Effects of Biochar on the Soil Carbon Cycle in Agroecosystems: An Promising Way to Increase the Carbon Pool in Dryland

Mengying Li[1], Youcai Xiong[2] and Liqun Cai[1*]

[1]College of Resources and Environmental Sciences, Gansu Agricultural University, Lanzhou 730070, China

[2]State Key Laboratory of Grassland Agro-ecosystems, Institute of Arid Agro-ecology, School of Life Sciences, Lanzhou University, Lanzhou, 730000, China

*Correspondence Author Email: cailq@gsau.edu.cn

Abstract. Dryland agriculture ecosystems occupy an extremely important position in ensuring global food security. However, they have faced problems of low soil organic matter content and poor long-term soil sustainability. Biochar is regarded as a new means of soil remediation and a pathway of carbon sequestration that has improved the soil structure and function of ecosystems due to its complex physical and chemical properties. Since there are few reviews of biochar's role in the carbon cycle of agricultural ecosystems, this article examines recent research about its influence on plant carbon assimilation, soil organic carbon mineralization and storage. We highlight the direct or potential effects of biochar on the relationships between plant root architecture and carbon storage, the soil priming effect and soil aggregation, to provide new perspectives on the study of its impacts on the carbon cycle and the implications for carbon management in dryland agriculture ecosystems.

1. Introduction

Terrestrial ecosystems are the world's largest organic carbon pool, containing approximately 2344 billion tons. Soil organic carbon (SOC) is a potential carbon sequestration sink that helps to mitigate climate change and has an impact on soil sustainability [1].The carbon cycle is based on plants assimilating carbon dioxide from the atmosphere to produce carbohydrates that are transported into the plant roots and enter into the soil to be subsequently released as CO_2 through soil respiration [1]. Arid and semi-arid area ecosystems both play a very important role in the terrestrial carbon cycle. However, factors such as frequent droughts and low nutrient availability in the regions they occupy can limit any increase in plant primary productivity and thus reduce their input into the soil carbon pool[2]. In the atmosphere–plant–soil ecosystem, carbon use efficiency and soil carbon storage are mainly improved in the following two ways: (1) by increasing the amount of CO_2 assimilated from the atmosphere and the amount of C input into the soil by enhancing the net primary productivity of plants (aboveground–underground biomass); and (2) by improving the soil to protect input plant organic matter and prevent ineffective or excessive mineralization.

Biochar is a carbon-rich by-product of pyrolysis of organic material in an oxygen-depleted environment that has been proposed as a soil ameliorant to improve soil properties and functions (e.g. improving soil fertility and stability and enhancing C sequestration) [3]. The effect of biochar on carbon emission and sequestration has attracted much attention in recent years, although there are few studies on the impact of biochar on the atmosphere–plant–soil perspective of the carbon cycle. Therefore, based on existing studies in recent years, this review focuses on the effects of biochar on the carbon turnover of aboveground–underground plants, the protective effect of soil aggregates on organic matter and the decomposition of microorganisms, and explains how it affects the ecosystem carbon cycle to provide implications for carbon management in dryland agricultural systems.

2. The Effects of Biochar on Plant Growth and the C Cycle

2.1. The Effect of Biochar on Aboveground Plants

Plants maintain their growth and metabolism through photosynthesis and underground nutrient resources. Biochar can affect the metabolic environment of plants by changing the level of available underground nutrients, thereby improving the ability of plants to assimilate CO_2 in the atmosphere. Meta-analysis found that biochar application increased crop productivity by an average of 10%, mainly due to soil “liming effects” and improved soil water retention capacity and soil nutrient availability [4]. The plant height, biomass and grain weight of oats increased with the application of a biochar-compost mixture, which was attributed to the increase in the total organic carbon and nitrogen of the soil [5].Research involving potting studies found that adding appropriate amounts of biochar can help improve nutrient availability (K and P-Al) and increase maize biomass by 120% under low nutrient supply conditions [6]. Studies have found that the combined effect of inoculation with arbuscular mycorrhizal fungi (AMF) and biochar can increase the absorption of nutrients (N, P and K) by plants as well as increase their biomass and alleviate cadmium impairment [7].

Biochar not only improves plant growth by regulating the availability of water and nutrients in the soil, but it also promotes excellent improvements in plant physiology and biochemistry. The photosynthetic performance of maize with biochar significantly affects leaf area index (LAI), leaf net photosynthetic rate (Pn), chlorophyll content, dry matter accumulation and other parameters [8]. High biochar addition is beneficial to increase LAI and Pn, and the addition of charcoal helps to extend the green time of crops and promote the increase of grain yield [8]. In addition, the application of biochar can weaken the photosynthetic “midday break” during the flowering and filling stages of winter wheat, and enhance photosynthetic performance. In addition, the application of biochar can weaken the photosynthetic “midday break” during the flowering and filling stages of winter wheat, and enhance photosynthetic performance [9]. Soil with 2% biochar content significantly increased maize biomass, because soil water content increased by 70% and stomatal conductance, soil water content and biomass showed a high correlation [6]. To sum up, biochar changes physical and chemical soil properties (e.g. it increases soil water holding capacity and improves soil cation exchange capacity) in favor of water and nutrient retention and soil nutrient availability. In addition, soil with added biochar improves the tolerance and growth performance of crops to various stress environments, and ultimately increases the assimilation rate of atmospheric CO_2, thus affecting the C cycle.

2.2. The Effects of Biochar on Carbon Input and Allocation in Plants

The organic carbon in the soil comes mainly from photosynthetic fixation of plants and reaches the soil through aboveground litter or underground rhizosphere deposition (for example, C-containing compounds released by roots or dead roots during turnover) [11]. Several studies have focused on the impact of biochar on crop yield and biomass, but there are few studies on the effect of root carbon input and allocation. Accordingly, we explain the impact of root carbon input on the soil carbon cycle from two aspects—first, the influence of root carbon input on soil carbon turnover and, second, how root architecture and properties affect soil carbon turnover—thus providing research ideas for further in-depth study of biochar on the carbon cycle mediated by roots.

