Research Progress on Effects of Continuous Cropping on Soil Microbial Florae and Its Restoration

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Abstract Continuous cropping has become a common form of agricultural production at present, but with the increase of continuous cropping years, continuous cropping obstacles such as soil-borne diseases and plant growth potential decline are becoming more and more common. At present, the causes of continuous cropping obstacles and continuous cropping restoration have become a hot issue in agricultural research. This paper summarized the effects of continuous cropping obstacles on soil microbial community structure and main technical methods to repair continuous cropping obstacles, such as agricultural measure management, microbial balance adjustment and soil improvement, aiming to provide theoretical reference for protecting the sustainable utilization of soil ecosystem and ensuring the stability of crop production.

Key words Continuous cropping obstacle; Rhizosphere soil; Microorganism; Soil remediation; Soil improvement

DOI:10.19759/j.cnki.2164-4993.2024.02.019

Due to the growing population base in the world, food production should also meet the growing population demand. Soil is the basic material for agricultural production. However, due to the limited amount of arable land available in the world and the fact that arable land is constantly occupied by the development of modern society, in order to ensure the stable supply of food and the sustainable development of social economy, specialized and highly-intensive agricultural planting methods have gradually become the main planting mode in China and even in the world. Continuous cropping refers to planting crops of the same species or the same family for more than two consecutive crops in the same field. After continuous cropping, even under normal cultivation and management conditions, plant diseases and pests will intensify, plant growth will be weakened, and yield and quality will decline. Such phenomena are called continuous cropping obstacles. Various manifestations of continuous cropping obstacle leading to the decrease of soil quality, plant yield and quality are called "continuous cropping diseases" in China[1], and it is called replant diseases or replant problems abroad[2]. Continuous cropping does bring some economic benefits in short-term production, but with the increase of continuous cropping years, many negative effects will continue to emerge. In order to realize the sustainable development and utilization of agricultural production, agricultural producers have to find new soil remediation methods or alternative ways to carry out reasonable land production management. The study of Wyngaard[3] shows that under the long-term continuous cropping mode, soil nutrients were reduced, and the contents of organic carbon, total nitrogen, available phosphorus and available potassium in the soil were significantly reduced. The main reason for the decrease of soil nutrients in the process of continuous cropping is that soil nutrients are absorbed by crops, thus inhibiting the mineralization of C and N, further limiting material transformation and material circulation, and further affecting soil nutrients. Microorganisms play an irreplaceable role in soil formation and decomposition and transformation of organic matter, and the richness of microorganisms and community composition structure further determine the basic trend of sustainable land use and sustainable agricultural development. Nowadays, the sustainable development of agricultural production has gradually become normal with the continuous cropping of land use, but in order to realize the sustainable development of agriculture, we have to actively explore new methods to restore and improve land.

At present, continuous cropping obstacles have become the main obstacle to sustainable development and utilization of soil and the safe production of food. Studies show that continuous cropping has a direct impact on microbial community structure, and the main reason for continuous cropping obstacles is that the structural balance of biological florae in soil ecosystem is destroyed. Therefore, scholars at home and abroad study the succession law of microbial florae in the soil with continuous cropping and the influence of continuous cropping on microbial florae, so as to further clarify the dominant functional flora in soil microbial community, including introducing some special functional florae and beneficial soil microbial populations for balancing and restoring the original microbial community and then inhibiting the proliferation of pathogenic bacteria, which is of great significance to effectively alleviating

Received: December 15, 2023 Accepted: February 18, 2024

Supported by National Natural Science Foundation of China (42067009); Scientific Research Project of Yunnan Provincial Department of Education (2024Y742; 2023Y0863); Project of Kunming Municipal Commission of Development and Reform (Kunming Spring City Industrial Technology Leading Talents); Science and Technology Major Project of Yunnan Province Science and Technology Department (202202AE090015-02); Yunnan Students' innovation and entrepreneurship training program (S202311393044; S202311393061).

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continuous cropping obstacles. The research on the remediation of continuous cropping soil has become a hot research direction for the healthy development of agriculture. Therefore, this paper summarized the main causes and harm of continuous cropping, the changes of soil microbial florae in the root system with continuous cropping and the research progress of later remediation, aiming to provide theoretical reference for the healthy production of agricultural soil environment.

