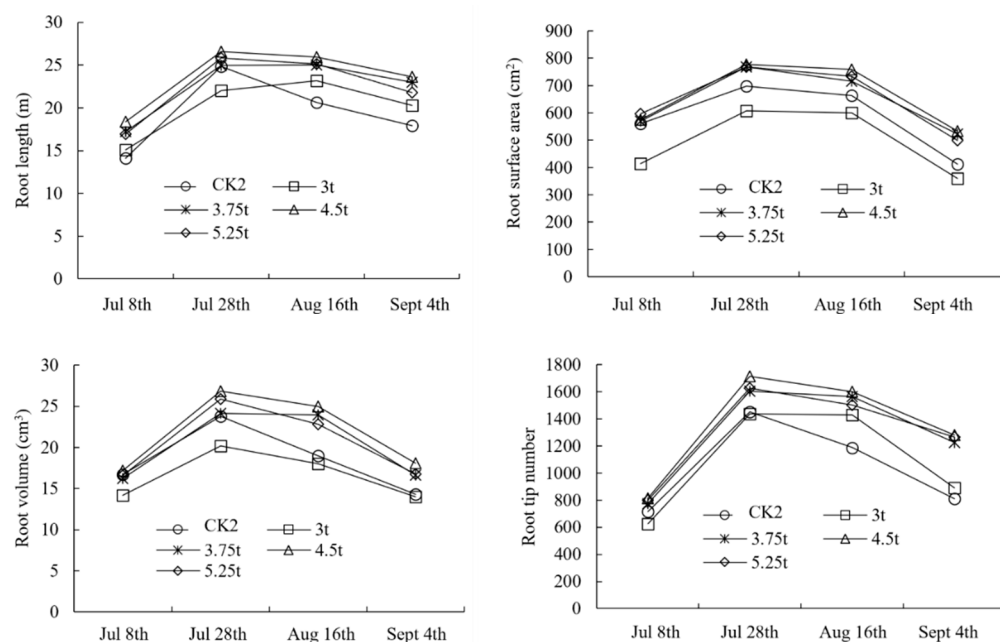


Figure 1. Effects of the carbon-based fertilizer on maize root morphology (taking Jingke 968 as an example).

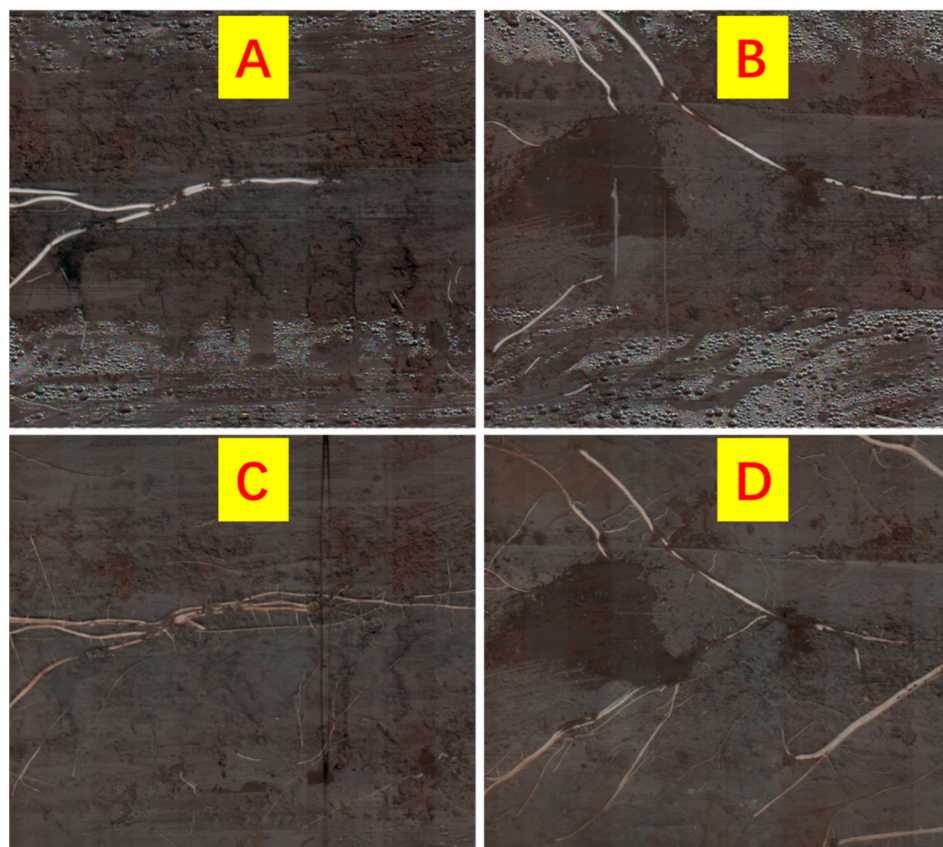


Figure 2. Root morphology difference of the micro-root window between the carbon-based fertilizer and the chemical fertilizer treatment at different sampling dates (taking Jingke 968 as an example). Note: (A,C) show the local root morphology on 8 July and 4 September under the fertilizer treatment, and (B,D) show the local root morphology on 8 July and 4 September under the carbon-based fertilizer treatment.

3.2. Root Dry Matter Distribution

The root biomass is an important parameter reflecting the number of roots, which is closely related to the growth and yield of the aboveground parts of plants. It can be seen from Figure 3 that the spatial distribution of the root biomass gradually decreases with the increase in soil depth. When the root biomass on the plant is 0–15 cm, 3.75 t, 4.5 t and 5.25 t are higher than that of the chemical fertilizer, which are 22.42%, 1.25% and 3.70% higher, respectively, of which 3.75 t is the largest. At 15–30 cm, the treatment of the carbon-based fertilizer was higher than that of the chemical fertilizer; 3 t, 3.75 t, 4.5 t and 5.25 t were higher than that of the chemical fertilizer: 97.59%, 114.52%, 298.49% and 110.22% higher, respectively. The difference between 30–70 cm is small. At 1/2 of the plant, at 0–15 cm, the root biomass was the highest under the treatment of the chemical fertilizer and 3.75 t. At 15–30 cm, the 3.75 t and 4.5 t treatments were 24.49% and 55.84% higher than the chemical fertilizers. At 30–45 cm, each treatment of the carbon-based fertilizer was higher than that of the chemical fertilizer, and the 3 t, 3.75 t, 4.5 t and 5.25 t treatments were 51.56%, 100.13%, 28.82% and 23.06% higher than that of the chemical fertilizer, respectively. At 45–60 cm, the difference between the treatments was small. At 60–75 cm, the chemical fertilizer was higher than the carbon-based fertilizer treatment and the difference was small. At 1/4 of the ridge, at 0–15 cm, the root biomass of the 3.75 t treatment was the highest, 25.79% higher than that of the chemical fertilizer, and the other treatments were lower than that of the chemical fertilizer. At 15–30 cm, the 4.5 t treatment was the highest, 4.98% higher than the chemical fertilizer, and the other treatments were lower than the chemical fertilizer. At 30–45 cm, the 3.75 t treatment was the highest and the rest were lower than the chemical fertilizer. At 45–60 cm, the treatment of the carbon-based fertilizer was lower than that of the chemical fertilizer. At 60–70 cm, the chemical fertilizer and the 3.75 t treatment were the highest. Compared with the chemical fertilizer treatment, the roots of the carbon-based fertilizer treatment have more biomass accumulation at 0–15 cm, 15–30 cm, 15–30 cm and 30–45 cm between the plants and 0–15 cm between the ridges (Figure 3).

