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Original Research

Research Advances on Carbon-Water Relationship of Forest Litter-Soil Interface

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Abstract

Litter is an important part of terrestrial ecosystem. It affects the formation of soil organic matter, the supply of plant nutrients and the absorption and storage of soil carbon. In order to explore the mechanism of carbon water coupling at litter soil interface and the interaction between the two, this study focuses on the changes of litter characteristics during litter decomposition and its impact on soil carbon pool and soil carbon water relationship. Litter decomposition is mainly reflected in the reduction of litter volume and carbon content. In the study of litter, scholars pay more attention to the rate of litter decomposition and the release of nutrient elements and other trace elements and organic constituents during litter decomposition. And the litter decomposition is significantly affected by temperature and moisture. Litter decomposition also has significant effects on soil organic carbon, soil respiration and chemical nutrients. The soil water holding capacity is enhanced during litter decomposition. The changes of soil water content contribute to the changes of soil structure and physical and chemical properties, and then affect the stability of soil organic carbon and soil microbial activity. This study is of great significance for accurately predicting the dynamic changes of carbon and water at the litter soil interface and the carbon cycle of terrestrial ecosystem in the future, which also provides a reference for the further study of the related mechanism of forest litter soil interface.

Keywords: the decomposition of litter, carbon-water relationship, water holding capacity, carbon flux

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Introduction

As an important part of terrestrial ecosystem, litter plays an important role in the nutrient cycle of soil and atmosphere [1]. The input of litter is the main source of soil organic matter and it is also an important factor to determine the quality and quantity of soil organic matter. The decomposition process of litter is mainly affected by litter matrix quality, soil, climate and biology [2]. The research methods of litter decomposition mainly include field decomposition bag method, indoor decomposition culture method, current quantity estimation method, isotopic tracer method and the detritus input and removal treatment (DIRT) [3-7]. In recent years, scholars at home and abroad have made relatively mature research results and theoretical basis on litter decomposition, element migration and transformation, and intercepted precipitation [8-10].

Litter layer is an important channel between vegetation and soil, and its decomposition process is a material cycle process dominated by carbon [11]. It also has a significant role in the terrestrial carbon cycle (Fig. 1). On the whole, the net content of carbon decreases during decomposition, and there are some differences in different decomposition periods [11]. Litter is the main source of topsoil organic matter, and plays an important role in changing soil properties, soil bulk density and porosity [12]. Quantifying the regional scale model of the current stock distribution of litter and studying the decomposition process of litter will help to improve the understanding of the mechanism of terrestrial carbon cycle and promote the accurate prediction of the response of terrestrial carbon cycle to future climate change [13].

This study focuses on carbon water coupling mechanism of forest litter-soil interface. To address this issue, several electronics databases were searched for relevant articles reporting three aspects: (1) the variation characteristics of water holding capacity and carbon content during litter decomposition, (2) the influence of litter on soil carbon pool, (3) the influence of litter on the relationship between carbon and water. This study contains a comprehensive review of different studies in the above three aspects, which provides the effects of litter decomposition process on soil carbon water mechanism. The results are of great significance for predicting soil carbon water coupling considering the process of litter decomposition, and the study also points out the key scientific problems in this field, and puts forward the research prospect.

Results and Discussion

Based on observations and analyses, litter decomposition affects soil carbon pool by affecting its own water holding characteristics and carbon content, so as to regulate soil carbon water relationship and promote the study of carbon water coupling mechanism at litter soil interface (Table 1). To clarify the carbon water coupling mechanism of litter soil interface, we investigate the changes of water holding capacity and carbon content of litter and the interaction with soil carbon and water during decomposition.

