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REVIEW

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Effect of straw returning on soil organic carbon in rice–wheat rotation system: A review

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Abstract
The rice–wheat rotation model of crop planting is widely used globally, and worldwide, straw returning is the main method of crop straw treatment. However, the straw return method commonly used in the modern rice–wheat rotation system has many adverse effects on the levels and improvement of soil fertility and crop yield, and there is no systematic theory of rice and wheat straw returning to use as a guide. In this paper, we concluded that: in the rice–wheat rotation system, returning 1,500–4,500 kg/ha of rice straw and 2,250–6,750 kg/ha of wheat straw to the field helps increase the organic carbon content and quality of the soil and promotes high annual yields; conventional mixing of straw into the field can increase the organic carbon content of the soil in a short time; long-term use of concentrated ditch-buried straw return has obvious advantages over other straw returning methods in increasing the accumulation of soil organic carbon; the combination of little or no tillage plus straw returning helps increase the content and quality of organic carbon in soil; and when the soil water content is 15%–22.5%, it is the most conducive to the accumulation of soil organic carbon. In addition, we also provide relevant suggestions for future research directions on straw returning via systematic analyses and thought processes.

KEYWORDS
rice and wheat rotation system, soil aggregates, soil microorganisms, soil organic carbon, straw returning

1 | INTRODUCTION

Rice and wheat are both important food crops globally, and rice–wheat rotation is an important planting pattern that is mainly used in east and southeast Asia; approximately 26 million ha are planted this way (Timsina & Connor, 2001), providing a stable source of food for more than 20% of the world's population (Kumari et al., 2011), which is of great

[Correction added on 29 April 2020, after first online publication: The author affiliations section has been reordered in this version] significance in ensuring regional and even global food security.

In recent years, with continuous increases in rice and wheat production, the production of rice and wheat straw has also increased. Due to economic development and improving standards of living, crop straw has been transformed from previously living energy and animal feed into agricultural waste. During the production process, to keep up with their farms, to save manpower and material resources, and to reduce other unnecessary effort, farmers burn large amounts of crop straw, which not only pollutes the environment and negatively affects people's production and lives but also wastes substantial valuable natural resources and puts great pressure on the soil ecosystem (Bellamy, Loveland, Bradley, Lark, & Kirk, 2005; Lal, 2002; Mann, 1986). Therefore, the utilization of these rice and wheat straw resources has become a major societal concern. Crop straw is a carbon-rich energy source that contains much nitrogen, phosphorus, potassium, and other nutrients necessary for crop growth (Ye, Xie, Wang, & Li, 2008); it plays a very important role in alleviating imbalances in the proportions of nitrogen, phosphorus, and potassium in farm soil and making up for deficiencies in phosphorus and potash fertility. Rice and wheat straw returning is one of the main research and promotion techniques of crop cultivation at present (Figure 1). As an effective straw treatment method, straw returning can not only solve the problem of excessive straw treatment but also avoid the pollution caused by straw burning. At the same time, the nutrients released by straw decomposition can be used to improve soil fertility, provide a good environment for microbial growth in the soil, promote crop growth, and increase crop yield (Hu, 2014; Suriyagoda, Costa, & Lambers, 2014; Yang, Yang, Yang, & Ouyang, 2004); it is a vital measure for the comprehensive and effective use of resources in agroecosystems and plays an important role in maintaining a strong cycle of soil fertility and sustainable agricultural development.

Soil organic carbon is a collective term for carbon in humus, animal and plant residues, and microorganisms formed in the soil by microbial action; it is the main source of carbon nutrients required for plant and biological life in the soil and constitutes the important physical and chemical properties of the soil, and its content in the soil is greatly affected by the type and abundance of soil microorganisms. Soil organic carbon can regulate the physical, chemical, and biological properties of soil and improve soil stability; its accumulation and transformation can directly or indirectly affect soil water, fertilizer, gas, heat and biochemical processes, and the absorption and release of substances (Štursová & Baldrian, 2011), and its content in soil is closely associated with soil quality and agricultural productivity (Sun, Shi, Yu, Wang, & Wang, 2014). Therefore, it is very important to study changes in the pool of soil organic carbon to maintain the sustainability of the global agroecosystem.

Thus, understanding the effects of straw returning on the soil organic carbon pool in the rice–wheat rotation system is essential to maintain sustainable agricultural development. The aims of the present paper were (a) to compare the effects of different straw returning measures on the soil organic carbon pool in the rice–wheat rotation system and (b) to optimize the straw returning technology of the rice–wheat rotation system to improve soil quality and provide theoretical guidance for maintaining healthy and sustainable agricultural development.

