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Research Progress in the Effect and Mechanism of Fertilization Measures on Soil Fertility

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Abstract This paper firstly summarized the domestic and foreign research progress in the relationship between fertilization measures and soil fertility. It elaborated the relationship between fertilization measures and basic physical and chemical properties, soil enzyme activity, soil microorganism fertility index, and soil animal fertility index. It pointed out future researches about the relationship between fertilization measures and soil fertility include: (i) the relationship between fine and high efficient input of organic fertilizer and soil fertility, (ii) in-depth research of soil zoology fertility index, (iii) soil biology about long-term fertilization, and (iv) soil fertilization and agricultural diffused pollution. It is intended to provide scientific reference for improving farmland soil fertility and maintaining excellent ecological environment of farmland through proper fertilization measures.

Key words Fertilization measures, Soil fertility, Soil enzyme activity, Soil microorganism, Soil animals

1 Introduction

Soil fertility refers to the ability of a soil to supply plant nutrients. It is fundamental resource for sustainable development of agriculture and fertilization is a major measure maintaining soil fertility and compensates loss of soil nutrients due to harvesting of agricultural products and removal of crop wastes (like straws)[1]. Fertilization is an essential agricultural measure for increasing crop yield, improving quality and keeping soil fertility. With increasing development intensity of agricultural land, both agricultural input and output have considerable increase. This promotes giant leap of agricultural productivity, but also leas to quite a few drawbacks[2]. Soil fertility and its evolution trend is a major issue concerning agricultural sustainable development and grain and ecological security. With constant increase of population, the carrying capacity of agricultural land is increasing and grain yield of unit land needs increasing. In this situation, it is urgently necessary to take proper fertilization measures to improve soil fertility and promote stable and high yield of grain. Although there are extensive researches about the relationship between fertilization measures and soil fertility both at home and abroad and considerable progress has been made, constantly changing agricultural planting system, mode of production, and input of chemicals bring new problems and challenges to the soil fertility.

2 The effect of fertilization measures on basic physical and chemical properties of soil

Long-term practice has shown combined application of organic and inorganic fertilizers can significantly improve basic physical and chemical properties of soil. Long term field experiments of Rothamst, Morrow, Askov and E-field indicate that combined application of organic and inorganic fertilizers can significantly increase soil organic carbon (SOC)[3]. According to long-term experiment results of Dang Tinghui *et al*[4], SOC with combined application of organic fertilizer and NP fertilizer increased about 5.61 g/kg after 9 years compared with soil without fertilization treatment. Wang Shaoming[5] also reached similar conclusion. Green manure fertilization is a common measure widely applied in traditional agriculture of China, Western Europe, Japan and India[6]. The experiment of Li Zhongpei *et al*[7] indicated that straw return to field combining application of phosphorus fertilizer can rapidly increase accumulation speed of SOC and increase the SOC of paddy soil about 4 - 10 g/kg in three years. Zhou Weijun *et al*[8] also obtained similar results. According to field experiment of Wang Boren *et al*[9], long-term combined application of organic and inorganic fertilizers can gradually increase organic matters of red soil, while the improvement degree is related to weight and property of organic fertilizer used. Through summarizing 11 years of straw return to filed, Zeng Muxiang *et al*[10] found that the volume of straw return to field in agricultural areas of middle and lower reaches of Yangtze River reached 3990 kg/hm^2, the average SOC increased 0.151%; the average volume of straw return to field in South China agricultural areas reached 875 kg/hm^2, the average SOC increased 0.125%. Wang Hongwu *et al*[11] found that the soil organic matters (SOM) rose from 16.5 g/kg in 1989 to 18.9 g/kg in 2007, the soil cation exchange capacity (CEC) reached to 11.81 cmol/kg (increasing about 1.76%), soil bulk density dropped from 1.22 g/cm^3 to 1.09 g/cm^3, and the soil general porosity, capillary porosity, and field capacity increased about 3.7%, 5.0% and 3.0% respectively. Long-term field experiment of Song Chun *et al*[12] in Hailun Agricultural Ecology Experimental Station of CAS showed that fertilizer application increased TP con-