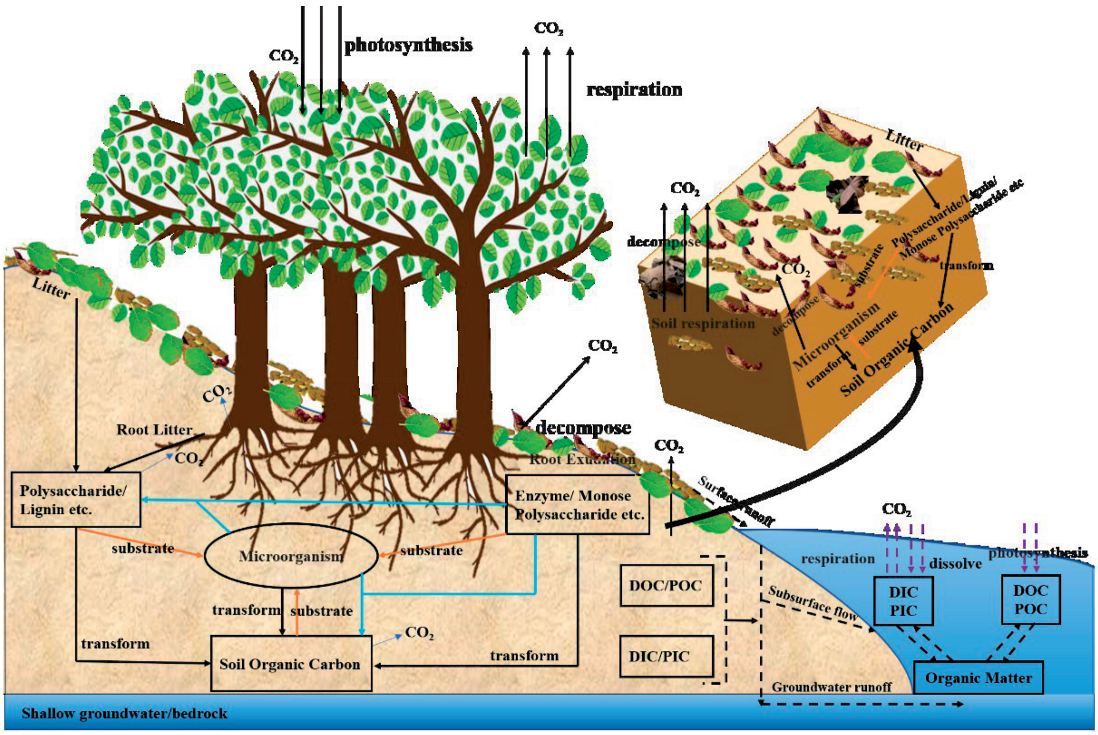

Fig. 1. Carbon cycle between litter and soil.

Table 1. A synthesis of the impacts of Carbon water coupling at litter soil interface.

Country, study site	Methods	Contents	Impact types	Impacts	Reference
Australia, Southeast Queensland	A 15-month in situ field experiment by changing the amount of litter	The effects of changed litter inputs on soil labile carbon (C) and nitrogen (N) pools	Carbon pool	After 15-month of decomposition, mean litter mass loss was 46.3% and 31.2% at the HQ and LQ sites, respectively.	[3]
China, Loess Hilly Region	Simulate the decomposition process of single leaf litter, mixed leaf litter and root by using litter bag	The effects of litter decomposition on soil chemical and biological properties. the correlation mechanism between litter decomposition characteristics and soil properties		The decomposition of litter and root had significant effects on soil organic carbon (SOC), chemical properties and microelements. Litter carbon presented wave release, with a release rate of 64.3~85.1%.	[6]
Germany, Thuringia	Partitioning of ^{13}C-labeled root or leaf litter C to CO_2.	Quantify medium term litter type. litter mixture effects on the translocation and transformation dynamics of root and leaf litter C during decomposition.		The proportions of C mineralized from ash leaf (34%) and root litter (29%) were higher than those from beech leaf (24%) and root litter (23%).	[14]
Austrian, Rosalien Mountains	Removed the litter layer and determine soil GHG fluxes with static chambers	How the litter layer controls soil GHG fluxes and microbial decomposer communities		Litter removal reduced CO_2 emissions by 30% and increased temperature sensitivity of CO_2fluxes. Diffusion of CH_4into soil was facilitated by litter removal and CH_4 uptake increased by16%.	[15]
Italy, Central	^{13}C-labelled, Gas chromatography (GC), GC-mass spectrometry (MS) and GC-combustion-isotope ratio (GC/C/IRMS)	Quantifying different fluxes of C lost by leaf litter decomposition		The litter had lost about 80% of its original weight. The fraction of litter C lost as an input into the soil (67±12% of the total C loss) was found to be twice as much as the fraction released as $CO_2$to the atmosphere (30±3%).	[16]
China, Natural honey secondary, Hebei	Geostatistical theory and methods	Quantifying the spatial heterogeneity of topsoil moisture and litter layers of different degree of decomposition	Soil water	Surface soil moisture and a decomposition layer had strong spatial correlation. the surface soil moisture and the spatial distribution pattern of litter had no significant to heterogeneity of structure characteristics.	[17]
Ivory Coast, Southern	Litter bags	Characterize the dynamics of the leaf litter decomposition and soil physico-chemical and biological parameters in rubber plantations of different ages.		The amount of soil water content and carbon/ nitrogen ratio significantly increased with the aging of the rubber plantations.	[18]
Argentina, Patagonian Monte	Litter bags	Explores the combined effects of UV radiation, soil water content, and litter mixtures with different proportions of shrubby components on litter decomposition.		Mass loss of litter was higher at high soil water content than at low soil water content. High soil water content was associated with the highest mass loss rates.	[19]
China, Northern	Optimal nonlinear equations Two treatments of litter and no litter Measuring soil respiration by chamber	The effect of aboveground litter on soil respiration		Aboveground litter had a significant effect on soil water content. Litter removal significantly decreased soil respiration and soil water content for all stand ages.	[20]