The input and allocation of root carbon reflect the allocation strategy of plants. The distribution of carbon relies on the development stage of the plant, but it also depends on the specific allocation strategy of the species [10],such as the preference for belowground storage compounds or the response to environmental conditions, such as drought [11], N deposition, atmospheric carbon dioxide concentration and other global change effects [12]. Root exudates directly affect the soil C cycle because they are mainly composed of carbon-based compounds[13]. At the same time, the release of root exudates into the soil is an important metabolic activity of plants, which helps to improve the availability of nutrients and promote nutrient absorption [14]. Previous studies have shown that about 1–20% of the net assimilated C of plants is released into the rhizosphere through root exudates [15]. In situ isotope labeling experiments have shown that more than 50% of the photo-absorbed carbon is transported underground [16]. In addition, studies have compared the effects of root carbon input and litter carbon input on organic carbon, showing that root carbon input is the primary source of organic carbon, accounting for 70% [17]. Theoretically, root exudates exhibit strong biochemical activity, which can be closely related to rhizosphere microorganisms and mineral surfaces, and promote the formation of organic carbon more effectively than dead litter input[17]. Recent studies have pointed out that rhizodeposition input to form organic carbon is more efficient than the carbon source input from dead roots or litter, by two to 13 times [18]. Compared with the root system and aboveground litter C inputs, root exudates can be immediately used by rhizosphere microorganisms and converted into microbial biomass, which has an important impact on the long-term stability of organic carbon in microbial residues [19].

The root system is most sensitive to soil moisture and nutrients, and its morphology responds to changes in the external environment. At the same time, changes in root morphology will in turn affect the absorption and utilization of water and nutrients by plants [20]. Biochar can reduce soil bulk density, improve soil porosity and optimize root growth space through its own characteristics (high porosity, high CEC value and its own oxygen-containing functional group, etc.), which is conducive to the extension of the root system and the improvement of the crop's ability to obtain underground nutrient resources [21]. Baronti et al. pointed out that the root system of grapes tends to increase the length of fine roots rather than their diameter when subjected to drought stress. The application of biochar increased the soil water content, increasing the diameter of the grape fine root system instead of the length, and optimizing the carbon investment of the plant [22].Similar studies have found that applying biochar can increase the diameter of fine roots of wheat [23]. The carbon sequestration potential of biochar could be improved by prolonging the life of the fine roots of biochar-treated plants [24]. Meta-analysis concluded that the turnover rate decreases with the increase of fine root diameter, as this will improve carbon sequestration [25]. This is the main structure in which plants are involved in water and nutrient acquisition, and nearly 33% of the annual global net primary productivity in terrestrial ecosystems is contributed to by the production of fine roots, while 50% of the daily photosynthetic products produced by plants is used to maintain the growth of fine roots [26–31]. Therefore, the lifespan of fine roots has an important impact on crop productivity and the growth of plants, as well as the soil carbon cycle [32]. While several studies have researched the effect of biochar on the plasticity of plant roots, less is known about the effect of biochar on root architecture and morphology corresponding to functions.

3. The Effects of Biochar on Soil Habitat and Soil C Cycle

Biochar, as a carbon-rich thermal stability product, has strong resistance to soil biotic or abiotic degradation and can potentially reduce total CO_2 emissions, and has thus been widely considered as a way to enhance the soil carbon sink [33]. Biochar changes to soil habitats are mainly due to its unique characteristics, such as its ability to improve the soil ion exchange capacity, soil water retention capacity and soil pH, and it can cause changes in the soil organic matter composition and soil microbial community under normal conditions [34]. Although biochar has been shown to have potential for carbon sequestration, the results of soil–biochar interactions are varied and it is thus difficult to predict responses due to differences in soil structure and soil habitat [35–37]. In order to clarify the importance of soil–biochar interactions in the soil carbon cycle, this section summarizes the research hotspots in recent years, and discusses the mineralization and protection roles of biochar for native soil organic matter (SOM). This includes two main aspects: the first is the interaction between biochar and soil microorganisms, and the second is the effect of biochar on protecting organic matter from soil aggregation.

3.1. The Effect of Biochar and Soil Environment on Soil Microorganism

Microorganisms are active participants in the entire dynamic process of SOM mineralization and formation. While biochar has a highly stable molecular structure (such as its highly concentrated aromatic structure), during the pyrolysis and carbonization of organic matter about 3% of unstable C sources (aliphatic C, carboxyl groups, carbohydrates) accompany the biochar as it enters the soil, which stimulates the growth of microorganisms in a short period and produces a special type of microbial community [38]. Studies have shown that the increase in microbial biomass is not due to the increase in oxidizable carbon sources after the addition of biochar, but instead because of the protection of microorganisms provided by the refuge of biochar [39]. Research using scanning electron microscopy found that the porous structure and large surface area of biochar provide an excellent environment for the colonization of microorganisms [40]. Isotope labeling also showed that the microbial biomass significantly increased after the addition of biochar. About 20% of microbial C comes from biochar prepared at 350 ℃ (BC350) and is significantly related to the content of microbial ATP, while biochar prepared at 700 ℃ (BC700) has no such significance. Different pyrolysis temperatures cause significant changes in the chemical structure and composition of biochar. Infrared spectroscopy analysis of the biochar surface found that the content of extractable water-soluble carbon in BC350 is many times more than that in BC700, and the aromatic C=C and aliphatic C=H bonds and carboxylic anions are significantly reduced. This means that BC350 is not only colonized by microorganisms but its carbon source is used as a substrate by microorganisms. Laboratory and field research results show that the addition of biochar can cause significant changes in soil microbial activity and community composition, thereby causing changes in the SOC mineralization rate [38,41,42], but there are studies that hold different views. Research by Tian et al. The study showed that the addition of biochar alone did not affect the microbial composition, and it only caused changes in the microbial community in combination with NPK fertilizer [43]. Studies of soils with different pH have found that the addition of biochar does not change the bacterial phyla in neutral soils [44]. The inconsistent research results are mainly due to the different environmental and biochar characteristics of soil–biochar interactions. For the soil habitat, when soil N and P are restricted, the addition of biochar will not lead to an increase in microbial biomass. At this time, plants and microorganisms compete for the source of nitrogen and, as a result, the availability of nitrogen is reduced and the assimilation of carbon by plants is weakened, eventually decreasing the number of microorganisms [43]. At the same time, different soil properties have different effects on microorganisms. Studies have found that the CO_2emissions of sandy loam soil with biochar added are two to four times that of sandy soil with the addition of biochar. However, the type of biochar has no significant effect on this process. This is because the sandy soil contains 90% sand and low nutrient, SOM and loam content, and so the microbial activity is low [45]. On the other hand, compared with sandy soil, the neutral pH (7.0–7.1) of sandy loam soil is beneficial to improved microbial activity because of the higher nutrient availability [46].