2 | DECOMPOSITION CHARACTERISTICS OF RETURNED STRAW

Rice and wheat straw is mainly composed of cellulose, hemicellulose, lignin, pectin, protein, amino acids, and soluble sugars, as well as a small amount of lipids and waxes and tannins (Chen, 2007). The decomposition of straw returned to the field is divided into two stages. The first stage is the rapid decomposition stage, in which the organic materials such as cellulose, hemicellulose, pectin, protein, amino acids, and soluble sugars are mainly decomposed, and the soil microorganisms are more diverse and show higher activity (Jiang, Yang, Xie, & Qu, 2001; Jiang, Yu, & Ma, 2001; Zhang & Wang, 2000); the second stage is the slow decomposition stage, in which lignins, tannins, waxes, and other substances that were not decomposed or were minimally decomposed in the previous stage are gradually decomposed through physical and chemical changes, which can last 2–3 years or longer (Dai, 2009). Therefore, the rice and wheat straw returned in the rice–wheat rotation system cannot be completely decomposed in one planting season. Liu et al. (2007) found that approximately 20% of the wheat straw returned to the field during the rice season still remains after the season, and approximately 40% of the rice straw returned to the field during the wheat season still remains at the end of that season. This difference may be explained by the higher soil moisture content and temperature during the rice season, which is more conducive to microbial activity and faster straw decomposition.

3 | EFFECT OF EXOGENOUS ADDITIVES ON THE DECOMPOSITION OF RETURNED STRAW

Soil microbes play a very important role in decomposing returned straw, and any factors that can affect soil microbial species, abundance, and activity will affect the decomposition of returned straw.

FIGURE 1 Wheat straw returning in the rice field (a), rice growth with wheat straw (b), rice straw returning in the wheat field (c), and wheat growth with rice straw (d)

The C/N ratio is an important factor affecting the decomposition of crop straw (Trinsoutrot et al., 2002). For every 100 g of straw decomposed by microorganisms, approximately 0.8 g of nitrogen is required (Henriksen & Breland, 2002), and the appropriate C/N ratio for soil microorganisms to decompose organic materials is approximately 25–30:1; while the C/N ratio of straw of Gramineae crops is generally higher than this value (Kochsick & Knops, 2013), the microbial decomposition of returned rice straw and wheat straw requires the original nitrogen in the soil, which leads to competition between microorganisms and crops for nutrients and reduces the decomposition rate of returned straw (Álvaro-Fuentes et al., 2013). In addition, straw has more soluble organic matter and a higher C/N ratio in the early stage of decomposition, and as it decomposes, the soluble matter and the C/N ratio gradually decrease. Therefore, an appropriate nitrogen fertilizer should be applied during the early stage of straw returning. The appropriate application of nitrogen fertilizer can increase the available nitrogen content of the soil, reduce the soil C/N ratio, promote soil microorganism growth and activity, increase cellulase and other hydrolase activities, inhibit oxidase activity, and promote the decomposition of returned straw; however, the excessive application of nitrogen fertilizer will inhibit the activity and chemical stability of lignin-decomposing enzymes in the soil, thereby delaying the decomposition of returned straw (Arcand, Knight, & Farrell, 2014; Magill & Aber, 1998; Riggs, 2016). Studies have shown that when the nitrogen content of the straw is less than 1.2%, inorganic nitrogen will be fixed into organic compounds; when the nitrogen content exceeds 1.5%, it is not necessary to supplement the external nitrogen in the process of straw decomposition (Mubarak & Rosenani, 2003; Wilhelm, Johnson, Hatfield, Voorhees, & Linden, 2004).

Straw ripening agents are a type of microbial agent composed of many bacteria, molds, yeast, and bacillus that can rapidly degrade straw. By secreting extracellular enzymes, microorganisms can induce the fibrosis of the microporous structure of returned straw (Arora, Chander, & Gill, 2002; Geisseler & Horwath, 2008; Wiedermann, Kane, Potvin, & Lilleskov, 2017) and decompose cellulose, hemicellulose, and lignin in the straw into small-molecule organic compounds or release CO_2, thus accelerating straw decomposition.