3.3. Root Bleeding Rate

The bleeding rate is an index of root activity, reflecting the changing characteristics of root activity. It can be seen from Figure 4 that the bleeding rate of the maize gradually decreased with the progress of the growth process. The bleeding rate of Xianyu 335 increased first and then decreased with the increase of the carbon-based fertilizer on 8 July. The fertilization treatment was significantly higher than no fertilization, and the 3.75 t and 4.5 t treatments were higher than the chemical fertilizer, with no significant difference. On 28 July, the bleeding rate decreased at first and then increased with the increase of the application amount of the carbon-based fertilizer. There was no significant difference between the 3 t, 5.25 t and chemical fertilizer treatments. The effect of the 4.5 t treatment on 16 August was the best, and there was no significant difference between the other treatments and chemical fertilizers. The bleeding rate was small on 4 September, and there was no significant difference between the carbon-based fertilizer and chemical fertilizer. On 8 July and 28 July, the bleeding rate of Jingke 968 increased first and then decreased with the increase of the carbon-based fertilizer. On 8 July, the bleeding rate of the fertilization treatment was significantly higher than that of the non-fertilization treatment, and the bleeding rate of the 3 t and 3.75 t treatments were significantly higher than that of the chemical fertilizer, which were 19.75% and 24.92% higher. There was no significant difference between the carbon-based fertilizer treatment and the chemical fertilizer treatment on 28 July. On 16 August, the fertilization treatment was significantly higher than the non-fertilization treatment, and the bleeding rate gradually increased with the increase of the application amount of the carbon-based fertilizer, reaching the maximum value of 5.25 t, significantly higher than the chemical fertilizer, which was 29.32% higher. On 4 September, there was no significant difference among the treatments except for 4.5 t (Figure 4).

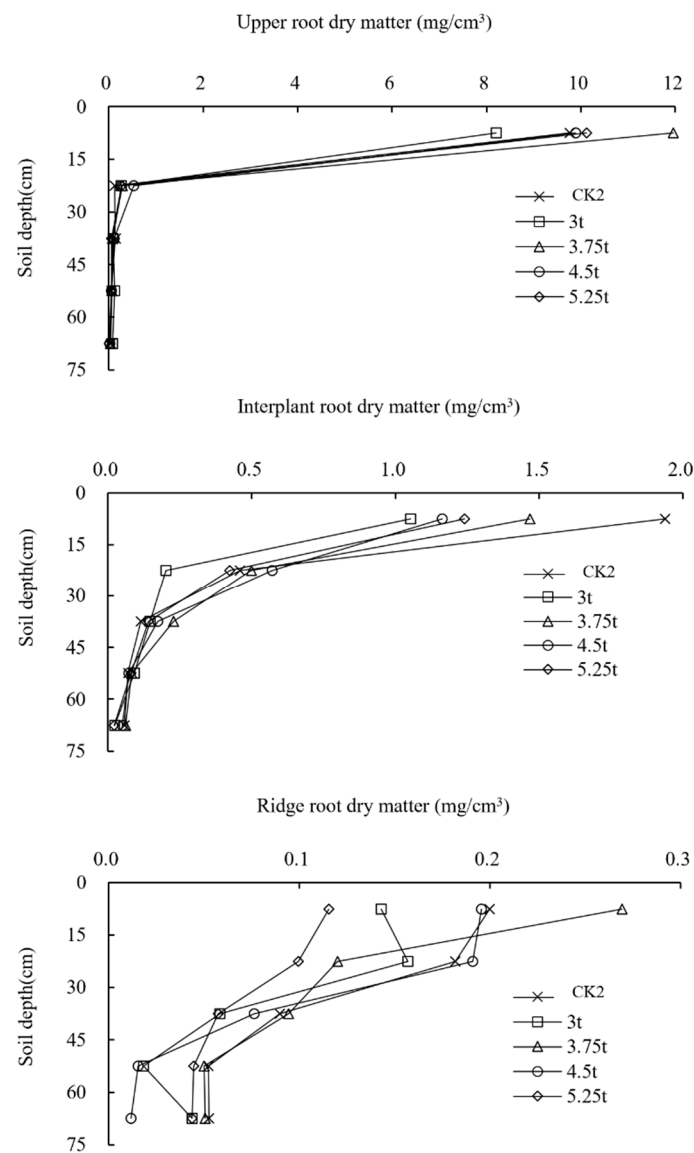


Figure 3. Effects of the carbon-based fertilizer on the maize root dry matter distribution (taking Jingke 968 as an example).

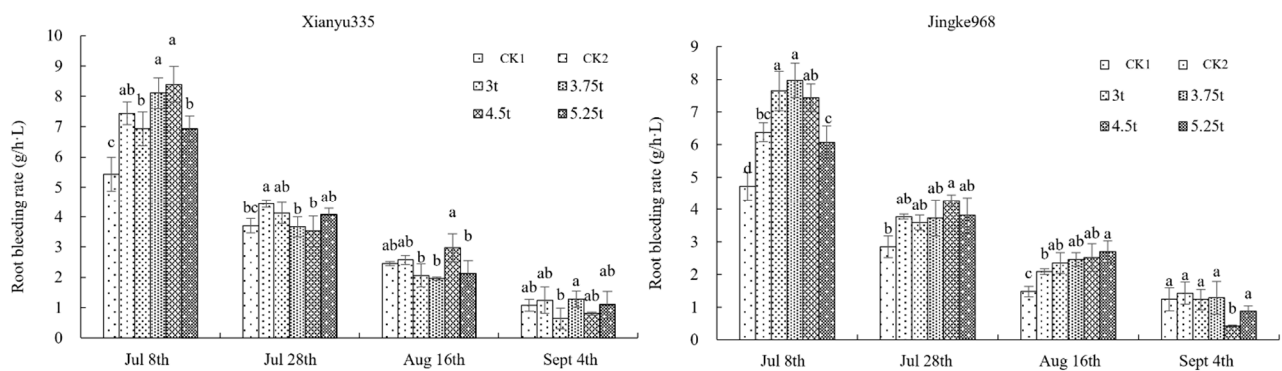


Figure 4. Effects of the carbon-based fertilizer on the maize root bleeding rate. Notes: data are expressed as mean $\pm$ standard deviation. Different letters within the same column indicate a significant difference at the 5% level.

