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Aggregate-related changes in soil microbial communities under different ameliorant applications in saline-sodic soils

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ABSTRACT

Soil ameliorants can improve soil physico-chemical properties and activate microbial communities in saline-sodic soils. However, there has been less focus on how aggregate fractions affect soil microbial communities under different ameliorant applications. Here, we used the phospholipid fatty acid (PLFA) analysis to explore the effects of soil ameliorants on microbial communities within mega-aggregates (diameter of > 2 mm, ME), macro-aggregates (diameter of 0.25–2 mm, MA), and micro-aggregates (diameter of < 0.25 mm, MI), based on an 8-year rice (*Oryza sativa* L.) field experiment. The five treatments included CK, non-amended control; SS, amended with sandy soil; DG, amended with desulfurization gypsum; FM, amended with farm manure; and M, amended with a mixture of sandy soil, desulfurization gypsum, and farm manure. Relative to the CK treatment, the SS, DG, FM, and M treatments significantly decreased the soil pH and electrical conductivity and significantly increased the soil organic carbon (SOC) content of the MI, while the FM and M treatments also significantly improved the SOC content of the MA and ME. Irrespective of the ameliorant used, the absolute abundance of total PLFAs and most microbial groups generally varied with the SOC content as follows: MA > ME > MI. Meanwhile, the proportional abundance of arbuscular mycorrhizal fungi (AMF) varied between different aggregate fractions as follows: ME > MA > MI. Additionally, the DG treatment significantly enhanced the soil aggregate stability by increasing the AMF abundance, AMF/saprotrophic fungi ratio, and SOC content of the MI. Furthermore, soil microbial groups were highly correlated with soil SOC ($P < 0.001$), C/N ratio ($P < 0.001$), pH ($P < 0.01$), total nitrogen ($P < 0.01$), and the proportion of aggregates with a > 0.25 mm diameter ($P < 0.05$). In conclusion, desulfurization gypsum is more effective for improving the properties of saline-sodic soils in the western Songnen Plain.

1. Introduction

Soil salinization is one of the greatest challenges for agricultural and animal production in arid and semi-arid regions (Qadir et al., 2008). Salt-affected soils account for approximately 25% of the world's total land area and are found in > 100 countries (Hajiboland, 2013; Sun et al., 2017). Salt-affected soils in China cover a total area of approximately 3.67×10^7 ha, and these soils are mainly distributed in the northeast Songnen Plain, North China Plain, northwest desert and semi-desert areas, and coastal areas (Yao, 2008; Liu et al., 2015). The western Songnen Plain is one of the three major regions with saline-sodic soils in the world and currently has over 3.0×10^6 ha of salt-affected soils (Dai et al., 2016; Yang et al., 2016). Plants grown in this region suffer from both Na^+ toxicity and high pH stress caused by excessive Na_2CO_3 and $NaHCO_3$, which cause more damage to plants than NaCl (Yu et al., 2010; Dai et al., 2016). Over the past 30 years, various theoretical and applied studies, such as hydraulic engineering, ameliorant application and phytoremediation, have been conducted to mitigate the salinization problem in the western Songnen Plain (Liu et al., 2010; Yu et al., 2010; Wang et al., 2010; Wang et al., 2011; Chi et al., 2012; Yang et al., 2016; Zhao et al., 2018). Recent studies have shown that rice cultivation is the most effective way to improve the utilization of saline-sodic soils under sufficient irrigation conditions, and this approach could improve ecological environment and promote economic development (Chi et al., 2012; Ghosh et al., 2016). Moreover, the agricultural income is further enhanced by “rice-crab” or “rice-duck” co-cultivation system, which combines rice cultivation with feeding crab or duck in the same rice field. In the western Songnen Plain, slightly

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salt-affected soils could be converted into paddy fields for planting rice directly; however, moderately or severely salt-affected soils need to be restored with suitable ameliorant first and then be utilized with sufficient irrigation conditions. Sand application changes soil compaction structure and contributes to flushing out excessive soluble salts from the surface water (Wang et al., 2010). Desulfurized gypsum (containing 93% $CaSO_4{\cdot}2H_2O$), a by-product of coal desulfurization from thermal power plants, provides a source of Ca^{2+} to replace exchangeable Na^+ (Chi et al., 2012). Manure amendment neutralizes soil sodicity and improves soil physical structure (Yu et al., 2010). It is worth noting that most ameliorant studies have focused on characterizing soil physiochemical properties and crop biomass (Chi et al., 2012; Ghosh et al., 2016; Zhao et al., 2018) rather than on elucidating soil microbial properties (Wu et al., 2013), although it has been confirmed that microorganisms also play critical roles in improving saline-sodic soils (Asghar et al., 2012).