Harm of Continuous Cropping Obstacles

The hazards caused by continuous cropping obstacles mainly include but are not limited to the aggravation of soil-borne diseases, the destruction of soil structure, the imbalance of microorganisms and the decline of plant quality. Soil microbial community structure is significantly related to soil chemical properties[4], and He *et al.* [5] found that the disease index of bacterial wilt and black shank increased with the increase of continuous cropping years. Yao *et al.* [6] found that soil pH, ammonium nitrogen, available potassium, microbial biomass carbon content and soil enzyme activity decreased gradually with continuous cropping years. Li *et al.* [7] found that continuous cropping obstacles not only affected the quality and yield of strawberries, but also the survival rate of strawberry planting. Li *et al.* [8] have found that continuous cropping led to the disorder of normal metabolic pathway of plants, which affected normal life activities of plants.

Main Causes of Continuous Cropping Obstacles

Accumulation of toxic substances in plants

Continuous cropping often affects the quality and yield of crops, and plants will release toxic substances to surrounding environment or plants through volatilization, leaching, root secretion or residue decomposition in the process of continuous cropping for many years[9]. After years of continuous planting of a single crop, the accumulation of toxic substances in the soil increases, which shows a series of continuous cropping obstacles such as structural damage of soil, imbalance of soil microbial florae, and decline of plant quality[10]. Plant root exudates include root substances that can activate soil nutrients and promote nutrient absorption and utilization, as well as root autotoxic substances that inhibit crop growth[11]. Yin *et al.* [12] believe that phenolic acids are the main autotoxic substances in root exudates of apple continuous cropping. In the continuous cropping system, the content of phenolic acid type of autotoxic substances in cultivated soil is accumulating with the increase of continuous cropping years, which not only inhibits the growth of crops themselves, but also intensifies the occurrence of diseases. The autotoxicity of root exudates on cucumber seed germination and seedling growth under different planting patterns increased with the increase of cucumber seedling culture times[13]. Wei *et al.* [14] found that root exudates and extracts of *Panax notoginseng* in continuous cultivation soil also showed significant autotoxicity on seedling emergence and growth.

Destruction of soil microbial balance

The formation of soil is inseparable from the interaction of microorganisms. A healthy soil environment is the result of the dynamic interaction between different microorganisms, and the change of microbial population ratio is closely related to the occurrence of continuous cropping obstacles[15]. Continuous cropping obstacles are the result of many factors, and the main reason is the imbalance of the proportion structure and diversity of beneficial microorganisms and pathogenic microorganisms in soil microflorae, which leads to plant diseases. The study of Limei *et al.* [16] showed that phenolic acids in the soil of continuous cropping *Panax notoginseng* could promote the growth of pathogenic bacteria, and the interaction between rhizosphere soil microorganisms and phenolic acids was the main reason for the disorder of rhizosphere microbial community of *Panax notoginseng*[17].

Changes of soil physical and chemical properties

The healthy growth of plants can only be realized under certain steady-state environmental conditions. Any change of external environment will affect normal life activities of plants. The underground roots of plant growth are the basis for plants to achieve good quality performance of the aboveground part with luxuriant foliage, and a good soil ecological environment provides basic growth conditions for plant growth. Dubey *et al.* [18] found that changes in soil physical and chemical properties directly or indirectly led to the formation of continuous cropping obstacles and rebuilding of the living environment for microorganisms, and continuous cropping led to a decrease in soil pH value. Long-term continuous planting of the same plant species, due to the high demand for a single element by the plant, leads to an imbalance of various elements in the soil, and antagonistic effects between internal elements in the soil can occur, leading to the disruption of soil acid-base balance[19]. Xu *et al.* [20] found that the cation exchange capacity (CEC) of the rhizosphere soil samples of *Trichosanthes kirilowii* was decreased after continuous cropping for four years, which indicated that the soil fertility conservation capacity had decreased. Gao *et al.* [21] found that the pH value in the soil of continuous cropping strawberry changed obviously, and its pH value ranged from 5.8 to 6.1, which obviously reached the range of soil acidification level. After soil acidification, some elements will become ionic, while the increase of NO_3^- and SO_4^{2-} will show some salt damage problems, resulting in continuous cropping obstacles[22].