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tent in different particle-sized water-stable aggregates and application of phosphorus fertilizer can significantly increase the available phosphorus in soil. Research of Guo *et al*[13] indicated that, compared with application of chemical fertilizer (NPK) only, the application of chemical fertilizer plus straw (SW-NPK) 7500 kg/hm^2 and application of chemical fertilizer plus straw (1/2 SW-NPK) 3750 kg/hm^2 dropped soil bulk density 10% for 0 – 15 cm soil layer and 6.9 – 9.4% for 15 – 20 cm soil layer respectively, available nitrogen (N) 17.43 – 35.19% for 0 – 25 cm soil layer, available potassium (K) 7.66 – 17.47%, and increased available phosphorus (P) 18.51 – 56.97% for 5 – 25 cm soil layer. Macci *et al*[14] found that application of organic fertilizer can increase availability of nutrients, microorganism activity and improve soil structure. Ailincăi *et al*[15] found that in sunflower - wheat - corn rotation system, application of high volume of mineral fertilizer [160 kg (N) /hm^2 and 80 kg (P)/hm^2] increased SOC for 22.7% [3.5 g (C) /kg soil] compared with no application of fertilizer. Our team studied the effect of 6 modes of fertilizer application (no application, tea tree formula fertilizer, 1/2 tea tree formula fertilizer + 1/2 organic fertilizer, organic fertilizer, tea tree formula fertilizer + leguminous green manure, 1/2 tea tree formula fertilizer + 1/2 organic fertilizer + leguminous green manure) on soil fertility of tea garden in 4 years. Results showed that compared with the control group (no application of fertilizer), all other modes can improve the basic soil fertility of tea garden to a certain extent. The "1/2 tea tree formula fertilizer + 1/2 organic fertilizer + leguminous green manure" mode had the best experimental effect, increased 1.29 times SOM, 1.7 times TN, 2.98 times TP, 1.59 times available nitrogen, 34.3 times available phosphorus, and 3.3 times available potassium for tea garden soil compared with the control group; reduced soil sand content (0.05 mm < particle diameter ≤ 2.0 mm) for 20.44%, soil powder content (0.002 mm < particle diameter ≤ 0.05 mm) for 33.21%; increased soil clay content (particle content < 0.002 mm) for 24.42%, water content for 40.79% and CEC for 29.62%[16-17]. These indicated that increasing application of organic fertilizer is an effective measure for promoting SOC accumulation and a key approach for soil fertilization. Soil TN is closely related with SOC, while the application of nitrogen fertilizer exerts little influence of soil TN (because nitrogen fertilizer is easy to lose) but can significantly influence soil available nitrogen. Shen Shanmin[18] summarized many domestic and foreign field experiments and reached the conclusion that combined application of organic and inorganic fertilizer can increase soil TN and available nitrogen pool and significantly increase soil nitrogen fertility. As we all know, the effect of general organic fertilizer can keep 2 – 3 years or longer[19 20], so application of organic fertilizer can increase soil nitrogen for a long time. Zhang Meiliang *et al*[21] 15N tracer experiment indicated that the residue of fertilizer nitrogen in manure + NPK and marsh fertilizer + NPK is 1 – 1.5 times higher than only application of chemical fertilizer. Lao Xiurong *et al*[22 23] proved that the soil available nitrogen is positively correlated with volume of straw return to field; in the condition of equal application of nitrogen fertilizer, the combined application of straw and chemical fertilizer can increase the soil available nitrogen for 30% (compared with application of straw only) and 40% (compared with application of chemical fertilizer solely) respectively. Besides, the combined application of straw and chemical fertilizer can inhibit the accumulation of nitrate nitrogen in soil[24]. Straw return to field and farming method also influence the nitrogen availability to a certain extent. Wang Jinping *et al*[25] proved that whole and half straw return to field has significant difference influence on TN and hydrolyzable nitrogen of 5 – 25 cm soil layer. Wu Chonghai *et al*[26] found that crop residue management can increase CEC, reduce soil bulk density for 0.15 – 0.2 g/cm^3, and increase the general porosity for 5.6 – 7.4%. Sun Haiguo *et al*[27] reached the conclusion that straw treatment has strongest influence on water stability of aggregates in sandy paddy soil. Research results of Li Zheng *et al*[28] indicated that rye grass application can significantly improve physical and chemical properties of soil; in the whole growing period of tobacco plant, the SOM, alkali – hydrolyzable N, available P, and available K increased 12.18 – 30.84%, 6.82 – 21.46%, 62.19 – 119.20 and 40.02 – 85.44% respectively; application of rye grass can better adjust pH value of soil and improve physical and chemical properties of soil. In sum, properly combined application of organic and inorganic fertilizer is an effective measure for maintaining excellent physical and chemical properties of farmland soil and also a key fertilization measure for keeping agricultural sustainable development.