Soils supply microorganisms with complex hierarchical habitats (e.g., pores and aggregates) (Jiang et al., 2017). The specific microenvironment conditions of different aggregate fractions affect microbial communities and soil organic carbon (SOC) stability (Muruganandam et al., 2010). Macro-aggregates generally contain more labile substrates that principally derive from plant residues, and exhibit higher fungal biomass than micro-aggregates (Jiang et al., 2017). In contrast, micro-aggregates provide a protective microenvironment for microbial growth and stable SOC (Six et al., 2000). Soil microbial communities regulate principal ecosystem processes such as soil nutrient cycling and organic matter formation and decomposition (Trivedi et al., 2017). Some functional groups, such as arbuscular mycorrhizal fungi (AMF) and actinomycetes, affect soil aggregation (Wilson et al., 2009). However, how aggregate fractions regulate microbial community composition and structure after different ameliorant applications has received less attention. The altered soil environments such as soil sodicity and salinity, nutrient condition, and aggregate structure that arise from ameliorant applications may cause some microorganisms to become competitively dominant over other microbial groups (Luo et al., 2017). In contrast, aggregate-related changes in soil microbial communities due to ameliorant applications may affect SOC sequestration and soil aggregation, and have additional impacts on the soil environment. The objective of this research was to explore the effects of the ameliorant applications and aggregate fractions on soil microbial community and soil aggregation. Firstly, based on an 8-year rice (*Oryza sativa* L.) field experiment, a dry-sieving method with fresh soil was applied to separate the aggregate fractions under different ameliorant applications. Secondly, we revealed the changes of soil microbial community composition and structure that corresponded to the ameliorant applications and aggregate fractions. Finally, we evaluated the influence of microbial community changes on soil aggregation. Therefore, we hypothesized that (1) the aggregate fractions would affect soil microbial communities and the SOC content in the micro-aggregate fraction would increase after different ameliorant applications, and (2) the aggregate-related changes in soil microbial communities (e.g., AMF) would improve soil aggregate stability.

2. Material and methods

2.1. Site description

The study was conducted from 2009 to 2016 at the Da'an Sodic Land Experiment Station of Northeast Institute of Geography and Agroecology, Chinese Academy of Sciences (45°36′ N, 123°51′ E, 132.1 m a.s.l.), which is located in Jilin Province, China. The region has a temperate zone continental monsoon climate (semi-humid and semi-arid area). The annual mean air temperature is 4.7 °C, and the average annual precipitation is 413.7 mm, with 88% falling from May to September. The annual mean evaporation is 1696.9 mm, and the annual reference evapotranspiration from May to September is 683.3 mm. The soil at the study site had clay loam texture according to the USDA texture classification system. Prior to the start of the experiment, the soil properties in the top 20 cm were as follows: bulk density at 1.61 g cm^{-3}; sand at 23.26%; silt at 39.14%; clay at 37.60%; pH at 10.47; electric conductivity (EC) at 2.36 dS m^{-1}; SOC at 2.80 g kg^{-1}; exchangeable sodium percentage at 79.66%. The main soluble cation was Na^+, while the anions were HCO_3^- and CO_3^{2-}. According to the World Reference Base for Soil Resources (IUSS Working Group, 2014), the main soil type was classified as Solonetz.

Table 1
Properties of the amendments used in the present study.

Property	Sandy soil	Desulfurization gypsum	Farm manure
pH	8.92	7.62	8.36
EC (ds m^{-1})	0.78	34.2	–
SOC (g kg^{-1})	4.23	–	263.3
K^+ (g kg^{-1})	0.0011	1.00	13.6
Na^+ (g kg^{-1})	0.0077	1.59	4.11
Ca^{2+} (g kg^{-1})	0.0954	265.3	7.49
Mg^{2+} (g kg^{-1})	0.0132	1.68	10.2

EC, electrical conductivity; SOC, soil organic carbon.

2.2. Experimental design and field management

The experiment was arranged in a randomized block design with three replicates of 20-m^2 plots. The five treatments included the following: (1) CK, without ameliorant amended, as a control; (2) SS, amended with sandy soil 10 cm thick; (3) DG, amended with desulfurization gypsum at 3 kg m^{-2}; (4) FM, amended with farm manure at 6 kg m^{-2}; (5) M, amended with the mixture of sandy soil, desulfurization gypsum and farm manure, the amounts of which are equal to those in the SS, DG, and FM treatments. Some essential properties of the amendments used in the present study are presented in Table 1. The soil ameliorants were manually mixed with the 0–20 cm soil layer before irrigation and the start of this experiment in 2009. Chemical fertilizers were broadcast over the soil annually at rates of 207 kg N ha^{-1} (as urea containing 46% N), 78 kg P ha^{-1} (as calcium super phosphate containing 12% P_2O_5) and 60 kg K ha^{-1} (as potassium sulfate containing 45% K_2O). The soil was then plowed to mix the fertilizers into the subsoil. The local rice cultivar (G19) was planted in this experiment.

2.3. Soil sampling and measurements

Soil samples obtained from each plot were comprised a mixture of soils collected from five places (an "S" distribution) at a depth of 0–20 cm on October 18, 2016, after harvest (Set 1). Undisturbed soil samples were also collected simultaneously from the 0–20 cm layer and stored in sterilized plastic containers for aggregate fractionation (Set 2). The soil samples were placed on ice for transport to the laboratory. In the laboratory, all visible roots and stones were removed from the field-moist soil samples. Soil samples (Set 1) were air-dried at room temperature, passed through a 2-mm diameter sieve before pH and EC measurements, and ground to pass through a 0.15-mm sieve before SOC and total nitrogen (TN) assessments. Soil pH and EC were measured in a soil:water suspension (1:5) after 3 min of shaking at 25 °C. The assessments of SOC and TN were performed as described by Luo et al. (2016). The concentrations of the soluble cations K^+, Na^+, Ca^{2+}, and Mg^{2+} were measured as described by Zhao et al. (2018).

2.4. Aggregate fractionation

Undisturbed soil samples (Set 2) were gently broken up along natural fractures and passed through an 8-mm sieve after removing large roots and stones. The sieved soil samples were placed in sterilized plastic containers and dried to approximately 10% gravimetric water