3.4. Content of Free Amino Acids and Its Transport Rate in Maize Root Bleeding

The content and transport rate of the components in the bleeding sap are important indicators reflecting the root absorption activity. According to Figure 5, the content of the free amino acids increases first and then decreases with the progress of the growth process. The content of the free amino acids in Xianyu 335 without fertilizer, chemical fertilizer and the 5.25 t treatment reached the maximum value on 28 July and reached the maximum value in other treatments on 16 August. There was no significant difference between the treatments on 8 July, and the treatment without fertilization was the highest on 28 July. There was no significant difference between the treatment of the carbon-based fertilizer and chemical fertilizer. On 16 August, the treatment of the carbon-based fertilizer was significantly higher than that of the chemical fertilizer, which was 22.16–53.46% higher than that of the chemical fertilizer. On 4 September, no fertilization was significantly higher than the treatments and the 3 t and 3.75 t treatments were significantly higher than the fertilizer treatments, which were 49.91% and 24.04% higher, respectively. The free amino acid content of Jingke 968 without fertilizer, chemical fertilizer and the 3 t and 4.5 t treatments reached the maximum on 28 July and the other treatments reached the maximum on 16 August. There was no significant difference among the treatments on 8 July and the highest was no fertilization on 28 July, and the difference between the carbon-based fertilizer and chemical fertilizer treatments was not significant. On 16 August, 3.75 t was significantly higher than the other treatments and 46.10% higher than that of the chemical fertilizer. There was no significant difference between the other carbon-based fertilizer treatments and the chemical fertilizer. On 4 September, the non-fertilization treatment was significantly higher than the other treatments, and the difference between 4.5 t and the fertilizer treatment was not significant (Figure 5).

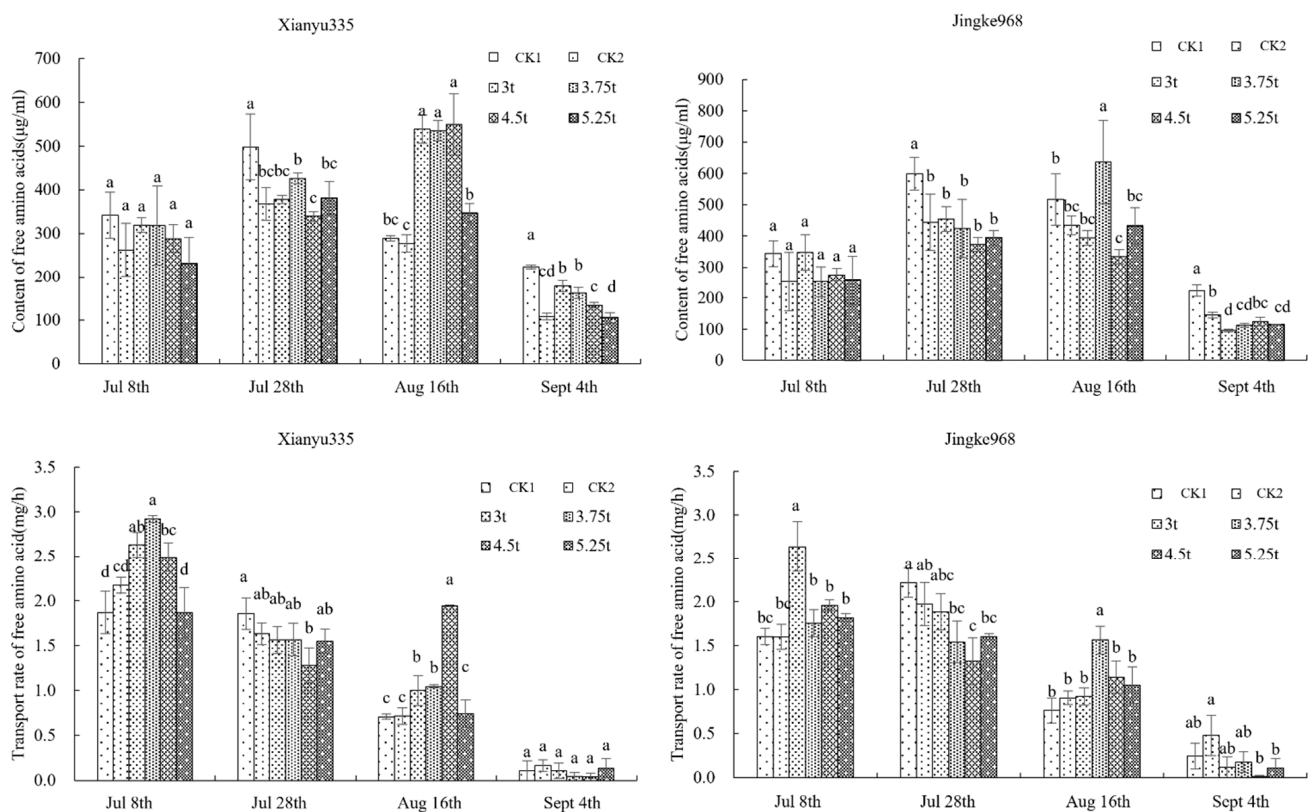


Figure 5. Effects of the carbon-based fertilizer on the content of the free amino acids and the transport rate of the free amino acid in the maize root bleeding. Notes: data are expressed as mean $\pm$ standard deviation. Different letters within the same column indicate a significant difference at the 5% level.

It can be seen from Figure 5 that the free amino acid transport rate of Xianyu 335 increased at first and then decreased with the increase of the application amount of the carbon-based fertilizer on 8 July, with 3.75 t reaching the maximum value and 3 t and 3.75 t being significantly higher than that of the chemical fertilizer treatment: 21.09% and 34.72% higher, respectively. There was no significant difference between the treatment of the carbon-based fertilizer and the chemical fertilizer on 28 July. On 16 August, the free amino acid transport rate increased at first and then decreased with the increase in the application amount of the carbon-based fertilizer. The 3 t, 3.75 t and 4.5 t treatments were significantly higher than those of the chemical fertilizer and non-fertilizer treatment, which were 38.91%, 45.23% and 169.44% higher than those of the chemical fertilizer, respectively. There was no significant difference between the treatments on 4 September. On 8 July, the free amino acid transport rate of the Jingke 968 treatment was significantly higher than that of the other treatments and 65.00% higher than that of the chemical fertilizer treatment. There was no significant difference between the other treatments. On 28 July, the free amino acid transport rate decreased at first and then increased with the increase of the application amount of the carbon-based fertilizer. Except for the 4.5 t treatment, there was no significant difference between the other carbon-based fertilizer treatment and the chemical fertilizer. On 16 August, with the increase in the application amount of the carbon-based fertilizer, it showed a trend of increasing at first and then decreasing. The 3.75 t treatment was significantly higher than that of the chemical fertilizer treatment, which was 72.52% higher. There was no significant difference among the other treatments. There was no significant difference in the fertilizer, 3 t and 3.75 t treatments on 4 September (Figure 5).