Variation Characteristics of Water Holding Capacity and Carbon Content during Litter Decomposition

Litter decomposition is completed under the comprehensive action of litter and enzyme system in soil. It usually consists of three sub-processes, namely leaching process, microbial degradation process and fragmentation process [21] (Fig. 2). Litter decomposition is mainly reflected in the reduction of litter volume and carbon content.

The core collection of Web of Science was used as the literature retrieval database, and "Litter, Soil Water and Soil Carbon" were used as the basic retrieval conditions. We found that the research on litter decomposition process at home and abroad mainly includes three aspects: (1) Some scholars have made some research on the rate of litter decomposition [22-25]. The CO_2 released by litter decomposition has obvious time variation characteristics. It is obviously affected by soil temperature and hydrothermal conditions [26]. The decomposition rate of different types of litter is also different. Mun S. et al. found that root decomposed more rapidly than stem litter at the later stage of decomposition by using the litterbag method [22]. (2) Release of nutrient elements (C, N, P) and other trace elements (S, Fe, Hg) during litter decomposition [22, 27-29]: previous studies have shown that the net release of carbon occurs in the process of litter decomposition, and the release decreases gradually with the increase of time [30-32]. The study of Mun S. et al. [22] reflected that approximately 86% of organic matter, 79% of N, 98% of P, 96% of K and Mg, and 67% of Ca were returned to the soil environment after 22 months through decomposition. (3) Release of organic constituents (lignin, carbohydrates, phenols, etc.) during litter decomposition [33-35]: the lignin content of litter showed the characteristics of fluctuating increase, gradual decrease, fluctuating increase and slight decrease [6]. As time went on, the lignin accumulation index showed the characteristics of fluctuating enrichment, gradually release, fluctuating enrichment and small release [6]. The study of Ma Z.L. et al. in subtropical evergreen broad-leaved forest showed that the concentration of cellulose in six kinds of litter had a downward trend, and the absolute amount of cellulose was released, and the decomposition of lignin litter was released first and then enriched [35].

Litter decomposition was positively correlated with water change. The weight loss rate and CO_2 emission of litter under high moisture conditions were higher than those under low moisture conditions [36, 37]. With the increase of water content, the utilization of substrate by microorganisms was enhanced, which made the rate of litter decomposition increased [38]. Although carbon mineralization is closely related to water, the effect of water on litter decomposition is not unique. To a certain extent, it can promote the litter decomposition, but it also may inhibit the litter decomposition with the change of water content.