3.2. The Short-term Impact of Biochar on the Mineralization of Soil Organic Matter

Although the application of biochar can strengthen the interaction between soil and microorganisms, this is not necessarily a good thing for SOC storage. Research found that the mineralization rate was about 10 mg C g^{-1} after adding oak tree biochar in sterilized soil, but reached 20 mg C g^{-1} after inoculation with microorganisms, indicating that microorganisms have an important role in SOM mineralization [47]. By comparing the soil CO_2emissions from the biochar and non-biochar treatment (control), the carbon released from the soil with biochar added was found to be higher. Additionally, the accumulated mineralized carbon increased with the decrease of the biochar production temperature, ranging from high lignification to vegetation biochar [48]. Further, research has found that the addition of 2–4% of apple tree biochar increased soil carbon emissions, but the addition of 1% reduced them [49].Carbon emissions after adding green fertilizer and biochar were respectively much larger from the former than the latter, and the sensitivity to temperature showed the same trend [50]. Similarly, studies have found that a straw–biochar mixed application and simple straw returned to the field have higher C emissions than adding biochar [51].

The phenomenon that the mineralization rate of the original organic matter changes due to the addition of fresh organic matter is called the "priming effect". The increase of mineralization rate is called the "positive priming effect", and the obverse is called the "negative priming effect" [52]. The C emission rate changes after adding biochar, mainly because biochar carries some easily oxidizable organic matter into the soil. This stimulates microbial activity in a short period of time, and the intensity and direction of the priming effect may vary depending on the materials used to prepare the biochar, soil texture, soil organic matter composition and other factors. We summarize the causes of positive or negative priming effects caused by biochar as follows (a–c are positive and d–e are negative): (a) biochar provides an ideal soil microhabitat environment for microorganisms; (b) biochar improves the availability of soil nutrients; (c) the co-metabolic effect of labile carbon input not only increases the secretion of microbial extracellular enzymes but also stimulates the degradation of native SOM [53]; (d) the "matrix-conversion effect" whereby microorganisms preferentially use labile biochar carbon without affecting the native dissolved organic matter (DOM) [54]; (e) physical protection, where the carbon is adsorbed by biochar adsorption to protect it from microbial decomposition, or by changing the soil microenvironment to make it less easy to make contact with microbes (e.g. via aggregates/pH/toxicity).

In addition, there are some difficult-to-define factors that also affect the occurrence of the priming effect, such as the chemical composition of biochar. Due to the difference in preparation materials and pyrolysis temperature, the content and composition of easily oxidizable carbon contained in biochar, such as C:N and O:C, may affect the assimilation of biochar by microorganisms [55]. Previous studies divided the reaction type of the priming effect according to the reaction speed of microorganisms into "r-strategy" and "k-strategy" [53]. The former adds fresh organic matter so that the microorganisms can proliferate and leads to a faster mineralization rate, while the latter adds ingredients that complicate organic matter, so the microbial community proliferates slowly and the mineralization time is long. For example, studies have found that adding grass wood biochar pyrolyzed at 250–450 ℃ has a very strong priming effect, while woody plant biochar pyrolyzed at 450–700 ℃ has no strong priming effect, with the differences mainly due to different degrees of carbonization. A low degree of carbonization will bring more organic matter that has not been carbonized, and will help improve nutrient availability [47].

3.3. The Long-term Effects of Biochar on the Mineralization of Soil Organic Matter

When considering the issue of carbon emissions caused by the addition of biochar, it is necessary to consider not only the short-term priming effect, but also the long-term effect, so as to better evaluate the carbon sequestration promoted by biochar. When the carbon source that can be mineralized by microorganisms is exhausted in a short period of time, the mineralization rate of the soil with the added biochar drops sharply, to almost equal the rate of soil without biochar [48]. The duration of mineralization rate is very dependent on the type of biochar materials and pyrolysis temperature, the amount of the addition and the soil conditions. Studies have found that the early mineralization rate of herbaceous biochar with low pyrolysis temperature was very fast, but that rate decreased in the later stages. At the same time, the carbon emission of wood biochar with high pyrolysis temperature decreased more obviously over an extended incubation time (250–500 days [48]. Isotope labeling experiments shown that 2–20% of biochar-derived carbon was mineralized by microorganisms after 60 days of cultivation, while after two months, the respiration rate was significantly reduced to ten times that of the previous period [56]. Research also found that, under conditions of low nitrogen supply, adding biochar reduced carbon emissions by 6.7–8.9% after three years [38]. In summary, the main reasons for the reduction of carbon emissions in the later period are the following: (a) the availability of carbon carried by biochar is reduced; (b) the soil microbial community changes to low C use efficiency; and (c) the biochar adsorbs SOM and reduces mineralization. We have previously described the first point in detail, and here we focus on the latter two. As stated, in the case of low nitrogen supply, the addition of biochar reduces C emissions by 6.7–8.9% and it also increases microbial biomass. This is mainly because the addition of biochar makes the soil microbial community shift to high microbial carbon use efficiency, such as with increased abundance of perinomycetes and rhizopus, and the metabolic quotient is decreased [38]. Studies have also found that biochar promoted the conversion of soil bacterial communities to low C turnover efficiency, such as by increasing the abundance of actinomycetes and acid bacteria [57].