3.5. Content of Inorganic Phosphorus and Its Transport Rate in Maize Root Bleeding

It can be seen from Figure 6 that the content of inorganic phosphorus in the bleeding fluid increased first and then decreased with the advancement of the growth process. Except for the treatment without fertilization, the other treatments reached the maximum value on 16 August. The content of inorganic phosphorus in Xianyu 335 decreased gradually with the increase of the application amount of the carbon-based fertilizer on 8 July. The treatment of 3 t was higher than that of the chemical fertilizer but the difference was not significant. On 28 July and 16 August, with the increase of the application amount of the carbon-based fertilizer, it showed a trend of increasing at first and then decreasing. On 16 August, the 3.75 t treatment had the best effect and 3 t and 3.75 t were significantly higher than the chemical fertilizer, which were 4.60% and 8.48% higher, respectively. On 4 September, no fertilization and the 3 t treatment were significantly higher than each treatment. On 8 July, Jingke 968 and the inorganic phosphorus content of the carbon-based fertilizer treatment was lower than that of the non-fertilization and the chemical fertilizer treatment, and the difference between the carbon-based fertilizer treatment was not significant. On 28 July, the four treatments with no fertilizer, the chemical fertilizer and the 3 t and 3.75 t treatments performed best, and the difference between the treatments was not significant. The inorganic phosphorus content of the 5.25 t treatment was the lowest and significantly lower than the other treatments. On 16 August, there was no significant difference among the other treatments except for 4.5 t. On 4 September, the treatment without fertilization was the highest and the carbon-based fertilizer treatment showed a gradual downward trend with the increase in the application amount. The treatments of 3 t, 3.75 t and 4.5 t were significantly higher than that of the chemical fertilizer, which were 62.59%, 61.92% and 31.03% higher, respectively (Figure 6).

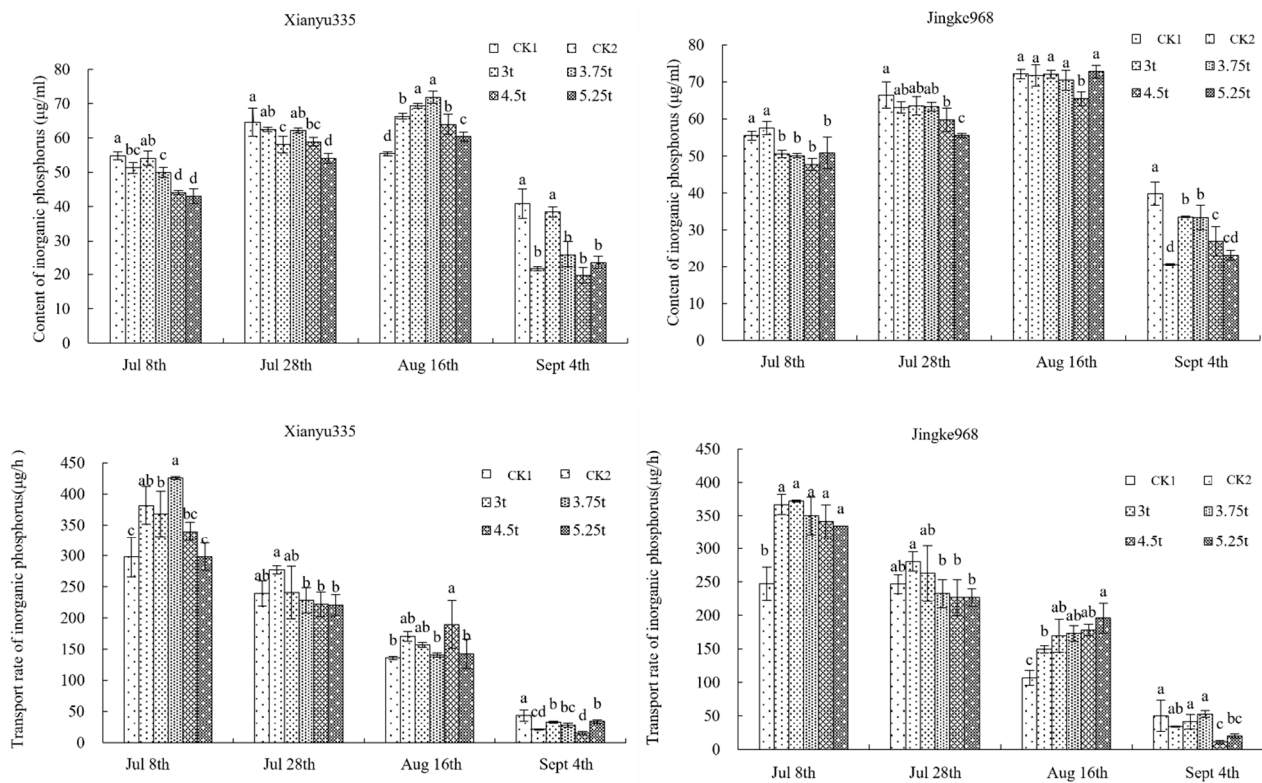


Figure 6. Effects of the carbon-based fertilizer on the content of the inorganic phosphorus and the transport rate of the inorganic phosphorus in maize root bleeding. Notes: data are expressed as mean $\pm$ standard deviation. Different letters within the same column indicate a significant difference at the 5% level.

It can be seen from Figure 6 that the transport rate of the inorganic phosphorus in the bleeding fluid gradually decreases with the advancement of the growth process. The content of the inorganic phosphorus in Xianyu 335 increased at first and then decreased with the increase in the application amount of the carbon-based fertilizer on 8 July. The content of inorganic phosphorus in the chemical fertilizer and 3 t and 3.75 t treatments was significantly higher than that of no fertilizer. The 3.75 t treatment had the highest value but there was no significant difference with the chemical fertilizer treatment. On 28 July, with the increase in the application amount of the carbon-based fertilizer, there was a gradual downward trend and there was no significant difference between the treatments of the carbon-based fertilizer. On 16 August, 4.5 t was higher than that of the chemical fertilizer, with no significant difference. On 4 September, no fertilizer was the highest and 3 t and 5.25 t were significantly higher than that of the chemical fertilizer, which were 21.56% and 28.74% higher, respectively. The inorganic phosphorus transport rate of Jingke 968 that was fertilized on 8 July was significantly higher than that of the non-fertilized treatment, and there was no significant difference between the chemical fertilizer and the carbon-based fertilizer. On 28 July, the treatment of the carbon-based fertilizer gradually decreased with the increase in the application amount. On 16 August, with the increase in the application amount of the carbon-based fertilizer, the trend was gradually rising. The treatment of the carbon-based fertilizer was higher than that of the chemical fertilizer, 5.25 t was significantly higher than that of the chemical fertilizer by 31.08%, and 3 t, 3.75 t and 4.5 t were also higher than that of the chemical fertilizer but the difference was not significant. On 4 September, with the exception of the 4.5 t treatment, the difference between the other carbon-based fertilizer treatment and the chemical fertilizer treatment did not reach a significant level (Figure 6).

3.6. Ammonium Nitrogen Content and Transport Rate in Maize Root Bleeding

It can be seen from Figure 7 that the change in the ammonium nitrogen content in the bleeding fluid gradually decreases with the advancement of the growth process. The ammonium nitrogen content of Xianyu 335 increased at first and then decreased with the increase in the application amount of the carbon-based fertilizer on 8 July, reaching the maximum value of 4.5 t, significantly higher than that of the chemical fertilizer treatment, which was 27.39% higher. On 28 July, it gradually decreased with the increase in the application amount of the carbon-based fertilizer, which showed that no fertilization > chemical fertilizer > 3 t > 3.75 t > 4.5 t > 5.25 t, and the treatment of the carbon-based fertilizer was significantly lower than that of no fertilization and chemical fertilizer. On 16 August, the fertilization treatment was lower than the non-fertilization treatment, and there was no significant difference between the carbon-based fertilizer and the chemical fertilizer treatment. There was no significant difference among the treatments on 4 September. On 8 July, the ammonium nitrogen content of Jingke 968 increased first and then decreased with the increase in the application amount of the carbon-based fertilizer, reaching the maximum value of 3.75 t, significantly higher than that of the chemical fertilizer and non-fertilizer treatment and 18.87% higher than that of the chemical fertilizer. On 28 July, the treatment of the carbon-based fertilizer was significantly lower than that of the non-fertilization and chemical fertilizer. On 16 August, the treatment of no fertilizer, chemical fertilizer and 3.75 t were better and the difference was not significant. There was no significant difference between the treatments on 4 September (Figure 7).