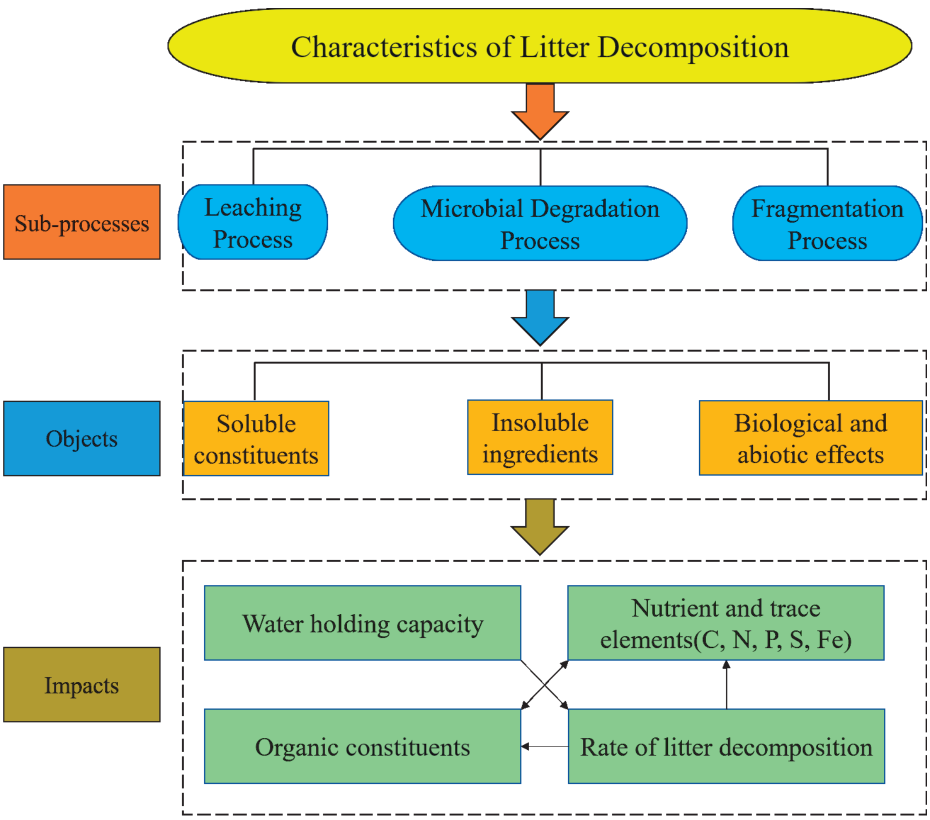

Fig. 2. Influence of litter decomposition on its characteristics.

Temperature and humidity have significant effects on the mineralization and humification of litter. They not only affect the mineralization rate of litter, but also affect the limit value of carbon loss in the process of organic matter mineralization [39]. When the water holding capacity of litter reaches more than 70%, the emission of CO_2 shows a decreasing trend [39].

Influence of Litter on Soil Carbon Pool

Soil is the largest carbon pool in terrestrial ecosystem, mainly including organic carbon pool and inorganic carbon pool. For soil inorganic carbon, the storage is small and relatively stable, while the storage of organic carbon is more within 1m depth, and shows obvious surface accumulation [40]. Litter decomposition affects soil carbon pool mainly by affecting soil inorganic carbon and organic carbon (Fig. 3). During the litter decomposition, the change of carbon can reflect soil nutrient supply and plant nutrient utilization [41]. The carbon in litter is mainly distributed in the form of mineralization, dissolved organic carbon leaching and fixation in mineral soil [14]. About 10%~25% carbon in litter is leached as dissolved organic carbon and transported to the soil layer. The dissolved organic carbon of fresh litter may not only be an important source of shallow soil organic carbon storage, but also an important source of carbon flux in soil, aquatic system and atmosphere [42].

Influence of Litter on Soil Organic Carbon

The organic carbon in litter is inhibited by the adsorption between organic carbon and soil matrix, and the direct assimilation and mineralization of soil microorganisms through the migration of soil profiles. The flux of dissolved organic carbon is an important mechanism for transporting carbon from litter to deep soil, and affects the formation of stable soil organic carbon compounds.