4. Biochar-mediated Soil Aggregation Protects Soil Organic Matter

4.1. The Direct Effects of Biochar On Soil Aggregation

Soil aggregation is a key process for the formation and stability of soil structure, and it has important implications for the biochemical reactions and microbial composition related to soil carbon storage

[58]. Biochar acts as a binder between the components of the aggregate and can thus improve its stability [59]. The main reason for this is that the biochar and clay minerals interact through surface hydrophilic–hydrophobic connections [60]. At the same time, biochar interacts with soil mineral multivalent cations to form a mineral organic matter complex, which enhances the stability of soil aggregates. On the other hand, biochar can act as the core component of aggregate and, like other particulate organic components or microorganisms, improve microbial activity [61]. The results of field and laboratory experiments have shown that biochar has a positive effect on aggregation in various soil structures, including sandy loam to clay [61–67]. In addition, biochar can significantly increase the proportion of large aggregates in the soil, and increase the organic carbon stored in these large aggregates, while enhancing stability.

Aggregates of different particle sizes play different roles in the maintenance, supply and transformation of nutrient elements [68], Research indicates that the organic matter stored in microaggregates (<250 μm) exhibits stronger resistance to decomposition, with a turnover time of 100–300 years, while the complete turnover time of organic matter stored in large aggregates (>250 μm) is only 15–50 years. Therefore, large aggregates provide organic matter with a short-lived, fragile protective coat [50]. Fung et al. pointed out that biochar provides free particulate organic carbon to soil clay particles (<53 μm) and promotes the migration of native SOC from large-particle aggregates to small particles[69].Kate et al. found that biochar increased the average weight diameter (MWD) by 126–217%, significantly improving the stability of the aggregates [34]. This is mainly because the biochar encapsulated the organic matter within large-particle aggregates, thereby providing physical protection for SOM. This not only improves carbon storage but also enhances the stability of the aggregates, similar to the results found by Zhang [70]. Grunwaldet al. found that in the >250 μm and 250–53 μm particle size of aggregates, the fine intra-aggregate particulate organic C (i-POC) significantly increased, along with the increase of C=O functional groups [71].

However, studies have found that adding biochar does not always improve the stability of aggregates. Research found that in coarse sand and clay soil, the addition of biochar showed very different results. Biochar promotes the form of soil aggregation mediated by organic matter, while in clay biochar enhances the repulsive force between particles with the same charge and monovalent cations. This results in chemical disturbances and de-aggregation of aggregates, which is mainly reflected in the change of soil micropore structure—the micropore structure in clay particles is increased by 22–29% with the condition of adding biochar [72]. The above indicates that, among the elements of soil carbon turnover affected by biochar, attention must be paid to the formation and de-aggregation process of aggregates, and different research results may be found for different soil properties.

4.2. The Indirect Effects of Biochar on Soil Aggregation

Biochar can not only improve the process of soil aggregation directly by taking advantage of its own physical and chemical properties, but it can also indirectly affect the process of soil aggregation by affecting microbial activity, plant root architecture and secretion, and symbiotic relationships with fungi. The interactions between biochar and mineral complexes and between biochar and mycorrhizal fungi enhance the formation and stability of soil aggregates and reduce the mineralization of native organic matter [73]. Previous studies have shown that AMF improves long-term soil carbon storage [74], but still increases CO_2emissions by enhancing microbial activity in a short period of time [75]. However, the carbon emission effect of AMF is alleviated by adding biochar [76]. The application of biochar can induce soil aggregation and reduce bulk density, which is helpful to the growth of plant roots. Meanwhile, the nutrients and porous structure of biochar play a positive role in fungal reproduction. While drought reduces the colonization ability of AMF, biochar could alleviate drought stress by increasing the number of spores and hyphae, as well as the colonization rate [77]. Research showed that biochar improved the symbiosis of arbuscular mycorrhiza and carrot roots, by improving the attachment of AMF on the surface of biochar [78].

The root exudates and hyphae can promote the formation of aggregates, and the adhesion of root exudates to soil particles strengthens the stability of soil aggregates in a short time [79]. Studies show that the protein and polysaccharide contained in root exudates play a similar role as glue in soil, and can bond mineral particles together, promoting the formation of large aggregates and improving stability [80,81]. In addition, some studies have also shown that organic binder complexes affect the stability of soil aggregates, and most of the short-term cohesive materials are mainly composed of microbial cells and exudates. Therefore, the effect of carbon input from roots on the activity of rhizosphere microorganisms greatly promotes the formation of soil aggregates. In addition, root exudates can stimulate fungi, enhance the elongation and extension of hyphae, assist roots to extend into the soil matrix, and help crops to absorb nutrients. Further, glomalin, a glycoprotein released by AMF during turnover and after death, has been proved to be a key soil adhesive in achieving increased aggregate stability [82].

Research by Ren et al. found that inoculation of AMF on dryland agricultural areas improved soil particulate organic C and light fraction organic C, mainly due to the increase of mycelia length and glomalin content. In addition, due to the plant growth-promoting effect of AMF, the carbon input to soil was also enhanced [83]. Studies have further shown that there is a significant correlation between the hyphae length and MWD and glomalin, and the formation of the hyphal network can improve soil aggregation and stability [86]. Some research also supports the positive effects of biochar and mycorrhizal fungi on soil aggregates and carbon sequestration [84]. Wangetal. [85] pointed out that soil aggregates, as soil biochemical reactors, regulate greenhouse gas (GHG) emissions at the soil interface, and their reaction performance has a strong relationship with the size and distribution of aggregates, as well as the biological and abiotic environment of the soil. At present there are few studies on the effects of biochar interaction with plant roots and mycorrhizal fungi on soil aggregation, which has hindered our in-depth understanding of the impact of biochar on the soil carbon cycle.

