Article

Carbon Footprint of the Production Process of Tropical Banana Plantation Based on the Life Cycle Approach: A Case Study of Chengmai County, Hainan Province, China

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Carbon Footprint of the Production Process of Tropical Banana Plantation Based on the Life Cycle Approach: A Case Study of Chengmai County, Hainan Province, China

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Abstract: Banana plantation is an important type of agro-ecosystem in the tropics, and it is important to carry out a quantitative assessment of the carbon footprint of the banana growing process for the development of low-carbon agriculture to cope with global warming. The carbon footprint of two banana cultivation processes was assessed using the life cycle assessment method through field trials and farmer surveys in Chengmai County, Hainan Province, China. The results showed that: (1) N_2O emissions caused by the application of nitrogen fertilizers and compound nitrogen fertilizers were the largest source of carbon emissions from banana plantation farmland, and the production and transportation of common compound fertilizer were the second largest source of carbon emissions. Banana fruits and plants were the main contributors to carbon fixation in banana plantation ecosystems, with about 24.72 t CO_2 eq hm^{-2} for Musa paradisiaca AA, and 34.66 t CO_2 eq hm^{-2} for M. AAA Cavendish var. Brazil. (2) The annual carbon emissions of Musa paradisiaca AA and M. AAA Cavendish var. Brazil farmland systems were 35.40 t CO_2 eq·hm^{-2} and 43.83 t CO_2 eq·hm^{-2}, respectively, and the annual carbon fixation was 38.23 CO_2 eq·hm^{-2} and 48.17 CO_2 eq·hm^{-2}, respectively. The banana plantations had a negative carbon footprint per unit area, showing a net carbon sink function. (3) Banana is a plant with high carbon emission and strong carbon fixation capacity. Scientific management in the field can achieve the decrease of agricultural inputs, high quality and abundant agricultural products, and the reduction of carbon footprint of farmland.

Keywords: life cycle assessment; carbon footprint; carbon emission; carbon fixation; banana; Hainan

1. Introduction

Global warming is one of the major environmental problems facing mankind, and governments are taking a cumulative number of countermeasures to slow it down. China's proposed targets of "carbon peaking" by 2030 and "carbon neutrality" by 2060 will promote the optimization, upgrading of the industrial structure and the adjustment of the energy structure, and lead the overall green transformation of the economy and society [1]. The IPCC Fifth Assessment Report points out that greenhouse gas emissions from agricultural sources account for 24% of the total global greenhouse gas emissions [2]. Agriculture is different from other industries in that, on the one hand, farmland ecosystems emit large quantities of greenhouse gases such as CO_2, N_2O, and CH_4, and at the same time, farmland which has the dual characteristics of a carbon source and a carbon sink fixes CO_2 through photosynthesis. Carrying out research on agricultural greenhouse gas emission reduction and carbon fixation and sink enhancement has become an important tool for promoting green development in agriculture.

Carbon footprint, as a quantitative greenhouse gas emissions research method, has received attention and recognition from many scholars and has been cited in the field of agriculture [3]. The use of life cycle assessment (LCA) to assess the greenhouse gas emissions of the agricultural production process, and the production and use of agricultural materials is conducive to the identification of the carbon footprint of agricultural activities as well as the optimization of emission reduction measures

[4]. In recent years, many scholars have conducted research on carbon footprint in agriculture and achieved preliminary results. Zhu Q et al. studied the carbon footprint of alpine organic rice and compared the carbon emissions of the carbon footprint of a variety of rice products at various stages, concluding that the planting process is the production stage with the highest carbon emissions [5]; Cao L et al. carried out a study on the rice production process, and concluded that nitrogen fertilizer application is considered to be the highest carbon-emitting stage in the production process[6]. Chinese agricultural carbon footprint studies mainly focus on grain crops, such as Li C et al. [7], Mao G [8], and Long J [9] studied the carbon footprints of grain crops such as wheat, maize, and millet, while the carbon footprint studies of cash crops are relatively weak. Due to the differences in natural conditions, crop species, and field management, the carbon footprint research results of grain crops cannot provide an accurate scientific basis for the green development of cash crops. At the same time, whether farmland ecosystems are net carbon sources or sinks remains controversial [10]. Banana plantations are an important farmland ecosystem type in Hainan Province [11], and conducting research on the carbon footprint of banana plantation ecosystems is of great significance in promoting the green development of tropical agriculture. In this study, Chengmai County was selected as the target area for the study. Through field research and one-year field location monitoring, the carbon footprint theory of agriculture and life cycle assessment were used to account for the carbon emissions of each link in the banana production process, to calculate the carbon sequestered by banana plants and farmland soils, to assess the carbon footprint of the tropical banana plantations, and the results of the study will provide theoretical basis and practical guidance for the optimization of the agricultural structure adjustment, the reduction of carbon emissions and the increase of carbon sinks in agriculture as well as the green development of agriculture.