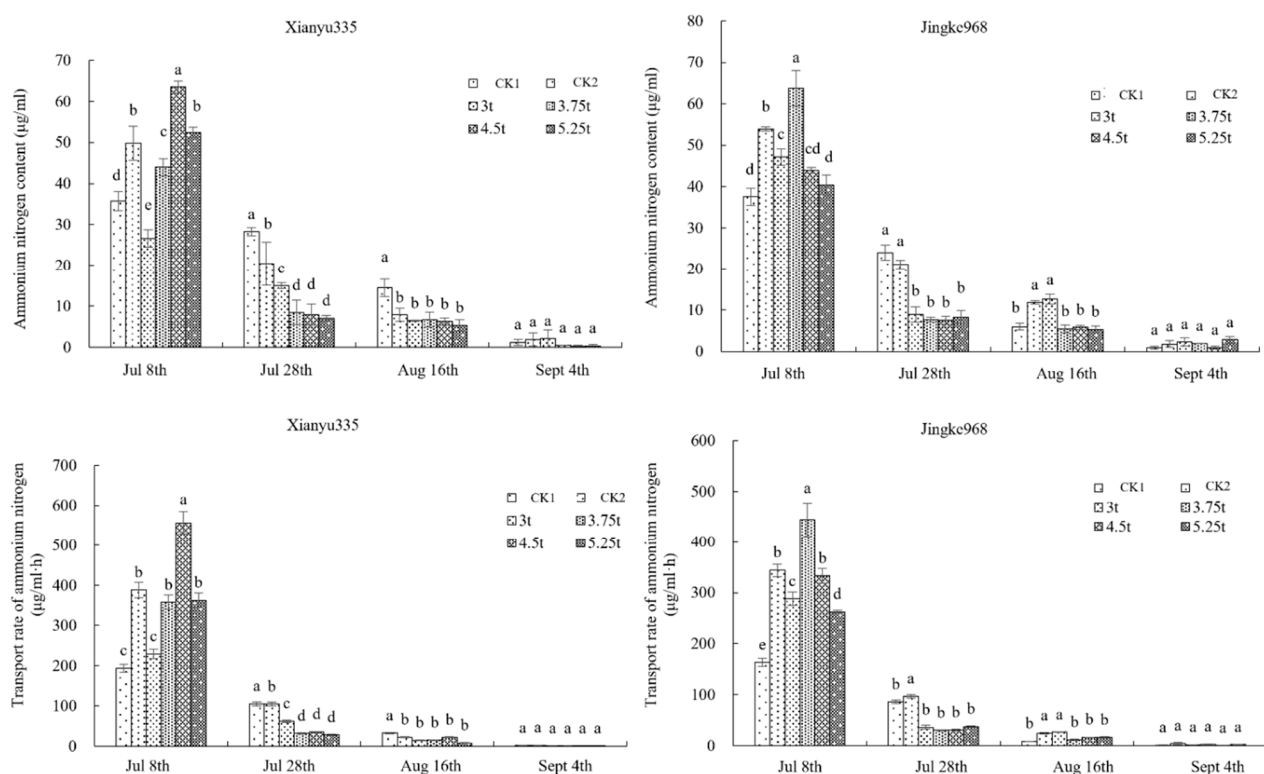


Figure 7. Effects of the carbon-based fertilizer on the ammonium nitrogen content and the transport rate in the maize root bleeding. Notes: data are expressed as mean $\pm$ standard deviation. Different letters within the same column indicate a significant difference at the 5% level.

It can be seen from Figure 7 that the transport rate of the ammonium nitrogen in the bleeding fluid gradually decreases with the advancement of the growth process. The ammonium nitrogen transfer rate of Xianyu 335 increased at first and then decreased with the increase in the application amount of the carbon-based fertilizer on 8 July. The treatment of 4.5 t was the best, significantly higher than the other treatments, and 48.57%

higher than the chemical fertilizer. The 3.75 t, 5.25 t treatments and chemical fertilizer had no significant difference. On 28 July, the treatment of the carbon-based fertilizer was significantly lower than that of the chemical fertilizer and no fertilizer. On 16 August, the treatment with no fertilization was the highest and there was no significant difference between the carbon-based fertilizer and the chemical fertilizer treatment, and there was no significant difference between the treatments on 4 September. On 8 July, the ammonium nitrogen transfer rate of Jingke 968 increased at first and then decreased with the increase in the application amount of the carbon-based fertilizer. The 3.75 t treatment showed the highest performance, significantly higher than the other treatments, and 28.96% higher than the chemical fertilizer, and 4.5 t showed no significant difference with the chemical fertilizer. On 28 July, the chemical fertilizer treatment and no fertilizer treatment were significantly higher than the carbon-based fertilizer treatment. There was no significant difference between 3 t and the chemical fertilizer treatment on 16 August. There was no significant difference between the treatments on 4 September (Figure 7).

3.7. Soluble Sugar Content and Transport Rate in Maize Root Bleeding

It can be seen from Figure 8 that the soluble sugar content of the bleeding fluid was low on 8 July, 28 July and 16 August and the soluble sugar content increased rapidly on 4 September. Xianyu 335 had the best performance in the fertilizer and 3.75 t treatment on 8 July but the difference was not significant. There was no significant difference among the treatments on 28 July. On 16 August, the chemical fertilizer treatment and no fertilizer treatment were significantly higher than the carbon-based fertilizer treatment, and there was no significant difference between the carbon-based fertilizer treatment. On 4 September, the soluble sugar content increased at first and then decreased with the increase in the application amount of the carbon-based fertilizer. The 4.5 t treatment was the best, significantly higher than the chemical fertilizer, and was 22.39% higher. On 8 July, the soluble sugar content of Jingke 968 was not significantly different between the carbon-based fertilizer and the chemical fertilizer treatments. On 28 July, the soluble sugar content increased first and then decreased with the increase in the application amount of the carbon-based fertilizer. There was no significant difference between the treatment of the carbon-based fertilizer and the chemical fertilizer. There was no significant difference among the treatments on 16 August. On 4 September, with the increase in the application of the carbon-based fertilizer, there was a trend of increasing at first and then decreasing. The 4.5 t treatment performed best and the 3.75 t and 4.5 t were significantly higher than the chemical fertilizer, which were 61.16% and 65.62% higher, respectively (Figure 8).