3 Effect of fertilization measures on soil enzyme activity

Soil enzyme is biologically activated substance with catalytic ability and also essential composition of soil. Despite tiny in weight, the soil enzyme participates in natural material cycle including biological chemical process and plays an important role. Soil enzyme has close connection with many essential physical, chemical and biological properties of soil. Urease, phosphatase and converting enzyme are closely connected with plant nutrition and are essential indicators for evaluating soil fertility and health condition[29]. Long-term fertilizer field experiment of He Wenxiang *et al*[30] indicated that the general enzyme activity of soil is barnyard manure > chemical fertilizer > no application of fertilizer. Yuan Ling *et al*[31], taking livestock manure as organic fertilizer to conduct experiment, found that urease activity of soil treated with pig manure is higher. Li Dongpo *et al*[32] added 5% Melilotus albus, corn straws, and wheat straws to chernozem to make comparative experiment, and the results indicated that the protease activity of soil is corn straw > wheat straw > Melilotus albus, while the activity of urease and phosphatase is Melilotus albus > corn straw > wheat straw. Fan Jun *et al*[33] tested dynamic parameters of soil enzyme in dry farmland for winter wheat in different fertilization conditions and found that the organic fertilizer has the highest influence on urease dynamic parameters Vmax and Vmax/Km and alkali phos-

phatase Km and Vmax, while the application of chemical fertilizer can slightly increase the soil enzyme activity. Application of chemical fertilizer can promote metabolism of crop root system, increase secretion of root system, and accelerate breeding rate of rhizosphere microbe, so as to improve the soil enzyme activity[34]. Ren Quan[29] found that different fertilization measures can significantly improve soil enzyme activity; the influence of water and temperature on soil enzyme activity is higher in summer harvest than autumn harvest; the urease, phosphatase, hydrogen peroxide enzyme, and invertase activity of red soil can be improved in combined application of organic and inorganic fertilizer and single application of organic fertilizer, while the single application of chemical fertilizer has little effect on improvement of soil enzyme activity. Our team found that different fertilization modes can improve protease, urease, and phosphatase activity of soil, especially 1/2 tea tree formula fertilizer + 1/2 organic fertilizer + leguminous green manure can increase the protease, urease, and phosphatase activity for 2.8 times, 7.73 times, and 0.33 times respectively, while long term application of chemical fertilizer has little effect on promoting activity of these enzymes. Besides, there is significantly positive correlation between SOM, TN, TP, hydrolyzable nitrogen, available P, available K, CEC, water content, tea plant height, tea yield and soil protease, urease, and phosphatase activity, indicating these enzymes react sensitively to fertilization modes and can be used as indicators for evaluating soil fertility and tea growth condition of tea gardens in red and yellow soil areas. The correlation with hydrogen peroxide enzyme is weak, indicating this enzyme activity not fully characterizing soil fertility[35]. Since different organic matters have different nutrients, C/N and lignin content, the influence on soil enzyme activity is also different. In general, the lower C/N and lignin content of organic matters, the higher microorganism activity, and the higher soil enzyme activity. Application of organic fertilizer can greatly improve soil enzyme activity. In a sense, application of organic fertilizer is a measure of adding enzyme. In addition, application method and weight of organic fertilizer have certain influence on soil enzyme activity[29].