2. Materials and Methods

2.1. Study Area

The study area is located in the northern part of Chengmai County, dominated by the tableland plains, with a tropical maritime monsoon climate, a multi-year average temperature of 23.2°C, an average annual precipitation of about 1700 mm, and obvious seasonal changes in precipitation, with the rainy season occurring from May to October, and the dry season occurring from November to April of the following year. The soil type is laterite with an average soil organic matter of 2.53% in the 0-30 cm layer. The soil texture is loamy-clay loam, deep and fertile, suitable for tropical crops such as bananas and coffee and other tropical crops.

Chengmai County is one of the main production areas of bananas in Hainan Province. The average annual banana harvesting area in the county in 2018-2020 is 9.17×10^3 hm^2, accounting for 20.95% of the banana planting area in Hainan Province, and the average annual production is 3.08×10^5 t, accounting for 24.70% of the province's banana production. The main species of bananas planted are Musa paradisiaca AA and M. AAA Cavendish var. Brazil. The newly planted bananas are transplanted from the group seedling, the second and third planted bananas are from retained buds, and bananas are harvested three times in two years.

2.2. Research Methods

2.2.1. Carbon Emission Terms and Measurement Methods for Banana Plantations

Greenhouse gas emissions in banana plantation ecosystems mainly include CO_2 emissions from the manufacturing process of agricultural materials, N_2O emissions from the farmland due to fertilizer application, and CO_2 emissions due to soil respiration. Carbon emissions from the manufacturing process of agricultural materials mainly include carbon emissions from fertilizer and pesticide application, as well as energy consumption of agricultural machinery and agricultural irrigation. The formula is as follows [12].

$$E_{CO_2} = \sum E_i = \sum Q_i \times \alpha_i \times 44/12 \qquad (1)$$

Where E_{CO_2} is the CO_2 equivalent emission，the unit is t CO_2eq, E_i is the carbon emission of each agricultural material in the agricultural production process, Q_i is the quantity of each agricultural material (including fertilizer, pesticide, agricultural machinery, agricultural irrigation and ploughing), and α_i is the carbon emission coefficient of each agricultural material, with reference to the relevant literature [13–18] （Table 1）. 44/12 is the conversion factor of carbon equivalent (CE) to CO_2 equivalent.

Table 1. Carbon emission coefficient of main carbon emission sources.

Carbon Source	Emission Factor	Data Source
Urea	2.041 kg CE/kg	[13]
Calcium Superphosphate	0.195 kg CE /kg	[13]
Potassium Chloride	0.168 kg CE /kg	[13]
Potassium Sulfate	0.409 kg CE /kg	[13]
Ternary Compound Fertilizer	0.939 kg CE /kg	[13]
High Potassium Low Phosphorus Compound Fertilizer	0.836 kg CE /kg	[13]
Bactericide	12.78 kg CE /kg	[14]
Insecticide	10.00 kg CE /kg	[14]
Herbicide	7.91 kg CE /kg	[14]
Preservative	12.78 kg CE /kg	[14]
Agricultural Electricity	0.917 kg CO_2 eq /kW·h	[15]
Diesel Fuel	3.933 kg CO_2 eq /kg	[16]
Agricultural Film	5.18 kg CO_2 eq /kg	[17]
Paper Bags	1.50 kg CO_2 eq /kg	[18]

N_2O emissions from banana plantations mainly come from nitrogen in fertilizers applied in field management, including: (1) direct emissions of N_2O from nitrogen in the process of nitrification and denitrification; (2) indirect emissions of N_2O due to the deposition of nitrogen-containing reactive substances after volatilization; (3) indirect emissions of N_2O due to nitrogen leaching and runoff. The formulae are as follows [19]:

$$N_2O_{direct} = N_{total} \times EF_{direct} \qquad (2)$$

$$N_2O_{\text{deposition}} = N_{total} \times EF_{\text{deposition}} \times \alpha_{\text{deposition}} \qquad (3)$$

$$N_2O_{\text{leaching}} = N_{total} \times EF_{\text{leaching}} \times \alpha_{\text{leaching}} \qquad (4)$$

$$E_{N_2O} = (N_2O_{direct} + N_2O_{\text{deposition}} + N_2O_{\text{leaching}}) \times 298 \qquad (5)$$