In the early stage of straw decomposition, applying lime can help break down nitrogen-containing substances in straw and produce a large amount of NH_3, which leads to a slightly alkaline soil environment and affects the increase in proliferation and activity of soil microorganisms, and compared with non-lime-treated farmland, lime treatment had no significant effect on the early decomposition rate of returned straw; in the later stage of straw decomposition, the nitrogen-containing substances in straw are largely consumed, and the NH_3 produced was greatly reduced, the soil pH returned to normal, the abundance and activity of soil microorganisms and the activity of enzymes related to straw decomposition in soil significantly improved, and the straw decomposition rate also significantly accelerated (Liao et al., 2018; Liu et al., 2017; Page, Allen, Dalal, & Slattery, 2009; Zhai, Liu, Li, & Xu, 2012). In addition, calcium ions in lime can promote the formation of soil aggregates, which are conducive to the accumulation of soil organic carbon (Chan & Heenan, 1998). In general, straw returning with lime can improve the straw decomposition rate and organic carbon content of the soil.

In the process of agricultural production, straw returning combined with nitrogen fertilizer, straw ripening agent, and lime all promote the decomposition of returned straw by improving the activities of soil microorganisms.

4 | EFFECT OF STRAW RETURNING ON SOIL MICROORGANISMS

The mineralization and decomposition of soil organic matter, the formation of humus, and the transformation and circulation of nutrients are inseparable from the activities of soil microbes (Icoz, Saxena, Andow, Zwahlen, & Stotzky, 2008; Stefanie, Meike, Rainer, & Joachim, 2011). Straw returning can improve soil structure, increase the organic matter content of the soil, and provide a good environment for the growth and reproduction of microorganisms, as well as sufficient carbon and nitrogen sources and energy, which improves the species, abundance, and activity of soil microorganisms (Lou, Liang, et al., 2011; Lou, Xu, Wang, Sun, & Zhao, 2011; Perucci, 1992; Rottmann, Dyckmans, & Joergensen, 2010). Bacteria account for 70%–90% of all soil microorganisms and are the most active factor in soil, playing an important role in the decomposition of cellulose in straw (Xu, Wang, Zhang, & Dai, 2010); an extracellular enzyme secreted by fungi is the main microbial enzyme used for straw decomposition (Henriksen & Breland, 2002); and actinomycetes play a very important role in the decomposition of lignin in straw (David, Penny, & Philip, 2001). The research results of Lou, Liang, et al. (2011)) and Lou, Xu, et al. (2011)) showed that straw returning could significantly increase the number of bacteria, fungi, and actinomycetes in soil.

5 | EFFECT OF STRAW RETURNING ON SOIL AGGREGATE STRUCTURE

Organic matter is the core of the formation of 100–200 μm agglomerates, the surfaces of which can adsorb soil cosmids and cement soil microaggregates into large agglomerates (Jastrow, 1996; Oades, 1988; Tisdall & Oades, 1982). Straw returning can increase the stability of soil aggregates by supplementing them with fresh organic matter, increasing the proportion of humus and the aggregate structure of soil and increasing the activity of soil microorganisms (Blanco-Canqui & Lal, 2008). In addition, returning straw can also reduce the impact of slap and leaching of rain on the soil, reduce the energy of rain falling to the ground (Fang, Li, Zhou, Yan, & Peng, 2018), and reduce damage to the soil aggregate structure (Blanco-Canqui & Lal, 2008).

Pan, Li, Zheng, Zhang, and Zhou (2008) showed that the accumulation of soil organic carbon increases as large aggregates increase and decreases as small aggregates increase (<250 μm), and the most high-activity particulate organic carbon exists in large aggregates. Karami, Homaee, Afzalinia, Ruhipour, and Basirat (2012) found that 90% of soil organic carbon in farmland topsoil is located in soil agglomerates, and the formation and stability of aggregates guarantee an increase in organic carbon content; simultaneously, soil organic carbon is the main cementing agent of aggregates, and microaggregates form large agglomerates with this cementation, which in turn increases the accumulation of soil organic carbon and creates a positive cycle (Six, Bossuyt, Degryze, & Denef, 2004). Fonte, Quintero, Velásquez, and Lavelle (2012) also found that soil organic carbon flux is faster in microaggregates than in macroaggregates.

In conclusion, straw mulching is conducive to the formation of soil aggregates, which are important vehicles for the formation and transformation of soil organic carbon and play an important role in the fixation of organic carbon.

6 | EFFECT OF STRAW RETURNING ON SOIL MOISTURE CONTENT

Soil water content is an important factor affecting the rate of straw decomposition. If the soil moisture content is too low, it will inhibit the activity of soil microorganisms and reduce the rate of straw decomposition; if the soil moisture content is too high, it will change the community structure of the soil microbes, inhibit the activity of soil microorganisms and enzymes, and reduce straw decomposition rate (Tang, 2017). Returning straw can reduce the evaporation of water caused by direct sunlight (Amir & Sinclair, 1996), reduce surface runoff (Bhatt & Khera, 2006), and improve soil saturated water conductivity (Zhang, Chan, Li, & Huang, 2008) and water infiltration (Singh & Malhi, 2006), thereby increasing soil moisture content.