4 Influence of fertilization measures on soil microorganism fertility indicator

Extensive domestic researches prove that fertilization measures can significantly influence microorganism biomass. Long-term (30 years of) fertilization experiment of Witter[36] indicated that long-term application of organic fertilizer (such as straw, green manure and farm manure) brings higher soil microorganism biomass carbon, while long-term application of peat and urban sludge brings lower soil microorganism biomass carbon. Research results of Ladd *et al*[37] indicated that the influence of surface cover or soil burial of organic debris on soil microorganism biomass carbon is not significant, while there is significant difference between the influence of burn of organic debris and soil burial on soil microorganism biomass carbon is significant. Shen Qirong *et al*[38] found that the soil microorganism biomass carbon and nitrogen without application of fertilizer significantly decreased in the growth period of barley, 37% and 51% less compared with that before experiment, while the soil microorganism biomass carbon and nitrogen with fertilization treatment had obvious increase in the growth period of barley. Experiment of Huang Min *et al*[39] showed that adding 5 g/kg straw, 5 g/kg glucose and 10 g/kg straw in red paddy soil, the soil microorganism biomass increased 1.0 time, 1.5 times, and 2.0 times compared with the control group, and improved the activity of soil microorganism biomass phosphorus. Combined application of phosphorus fertilizer and organic fertilizer can significantly improve availability of soil phosphorus. The soil microorganism biomass is also influenced by fertilizer types and fertilization methods. Farmland with regular application of farm manure has higher biomass nitrogen than that with application of chemical fertilizer. Xu Yangchun *et al*[40] found that in different fertilization conditions, the sequence of biomass carbon and phosphorus from high to low is: pig manure + chemical fertilizer, straw + chemical fertilizer, chemical fertilizer + green manure, chemical fertilizer, and the control group; the sequence of biomass nitrogen from high to low is pig manure + chemical fertilizer, green manure + chemical fertilizer, chemical fertilizer, chemical fertilizer, and the control group. Zhu Haiping *et al*[41] found that different fertilizers have different abilities of increasing the soil microorganism biomass: barnyard manure > straw > chemical fertilizer; different fertilization measures can lead to different changes in microbial metabolic quotient and microorganism functional diversity, so as to form certain different soil microorganism population. Therefore, organic fertilizer has better effect than inorganic fertilizer on increasing the biomass of soil microorganism, while combined application of organic and inorganic fertilizer is optimum method. In SOC, nitrogen and phosphorus, the biomass carbon, nitrogen and phosphorus have the highest activity. Although the biomass carbon takes up a small portion in the total carbon of soil, it is active part in SOM, and it can reflect available nutrients and biological activity and quantity of microorganism, so it is an essential indicator for evaluating quantity of soil microorganism and soil fertility[42 44]. Soil microorganism nitrogen is an essential part in conversion of soil nitrogen. Paul *et al*[45] divided soil organic nitrogen into biomass nitrogen, active non-biological nitrogen (new organic debris nitrogen), stable nitrogen and ancient organic nitrogen. The mineralization speed of biomass nitrogen is highest (up to 5.0 times other organic nitrogen) and has the largest contribution to mineralization of soil nitrogen. But the biomass nitrogen and active nitrogen take up small portion of soil nitrogen. Through calculation, Clark *et al*[46] found that in short grassland, the nitrogen transferred to root through microorganism takes up 33% of total nitrogen needed by ground plants. Similarly, the biomass phosphorus plays a great role in crop growth. Brookes[47] found that the microorganism phosphorus is also an active part in soil organic phosphorus, while organic phosphorus is relatively stable in other parts; in farmland soil, the biomass phosphorus takes up 3.0% of the organic phosphorus, while in grassland, it is about 19.0%.