N_2O_{direct}, $N_2O_{deposition}$ and $N_2O_{leaching}$ represent N_2O direct emissions, N_2O indirect emissions due to deposition and N_2O indirect emissions due to leaching runoff, respectively; and N_{total} represents the total input of nitrogen. EF_{direct}, $EF_{deposition}$, and $EF_{leaching}$ respectively represent N_2O direct emission coefficient, N_2O indirect emission coefficient due to deposition, and N_2O indirect emission coefficient due to leaching runoff. The coefficients are 1%, 1% and 1.1%, respectively; $\alpha_{deposition}$ is the rate of volatilization of nitrogen from agricultural land, with a value of 11%; and $\alpha_{leaching}$ is the rate of nitrogen leaching and runoff from banana plantations, with a value of 24% [19]. E_{N_2O} is the CO_2 equivalent converted from total N_2O emissions, unit is t CO_2eq. 298 is a conversion coefficient based on the warming potential of N_2O converted to CO_2 equivalent [14].

CO_2 absorbed from the air by plants through photosynthesis, part of which is returned to the atmosphere through root respiration and leaf respiration, and the other part is stored in the plant as organic matter, i.e., net primary production (NPP) [10]. To avoid double counting of CO_2 released by

root respiration, banana plant roots should be physically isolated when monitoring soil respiration fluxes in agricultural fields. The formula is as follows.

$$C_{SR} = R_{soil} \times T \times A \tag{6}$$

C_{SR} represents CO_2 emissions due to soil respiration in t CO_2eq, T represents time in a, A represents the area of banana plantation in hm^2, and R_{soil} is the soil respiration flux from agricultural land in $\mu mol \cdot m^{-2} \cdot s^{-1}$.

2.2.2. Carbon Fixation Term and Measurement Methods for Banana Plantations

The carbon pool of banana plantations mainly consists of two parts: banana plants and banana plantation soils. The carbon fixation of banana plants is calculated as follows.

$$C_{plant} = \sum_i C_i = \sum_i G_i t_i (1 - w_i) \tag{7}$$

Where C_{plant} denotes the carbon fixation of a single banana plant in g C; i denotes an organ of the banana; C_i denotes the carbon fixation of the organ in g C; G_i denotes the weight of the organ in g; t_i denotes the carbon content of the organ and w_i denotes the water content of the organ of the banana.

Soil carbon fixation is calculated as follows [20].

$$C_{soil} = \gamma \cdot d \cdot C_{SOC} \cdot S \tag{8}$$

$$\Delta C_{soil} = \frac{(C_{soil\,t} - C_{soil\,0})}{t - o} \tag{9}$$

where C_{soil} denotes soil carbon content in g C; γ denotes soil bulk density in $g \cdot cm^{-3}$; d denotes soil depth in cm; C_{SOC} denotes soil organic carbon content in %; S denotes area in cm^2; ΔC_{soil} denotes soil carbon increase in g C; $C_{soil\,t}$ denotes soil carbon content in period t, and $C_{soil\,0}$ denotes soil carbon content in the base period, and t-o denotes the length of time in years.

2.2.3. Experiments and Data Collection

(1) Data on carbon emissions from agricultural materials used in agricultural production were derived from the 2018-2020 household survey, in which 30 households each of Musa paradisiaca AA growers and M. AAA Cavendish var. Brazil were selected for the study, with continuous tracking and investigation of the production information of the growers over the two-year production process. The research farmers all had more than 2 years of experience in banana planting and had more than 3 hm^2 of cultivated area, and the total area of the research banana plantation was about 450 hm^2. The questionnaire mainly consisted of banana varieties, planting area and density, yield, amount of fertilizer, pesticide and bagging, electricity consumption for irrigation, and diesel consumption of farming machinery, and other production information.

(2) Soil respiration carbon emissions were continuously monitored from October 2019 through December 2020 for the second and third banana growing cycles. Two banana plantations close to the average fertilizer application were selected as sample plots for soil CO_2 flux measurements, and soil rings were installed at three measurement points in each sample plot, and a 60 cm deep trench was dug around the soil rings, with a double-thick plastic film placed inside the trench to isolate the surrounding plant roots and to monitor soil respiration without root respiration of the banana plants. Using the Li-8100A soil respiration monitoring system, the measurement points were monitored once a month for a continuous period of 48h, with 1h intervals between measurements, and each measurement was repeated three times.