Effects of Continuous Cropping on Microbial Communities

Soil is a living organism, and the stability of soil micro-ecological environment provides basic environmental conditions for microorganisms to realize soil organic matter mineralization and nutrient transformation. Continuous cropping will lead to changes in soil microbial biomass and population distribution structure, thus affecting normal life growth of plants[23]. There is a competitive relationship between organisms in niche. When a certain population in the soil is dominant in quantity, it will lead to the

change of soil properties. Ding *et al.* [24] reported that with the increase of continuous cropping years, the total amount of microbes and biological activity in the soil showed a trend of increasing first and then decreasing. As we all know, microbial community structure often has the attribute of "identity recognition" to plant types and has a special response to changes in soil environmental conditions and climate characteristics[25]. Jiao *et al.* [26] studied the combined structure of archaea, bacteria and fungi communities in different habitats in eastern China, indicating that the composition of microbial communities is mainly influenced by the types of crops planted. Continuous cropping may also reduce the quantity of probiotics in the soil, affect the growth and activity of beneficial microorganisms, and then affect the health of the soil. The effect of continuous cropping on microbial florae is mainly that long-term planting of the same crop leads to excessive consumption of some specific nutrients in the soil, which will further affect the diversity and richness of microorganisms in the soil. In addition, the continuous cropping of a certain crop for many years will lead to the condition that the residue of this specific crop may also become the host or habitat of some specific pathogenic microorganisms, thus increasing the risk of diseases.

Long-term monoculture of crops significantly reduces the composition of soil microbial diversity, changes the composition and structure of microbial communities, decreases the buffering capacity of crops to biotic and abiotic stresses, increases the incidence of diseases, and then affects plant health[27]. Microbial community composition will show selective enrichment due to the influence of root exudates, which will lead to changes in soil microbial community composition[28]. He *et al.* [29] reported that long-term continuous cropping could induce the decrease of the diversity of soil bacteria and fungi communities in the root zone of *Lycium barbarum* and the increase of plant pathogens. Zhu *et al.* [30] also confirmed that with tobacco continuous cropping, the relative richness of microbial species decreased. Stephane *et al.* [31] confirmed that continuous cropping had different effects on beneficial and pathogenic microorganisms in soil, and continuous cropping intensified the competition between beneficial and pathogenic microorganisms in soil, so that the quantity and richness of beneficial microorganisms in soil showed a downward trend, while the quantity of pathogenic microorganisms increased. Soil includes microbial groups that affect plant growth performance and microbial susceptibility to diseases. For example, Peralta *et al.* [32] found that some soil microorganisms could inhibit the growth of plant pathogens by producing antibacterial compounds, which could bring benefits to sustainable agricultural land management. Soil microorganisms play an important role in maintaining ecosystem sustainability and plant health. Continuous cropping of different crops will lead to changes in soil microbial florae, destruction of community structure and reduction of pathogenic antagonistic bacteria. Continuous cropping will lead to the enrichment of phenolic acids in tobacco-growing soil[33]. Li *et al.* [34] found that phenolic acids in the root exudates of Tieguanyin tea varieties were an important factor leading to the imbalance of rhizosphere microbial community structure. The increase in the quantity of pathogenic microorganisms is one of the main factors that hinder continuous cropping and affect crop quality and yield[35]. Fan *et al.* [36] found that the occurrence of soil-borne disease bacterial wilt was closely related to the structure of soil microbial community.