7 | EFFECT OF STRAW RETURNING ON RICE AND WHEAT YIELD

The appropriate amount of rice and wheat straw returning can promote the growth of crop roots, reduce the evaporation rate of soil water, reduce evaporation, enhance soil water storage capacity, and create suitable soil moisture conditions for crop growth, thereby increasing rice and wheat yield, and within a certain range, the yield of rice and wheat increases as the amount of previous crop straw returning increases (Suriyagoda et al., 2014; Wu et al., 2012; Yang et al., 2004). However, if the amount of straw return is too high, the relatively high C/N ratio of the straw will promote the absorption of mineral nitrogen from the soil by microorganisms and reduce the nitrogen available for plant growth and development. So a large amount of nitrogen will be needed to support the growth of microorganisms during the early stage of decomposition of returned wheat straw in the rice season, reducing the ineffective tillering of rice, improving the population structure, and releasing many nutrients as the straw decomposes, thereby increasing the dry matter accumulation of the rice population from heading to maturity and improving yield. However, the soil mean temperature in wheat season is relatively lower, and the rice straw decomposes more slowly after returning, creating long-term "competition for nitrogen" between microorganisms and crops and hindering the growth and tillering of wheat, resulting in low effective panicle and panicle grain numbers and reducing wheat yields (Fog, 1988; Witt et al., 2000). In addition, in the early stage of straw decomposition, many organic acids, phenols, and other allelochemicals are produced, which will affect the growth of crops at the seedling stage (Hick, Wendt, Gannanway, & Baker, 1989; Ma, Liu, Yuan, & Sun, 1996; Shan, Cai, Han, Sarah, & Roland, 2006). Improper straw returning methods will result in the accumulation of a large amount of straw in the tillage layer, making it difficult to cultivate and reducing the quality of the soil preparation, which prevents crop seeds from fully contacting the soil, affecting the entire seedling and the crop roots and seriously affecting rice and wheat yield. Hu et al. (2015) found that compared with other straw returning rates, 25% (2,250 kg/ha rice straw, 1,500 kg/ha wheat straw) and 50% (4,500 kg/ha rice straw, 3,000 kg/ha wheat straw) straw returning rates most significantly increased rice and wheat yields. Zhu et al. (2015) also found that rice and wheat yields increased first and then decreased with increasing straw return rates, and the yields were the highest with a 50% (4,500 kg/ha rice straw, 3,000 kg/ha wheat straw) straw return rate. However, the research of Xu, Hu, Zhang, and Zhu (2016) showed that a 75% (6,750 kg/ha rice straw, 4,500 kg/ha wheat straw) straw return rate has the most significant effect on the annual yield of rice and wheat (Table 1). These differences may be attributed to the differences in climatic factors and soil physicochemical properties in the test areas, because the rate of straw decomposition was determined by hydrothermal conditions and soil physicochemical properties.

In the rice–wheat rotation system, the annual yield of rice and wheat can be significantly increased when the amount of wheat straw returned is 1,500–4,500 kg/ha in the rice season and when 2,250–6,750 kg/ha of rice straw is returned in the wheat season.

8 | EFFECT OF STRAW RETURNING ON ORGANIC CARBON IN THE RICE–WHEAT ROTATION SYSTEM

8.1 | Soil organic carbon loss pathway

Loss and decomposition mineralization are two main pathways for the loss of soil organic carbon. Loss refers to the migration of soil organic carbon with surface runoff (Kaiser & Guggenberger, 2005). Decomposition mineralization refers to the mineralization of soil organic carbon via the action of microorganisms to generate CO_2 and CH_4 that escape into the atmosphere; decomposition mineralization leads to the most loss of soil organic carbon (Li & Gao, 2008). When the soil is in an aerobic state, methane-oxidizing bacteria and other aerobic microorganisms in soil proliferate greatly, and the soil organic carbon mineralizes and is lost mainly in the form of CO_2; when the soil is in a reducing anaerobic state, the redox potential of the soil decreases, methanogens and other anaerobic microorganisms in the soil proliferate greatly, and soil organic carbon mineralizes and is lost mainly in the form of CH_4 (Chen, Lu, Duan, Wassmann, & Lantin, 2002; Le Mer & Roger, 2001; Sun, Liu, Wang, & Zhang, 2007). Studies have shown that in the rice–wheat rotation system, straw returning can significantly increase CO_2 and CH_4 emissions and accelerate the mineralization loss of soil organic carbon (Hu et al., 2016; Ma, Xu, Yagi, & Cai, 2008; Zhang et al., 2015).