In recent studies, the detritus input and removal treatment and field decomposition bag method are often used to study how the input source and rate of litter affect the dynamic process of soil organic matter and nutrient accumulation. Scholars at home and abroad have conducted a lot of researches by the detritus input and removal treatment [43, 44]. They found that the content of soil organic carbon decreased with the decrease of litter input at the first 5 years of the experiment [43]. The addition of litter in the whole ecosystem increases the organic carbon of surface mineral soil, and a large amount of new carbon input can make up for the old carbon decomposed in the excitation effect [44]. The decomposition of litter has a significant impact on soil organic carbon, chemical nutrients and trace elements in soil [6]. With the continuous of litter decomposition, soil organic carbon shows the characteristics of fluctuating decline and rapid rise [6]. By using the Detritus Input and Removal Treatments, Bowden R.D. et al. found that soil organic carbon was reduced by 24% and 33% with

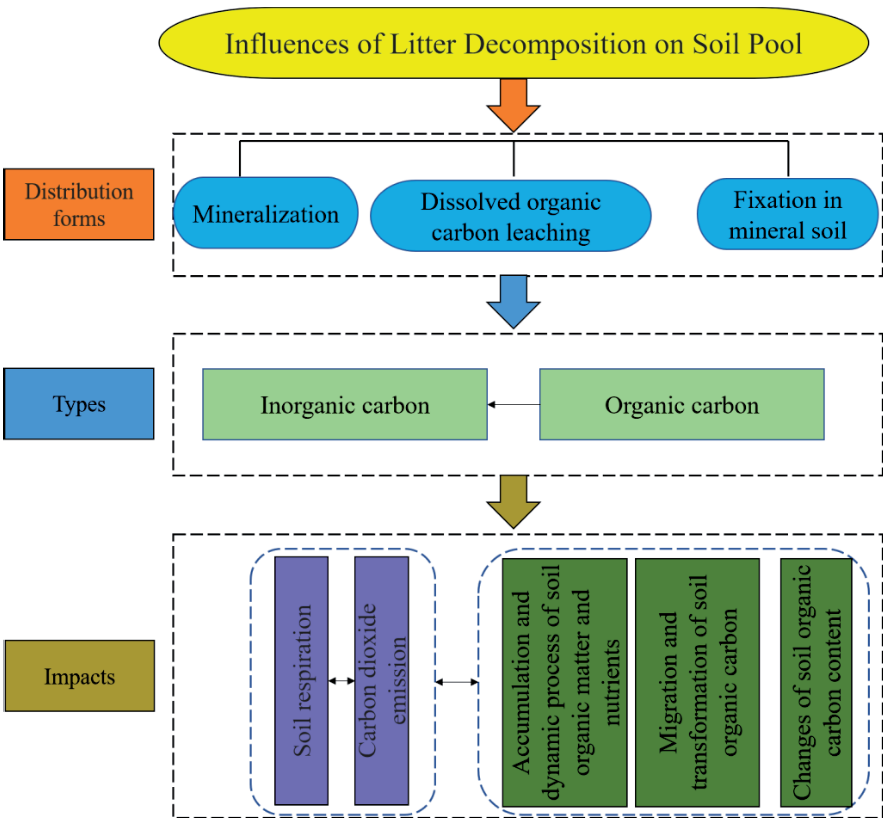

Fig. 3. Influence of litter decomposition on soil carbon pool.

litter removal and no litter input, respectively [45]. Some scholars also found that the organic carbon of 0-50cm soil decreased by 18% after removing litter in Harvard Forest [46]. In addition, there are some differences in the effects of aboveground and underground litter on soil carbon. The control effect of root carbon input on soil carbon concentration and microbial community structure is stronger than that of aboveground litter. The input of underground litter has a greater impact on soil carbon than aboveground litter, but the impact of aboveground litter on soil carbon storage is variable. Wang Y. et al. found that the doubling of aboveground litter significantly increased the organic carbon content and active carbon metabolism of oak forest, while pine forest did not by studying the carbon input of different types of litter and underground roots [47].

However, some scholars have obtained different research results. Whatever the quality and quantity of litter, the content of soil active carbon did not change significantly due to the change of litter input. It may be that the soil unstable carbon pool is resistant to the short-term change of litter input [3]. The addition of litter had no significant effect on soil carbon pool, and the reason for the phenomenon may be that the potential soil carbon loss is offset by the increase of litter carbon input [48].