5. Conclusion

Biochar can enhance the ability of crops to acquire resources and promote the activities of soil enzymes and the microbial community on the basis of improving soil structure and function. The synergetic effect of biochar is conducive to promoting the sustainability of dryland agricultural ecosystems from two aspects: improving crop resource acquisition characteristics and soil ecological functions. However, as a new soil improvement measure, the impact of biochar on soil ecological security has not been fully established. We must therefore be cautious in the implementation of this technology [3]. At present, there are many scientific problems waiting to be explained in the research of this field. Based on the production conditions of dryland agriculture ecosystems combined with biochar research, the following research prospects are put forward:

a. There are many types and textures of dryland soil. How to effectively utilize biochar produced by different materials and pyrolysis temperatures to meet production requirements under different soil conditions is an important area to be studied.

b. Where the organic matter content of dryland farmland was low, biochar increased the organic matter content, but it could not be equated with traditional organic matter because of its high stability. It is necessary to conduct a long-term positioning study (2–x) based on the soil microbial community structure and function to comprehensively analyze and evaluate the short-term (0–2 y) carbon priming effect and long-term (2–x) carbon storage effect of biochar.

c. The change of soil structure caused by biochar affects the morphological plasticity of the crop root system. Whether this change can improve the ability of plants to obtain resources and thus help crop growth is still unknown.

d. There is a serious lack of soil moisture and poor soil structure in dryland agricultural systems. At present, there are many studies on the effect of biochar on GHGs. Whether biochar can improve the soil aggregate structure and water retention, and optimize the composition and biological activity of microbial community in the aggregates so as to decrease GHG emissions, is yet to be researched.

e. Root exudates and mycorrhizal symbiosis systems of plants have a strong impact on soil carbon cycle. The biochar how to affect the function and structure of the soil is not clear to us at present, and it needs to be further researched.

6. Authors' Contribution

The authors have no conflicts of interest to declare. Specially, YouCai Xiong and LiQun Cai were responsible for experimental design. MengYing Li is responsible for the original draft preparation. All authors have read and approved the final manuscript.

7. Acknowledgment

This work is financially supported by the National Natural Science Foundation of China (Number: 41661049; Host by LiQun Cai). We would like to thank the professor Xiong's valuable advice. Also, we show sincere gratitude to the anonymous reviewers for their valuable comments and suggestions.

8. References

[1] Chang X, Chai Q, Wu G, Zhu Y, Li Z, Yang Y and Wang G 2017 Soil Organic Carbon Accumulation in Abandoned Croplands on the Loess Plateau *L. Degrad. Dev.* doi: 10.1002/ldr.2679.

[2] Lal R 2004 Carbon sequestration in dryland ecosystems *Environmental Management* 39, 1-10.

[3] Wen-fu C, Wei-ming Z and Jun M 2013 Advances and Prospects in Research of Biochar Utilization in Agriculture *Biodivers* 46, 3324–3333

[4] Jeffery S, Verheijen F G A, van der Velde M and Bastos A C 2011 A quantitative review of the effects of biochar application to soils on crop productivity using meta-analysis *Agric. Ecosyst. Environ* 144, 175–87

[5] Schulz H, Dunst G and Glaser B 2013 Positive effects of composted biochar on plant growth and soil fertility *Agron. Sustain. Dev* 33, 817–827

[6] Pandit N R, Mulder J, Hale S E, Martinsen V, Schmidt H P and Cornelissen G 2018 Biochar improves maize growth by alleviation of nutrient stress in a moderately acidic low-input Nepalese soil *Sci. Total Environ* 625, 1380–1389

[7] Zhang F, Liu M, Li Y, Che Y and Xiao Y 2019 Effects of arbuscular mycorrhizal fungi, biochar and cadmium on the yield and element uptake of Medicago sativa *Sci. Total Environ* 655, 1150–1158

[8] Zhang N, Li J, Li XH , Li Y, Wang YP, Liu HY and Liao YC 2014 Effects of Biochar on Growth and Yield of Summer Maize *Journal of Agro-Environment Science*

[9] Kan ZR, Ma S and Qi JY 2019 Effects of biochar application on photosynthetic potential and grain yield of winter wheat. *Journal of triticeae crops* 39, 719-727

[10] Weiner J 2004 Allocation, plasticity and allometry in plants *Perspect. Plant Ecol. Evol. Syst* 6, 207-215

[11] Sanaullah M, Chabbi A, Rumpel C and Kuzyakov Y 2012 Carbon allocation in grassland communities under drought stress followed by 14C pulse labeling *Soil Biol. Biochem* 55, 132-139.

[12] Grayston S J, Vaughan D and Jones D 1997 Rhizosphere carbon flow in trees, in comparison with annual plants: The importance of root exudation and its impact on microbial activity and nutrient availability *Appl. Soil Ecol* 5, 29-56

[13] Bais H P, Weir T L, Perry L G, Gilroy S and Vivanco J M 2006 The role of root exudates in rhizosphere interactions with plants and other organisms *Annu. Rev. Plant Biol* 57, 233-266.

[14] Badri DV and Vivanco JM 2009 Regulation and function of root exudates *Plant, Cell Environ.* doi: 10.1111/j.1365-3040.2009.01926.x.

[15] Jones DL, Hodge A and Kuzyakov Y 2004 Plant and mycorrhizal regulation of rhizodeposition *New Phytol* 163, 459-480.