8.2 | Effect of the amount of returned straw on soil organic carbon accumulation

Determining the appropriate amount of straw to return is generally based on two considerations: One is to maintain or even improve soil productivity and ensure the sound operation of the farmland ecosystem; the other is not to adversely affect that ecosystem.

Most studies at home and abroad have shown that compared with systems that do not use straw returning, straw returning can significantly increase the content of total organic carbon, labile organic carbon, and stable organic carbon in the topsoil (Nakajima et al., 2016; Wang, Lai, Wang, Pan, & Zeng, 2015; Wang, Yang, et al., 2015; 2017), and the total organic carbon content in soil increases within a certain range as the amount of returned straw increases (Dolan, Clapp, Allmaras, Baker, & Molina, 2006; Lou, Liang, et al., 2011; Lou, Xu, et al., 2011). After 20 years of positioning experiments, Li, Huang, Peng, Huang, and Zhang (2009) found that the total organic carbon content of straw-returned soils increased by 30.8% over that of soil without straw returning, and the additional organic carbon was mainly oxidized organic carbon. However, Chen et al. (2017) showed that straw returning has no significant effects on the content of oxidizable organic carbon in the soil. Wang, Lai, et al. (2015)) and Wang, Yang, et al. (2015)) also showed that straw returning could increase the content of labile organic carbon in the soil. However, Xu et al. (2006) found that although straw returning could improve the total organic carbon content of soil, it had no obvious effect on improving medium- and high-activity carbon content. This situation may be affected by the amount of straw returned.

TABLE 1 Effects of different amounts of returned straw on crop yields in the rice–wheat rotation system

Study	Straw returning amount	Rice yield (t/ha)	Wheat yield (t/ha)	Annual yield (t/ha)
Zhu et al. (2015)	0 kg/ha rice straw, 0 kg/ha wheat straw	8.46 c	4.69 b	13.15 b
	2,250 kg/ha rice straw, 1,500 kg/ha wheat straw	9.23 ab	5.59 a	14.82 a
	4,500 kg/ha rice straw, 3,000 kg/ha wheat straw	9.39 a	5.73 a	15.12 a
	6,750 kg/ha rice straw, 4,500 kg/ha wheat straw	9.17 ab	5.37 ab	14.54 a
	9,000 kg/ha rice straw, 6,000 kg/ha wheat straw	8.80 bc	4.72 b	13.52 b
Xu et al. (2016)	0 kg/ha rice straw, 0 kg/ha wheat straw	9.32 c	4.68 b	14.00 bc
	2,250 kg/ha rice straw, 1,500 kg/ha wheat straw	9.58 bc	5.09 ab	14.67 b
	4,500 kg/ha rice straw, 3,000 kg/ha wheat straw	9.70 b	5.37 a	15.07 ab
	6,750 kg/ha rice straw, 4,500 kg/ha wheat straw	10.52 a	5.08 ab	15.60 a
	9,000 kg/ha rice straw, 6,000 kg/ha wheat straw	10.56 a	4.82 b	15.38 a

Note: Different lower case letters within a column indicate significant differences at the 5% level.

Returning too much or too little straw is not conducive to soil organic carbon accumulation and crop growth. If the amount of straw returned is too high, because crop straw has a relatively high C/N ratio, it will compete with crops for nitrogen as it decomposes, affecting the growth of crops and the proliferation of microorganisms and thus affecting the decomposition of returning straw (Hu et al., 2015); if the amount of straw returned is too low, although the decomposing returned straw can increase the content of organic carbon in the soil to a certain extent, surface runoff and the mineralization of soil organic matter will consume more organic carbon, and the overall content of soil organic carbon will be reduced. Hu et al. (2015) showed that in the rice–wheat rotation system, compared with other straw returning rates, returning 50% rice and wheat straw (4,500 kg/ha rice straw, 3,000 kg/ha wheat straw) can significantly improve the total organic carbon and microbial biomass carbon content of the soil, while returning 25% rice and wheat straw (2,250 kg/ha rice straw, 1,500 kg/ha wheat straw) can significantly increase the water-soluble organic carbon and labile organic carbon content of the soil. Zhu et al. (2015) also found that the contents of total organic carbon, soluble organic carbon, easily oxidizable organic carbon, and carbon from microbial biomass in 0–21 cm deep soil under a 50% straw return rate (4,500 kg/ha rice straw, 3,000 kg/ha wheat straw) were significantly higher than those of soil with other straw return rates. The research results of Xu et al. (2016) showed that compared with other straw returning rates, a 75% rice and wheat straw returning rate (6,750 kg/ha rice straw, 4,500 kg/ha wheat straw) had the most significant effect on the improvement of the content and quality of soil organic carbon (Table 2). This difference may be influenced by climatic conditions such as water and heat and soil conditions such as soil texture, pH, and moisture content in the test area.