(3) Measuring banana biomass. During the banana ripening and harvesting period, 50 representative plants were selected from each of the eight near-average fertilizer-applied plantations of M. AAA Cavendish var. Brazil and Musa paradisiaca AA. Biological parameters such as plant height, diameter at breast height and leaf length were measured and the mean values were calculated.

Each of the eight households selected one banana plant close to the average value of each parameter as a standard plant, the whole plant was cut down and above-ground organs such as pseudo stems, leaves, and fruits were weighed separately, and the underground parts were excavated, washed and weighed, and samples were taken back to the laboratory for the determination of its water content and carbon content, respectively. Water content was determined by drying method, and the samples were dried to constant weight at a constant temperature of 60°C to calculate water content of each organ. Banana plant samples were dried and ground into powder, passed through a 0.25 mm sieve, and the carbon content of the samples was determined by potassium dichromate-sulfuric acid oxidation method to derive the amount of carbon sequestered in the dry matter of a single banana plant, and the amount of carbon sequestered by banana plants in the banana plantations was calculated based on the density of banana plantations.

(4) Measuring soil carbon fixation. Soil organic carbon pools were accounted for on a two-year cycle, with September 2018 before banana planting as the base period and October 2020 when plantains were harvested as the end period.

Five sampling points were selected between plants and rows of each banana plantation sample plot, and soil samples were taken at 0-10 cm, 10-20 cm, and 20-30 cm depths for each sampling point to determine the soil organic carbon content by using the potassium dichromate oxidation-spectrophotometry method, and the soil bulk weight was determined by using the ring knife method at each sampling point. Accordingly, the soil carbon contents of the base period and the final period were calculated, and the difference between the two soil carbon contents was divided by 2, which was the average annual soil carbon fixation.

3. Results and Analysis

3.1. Carbon Emission of Banana Plantation Ecosystems

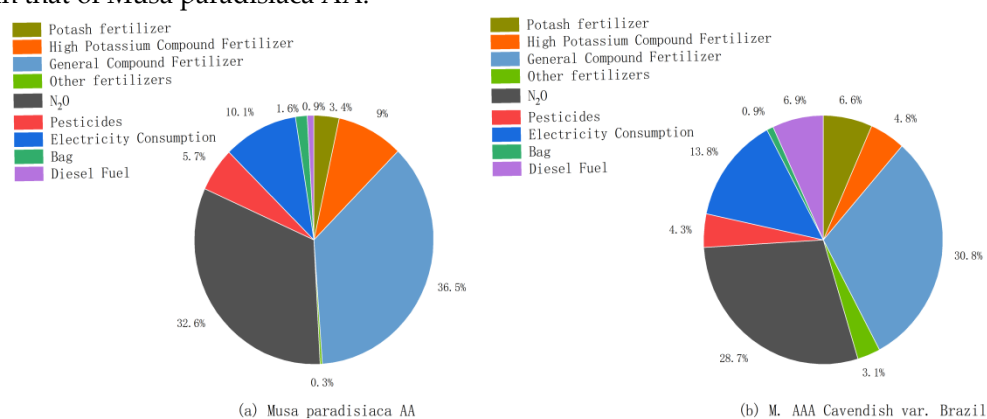#### 3.1.1. Carbon Emission of Agricultural Material

As shown in Figure 1, there were large differences in carbon emissions from agricultural materials per unit of production and per unit of area for different varieties of bananas. The carbon emission per unit of production of Musa paradisiaca AA was 464.05 g CO_2 eq·kg^{-1}, and the carbon emission per unit of planted area was 15.03 t CO_2 eq·hm^{-2}. The carbon emission of M. AAA Cavendish var. Brazil was 395.88 g CO_2 eq·kg^{-1} and 23.46 t CO_2 e /hm^{-2}, respectively.
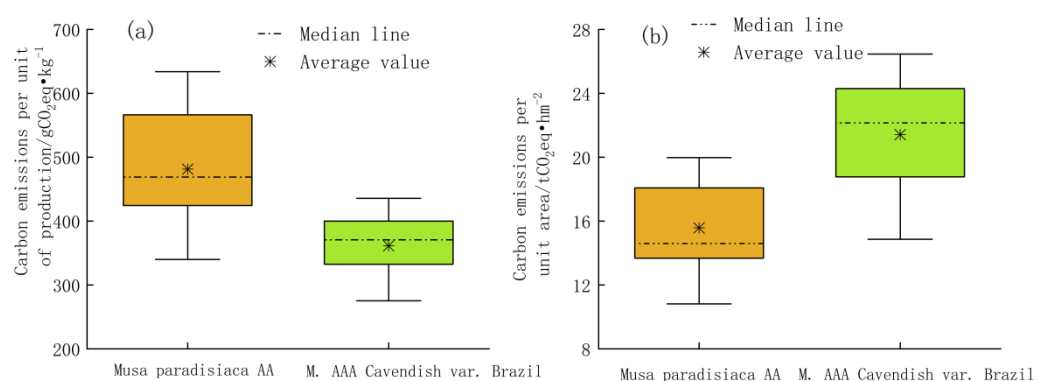
Figure 1. (a) Carbon emissions from agricultural inputs per unit of production; (b) per unit area of different varieties of bananas.