Effects of continuous cropping on soil fungi

A higher bacterial/fungal (B/F) value in soil indicates a more stable structure of soil ecosystem and a stronger ability to resist diseases[37]. The quantity of microorganisms has always been an important indicator to measure microbial florae in soil. Sun *et al.* [38] reported that the quantity of fungi in continuous cropping peanut increased by 140% – 220% compared with 1 – 5 years rotation. Ma *et al.* [39] found that the proportions of bacteria and fungi decreased by 64.70% and 9.18% – 32.11% respectively after potato continuous cultivation compared with the control soil, which indicated that the soil type would be transformed into the fungal type with the increase of planting years. Ma *et al.* [40] found that the amount of fungi increased linearly with the increase of continuous cropping years. Hua *et al.* [41] reported that with the increase of crop planting years, the soil microbial environment around sesame rhizosphere deteriorated, which changed the composition structure of microbial florae. On the whole, the quantities of bacteria and actinomycetes decreased, while the quantity of fungi was on the rise. Chen *et al.* [42] found that with the increase of crop planting years, the quantities of bacteria, actinomycetes and fungi increased, but the increase of bacteria was not significant, while the difference between actinomycetes and fungi reached a very significant level.

Effects of continuous cropping on soil bacteria

Bacteria are the most abundant microorganisms in soil organisms and can be used as functional indicators to judge soil quality and soil ecological environment[43]. In the production process, Solanaceae crops such as pepper, eggplant and tomato will be accompanied by soil-borne bacterial diseases[44]. Li *et al.* [45] found that the richness and diversity of bacteria in the rhizosphere soil of continuous cropping tomato were significantly lower than that in the rotation soil. Hu *et al.* [46] studied the changes of main microbial groups in cucumber root soil with continuous cropping times. The results showed that with the increase of continuous cropping times, the quantity of culturable microorganisms in the soil decreased, the population change showed a single trend, and the level of microbial diversity decreased. The quantity of bacteria decreased more obviously, and they were highly sensitive to continuous cropping. Yan *et al.* [47] reported that the quantity of bacteria in greenhouse soil decreased obviously with the increase of continuous cropping years, while the quantity of fungi showed an upward trend, and the soil changed from high-fertilizer bacterial type to low-fertilizer fungal type.

Main Ways to Remediate Continuous Cropping Obstacles

At present, continuous cropping has led to the decline of

agricultural product mass and quality, which has become a major and difficult problem faced by grain production all over the world. The remediation of continuous cropping soil is the development direction to realize sustainable land use. At present, continuous cropping soil is mainly remediated through agricultural operation management, restoring the balance of soil microbial florae and improving the structural properties of cultivated soil.

Optimizing the management of farming system

Reasonable rotation planting can help to restore the balance and diversity of microbial florae in soil, reduce the proliferation of pathogenic microorganisms and promote the reproduction of probiotics in soil. Planting different crops by rotation can help to maintain the richness of microbial florae in soil, thus improving soil fertility and crop yield. Rotation is an effective way to solve the problem of continuous cropping all over the world, and the number of fungal populations can be significantly reduced through rotation[48]. There is evidence that crop rotation can improve soil fertility and tend to promote microbial diversity. Crop rotation can affect soil bacterial composition by diversified cultivated plants or enhance disease inhibition by increasing the abundance of soil disease-resistant microorganisms. Song *et al.*[49] have shown that continuous cropping and fallow management of soybeans led to the selective stress of soil fungi and pathogenic fungi, resulting in the formation of soil with fungi-dominated florae, while fallow and corn-soybean rotation could reduce this trend and was beneficial to the healthy growth of plants. Crop rotation significantly increases the relative abundance of bacterial groups involved in nitrification and denitrification. In fungal functional groups, the relative abundance of pathogenic microorganisms decreases during rotation, while the beneficial mycorrhizal microorganisms increase[50]. Reasonable land cultivation methods in the process of agricultural operation are of great significance to the formation of soil aggregate structure and soil porosity, and intertillage among them can not only remove weeds but also expose pathogens in deep soil to the ground, thus reducing the accumulation of soil pathogens. The application of soil improvers can restore the efficacy of soil to a certain extent. It is found that spraying loosening agents can reduce soil pH and soil bulk density, and increase soil organic matter content, soil porosity and soil microbial populations[51]. The application of organic fertilizers is beneficial to the improvement of soil properties. Yang *et al.*[52] found that the soil fertility, enzyme activity and soil structure of continuous cropping cucumber could be improved by combining different organic fertilizers with soil conditioners. The application of biochar can solve the problems such as the change of soil physical and chemical properties, the change of soil microbial florae, allelopathy and autotoxicity caused by continuous cropping of medicinal plants[53].