Influence of Litter on Soil Inorganic Carbon

In order to research the effect of litter input on soil CO_2 emission, carbon isotope and infrared gas analyzer system are used to measure soil respiration rate. Soil respiration increased significantly with the addition of litter, and the removal of litter and roots significantly reduced the soil respiration rate [49, 50]. Soil respiration is obviously affected by soil temperature, soil water content, litter removal and root system. Soil respiration increases with the increase of soil water content until it reaches the threshold, and then decreases [51].

Studies have shown that litter layer decomposition accounts for about 5% to 45% of the total soil CO_2 emission [15, 52]. In order to reveal the mechanism of continuous mineralization and transformation of carbon in litter, Rubino et al. found that 2/3 of the carbon in the litter enters the soil in the form of soluble carbon or debris and 1/3 enters the atmosphere in the form of CO_2 by using ^{13}C isotope tracing technology [16]. The addition of litter had a significant effect on the rate of soil CO_2 release, and also significantly increased the contents of soil dissolved organic carbon and microbial biomass carbon [53].

Influence of Litter on Soil Water

Litter cover can improve the vertical spatial distribution of rainfall runoff, reduce surface runoff, and significantly increase soil interflow and base flow. Litter can effectively absorb and intercept water, thus affecting the distribution and dynamics of soil water. Surface litter regulates soil water content by reducing soil evaporation and absorbs part of precipitation, while root exclusion will increase soil water due to the loss of transpiration [49, 54]. The litter layer affects the distribution and dynamics of soil moisture by inhibiting the evaporation of soil moisture.

The amount of litter directly determines the ability of different litter types to retain water to conserve water and affect soil water holding capacity. A certain thickness of litter layer can keep the soil water content in a relatively stable state [55]. Studies have shown that with the increase of the thickness of the litter layer, the effect of the litter layer in inhibiting soil evaporation is greater [56]. The main reason is that after the soil surface is covered with litter, the direct exchange of evaporative water on the soil surface and atmospheric water vapor is hindered, the refraction, reflection and absorption of sunlight are increased, the evaporation power is reduced, and the soil evaporation is reduced. In addition, with the increase of litter thickness, the migration distance of water molecules in the litter increases, evaporation resistance increases, and evaporation decreases. The study of Han et al. found that soil moisture was usually reduced after the removal of litter, and soil moisture showed a downward trend [57].

Influence of Litter on the Relationship between Carbon and Water

Litter layer can change the effective amount of soil infiltration runoff, and the water holding capacity of litter is an important parameter of hydrological simulation [58]. The relationship among litter, soil carbon and soil water is not single, but related to each other (Fig. 4). Surface litter regulates soil water content by reducing soil evaporation and absorbs part of precipitation, while root exclusion will increases soil water due to the loss of transpiration [49]. Litter can effectively absorbs and intercepts water, reduces surface evaporation and improves the soil water content. After the decomposition, litter enters the soil which enhances the water holding capacity of soil by absorbing water. The decomposition of litter has a significant impact on the improvement of soil physical and chemical properties, soil water holding capacity and soil microbial activities [59].

In the terrestrial forest ecosystem, the litter layer significantly reduces the soil temperature, which leads to the decrease of the activity of plant roots and soil microorganisms, and then reduces the decomposition rate of soil organic matter [60]. Furthermore, the litter layer can also affects the decomposition rate of soil organic matter by its own water holding capacity [54]. The changes of soil water content can change soil structure and soil physicochemical properties, and affect the stability of soil organic carbon and soil microbial activities. The interaction between water and litter has a significant effect on the content of soil

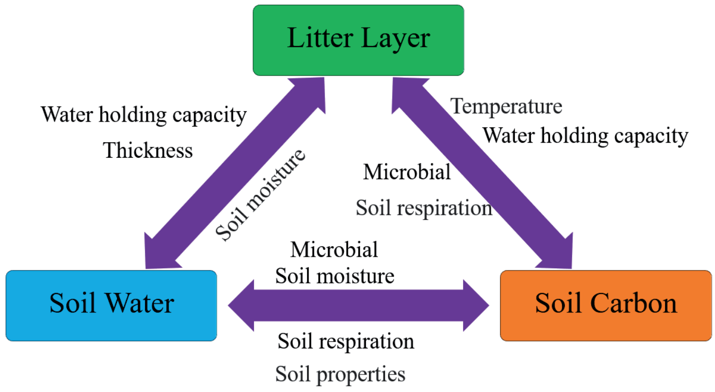

Fig. 4. Conceptual figure of interaction among litter, soil carbon and soil water.

soluble organic carbon. The change of water affects the activity of microorganisms in soil, thus affecting the decomposition of litter and the release of litter nutrients, and finally leading to the change of bioavailable substrate [61].