As shown in Figure 2, differences in the ranking of carbon emission sources from agricultural materials and the contribution of carbon emission components were found between the Musa paradisiaca AA and M. AAA Cavendish var. Brazil. The largest source of carbon emissions for both Musa paradisiaca AA and M. AAA Cavendish var. Brazil was the production of compound fertilizers, which accounted for 36.50% and 30.80% of the carbon emissions from total agricultural materials,

respectively. The second largest source of emissions was both N_2O emissions due to the application of nitrogenous fertilizers and nitrogenous composite fertilizers, with Musa paradisiaca AA and M. AAA Cavendish var. Brazilian contributing 32.60% and 28.70% of the carbon emissions, respectively. The contribution of carbon emissions from agricultural materials of potash fertilizers (including potassium chloride, potassium sulphate and high-potassium compound fertilizers) for Musa paradisiaca AA was 12.40%, which was slightly higher than that of M. AAA Cavendish var. Brazilian at 11.40%. Carbon emissions from agricultural energy consumption as a percentage of carbon emissions from total agricultural materials varied greatly between Musa paradisiaca AA, which accounted for 11.00%, and M. AAA Cavendish var. Brazilian, which accounted for 20.70%, respectively. The difference was due to the fact that all the plantations in the study area were irrigated with water and fertilizer, and deep wells were mostly pumped for irrigation during the dry season; the former required relatively less water, whereas the latter had a high frequency of fertilizer application and consumed a large amount of water. Secondly, the latter had a high yield per plant, and during the fruiting period it is necessary to use a diesel engine to punch holes to fix brackets to support the stalks, which increases energy consumption. Third, pesticide consumption account for a relatively small percentage of carbon emissions for both Musa paradisiaca AA and M. AAA Cavendish var. Brazilian, 5.70% for the former and 4.33% for the latter, because of the dense foliage of the latter, growers mostly use diesel engines to spray pesticides, while the former growers usually spray pesticides manually, which increases the energy consumption of M. AAA Cavendish var. Brazilian. The combination of the three factors resulted in the contribution of carbon emissions from agricultural energy consumption of M. AAA Cavendish var. Brazil being nearly one times higher than that of Musa paradisiaca AA.

Figure 2. Carbon emission composition of agricultural inputs of different banana varieties (a for Musa paradisiaca AA, b for M. AAA Cavendish var. Brazil).

3.1.2. Carbon Emission of Soil Respiration

As shown in Figure 3, daily and monthly changes in soil respiration in sample banana plantations showed a single-peaked curve. Soil respiration in the banana plantation continued to rise after 6:00 a.m. and reaching a peak of about 1.68 $\mu mol \cdot m^{-2} \cdot s^{-1}$ at 15:00 a.m. Soil respiration continued to decline after the peak, and fell to a lower level of about 1.37 $\mu mol \cdot m^{-2} \cdot s^{-1}$ around 22:00 at night and continued until around sunrise. Soil respiration was higher from April to August, with the maximum value occurring in June at about 1.76 $\mu mol \cdot m^{-2} \cdot s^{-1}$ and soil respiration was lower from September to March of the following year, with the minimum value occurring in February at about 1.17 $\mu mol \cdot m^{-2} \cdot s^{-1}$. The average value of soil respiration in banana plantations for the whole year was 1.47 $\mu mol \cdot m^{-2} \cdot s^{-1}$, and the CO_2 emission from soil respiration in banana plantations in the study area was about 20.37 $t \cdot hm^{-2} \cdot a^{-1}$.
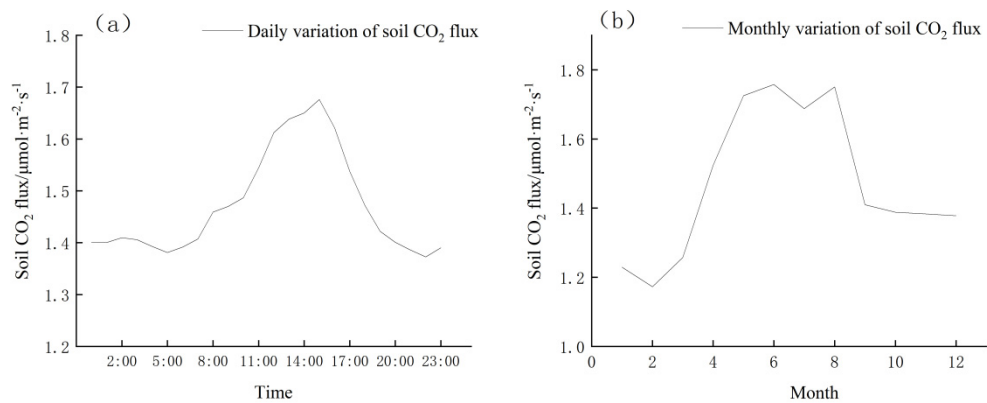
Figure 3. (a) Daily variation of soil heterotrophic respiratory fluxes in banana plantations; (b) annual variation of soil heterotrophic respiratory fluxes in banana plantations.