It can be seen from Figure 8 that the transport rate of the soluble sugar was lower on 8 July, 28 July and 16 August and increased rapidly on 4 September. Xianyu 335 had the highest transport rate of the soluble sugar in the 3.75 t and fertilizer treatments on 8 July, which was significantly higher than the other treatments. There was no significant difference among the treatments on 28 July. On 16 August, the chemical fertilizer and no fertilizer treatments were significantly higher than the carbon-based fertilizer treatment, and there was no significant difference between the carbon-based fertilizer treatment. On 4 September, the transport rate of the soluble sugar increased at first and then decreased with the increase in the application amount of the carbon-based fertilizer. The treatment of 3.75 t was the best and significantly higher than that of the chemical fertilizer, which was 31.23% higher, and the difference between the 4.5 t and chemical fertilizer was not significant. On 8 July, the transport rate of the soluble sugar in Jingke 968 increased gradually with the increase in the application amount of the carbon-based fertilizer, with 5.25 t being the highest. There was no significant difference between the treatment of the carbon-based fertilizer and the chemical fertilizer. There was no significant difference among the treatments on 28 July. On 16 August, there was no significant difference between the carbon-based fertilizer and the chemical fertilizer treatment. On 4 September, the 3.75 t treatment performed the best and was significantly higher than the chemical fertilizer and

the no fertilizer treatments. The 3.75 t treatment was 72.64% higher than the chemical fertilizer treatment (Figure 8).

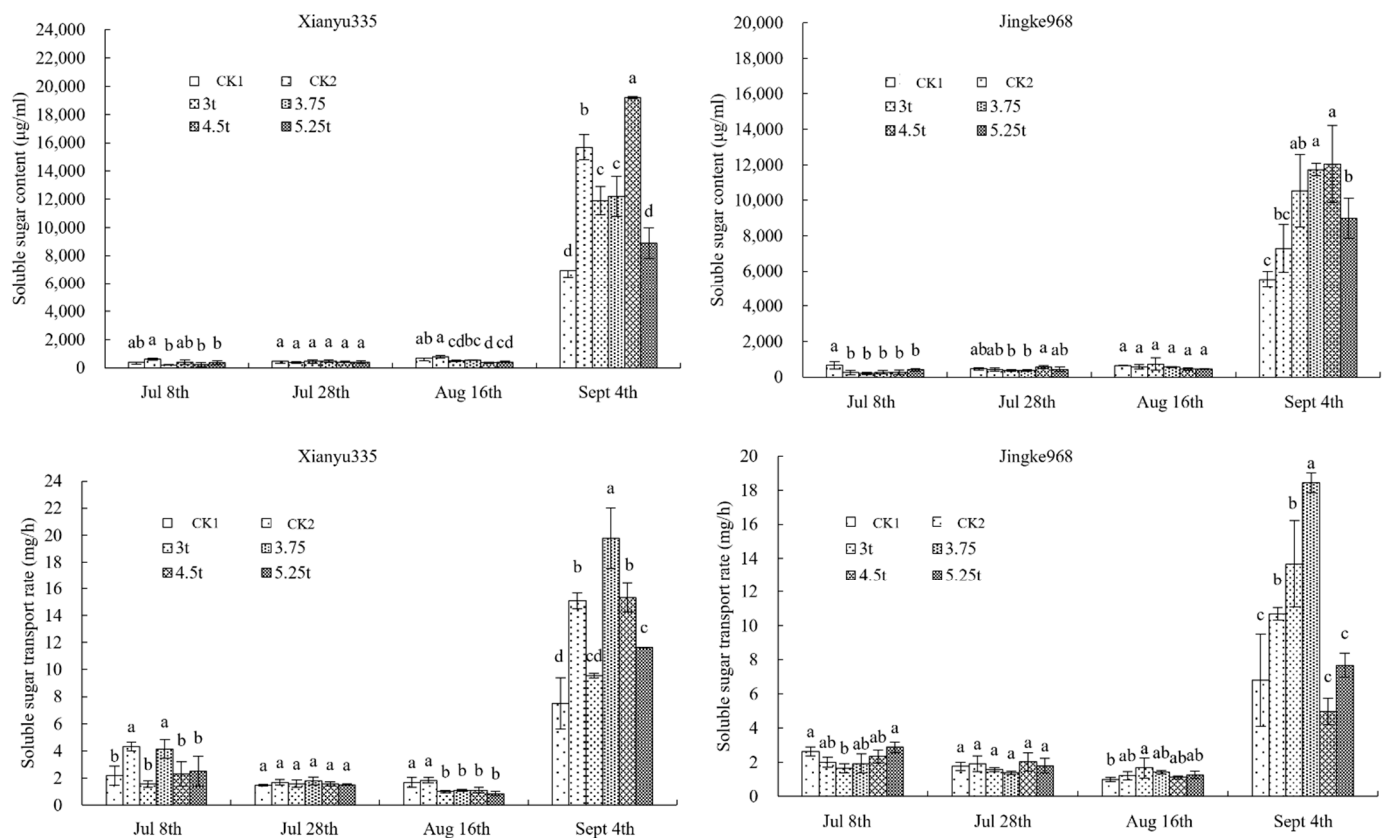


Figure 8. Effects of the carbon-based fertilizer on the soluble sugar content and the transport rate in the maize root bleeding. Notes: data are expressed as mean $\pm$ standard deviation. Different letters within the same column indicate a significant difference at the 5% level.

3.8. Maize Yield and Its Components

It can be seen from Table 1 that there is no significant difference between the effective panicle number and row number per panicle of Xianyu 335. The grains number per row of fertilizer and the carbon-based fertilizer treatment is significantly higher than that of no fertilizer and the treatment of the carbon-based fertilizer. The 3.75 t, 4.5 t and 5.25 t treatments are higher than that of the fertilizer but the difference is not significant. The 100-grain weight of the chemical fertilizer and the carbon-based fertilizer treatment was significantly higher than that of non-fertilization: 15.54%, 10.85%, 15.04%, 15.20% and 19.20% higher than that of non-fertilization, respectively. There was no significant difference between the carbon-based fertilizer and the chemical fertilizer treatment. Under the condition of fertilization, the yield was significantly higher than that without fertilization, which was 61.36–83.15% higher. The yield of the carbon-based fertilizer treatment increased first and then decreased with the increase in the amount of carbon-based fertilizer. The yield of the 4.5 t treatment was the highest, which was significantly higher than that of the chemical fertilizer, which was 15.02% higher. There was no significant difference between the other treatments and the chemical fertilizer treatment. The number of effective panicles and rows per panicle of Jingke 968 had no significant difference among the treatments. The number of grains per row increased first and then decreased with the increase in the application amount of the carbon-based fertilizer. There was no significant difference between the treatment of the carbon-based fertilizer and the chemical fertilizer. The treatment of 3.75 t and 4.5 t performed better and was 9.92% and 10.39% higher than that of the chemical fertilizer, respectively. The 100-grain weight of the chemical fertilizer and the carbon-based

fertilizer treatment was significantly higher than that of the non-fertilization treatment, which was 26.82–31.43% higher than that of the non-fertilization treatment, respectively. There was no significant difference between the carbon-based fertilizer and the chemical fertilizer treatment. The yield of the fertilization treatment was significantly higher than that of the non-fertilization treatment. Under the condition of the carbon-based fertilizer treatment, the yield first increased and then decreased with the increase in the application amount of the carbon-based fertilizer. The treatment of 4.5 t was the best, significantly higher than that of the chemical fertilizer by 18.24%. The difference between the 3 t, 3.75 t and chemical fertilizer treatments was not significant (Table 1).