Adjusting soil microbial flora structure

Continuous cropping leads to the imbalance of soil microbial community organization structure. Remolding microbial soil structure is beneficial to the development of healthy soil, and adding beneficial microbial community can balance or inhibit the growth of pathogenic bacteria. It was found that reasonable application of microbial fertilizers can promote tomato quality, improve soil properties and improve microbial activity[54]. Studies show that inoculation with plant growth promoting rhizobacteria (PGPR) can significantly improve the yield of different crops and seed germination and emergence, promote root nutrient absorption and plant total biomass, increase seed weight, induce early flowering and systemic resistance, facilitate beneficial plant-microorganism symbiosis, and interfere with pathogen toxin production. Yao *et al.*[55] inoculated alfalfa with *Bacillus amyloliquefaciens* GB03, and the overall growth of the plant was improved under salt stress, and meanwhile, the nitrogen fixation performance of the plant was improved. *Trichoderma harzianum* is a biological agent fertilizer. Qi *et al.*[56] found that applying *T. harzianum* fertilizers through holes could promote the growth of Heishuai watermelon in greenhouse, significantly improve the yield and quality of watermelon, and enhance the resistance of Heishuai watermelon to *Fusarium* wilt, gummy stem blight and anthracnose.

Strengthening the improvement of soil properties

Soil can provide water and mineral nutrients needed by plant growth, and meanwhile, the decomposition of soil organic matter can provide energy sources for microorganisms. A good soil structure can ensure balanced supply of water, steam and heat in soil, and can provide basic living conditions for the survival of microorganisms and the growth of plants. Due to the continuous cropping years of crops, soil structure problems such as quality degradation, acidification and salinization have occurred year by year[57]. Therefore, soil quality can be reduced or improved through soil improvement. Zhou *et al.*[58] found that strain 3A-2 had the function of salt tolerance and growth promotion by applying salt-tolerant growth-promoting bacteria in secondary saline-alkaline land, and can be used to improve soil salinization. Long-term application of chemical fertilizer causes soil hardening, and optimizing fertilization methods can improve soil bulk density and void condition to a certain extent, and adjust the coordination among soil water, fertilizer, steam and heat[59]. It is reported that the compound application of organic fertilizer and lime has a good effect on improving acid soil in South China[60]. Land tillage methods have a great influence on soil physical and chemical properties[43]. Su *et al.*[61] significantly reduced soil bulk density, increased soil porosity, and improved soil three-phase ratio of tea gardens through deep loosening and rotary tillage. Deep loosening and rotary tillage can not only enhance soil water storage and retention functions, but also promote plant nutrient absorption and conversion capacity. Continuous cropping aggravates the occurrence of soil-borne diseases mainly due to the accumulation of soil-borne pathogens, and physical and chemical soil disinfection treatment can eliminate and reduce pathogenic microorganisms in the soil to some extent. Xu *et al.*[62] treated continuous cropping soil of *Hypericum* with high incidence of nematodiasis in Yunnan Province with reductive soil disinfestation (RSD), and found that the relative abundance of beneficial bacterial-feeding nematodes in the soil increased after

RSD treatment, while the quantity and relative abundance of phytophagous nematodes decreased obviously.

Conclusions and Prospects

Continuous cropping obstacles are a modern agricultural product formed by the interaction of soil, microorganisms and plants in the underground part and external agricultural management including fertilization, pesticide and agricultural management. The remediation of continuous cropping obstacles is to restore the soil ecosystem damaged by continuous cropping through a series of measures, so that it can regain health and maintain a balanced state. In the future, more attention will be paid to the research on the specific effects of continuous cropping on microbial flora structure, and more attention will be paid to sustainable agricultural practices, including crop rotation, organic fertilization and soil microbial diversity protection. It is expected to cultivate more pest-resistant varieties using advanced techniques such as gene editing and digital agriculture. Meanwhile, agricultural producers will adopt more modern methods of integrated management to reduce the impact of continuous cropping obstacles on soil and crop yield. Continuing scientific research and technological innovation will help realize the sustainable development of continuous cropping obstacle repair and bring better prospects and development for agricultural production and environmental protection.

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