[16] Wu Y, Tan H, Deng Y, Wu J, Xu X, Wang Y, Tang Y, Higashi T and Cui X 2010 Partitioning pattern of carbon flux in a Kobresia grassland on the Qinghai-Tibetan Plateau revealed by field 13C pulse-labeling *Glob. Chang. Biol* 16, 1365-1386.

[17] Jackson RB, Lajtha K, Crow SE, Hugelius G, Kramer MG and Piñeiro G 2017 The Ecology of Soil Carbon: Pools, Vulnerabilities, and Biotic and Abiotic Controls *Annu. Rev. Ecol. Evol. Syst* doi: 10.1146/annurev-ecolsys-112414-054234.

[18] Sokol NW, Kuebbing SE, Karlsen-Ayala E and Bradford MA 2019 Evidence for the primacy of living root inputs, not root or shoot litter, in forming soil organic carbon *New Phytol* 221, 233–46

[19] Shen X, Yang F, Xiao C and Zhou Y 2020 Increased contribution of root exudates to soil carbon input during grassland degradation *Soil Biol. Biochem* 146, 107817

[20] De Dorlodot S, Forster B, Pagès L, Price A, Tuberosa R and Draye X 2007 Root system architecture: opportunities and constraints for genetic improvement of crops *Trends Plant Sci* 12,474-481

[21] Oguntunde P G, Abiodun B J, Ajayi A E and Van De Giesen N 2008 Effects of charcoal production on soil physical properties in Ghana *J. Plant Nutr. Soil Sci* 171, 591-596

[22] Baronti S, Vaccari F P, Miglietta F, Calzolari C, Lugato E, Orlandini S, Pini R, Zulian C and Genesio L 2014 Impact of biochar application on plant water relations in Vitis vinifera (L.) *Eur. J. Agron* 53, 38-44

[23] Li RX, Hong HJ and Huo YL 2018 Effects of biochar on root morphology and endophytic fungal diversity of Winter wheat in North China. *Journal of Agricultural Machiner*y 49, 235-242.

[24] Guo D, Li H, Mitchell R J, Han W, Hendricks J J, Fahey T J and Hendrick R L 2008 Fine root heterogeneity by branch order: Exploring the discrepancy in root turnover estimates between minirhizotron and carbon isotopic methods *New Phytol.* 177 443–56

[25] Gill R A and Jackson R B 2000 Global patterns of root turnover for terrestrial ecosystems *New Phytol* 147, 13-31

[26] Montagnoli A, Terzaghi M, Di Iorio A, Scippa G S and Chiatante D 2012 Fine-root morphological and growth traits in a Turkey-oak stand in relation to seasonal changes in soil moisture in the Southern Apennines, Italy *Ecol. Res* 27, 1015-1025

[27] Montagnoli A, Terzaghi M, Di Iorio A, Scippa G S and Chiatante D 2012 Fine-root seasonal pattern, production and turnover rate of European beech (Fagus sylvatica L.) stands in Italy

Prealps: Possible implications of coppice conversion to high forest *Plant Biosyst* doi: 10.1080/11263504.2012.741626.

[28] Mainiero R, Kazda M, Häberle K H, Nikolova P S and Matyssek R 2009 Fine root dynamics of mature European beech (Fagus sylvatica L.) as influenced by elevated ozone concentrations *Environ. Pollut* 157, 2638-2644

[29] Montagnoli A, Di Iorio A, Terzaghi M, Trupiano D, Scippa G S and Chiatante D 2014 Influence of soil temperature and water content on fine-root seasonal growth of European beech natural forest in Southern Alps, Italy *Eur. J. For. Res* 133, 957-968

[30] McCormack M L, Dickie I A, Eissenstat D M, Fahey T J, Fernandez C W, Guo D, Helmisaari H S, Hobbie E A, Iversen C M, Jackson R B, Leppälammi-Kujansuu J, Norby R J, Phillips R P, Pregitzer K S, Pritchard S G, Rewald B and Zadworny M 2015 Redefining fine roots improves understanding of below-ground contributions to terrestrial biosphere processes *New Phytol* doi: 10.1111/nph.13363.

[31] Terzaghi M, Di Iorio A, Montagnoli A, Baesso B, Scippa G S and Chiatante D 2016 Forest canopy reduction stimulates xylem production and lowers carbon concentration in fine roots of European beech *For. Ecol. Manage* doi: 10.1016/j.foreco.2016.08.010

[32] Amendola C, Montagnoli A, Terzaghi M, Trupiano D, Oliva F, Baronti S, Miglietta F, Chiatante D and Scippa G S 2017 Short-term effects of biochar on grapevine fine root dynamics and arbuscular mycorrhizae production *Agric. Ecosyst. Environ* 239,236-245

[33] Zheng H, Wang X, Luo X, Wang Z and Xing B 2018 Biochar-induced negative carbon mineralization priming effects in a coastal wetland soil: Roles of soil aggregation and microbial modulation *Sci. Total Environ* 610–611, 951–60

[34] Wang D, Fonte S J, Parikh S J, Six J and Scow K M 2017 Biochar additions can enhance soil structure and the physical stabilization of C in aggregates *Geoderma* 303,110–7

[35] Mašek O, Buss W, Brownsort P, Rovere M, Tagliaferro A, Zhao L, Cao X and Xu G 2019 Potassium doping increases biochar carbon sequestration potential by 45%, facilitating decoupling of carbon sequestration from soil improvement *Sci. Rep* doi: 10.1038/s41598-019-41953-0

[36] Campbell J L, Sessions J, Smith D and Trippe K 2018 Potential carbon storage in biochar made from logging residue: Basic principles and Southern Oregon case studies *PLoS One* doi: 10.1371/journal.pone.0203475.