Table 1. Effects of the carbon-based fertilizer on the maize yield and its components.

Variety	Treatment	Effective Ear Number (Ten Thousand)	Ear Row Number	Grain Number Per Row	100-Grain Weight (g)	Yield (kg/hm ²)
Xianyu335	CK1	6.97 ± 0.94 a	15.33 ± 1.15 a	23.00 ± 1.00 c	28.26 ± 20.7 b	5781.57 ± 52.39 c
	CK2	6.80 ± 0.69 a	15.67 ± 0.58 a	31.93 ± 0.74 ab	32.65 ± 1.59 a	9590.72 ± 472.64 b
	3 t	7.05 ± 0.56 a	16.33 ± 0.58 a	30.67 ± 1.04 b	31.33 ± 0.27 a	9548.17 ± 392.55 b
	3.75 t	7.02 ± 0.15 a	16.33 ± 0.58 a	33.00 ± 0.87 ab	32.51 ± 1.66 a	9950.89 ± 497.00 ab
	4.5 t	7.36 ± 0.25 a	16.33 ± 1.53 a	35.67 ± 2.36 a	32.56 ± 0.42 a	10,915.85 ± 389.12 a
	5.25 t	6.85 ± 0.45 a	16.67 ± 0.58 a	32.67 ± 1.53 ab	33.64 ± 0.34 a	9613.44 ± 185.08 b
Jingke968	CK1	7.31 ± 0.05 a	14.67 ± 2.08 a	30.50 ± 2.00 b	24.96 ± 0.58 b	8380.90 ± 588.93 d
	CK2	6.99 ± 0.13 a	15.33 ± 1.15 a	35.33 ± 2.52 ab	32.80 ± 0.59 a	11,060.74 ± 529.14 bc
	3 t	7.14 ± 0.64 a	15.67 ± 1.53 a	35.67 ± 1.26 ab	32.31 ± 2.17 a	10,998.75 ± 670.19 bc
	3.75 t	7.05 ± 0.27 a	15.33 ± 1.15 a	38.83 ± 2.02 a	32.43 ± 2.92 a	12,116.80 ± 315.33 ab
	4.5 t	6.97 ± 0.38 a	16.67 ± 1.15 a	39.00 ± 1.67 a	32.65 ± 0.59 a	13,117.35 ± 530.66 a
	5.25 t	6.83 ± 0.42 a	16.00 ± 1.00 a	36.17 ± 3.25 ab	32.72 ± 0.70 a	10,401.00 ± 765.20 c

Notes: data are expressed as mean ± standard deviation. Different letters within the same column indicate a significant difference at the 5% level.

4. Discussion

The root system is the most important component of crop material absorption, which not only plays the role of absorption, fixation and support but is also the synthetic site of various amino acids and hormones [28]. The growth and development of crop roots are closely related to soil environmental conditions [29]. The differences in the soil environment directly affect the growth, distribution, structure and physiological metabolism of roots, and ultimately affect the growth and development of maize [30]. Previous studies have shown that a carbon-based fertilizer can not only provide sufficient nutrients, but also improve soil physical and chemical properties and air permeability, and provide a good environment for root growth [29,30]. The biochar in a carbon-based fertilizer can promote root growth to a certain extent, delay root senescence and increase the total root length, root surface area and root active absorption area [31]. The addition of a carbon-based fertilizer significantly increased the root tip number of apple seedlings, the number of roots increased 3.25 times and the number of new roots significantly increased [32]. The peanut root dry matter peak of the carbon-based fertilizer treatment was later [33]. This experiment showed that the carbon-based fertilizer increased the length, volume, area and number of root tips of maize roots. Additionally, in the scanning pictures of the micro-root window, it can be observed that the root diameter of the carbon-based fertilizer treatment is thick, the number is large and the distribution is wide. On 16 August, most of the root color of the chemical fertilizer changed from milky white to dark brown, the root clarity decreased, the number of roots decreased, the root volume significantly decreased and the root began to age. The root color of the carbon-based fertilizer treatment was milky white, the shape and structure were clear and there was basically no aging. It can be seen that the carbon-based fertilizer can significantly improve the root morphological characteristics and delay root senescence, consistent with previous research results. It is generally believed that developed roots can effectively absorb soil nutrients, improve synthesis and secretion activities and provide good conditions for aboveground growth. The growth of maize roots depends on the organic matter supplied by the ground and the nutrients absorbed by the roots [34]. Root

biomass is an important indicator to measure root growth and material distribution. In this study, the root drill method was used to study the biomass accumulation of roots at different soil depths. The study found that the treatment of the carbon-based fertilizer increased the biomass of the roots in 1/2 of the plants and 1/4 of the ridges, indicating that the carbon-based fertilizer is beneficial to the growth and development of the underground parts of maize.

The plant roots and aboveground parts are interdependent and mutually reinforcing [35]. On the one hand, the root system grows in the soil and is the main organ for water and nutrient absorption. It not only provides the necessary water and mineral nutrients for the growth of the aboveground part but also synthesizes the necessary nutrients and regulating substances, such as hormones, organic acids and amino acids, to supply and regulate the growth and development of the aboveground part. Its morphology and physiological characteristics are closely related to the growth and development, yield and quality of the aboveground part [36]. On the other hand, the life activities of the root system must depend on the aboveground photosynthetic products, such as carbohydrates, proteins, vitamins and some growth substances, which largely determine the growth and development of the root system [37]. From the physiological point of view, root growth is more dependent on assimilates than the stem and leaf, while the stem and leaf are more affected by water and mineral nutrition. With the growth and development of the plant, the material accumulation, population change, plant aging and yield formation of the root and aboveground parts change regularly [38]. Predecessors have done a lot of research on the relationship between the root system and crop aboveground growth [39–41]. The growth and distribution of the roots in the soil are directly related to the growth and development of the aboveground parts and the utilization efficiency of water and the nutrients of plants [42]. Therefore, it is necessary to establish a strong root system before silking to ensure root vitality, promote the production of new roots and extend to the depth of the soil layer and delay root aging [43]. Previous studies have found that root morphology is closely related to many agronomic traits, such as leaf shape, stress resistance and plant height. During the whole growth period, the root biomass and root absorption area, aboveground biomass and green leaf absorption area are highly correlated [44,45]. The root biomass of maize with different plant types was significantly positively correlated with the aboveground biomass and leaf area [46]. The study found that inhibiting root growth or cutting off part of the roots significantly reduced the photosynthetic rate of the leaves, indicating that there is a close relationship between root and leaf photosynthesis [47].