To a certain extent, the soil water content inhibits the decomposition of litter. The gas exchange between soil and litter is interdicted due to high moisture content. After the original is exhausted, the soil is in an anaerobic environment, and the decomposition of soil microorganisms is also affected [62]. The litter layer affects the distribution and dynamics of soil moisture by inhibiting the evaporation of soil moisture. A certain thickness of litter layer can keeps the soil water content in a relatively stable state, which is very beneficial to soil microbial activities and community distribution [54]. Soil moisture condition and hydrological fluctuation are important factors affecting litter decomposition. The change of soil moisture content will affects soil aeration and the transformation of soil organic matter [63]. The difference of soil moisture content leads to the difference of soil aeration conditions, which affects the decomposition rate of soil organic matter and litter [64]. Water and the coverage of litter can affect the release of soil carbon, and the release rate decreases with the increase of training cycle. The effect of soil moisture on soil respiration is not only promoted or inhibited, but also a bidirectional regulation [65].

Temperature and moisture are key environmental factors affecting carbon flux. Studies have shown that soil carbon flux is positively correlated with temperature, humidity and organic carbon content [66]. Soil moisture affects soil respiration mainly by affecting soil physical and chemical properties and soil microbial activity. Within a certain range of soil water content, the CO_2 emission rate increases with the increase of soil water content, and varies with the soil organic carbon content. The researches have shown that 60%-70% water content is most conducive to soil respiration, and soil moisture that is too low or too high will inhibit soil CO_2 release [67, 68]. High water content will reduces soil voids and oxygen content, which will inhibits soil microbial respiration and gas exchange process [69]. The impact of soil moisture on soil C and nutrient dynamics cannot be ignored because soil microbes mediate these processes, and fluctuations in microbial activity in response to changes in soil moisture are prevalent [70]. The research of Tu shows that the relationship between soil water content and soil respiration is not a simple linear relationship, and there is a nonlinear coupling relationship between carbon and water [71].

Summary and Prospect

At present, the research on the mechanism of carbon water relationship at the litter soil interface mainly focuses on the litter decomposition process, and comprehensively uses the technical means such as indoor simulation control experiment and field prototype observation to study the release and decomposition rate of various elements in the litter decomposition process. The overall performance are as follow: (1) The research on litter mostly focuses on the relevant theoretical analysis of litter decomposition rate, mineralization process and element release, while the relevant theoretical equations or relevant equations of litter decomposition are rarely modified by comprehensively considering various factors; (2) Based on control experiment and *in-situ* observation experiment and combined with the characteristics of each element over time, the related impact analysis is analyzed, while the research on mechanism is relatively few; (3) There are many studies on the relationship between litter and soil respiration, but less attention is paid to the litter soil interface. Especially under the influence of litter, how the interface carbon water relationship changes and the theoretical equation between them. In conclusion, the future research on the relationship between carbon and water at the litter soil interface needs to be strengthened in the following aspects.

1) The study on decomposition process of litter with different humification degree should be strengthened. At present, the research on litter decomposition

process is mainly through long-time series field in-situ observation. However, the composition of litter with different humification degrees is different, and the determination of litter humification degree lacks corresponding evaluation parameters. Therefore, it can be considered to combine the advantages of control experiment and prototype observation in later research, and determine the evaluation parameters of litter humification and focus on the decomposition of litter with different humification degrees.

2) Strengthen the research on the influence mechanism of litter decomposition process on litter water holding capacity and soil water movement, comprehensively consider various influencing factors, and carry out the research on relevant theoretical equations or models of litter decomposition.

3) Strengthen the study on the mechanism of litter soil interface. The carbon water process at the interface was studied by considering the relevant influencing factors of litter decomposition, and quantifying carbon release during litter decomposition and its influence mechanism on soil carbon flux.

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Conflict of Interest

The authors declare no conflict of interest.

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