In summary, in the rice–wheat rotation system, if the amount of straw returned is too high or too low, it is not conducive to the accumulation of soil organic carbon, but

TABLE 2 Effects of different amounts of returned straw on the soil organic carbon pool in the rice–wheat rotation system

Study	Depth (cm)	Amount of straw returned	TOC (g/kg)	LOC (g/kg)	DOC (mg/kg)
Hu et al. (2015)	0~20	0 kg/ha rice straw, 0 kg/ha wheat straw	15.32 b	235.18 c	235.18 c
		2,250 kg/ha rice straw, 1,500 kg/ha wheat straw	16.25 a	376.92 a	376.92 a
		4,500 kg/ha rice straw, 3,000 k/ha wheat straw	16.37 a	314.03 b	314.03 b
		6,750 kg/ha rice straw, 4,500 kg/ha wheat straw	15.64 ab	232.40 c	232.40 c
		9,000 kg/ha rice straw, 6,000 kg/ha wheat straw	16.10 ab	336.25 ab	336.25 ab
Xu et al. (2016)	0~21	0 kg/ha rice straw, 0 kg/ha wheat straw	14.81 b	—	172.57 b
		2,250 kg/ha rice straw, 1,500 kg/ha wheat straw	15.53 ab	—	190.65 a
		4,500 kg/ha rice straw, 3,000 kg/ha wheat straw	15.49 ab	—	197.34 a
		6,750 kg/ha rice straw, 4,500 kg/ha wheat straw	15.63 a	—	199.73 a
		9,000 kg/ha rice straw, 6,000 kg/ha wheat straw	15.40 ab	—	189.38 a
Chen et al. (2017)	0~20	0 k/ha rice straw, 0 kg/ha wheat straw	15.64 b	—	445.50 b
		8,000 kg/ha rice straw, 5,000 kg/ha wheat straw	17.70 a	—	654.58 a

Note: Different lower case letters within a column indicate significant differences at the 5% level.

Abbreviations: DOC, dissolvable organic carbon; LOC, labile organic carbon; TOC, total soil organic carbon.

returning 1,500–4,500 kg/ha wheat straw during the rice season and returning 2,250–6,750 kg/ha rice straw during the wheat season show the most benefit in improving the content and quality of soil organic carbon.

8.3 | Effect of straw returning over consecutive years on soil organic carbon accumulation

The number of consecutive years of straw returning also affects the soil organic carbon content. Generally, the total organic carbon and labile organic carbon contents of the soil increase as the number of consecutive straw returning years increases, but the growth rate gradually decreases, and when the soil organic carbon content reaches saturation, the continued input of exogenous organic carbon triggers a priming effect and accelerates the mineralization of soil organic carbon. At that point, continuous straw returning will not increase the soil organic carbon content and will even lead to a decrease in soil organic carbon content (Cui et al., 2019; Hooker, Morris, Peters, & Cardon, 2005; Ranaivoson et al., 2017; Yemadje, Chevallier, Guibert, Bertrand, & Bernoux, 2017). There are different opinions about the effect of short-term straw returning on organic carbon accumulation in soil. Some people believe that short-term straw returning can increase the total organic carbon and labile organic carbon content of the soil and significantly improve the quality of organic carbon (Chen, Zhu, Liu, Shu, & Wang, 2008). However, some people think that short-term straw returning has no significant effect on the total organic carbon or labile organic carbon content of the soil (Guo, Zhang, Wang, Li, & Cao, 2014; Xu et al., 2006). This may be due to differences in the climate and soil environment and the amount of straw returning in different experimental areas.

In the rice–wheat rotation system, continuous and appropriate straw returning is beneficial for the accumulation of soil organic carbon. In the actual agricultural production process, taking into account the straw residue in the early stage of return to the field, the amount of straw being returned to the farmland during continuous straw returning should be appropriately reduced as the number of consecutive years of straw returning increases.

8.4 | Effect of straw returning methods on organic carbon accumulation in soil

The methods for returning crop straw can be divided into two categories, direct returning and indirect returning. Direct returning is a way to return straw directly to the field without treatment or after a simple treatment, which is usually performed in combination with soil tillage. Indirect returning refers to subjecting the straw to long-term high-temperature retting, microbial decomposition and other methods and then putting it into the field (Cui, Zhang, Wu, & Peng, 2014). Because of the heavy workload and high cost of indirect straw returning, in current agricultural production processes, straw is generally returned to the field directly.