The root absorbs water and inorganic ions. In addition to meeting the growth and development of the root itself, it also supplies the aboveground part through the xylem to ensure the normal growth of the aboveground part. The ability of roots to absorb water and transport nutrients can be reflected by the sap flow and sap composition, which is also an important indicator of root activity and can judge the transport of elements in the plant and the relationship with the other parts. The bleeding intensity is not only closely related to environmental factors, such as the water and fertilizer, ventilation, temperature, etc. [48], but also varies with the distribution of the plant roots, the degree of development, the growth of the stems and leaves and other growth conditions, and also presents a phased change trend due to the different water requirements of plants at different growth stages [49]. According to some studies, the bleeding flow of maize is the largest at the jointing stage [50]. Other studies have also shown that maize bleeding reached a peak at flowering [51]. Nitrogen fertilizer has an obvious effect on bleeding and bleeding components [52], and the bleeding intensity of applying potassium fertilizer significantly increased [53]. In this study, the bleeding rate was the highest on 8 July, indicating that the root absorption capacity and the ability to transport water to the upper part were the strongest at this stage, and the root activity was vigorous. Different results from previous studies may be related to maize varieties, soil environment, management measures and other factors. On 8 July, the bleeding rate of fertilization treatment was significantly higher than that of non-fertilization treatment, indicating that fertilization had a significant

effect on the bleeding rate. It may be because the treatment of the carbon-based fertilizer improved the physical and chemical properties of the soil, optimized the distribution of the roots, built developed roots, increased the effective absorption area and absorption activity of the roots and thus increased the bleeding rate.

Plants transport water, amino acid, soluble sugar and other nutrients from the roots to the ground through the xylem, which is the main form of root-cap communication and directly affects the growth and metabolism of the aboveground [33]. The nutrient elements absorbed by the root system and the synthetic hormones, amino acids and other substances are mainly transported with water. Therefore, the transport of plant nutrients is largely affected by the bleeding flow and bleeding rate. The increase in the bleeding flow can dilute the nutrient elements to a certain extent, leading to the reduction of some components. On the other hand, a larger bleeding rate can accelerate the nutrient transport rate and play the role of adjusting fertilizer with water [54,55]. The nutrient ions in the bleeding fluid are the result of root absorption and transformation, and the supply level of nutrient elements has a great impact on the bleeding components [56,57]. Under the condition of phosphorus deficiency, the transport rate of amino acid, soluble sugar and inorganic phosphorus in the maize bleeding fluid decreased significantly [58]. Water and nitrogen supply promoted root growth and increased the contents of nitrate, ammonium nitrogen, free amino acid, phosphorus and potassium in the plant sap [58,59]. In this study, the carbon-based fertilizer treatment increased the content and transport rate of the amino acids, indicating that the carbon-based fertilizer can effectively improve the ability of the roots to synthesize and transport amino acids. The effect of the carbon-based fertilizer on the inorganic phosphorus content and transport rate is not significant, which may be due to the relatively high content of basic phosphorus in the soil, which can meet the needs of the normal growth of maize. The continued addition of phosphorus cannot significantly increase the inorganic phosphorus content in the bleeding fluid. The carbon-based fertilizer increased the content and transport rate of ammonium nitrogen in the sap on 8 July, indicating that the carbon-based fertilizer can improve the ability of the roots to absorb and transport ammonium nitrogen. The content and transport rate of ammonium nitrogen gradually decreased with the advancement of the growth process, which may be due to the high content of ammonium nitrogen in the soil in the early stage, and then gradually decreased, or because the absorption capacity of ammonium nitrogen by the maize in the late stage was weakened due to the absorption of nitrate nitrogen. The soluble sugar content was relatively low in the early stage and increased rapidly on 16 September, indicating that the root system transferred organic carbon to the upper part of the ground at the later stage of maize growth, and the fertilization treatment was significantly higher than without fertilization. The carbon-based fertilizer treatment showed a trend of rising and falling with the increase of the application amount, which may be due to the accumulation of more carbohydrates in the root system of the fertilization treatment, and the matter was transferred to the upper part in the form of soluble sugar at the later stage of growth.

The effect of the root on the yield is mainly realized by the influence of the root's physiological absorption activity and morphological characteristics on the yield components [60]. Previous studies on rice have shown that the upper root system of rice has large root quantity, vigorous vitality and strong absorption capacity in the late growth stage due to its relatively young physiological age, which not only has a significant effect on increasing the number of grains per ear but also has a significant effect on extending the leaf life, improving the plant type of crops, improving the photosynthetic productivity in the late production stage and increasing the grain weight [61]. The number of short roots and the length of the long roots have a very important impact on crop yield, while the runoff has the smallest impact on the yield [62]. Therefore, the predecessors put forward the ideal root system of high-yield maize, which is that the root system is deep and the lateral root is vigorous. Promoting the construction of deep roots and reducing the distribution of surface roots can improve nutrient absorption and utilization and achieve a high yield [63,64]. The growth of the maize roots is characterized by an increase in weight and

length. The root weight is more important than the root number for maintaining above-ground production and function [65]. The relationship between the roots and aboveground parts is also reflected in mutual constraints. Although roots can absorb nutrients, they also need to consume photosynthetic products transported by the aboveground parts for root construction. Strong roots are the basis for forming a high yield, but it is not that the larger the root quantity and the more vigorous the root activity are, the more beneficial it is for achieving a high yield. The key lies in the coordination between the roots and aboveground parts [42]. In some special environments, root growth is often too fast, resulting in redundancy, affecting the distribution of the plant material and resulting in reduced production [66]. In the statistics of yield components, it was found that the carbon-based fertilizer had a small impact on the number of ears and grains per ear of maize, and the main factor for improving the yield of the carbon-based fertilizer was the increase of grain weight. Previous studies have found that a carbon-based fertilizer increases the yield of Xianyu 335 and has a variety of specificity [67]. A carbon-based fertilizer can effectively promote the growth and development of maize, shorten the growth cycle, improve the yield characteristics of maize and achieve the purpose of increasing the yield [68]. The results of this study showed that the yield of Xianyu 335 and Jingke 968 reached the maximum at 4.5 t treatment, which was significantly higher than that of chemical fertilizer. The treatment of carbon-based fertilizer can significantly improve the yield of maize, mainly because the application of a carbon-based fertilizer leads to fertilizer-soil-crop cooperation, which realizes the construction of a high-yield root system, effectively improves the absorption capacity of the root system, provides sufficient nutrients for the upper part of the ground, increases the photosynthetic capacity and dry matter accumulation, forms an efficient canopy population, effectively improves the utilization rate of resources and provides a basis for material accumulation and transportation.

5. Conclusions

The carbon-based fertilizer increased the root length, root volume, root area and root tip number of maize roots, and the root length, root volume, root area and root tip number of 4.5 t treatment performed better in each period. The carbon-based fertilizer treatment delayed root senescence and increased root absorption activity. The carbon-based fertilizer treatment had more upper roots and the proportion of root depth and deep roots increased. The carbon-based fertilizer significantly increased the bleeding rate on 8 July and Xianyu 335 and Jingke 968 reached the maximum value at 4.5 t and 3.75 t, respectively. The carbon-based fertilizer increased the ammonium nitrogen content and transport rate and the two varieties were significantly higher than the chemical fertilizer treatment at 4.5 t and 3.75 t, respectively. The effect of the carbon-based fertilizer on the soluble sugar was significant. On 4 September, the soluble sugar content of the two varieties reached the maximum at 3.75 t. The transport rate of the soluble sugar reached the maximum at 4.5 t, which was significantly higher than that of the chemical fertilizer treatment. The carbon-based fertilizer significantly increased the number of grains per row and the yield of maize, and Xianyu 335 and Jingke 968 reached the maximum value at the 4.5 t/hm² treatment.

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