[37] Roobroeck D, Hood-Nowotny R, Nakubulwa D, Tumuhairwe J B, Mwanjalolo M J G, Ndawula I and Vanlauwe B 2019 Biophysical potential of crop residues for biochar carbon sequestration, and co-benefits, in Uganda *Ecol. Appl.* doi: 10.1002/eap.1984

[38] Li S, Wang S, Fan M, Wu Y and Shangguan Z 2020 Interactions between biochar and nitrogen impact soil carbon mineralization and the microbial community *Soil Tillage Res* 196,104437

[39] Liang B, Lehmann J, Sohi S P, Thies J E, O'Neill B, Trujillo L, Gaunt J, Solomon D, Grossman J, Neves E G and Luizão F J 2010 Black carbon affects the cycling of non-black carbon in soil *Org. Geochem* 41, 206-213

[40] Luo Y, Durenkamp M, De Nobili M, Lin Q, Devonshire B J and Brookes P C 2013 Microbial biomass growth, following incorporation of biochars produced at 350 ℃ or 700 ℃, in a silty-clay loam soil of high and low pH *Soil Biol. Biochem* 57,513–23

[41] Cheng J, Lee X, Tang Y and Zhang Q 2019 Long-term effects of biochar amendment on rhizosphere and bulk soil microbial communities in a karst region, southwest China *Appl. Soil Ecol* 140,126–34

[42] Qin X, Li Y, Wang H, Liu C, Li J, Wan Y, Gao Q, Fan F and Liao Y 2016 Long-term effect of biochar application on yield-scaled greenhouse gas emissions in a rice paddy cropping system: A four-year case study in south China *Sci. Total Environ* 569–570, 1390–401

[43] Tian J, Wang J, Dippold M, Gao Y, Blagodatskaya E and Kuzyakov Y 2016 Biochar affects soil organic matter cycling and microbial functions but does not alter microbial community structure in a paddy soil *Sci. Total Environ.* 556,89–97

[44] Sheng Y and Zhu L 2018 Biochar alters microbial community and carbon sequestration potential across different soil pH *Sci. Total Environ.* 622–623,1391–9

[45] El-Naggar A, Lee S S, Awad Y M, Yang X, Ryu C, Rizwan M, Rinklebe J, Tsang D C W and Ok Y S 2018 Influence of soil properties and feedstocks on biochar potential for carbon mineralization and improvement of infertile soils *Geoderma* 332,100–8

[46] USDA-NRCS 2004 Estimation of Direct Runoff from Storm Rainfall *Natl. Eng. Handb.*

[47] Zimmerman A R 2010 Abiotic and microbial oxidation of laboratory-produced black carbon (biochar) *Environ. Sci. Technol* doi: 10.1021/es903140c.

[48] Zimmerman A R, Gao B and Ahn M Y 2011 Positive and negative carbon mineralization priming effects among a variety of biochar-amended soils *Soil Biol. Biochem* 43,1169–79

[49] Li S, Liang C and Shangguan Z 2017 Effects of apple branch biochar on soil C mineralization and nutrient cycling under two levels of N *Sci. Total Environ* 607–608,109–19

[50] Grunwald D, Kaiser M and Ludwig B 2016 Effect of biochar and organic fertilizers on C mineralization and macro-aggregate dynamics under different incubation temperatures *Soil Tillage Res.* 164,11–7

[51] Huang R, Tian D, Liu J, Lv S, He X and Gao M 2018 Responses of soil carbon pool and soil aggregates associated organic carbon to straw and straw-derived biochar addition in a dryland cropping mesocosm system *Agric. Ecosyst. Environ* 265,576–86

[52] Bingeman CW, Varner JE and Martin WP 1953 The Effect of the Addition of Organic Materials on the Decomposition of an Organic Soil *Soil Sci. Soc. Am. J.* doi:10.2136/sssaj1953.03615995001700010008x.

[53] Kuzyakov Y 2010 Priming effects: Interactions between living and dead organic matter *Soil Biol. Biochem* 42, 1363-1371.

[54] Zimmerman A R and Ouyang L 2019 Priming of pyrogenic C (biochar) mineralization by dissolved organic matter and vice versa *Soil Biol. Biochem* 130,105–12

[55] Spokas K A, Koskinen W C, Baker J M and Reicosky D C 2009 Impacts of woodchip biochar additions on greenhouse gas production and sorption/degradation of two herbicides in a Minnesota soil *Chemosphere* 77,574–81

[56] Kuzyakov Y, Subbotina I, Chen H, Bogomolova I and Xu X 2009 Black carbon decomposition and incorporation into soil microbial biomass estimated by 14C labeling *Soil Biol. Biochem* 42, 210-219

[57] Zheng H, Wang X, Luo X, Wang Z and Xing B 2018 Biochar-induced negative carbon mineralization priming effects in a coastal wetland soil: Roles of soil aggregation and microbial modulation *Sci. Total Environ* 610–611,951–60

[58] Gupta V V S R and Germida J J 2015 Soil aggregation: Influence on microbial biomass and implications for biological processes *Soil Biol. Biochem* 80,A3–9

[59] Du ZL, Zhao JK, Wang YD and Zhang QZ 2017 Biochar addition drives soil aggregation and carbon sequestration in aggregate fractions from an intensive agricultural system *J. Soils Sediments* 17, 1-9

[60] Joseph S D, Camps-Arbestain M, Lin Y, Munroe P, Chia C H, Hook J, Van Zwieten L, Kimber S, Cowie A, Singh B P, Lehmann J, Foidl N, Smernik R J and Amonette J E 2010 An investigation into the reactions of biochar in soil *Australian Journal of Soil Research* 48, 501-515

[61] Lehmann J, Rillig M C, Thies J, Masiello C A, Hockaday W C and Crowley D 2011 Biochar effects on soil biota - A review *Soil Biol. Biochem* doi: 10.1016/j.soilbio.2011.04.022.

[62] Herath HMSK, Camps-Arbestain M and Hedley M 2013 Effect of biochar on soil physical properties in two contrasting soils: An Alfisol and an Andisol *Geoderma* doi: 10.1016/j.geoderma.2013.06.016.