The method of straw returning has a great influence on soil organic carbon accumulation. Straw tumbling is more conducive to total organic carbon accumulation in the soil than is straw mulching, but straw mulching is more conducive to the accumulation of labile organic carbon

(Wang, Wang, & Tian, 2014). Conventional mixed-rotating straw has better contact with the soil and decomposes more quickly than does soil with ditch-buried straw and thus can improve the soil organic carbon content, the easily oxidized organic carbon content, and the carbon pool management index in a short time, but they gradually reduce over time. However, the decomposition rate of straw buried in concentrated ditches is relatively slow; the soil organic carbon content will increase slowly over time, and the difference between the two will be smaller and smaller, and finally higher than that of soil subjected to straw conventional mixed-rotating (Wu, 2014). Plowing brings the returning straw in close contact with the soil, which results in faster straw decomposition and faster accumulation of soil organic carbon, but if the intensity of tillage is too large, it will destroy the original soil structure and increase the effects of drying–rewetting and freezing–thawing on the soil, intensifying the destruction of large carbon-rich aggregates in the soil, affecting the formation and stability of large aggregates, damaging the physical protection of organic carbon by aggregates, and forming many small aggregates containing organic carbon and free organic matter; however, the small aggregates have a limited ability to retain soil organic carbon, and the stability of free organic matter is poor, which accelerates the mineralization of soil organic matter and increases the loss of soil organic carbon (Beare, Hendrix, & Coleman, 1994; Chen et al., 2009; Mikha & Rice, 2004; Six, Elliott, & Paustian, 1999; Wang, Zhang, & Li, 2008; Yang, Han, Huang, & Pan, 2003). However, no tillage, low tillage, and other conservation tillage methods cause less disturbance to the soil, reduce the disturbance and destruction of soil aggregates, slow the turnover of soil macroaggregates, keep soil aggregates separated between areas of biological accumulation and mineralization, reduce the mineralization rate of the organic carbon in soil aggregates, prolong the storage period of organic carbon in the aggregates, slow the circulation rate in soil, and increase the soil organic carbon content (Barto, Alt, Oelmann, Wilcke, & Rillig, 2010; Dalal & Chan, 2001; Mikhailova, Bryant, Vassenev, Schwager, & Post, 2000; Muramoto & Werner, 2002; Oades, 1984; Paterson, 2003). Zhu, Hu, Yang, Zhan, and Zhang (2014) found that in the rice–wheat rotation system, the contents of organic carbon and labile organic carbon in the soil of fields with rice and wheat double-season straw returning are higher than that in soil with single-season straw returning; the content of total organic carbon in soil with wheat straw returned during the rice season alone was higher than that of soil with rice straw returned during the wheat season alone

TABLE 3 Effects of different straw returning methods on the soil organic carbon pool in the rice–wheat rotation system

Study	Depth (cm)	Straw returning method	TOC (g/kg)	DOC (mg/kg)	EOC (g/kg)	MBC (mg/kg)
Zhu et al. (2014)	0~7	No straw return	21.40 c	152.25 c	3.97 b	266.73 c
		Only rice straw return	23.01 bc	177.61 b	4.88 ab	411.67 b
		Only wheat straw return	23.65 b	176.92 b	6.23 a	398.57 b
		Rice and wheat straw both return	25.68 a	204.04 a	6.32 a	535.79 a
	7~14	No straw return	16.28 c	141.49 d	3.62 c	172.63 c
		Only rice straw return	17.63 bc	167.39 b	3.90 bc	315.19 b
		Only wheat straw return	18.50 b	155.47 c	4.39 ab	313.93 b
		Rice and wheat straw both return	21.47 a	189.98 a	5.04 a	434.09 a
	14~21	No straw return	9.28 d	136.34 b	2.58 c	114.99 d
		Only rice straw return	10.99 c	123.67 c	3.66 b	239.95 b
		Only wheat straw return	11.97 b	161.19 a	3.91 b	238.92 c
		Rice and wheat straw both return	13.56 a	162.93 a	4.90 a	341.67 a
Wang, Zhou, Huang, Li, and Cao (2013)	0~20	Plowing tillage with no straw return	28.52 b	—	7.54 b	1.15 a
		Plowing tillage with straw return	32.05 a	—	13.06 a	1.20 a
		No tillage with straw return	31.39 a	—	14.37 a	1.50 a

Note: Different lower case letters within a column indicate significant differences at the 5% level.

Abbreviations: DOC, dissolvable organic carbon; EOC, easily oxidizable carbon; MBC, microbial biomass carbon; TOC, total soil organic carbon.