Experiment of Brookes *et al*[47 48] indicated that after the grassland is changed to farmland, the drop of 50% organic phosphorus is resulted from drop of biomass phosphorus. Proper fertilization measure can significantly increase soil microorganism biomass carbon, nitrogen and phosphorus. Experiment of Hu Cheng *et al*[49] showed that application of fertilizer can increase soil microorganism biomass carbon and the combined application of chemical fertilizer and organic fertilizer has better effect. For low fertility farmland, combined application of chemical fertilizer and organic fertilizer is an optimum fertilization measure. Ren Quan[29] surveyed the red soil tea garden in Hunan Province and found that fertilization measure can significantly increase biomass carbon, nitrogen, and phosphorus, and the combined application of chemical fertilizer and organic fertilizer has optimum effect. Research of Liang Bin *et al*[50] indicated that combined application of chemical fertilizer and organic fertilizer can significantly increase SMBC and SMBN of 0 – 10 cm and 10 – 20 cm soil layer, single application of chemical fertilizer can increase SMBN of 0 – 10 cm soil layer, and the proportion of SMBC/TOC and SMBN/TN is free from influence of fertilization measure and planting system. Our research indicated that 1/2 tea tree formula fertilizer + 1/2 organic fertilizer, tea tree formula fertilizer + leguminous green manure and organic fertilizer can increase SMBC for 1.87 times, 1.26 times and 1.49 times compared with CK, and increase SMBN 2.18 times, 1.32 times and 1.70 times respectively, while SMBC and SMBN treated wholly by chemical fertilizer decrease 0.46 times and 0.59 times respectively[51]. At present, there are few researches about the relationship between fertilization measures and SMBC, SMBN, and SMBP, and it needs further and in-depth research in future.

5 Influence of fertilization measures on soil animal fertility indicator

Soil animals are manufacturers of soil nutrients[52]. They crush ground or underground organic matters (such as withered branches and fallen leaves, plant roots, animal bodies and manure, *etc*), decompose the crushed things in the action of soil microorganism to nutrients that can be used by plants. Mixed with soil, they become fertile humus. Existence and activity of soil animals can improve soil ecological environment, improve soil fertility, increase nutrients necessary for plants, thus activity strength of soil animals is an essential indicator for characterizing soil fertility[53 – 54]. Soil animal community or population characteristics are significantly influenced by farmland management measures such as farming and fertilizer application. Farming and fertilizer application not only change physical and chemical properties of soil and living environment of soil animals, but also decrease animal diversity and total number[55 – 57]. Although the effect of soil animals in improving soil structure and environment has been proved by Rothamsted Experimental Station through 150 years of researches, there are few researches about the relationship between farmland soil animals and soil factors and most researches are descriptive[58]. At present, researches about agricultural soil animals focus on the influence of farming or fertilizer application on few animal species (such as nematode and collembolan)[59]. In recent years, with the aid of various advanced instruments and research methods, the relationship between soil animal biological productivity and human beings and environment has entered the research stage, and the research about soil fauna and diversity has become hot spot and frontier topic[60 – 61]. Fertilization measures have obvious influence on population distribution of soil animals. Cao Zhiping *et al*[62] found that application of chemical fertilizer obviously inhibits abundance of protozoan, while application of organic fertilizer obviously promotes abundance of protozoan; in soil with higher fertility, major protozoan are flagellate and Sarcodina (accounting for 39.47% and 59.22% respectively, infusorian only takes up 1.31%); seasonal change characteristics of abundance of protozoan does not vary from fertilization measures and straw return to field. Zhu Qianggen *et al*[63] also obtained similar results. Lin Yinghua *et al*[64] found that SOM, field capacity and TN load (or weight coefficient) are higher; the load of nematode, ticks and mites, and coleopteran is higher; SOM, TN, and field capacity have the highest function for nematode, ticks and mites, and have higher influence on coleopteran. Research results of Cao Zhiping *et al*[65] indicated that on the basis of equal application of chemical fertilizer, quantity of earthworms increase with increase of input of organic matters, and single application of chemical fertilizer has significantly negative influence on earthworms. There is significant positive correlation between SOM and types and quantity of earthworms. Earthworms can improve soil fertility, increase soil permeability, and improve physical structure of soil[66 – 67]. Earthworms also can establish benign interaction with soil microorganisms, earthworm activity can greatly accelerate degradation of SOM, expand living space of microorganisms, and increase quantity of microorganisms, while the increase of microorganisms further promotes accelerated decomposition of SOM[68 – 69]. The distribution of soil animal fauna is closely related with soil fertility, but how to use soil animal fauna to characterize soil fertility? Few researches are touched upon on this point and it needs in-depth researches in future.