3.2. Carbon Fixation of Banana Plantation Ecosystem

3.2.1. Plant Carbon Fixation of Banana Plantations

Table 2 shown mean water content and carbon content varied considerably between the various organs of Musa paradisiaca AA and M. AAA Cavendish var. Brazil, while the differences between Musa paradisiaca AA and M. AAA Cavendish var. Brazil were small for the same organ. The water content of each organ of banana of the two varieties in descending order was pseudo stem, root system, leaves, and fruit. The carbon content in descending order was leaves, fruit, pseudo stem, and root system. The two varieties of bananas did not differ much in water content and carbon content of each organ, and Musa paradisiaca AA had slightly lower water content and slightly higher carbon content than M. AAA Cavendish var. Brazil.

**Table 2.** water content and carbon content of different banana varieties.

Projects	Species	Pseudostem	Leaf	Fruit	Root System	Average Whole Plant
Moisture Content	Musa paradisiaca AA	94.6%	86.0%	77.9%	89.2%	88.96%
	M. AAA Cavendish var. Brazil	94.9%	88.1%	81.4%	89.9%	89.64%
Carbon Content	Musa paradisiaca AA	38.1%	41.0%	40.9%	36.4%	39.23%
	M. AAA Cavendish var. Brazil	36.4%	40.6%	40.4%	36.2%	38.66%

Carbon fixation of Musa paradisiaca AA per plant and per unit area was smaller than that of M. AAA Cavendish var. Brazil. The former had a smaller individual biomass than the latter, and carbon fixation per plant was 36.77% smaller than the latter. The former fixed an average of 2.31 kg CE per plant, which was 8.46 kg CO_2 eq, while the latter fixed an average of 3.65 kg CE per plant, which was 13.38 kg CO_2 eq. The carbon fixation per hectare of the former was about 24.72 t CO_2 eq and that of latter was about 34.66 t CO_2 eq, that is, carbon fixation per unit area of the former was 28.68% smaller than that of the latter. As shown in Figure 4, the ordering of the contribution rates of carbon sink in the organs of Musa paradisiaca AA and M. AAA Cavendish var. Brazil was consistent, and was fruit, root system, pseudo stem, and leaf in descending order. Fruits were the most important component of carbon sinks for Musa paradisiaca AA and M. AAA Cavendish var. Brazil, accounting for 38.65% and 47.53%, respectively, and leaves accounted for the smallest portion of carbon sinks, 18.32% and

12.88%, respectively. Musa paradisiaca AA and M. AAA Cavendish var. Brazil had intermediate percentages of pseudo stem and root carbon sinks and small differences between species.
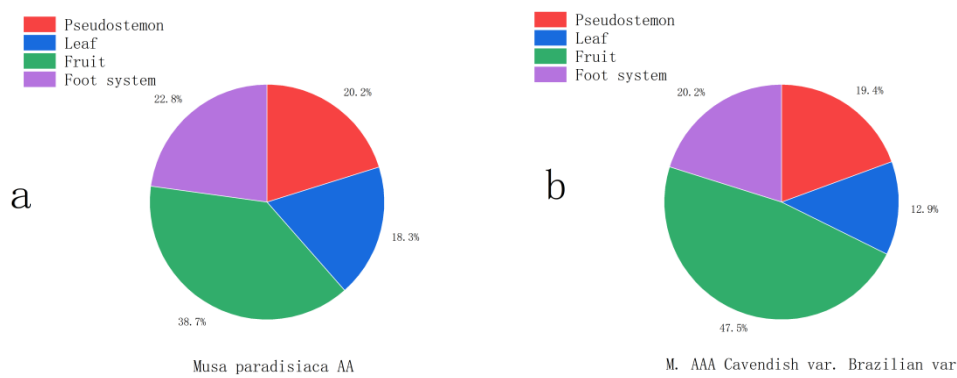
Figure 4. Carbon sink composition of banana plants of different varieties (a for Musa paradisiaca AA, b for M. AAA Cavendish var. Brazilian var.).