(Table 3), and this may be related to the higher soil water content and temperature during the growth period of rice and the faster rate of straw decomposition. However, the amount of decomposed straw during the wheat growth period may still be more than that during the rice growth period because the wheat growth period is longer and the decomposing rate of returned straw during the wheat season is slower than that of returned straw during the rice season. Liu et al. (2007) showed that after one season of wheat planting, the residual percentage of straw in the topsoil is approximately 60%, and that in the middle and lower layers is approximately 40%; after one season of rice planting, the residual percentage of straw in the topsoil is only approximately 25%, while that in the middle and lower layers is only approximately 20%.

In summary, the combination of straw returning with conservation tillage measures, such as no tillage and less tillage, is conducive to the accumulation of soil organic carbon. In the current agricultural production process, if the sustainability and long-term nature of straw returning are considered, ditch-buried straw return is an ideal method. In the rice–wheat rotation system, because the soil conditions in the rice season are more conducive to straw decomposition, the amount of returned straw in the rice season can be appropriately increased, and the amount of returned straw in the wheat season can be reduced.

8.5 | Effect of soil moisture content on soil organic carbon accumulation under straw returning

Some studies have found that returned straw decomposes faster in the range of 15%–22.5% soil water content and slower when it is lower than 15% (Jiang, Yang, et al., 2001; Jiang, Yu, et al., 2001; Zuo & Jia, 2004), while soil organic carbon decomposes the fastest when the soil water content is medium (60% water-filled pore space; Jassal, Black, Novak, Gaumont-Guay, & Nesic, 2008; Linn & Doran, 1984; Oberbauer et al., 1992). Gao (2015) showed that the soil organic carbon content decreased with increasing soil water content under aerobic conditions, while under anaerobic conditions, the soluble organic carbon content of the soil increased with increasing soil water content. Some studies have shown that the anaerobic environment produced under waterlogging conditions could reduce the species and abundance of soil microorganisms, thereby reducing the mineralization rate of soil organic matter and increasing the content of soil organic carbon (Kabiri, Raiesi, & Ghazavi, 2016; Muhammad, Aziz, Brookes, & Xu, 2017). From the above description, when the soil water content is moderately low (15%–22.5%), it is conducive to the accumulation of soil organic carbon.

9 | CONCLUSION

In the actual agricultural production process, much crop straw was burned directly due to a lack of straw utilization technology and high production costs, which not only wasted many organic fertilizer sources but also caused serious environmental pollution. In recent years, with the implementation of a straw burning ban, returning straw directly to the field has become the most economical and convenient method of straw disposal. Due to the lack of a systematic straw return theory, the straw returning method commonly used by farmers in the production process has many adverse effects on the maintenance and improvement of soil fertility and the realization of sustainably high crop yields. In this paper, we conclude that in the rice–wheat rotation system, returning 1,500–4,500 kg/ha rice straw and 2,250–6,750 kg/ha wheat straw to the field promotes increased soil organic carbon content and quality, as well as high annual grain yield. Conventional mixed-rotating straw is in full contact with the soil, which can increase the soil organic carbon content in a short time. But if the sustainability and long-term nature of straw returning are considered, it is ideal to bury the straw in a concentrated ditch. Combining conservation tillage, such as no tillage or less tillage, straw returning can improve the content and quality of soil organic carbon. When the soil moisture content is 15%–22.5%, the rate of straw decomposition is faster and the mineralization rate of soil organic matter is slower, which provides the most benefit for the accumulation of soil organic carbon.

In recent years, with continuous increases in rice and wheat production, the production of rice and wheat straw is also increasing, and excessive straw returning will not only affect the quality of cultivated land and the emergence of crops but also affect the growth and development of crops due to allelopathy after straw returning; in addition, the pathogens and the eggs, larvae, and pupae of the pests remaining in the returned straw will also increase crop diseases and pests. Therefore, the next focus in agricultural research should include the following: screening of the straw-decomposing bacteria, improving the decomposition rate of returned straw, strengthening research on the allelopathic effects of straw returning and building a comprehensive prevention and control technology system to reduce the harmful factors of straw returning, developing a new type of special fertilizer for rice and wheat straw returning that will kill pathogens and pests and optimize fertilization to make up for the deficiency of nitrogen in crop straw, avoid competition with the crop for nutrients in the process of straw decomposition, and reduce or even eliminate the influence of diseases and pests caused by straw returning on the subsequent crop. It is needed to develop new technologies and equipment for straw returning and other utilization methods to improve the utilization efficiency and benefit of straw. Quantification of the optimal amount of straw returning suitable for local agricultural production based on the holistic situations of different regions will be crucially important.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

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