[63] Ouyang L, Wang F, Tang J, Yu L and Zhang R 2013 Effects of biochar amendment on soil aggregates and hydraulic properties *J. Soil Sci. Plant Nutr* 13

[64] Khademalrasoul A, Naveed M, Heckrath G, Kumari K G I D, Wollesen De Jonge L, Elsgaard L, Vogel H J and Iversen B V. 2014 Biochar effects on soil aggregate properties under no-till maize *Soil Sci.*

[65] Zong Y, Xiao Q and Lu S 2016 Acidity, water retention, and mechanical physical quality of a strongly acidic Ultisol amended with biochars derived from different feedstocks *J. Soils Sediments* doi: 10.1007/s11368-015-1187-2.

[66] Liu Z, Chen X, Jing Y, Li Q, Zhang J and Huang Q 2014 Effects of biochar amendment on rapeseed and sweet potato yields and water stable aggregate in upland red soil *Catena* doi: 10.1016/j.catena.2014.07.005.

[67] Awad Y M, Blagodatskaya E, Ok Y S and Kuzyakov Y 2013 Effects of polyacrylamide, biopolymer and biochar on the decomposition of 14C-labelled maize residues and on their stabilization in soil aggregates *Eur. J. Soil Sci* 64, 488-499

[68] Wang, Q. K.; Wang, S. L. Formation and stabilization mechanism of soil aggregates and its influencing factors. *Chinese Journal of Soil Science* 36, 415-421.

[69] Fungo B, Lehmann J, Kalbitz K, Thionġo M, Okeyo I, Tenywa M and Neufeldt H 2017 Aggregate size distribution in a biochar-amended tropical Ultisol under conventional hand-hoe tillage *Soil Tillage Res* 165,190–197

[70] Zhang Q, Du Z L, Lou Y and He X 2015 A one-year short-term biochar application improved carbon accumulation in large macroaggregate fractions *Catena* 127,26–31

[71] Grunwald D, Kaiser M, Junker S, Marhan S, Piepho H P, Poll C, Bamminger C and Ludwig B 2017 Influence of elevated soil temperature and biochar application on organic matter associated with aggregate-size and density fractions in an arable soil *Agric. Ecosyst. Environ* 241,79–87

[72] Pituello C, Dal Ferro N, Francioso O, Simonetti G, Berti A, Piccoli I, Pisi A and Morari F 2018 Effects of biochar on the dynamics of aggregate stability in clay and sandy loam soils *Eur. J. Soil Sci* 69,827–42

[73] Cross A and Sohi S P 2011 The priming potential of biochar products in relation to labile carbon contents and soil organic matter status *Soil Biol. Biochem* 43, 2127-2134.

[74] Cheng L, Booker F L, Tu C, Burkey K O, Zhou L, Shew H D, Rufty T W and Hu S 2012 Arbuscular mycorrhizal fungi increase organic carbon decomposition under elevated CO2 *Science* 337,1084.

[75] Bender SF, Plantenga F, Neftel A, Jocher M, Oberholzer HR, Köhl L, Giles M, Daniell TJ and Van Der Heijden MGA 2014 Symbiotic relationships between soil fungi and plants reduce N2O emissions from soil *ISME J* doi: 10.1038/ismej.2013.224.

[76] Liang J F, An J, Gao J Q, Zhang X Y, Song M H and Yu F H 2019 Interactive effects of biochar and AMF on plant growth and greenhouse gas emissions from wetland microcosms *Geoderma* 346, 11-17

[77] Hashem A, Kumar A, Al-Dbass A M, Alqarawi A A, Al-Arjani A B F, Singh G, Farooq M and Abd_Allah E F 2019 Arbuscular mycorrhizal fungi and biochar improves drought tolerance in chickpea *Saudi J. Biol. Sci* doi: 10.1016/j.sjbs.2018.11.005.

[78] Hammer E C, Balogh-Brunstad Z, Jakobsen I, Olsson P A, Stipp S L S and Rillig M C 2014 A mycorrhizal fungus grows on biochar and captures phosphorus from its surfaces *Soil Biol. Biochem* doi: 10.1016/j.soilbio.2014.06.012.

[79] Leifheit EF, Veresoglou SD, Lehmann A, Morris EK and Rillig MC 2014 Multiple factors influence the role of arbuscular mycorrhizal fungi in soil aggregation-a meta-analysis *Plant Soil* 374, 523-537

[80] Faucon MP, Houben D and Lambers H 2017 Plant Functional Traits: Soil and Ecosystem Services *Trends Plant Sci* doi: 10.1016/j.tplants.2017.01.005.

[81] Li Y, Zhong B, Chen D, Zhang N and Sun G 2019 Effects of root exudates of different carbon concentrations and sources on soil aggregate stability *Chinese J. Appl. Environ. Bio* doi: 10.19675/j.cnki.1006-687x.2018.12036.

[82] Bardgett R D, Mommer L and De Vries F T 2014 Going underground: Root traits as drivers of ecosystem processes *Trends Ecol. Evol* doi: 10.1016/j.tree.2014.10.006.

[83] Ren A T, Mickan B S, Li J Y, Zhou R, Zhang X C, Ma M S, Wesly K and Xiong Y C 2020 Soil labile organic carbon sequestration is tightly correlated with the abundance and diversity of arbuscular mycorrhizal fungi in semiarid maize fields *L. Degrad. Dev.* doi: 10.1002/ldr.3773.

[84] Warnock D D, Lehmann J, Kuyper T W and Rillig M C 2007 Mycorrhizal responses to biochar in soil - Concepts and mechanisms *Plant Soil* 300, 9-20

[85] Wang B, Brewer P E, Shugart H H, Lerdau M T and Allison S D 2019 Soil aggregates as biogeochemical reactors and implications for soil–atmosphere exchange of greenhouse gases—A concept *Glob. Chang. Biol* 25,373–85