3.2.2. Soil Carbon Fixation of Banana Plantations

Table 3 shown that Soil organic carbon content in the 0-30 cm soil layer of banana plantations increased from 2018 to 2020, and the increase between rows was significantly higher than that between plants, and the annual average soil carbon change was the soil carbon fixation in banana plantations. There were temporal and spatial differences in soil carbon content between rows and plants in banana plantations. The soil organic carbon content between plants and rows in the 0-30 cm soil layer decreased with increasing depth, and the organic carbon content of all soil layers between rows was higher than that between plants. The soil organic carbon content of the soil layer between plants in the depth of 0-30 cm increased by an average of 13.47% in the period from 2018 to 2020, whereas the average increase between rows amounted to 24.48%. The soil bulk density between rows was slightly higher than that between plants in banana plantations, and the change in soil bulk density was small during the study period. The soil carbon content of banana plantations in the sample site was 45.62 t C·hm^{-2} in the base period of 2018 and 52.99 t C·hm^{-2} in the end period of 2020, with an average annual increase in soil organic carbon of 3.68 t C·hm^{-2}, or 13.51 t CO_2 eq·hm^{-2}.

Table 3. Changes of soil organic carbon content in different depths.

Depth (cm)	September 2018		October 2020	
	Interplant	Between Rows	Interplant	Between Rows
0-10	1.43%	1.47%	1.48%	1.68%
10-20	1.27%	1.22%	1.40%	1.62%
20-30	1.05%	1.10%	1.33%	1.39%
Soil Capacity /g·cm^{-3}	1.18	1.24	1.18	1.20

3.3. Carbon Footprint of Banana Plantation Ecosystems

The carbon sources of banana plantation ecosystems mainly included agricultural material use and soil respiration. The carbon emissions of Musa paradisiaca AA were 35.40 t CO_2 eq·hm^{-2}, and the carbon emissions caused by agricultural material and soil respiration accounted for 42.46% and 57.54%, respectively. The carbon emissions from M. AAA Cavendish var. Brazil were 43.84 t CO_2 eq·hm^{-2}, accordingly, agricultural material and soil respiration accounted for 53.53% and 46.47%, respectively. The carbon sinks of banana plantation ecosystems mainly included plant and soil carbon fixation. Musa paradisiaca AA orchard plantation fixed 38.23 t CO_2 eq·hm^{-2}, with 64.66% plant carbon fixation and 35.34% soil carbon fixation. M. AAA Cavendish var. Brazil plantation fixed 48.17 t CO_2 eq·hm^{-2}, with 71.95% plant carbon fixation and 28.05% soil carbon fixation.

4. Discussion

4.1. Comparison of Carbon Emissions from Agricultural materials of Banana and Other Crops

The carbon emissions from agricultural materials per unit of production of Musa paradisiaca AA and M. AAA Cavendish. var. Brazil were 464.05 g CO_2 eq·kg^{-1} and 395.88 g CO_2 eq·kg^{-1} and the annual carbon emissions per unit of area were 15.03 t CO_2 eq·hm^{-2}·a^{-1} and 23.46 t CO_2 eq·hm^{-2}·a^{-1}. Table 4 shown that Musa paradisiaca AA and M. AAA Cavendish var. Brazil had higher carbon emissions per unit area than wheat, maize, cotton and other crops, while carbon emissions per unit of production were lower. Carbon emissions per unit area in banana plantations were lower than that of pomelo plantations, while carbon emissions per unit of production were slightly higher [21].

Table 4. Comparison of carbon emissions from agricultural inputs of different crops.