6 Research prospects

6.1 Researches about the relationship between fine and high-efficient input of organic fertilizer and soil fertility A key measure for improving farmland soil fertility is effective input of organic fertilizer. However, predatory resource development leads to unbalance of soil nutrients and degradation of soil fertility. Besides, improper farming methods exacerbate soil erosion, barren trend of soil nutrients and decline of soil fertility. Therefore, rebuilding soil nutrient pool, improving soil fertility and increasing crop yield have become difficult problems urgently to be solved. Single application of chemical fertilizer can increase crop yield to a certain extent, increase available nutrients of soil, but it will lead to drop of fertilizer utilization efficiency, degradation of physical and chemical properties, drop of soil microorganism fer-

tility indicator, as well as serious agricultural diffused pollution. Increasing input of organic fertilizer can significantly improve soil fertility, but application of traditional organic fertilizer needs large and expensive labor and gradually gets replaced by chemical fertilizer. As a result, it leads to many crops or farmland failure to obtain supply of organic fertilizer and land becomes barren, both crop yield and quality decline, and grain security and ecological security face tremendous challenges. Therefore, it is recommended to strengthen researches about fine and high-efficient input of organic fertilizers, such as extracting water-soluble organic carbon from traditional organic matters, conducting research and production of soluble carbon fertilizer, effect of farmland application, research and manufacture of biological black carbon, to get rid of shortage of organic fertilizer.

6.2 In-depth researches about soil zoology fertility indicator Soil animal is an essential part of soil organisms. Activities of soil animals can effectively improve soil fertility. Some soil animals (like earthworms) are important indicators of evolution of soil ecosystem and soil fertility. Nevertheless, there are few researches about fertilization measures and soil zoology and using soil zoological characteristics to characterize soil fertility is not mature. Therefore, in future, it is required to strengthen researches about application of soil zoology indicators in soil quality evaluation system, formulate more proper and effective farmland soil management measures, to further increase productivity and realize objective of sustainable development.

6.3 Researches about soil biology for long-term soil fertilization With more than a hundred years of field experiment researches about soil fertilizer, the research scope has involved many aspects and made important achievements in many fields. In future, researches about SOM and soil biological process should focus on following points: researches about composition and evolution of physical and chemical properties of SOM in the condition of long-term combined application of organic and chemical fertilizers; researches about interaction between soil microorganisms, soil enzyme activity and conversion of SOM; researches about the relationship between SOM abundance, component, conversion, and availability of soil trace elements; form and conversion of SON, P, S; ecological security of application of organic fertilizers.

6.4 Researches about problem of soil fertilization and agricultural diffused pollution Soil fertilization is a key measure for improving soil fertility and high yield and quality of crops, but improper application of fertilizer will lead to deterioration of agricultural diffused pollution. Practice has proved that reasons for agricultural diffused pollution are various, but improper application of fertilizer is one of them. Therefore, it is particularly important to carry out researches about scientific and reasonable environment-friendly application of fertilizer. In future, it is recommended to strengthen in-depth researches about new soil fertilization technologies centered on increasing fertilization efficiency utilization rate, explore high yield, high quality of crops and stable increase of soil fertility, so as to control the increasingly deteriorating agricultural diffused pollution from the source.

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a correlation analysis of the number of microbes and environmental factors, and the results show that temperature is significantly positively correlated with the number of microbes due to the effect of enzyme activity. Salinity is highly correlated with the number of microbes, mainly due to dramatic changes in salinity levels in the intersection of coastal zone and estuary. Dissolved oxygen is negatively correlated with the number of microbes, and aerobic and facultative microbes mainly grow in the surface waters. There is a complex correlation between nutrient salt and the number of microbes, and it is not completely same as previous studies[17-19], which may be related to geographical environment of waters and the surrounding ecological environment. In this study, there are a lot of drawbacks. First, there is no study on the hierarchical structure of waters, and it should be regarded as the main direction in subsequent experiments; second, the separation of microbes is not comprehensive enough; third, there is no microbiological purification and active research. Therefore, these problems should be solved in subsequent studies.

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