Species	Study Area	Carbon emissions per unit area t CO_2eq·hm^{-2}	Carbon emissions per unit of production kg CO_2eq·kg^{-1}	Source
cotton	Hebei	3.99	1.10	[22]
Wheat-corn rotation	Gaomi, Shandong	8.96	0.53	[23]
maize	Shanghai	11.81	1.23	[6]
millet	Miyun Beijing	7.71	5.13	[8]
pomelo	Guanxi, Fujian	27.80	0.44	[21]

The composition of carbon emissions from the banana production process was similar to that of other crops, with fertilizer (especially nitrogen fertilizer) application being the main source of CO_2 and N_2O emissions from farmland, contributing 81.73% of the carbon emissions per unit of production of Musa paradisiaca AA, and 74.00% of M. AAA Cavendish var. Brazil. It was higher than that of winter wheat-summer maize rotation farmland, where CO_2 and N_2O emissions from fertilizer application accounted for 68.56% of the total carbon emissions from all agricultural materials [23]. High temperatures generally produce higher direct emissions of CO_2 and N_2O from fertilizer application in tropical regions than those in subtropical and temperate regions [19] [20] [24], which is the reason for the high carbon emission contribution of banana plantations in this study.

4.2. Factors Affecting Carbon Fixation of Banana Plantation Ecosystems

Banana fruits and plants were the main contributors to carbon fixation in banana plantation ecosystems, and carbon fixation in banana plantations was influenced by factors such as biomass, water content, carbon content and planting density. Despite the fact that the water content of banana fruits reached 80%, the water content of plants was as high as 90%, and the carbon content of dry matter was less than 40%, the carbon fixation per unit area of banana was higher because of the large biomass of banana single fruits and plants, and because bananas were planted with 2,700 to 3,000 plants per hectare at a higher planting density.

Conservation tillage could reduce the loss of soil organic carbon and increases soil carbon fixation [25,26]. Field management of banana plantations in the study area was mostly 3 crops in 2 years, with the 2nd and 3rd crops being left to bud, and no-tillage and less-tillage to reduce soil disturbance and decrease the rate of mineralization of soil organic carbon, which promoted the increase of soil organic carbon, and the soil organic matter showed an increasing trend in the banana plantations in the study area. Previous long-term positioning experiments on winter wheat land, as well as other types of farmlands, also found that the rate of carbon sequestration was higher in no-tillage than in tilled land, and that the soil organic carbon content of no-tillage was significantly higher than that of conventional tillage patterns [27,28].

4.3. Scientific management and development of agricultural land

The problem of over-fertilization is common in banana plantations, and studies have shown that scientific fertilization can reduce the amount of chemical fertilizer by 1/3 without decreasing banana yields [29,30]. Fertilizer application was the main source of carbon emissions from farmland, and fertilizer application accounted for 80-90% of the carbon emissions from agricultural materials in banana plantations, which showed that there was a greater potential for controlling the amount of fertilizer application in the green development of agriculture. The degree of modernization of field management also affected carbon emissions from agricultural materials per unit of production. Field management of Musa paradisiaca AA plantations was managed traditionally and manually, while field management of M. AAA Cavendish var. Brazil plantain plantations was more modernized, with the former emitting an average of 464.05 g CO_2 eq·kg^{-1} of carbon per unit of production, and the latter emitting an average of 395.88 g CO_2 eq·kg^{-1} of carbon per unit of production. Similar findings have been reported for vegetable plots, orchards, and other crops [31,32]. Farmland fertilizer reduction, agricultural product yield enhancement and farmland soil carbon increase have become research hotspots for green development of agriculture [33]. Moderate input of chemical fertilizers into farmland has contributed to increased net primary productivity and reduced net CO_2 emissions [11]. The net farmland carbon sink per unit area of M. AAA Cavendish var. Brazil is higher than that of Musa paradisiaca AA, and summer maize is higher than that of winter wheat [34], suggesting that optimization and adjustment of agricultural planting structure can increase farmland carbon sinks [35]. In addition, the comprehensive application of measures such as energy saving, pesticide reduction, and water-saving irrigation can also reduce greenhouse gas emissions and promote green development of agriculture [36].

5. Conclusion

Throughout the life cycle of banana cultivation, N_2O emissions from the application of nitrogenous fertilizers and carbon emissions from the production and transportation of fertilizers are the most important sources of greenhouse gas emissions, and banana fruits and plants are the main contributors to carbon fixation in the banana production process. Both Musa paradisiaca AA and M. AAA Cavendish var. Brazil farmland systems have annual carbon emissions lower than annual carbon fixation, and both have negative carbon footprints per unit area, and the banana ecosystem has the function of carbon sequestration. Scientific management in the field can achieve carbon reduction and sink increase, reduce farmland carbon footprint, and promote green development of tropical agriculture.

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