Geoderma 325 (2018) 49–58

Contents lists available at ScienceDirect

Geoderma

journal homepage: www.elsevier.com/locate/geoderma

Rotation and manure amendment increase soil macro-aggregates and associated carbon and nitrogen stocks in flue-cured tobacco production

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ARTICLE INFO

Handling Editor: M. Vepraskas

Keywords:
Flue-cured tobacco
Manure
Rotation
Water-stable aggregate
Yunnan

ABSTRACT

Flue-cured tobacco production in China is typically over-fertilised and mono-cropped. To understand how this agronomic management affects soil structure and organic matter, this study investigated the effect of rotation, fertilizer rate, and manure amendment on the proportion of water stable aggregates and aggregate-associated soil organic carbon (SOC) and total soil nitrogen (TSN) concentrations and stocks in tobacco production. Two tobacco management systems (Tobacco monoculture and Tobacco-rice rotation) with four fertilizer treatments (0, 75, and 112 kg N/ha, and 60 kg N/ha + manure) were established in 1998. After 18 years, soil aggregation and aggregate-associated SOC and TSN were significantly affected by rotation and fertilizer management. Compared to tobacco monoculture and current fertilizer management, rotation and manure amendment increased macroaggregate (> 250 μm) proportion and geometric mean diameter and decreased the proportion of microaggregates and silt-clay sized fractions (< 250 μm). Simultaneously, rotation and manure amendment increased macroaggregate-associated SOC and TSN stocks at the expense of the microaggregate and silt-clay size class and their associated SOC and TSN stocks. Rotation and/or manure treatment can maintain satisfactory physico-chemical soil properties through macroaggregate stabilization in tobacco production, which contributes to conserving SOC and TSN stocks.

1. Introduction

China currently grows about one-third of the world's tobacco (*Nicotiana tobacum* L.) and China's tobacco industry nets > 1 trillion yuan annually, accounting for about 10% of the national tax income. Raising tobacco is the main income source for most Yunnan farmers and flue-cured tobacco production in Yunnan accounts for around 40% of China's and 20% of the world's production (Hu et al., 2010). However, flue-cured tobacco production in China is typically over-fertilised with nitrogen (N) and is widely mono-cropped (Zhang et al., 2012). This agronomic management for tobacco production potentially degrades soil structure and decreases soil organic carbon and nitrogen pools simultaneously (Zou et al., 2015).

The physical and chemical properties of soil have great influence on tobacco's appearance and chemical quality (Zhang et al., 2012). Sound soil structure and SOM content promote nutrient cycling in the rhizosphere, leading to improved soil fertility, which eventually promotes tobacco growth and increases leaf quality and value (Causarano et al., 2008). The effects of rotation and manure amendment practices on tobacco productivity have been demonstrated (Jin et al., 2002; Zhang et al., 2012), but few studies have been conducted on how soil aggregate stability and its associated SOC and TSN stocks in flue-cured tobacco production systems respond to these conservation practices.

Tobacco growth in rotation systems has benefits in yield and disease-resistance (Reed et al., 2012) and crop rotation management is effective at increasing the whole SOC and TSN stocks and active soil C and N fractions in agricultural ecosystems (West and Post, 2002). In terms of SOC sequestration, most studies show positive results (Sainju and Singh, 2008)· Converting a monoculture to a crop rotation usually leads to SOC sequestration due to increases in residue inputs to soil (Halvorson et al., 2002; Veum et al., 2012), because crops grown in rotation usually have higher biomass yield than those grown in monoculture. Increased SOC may not occur in crop rotations that include frequent use of low residue producing crops such as soybean

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https://doi.org/10.1016/j.geoderma.2018.03.017
Received 11 December 2017; Received in revised form 12 March 2018; Accepted 18 March 2018
Available online 30 March 2018

(*Glycine* max L.) (Studdert, 2000). Thus, the quantity and quality (C/N ratio) of crop residue returned to the soil could regulate SOC sequestration (Wright and Hons, 2005). Compared to other row or sod crops, flue-cured tobacco production returns fewer residues to soil because most types of tobacco are short-season, shallow-rooted, and the entire above ground portion of the plant is harvested.

Flue-tobaccos' high cash value can easily lead to excessive and ineffective N fertilization, much like other types of tobacco (MacKown and Sutton, 1998). There may be two impacts of excessive fertilizer N application on aggregation and SOC and TSN sequestration, with contrary results. Fertilizer N could positively influence SOM accumulation and macroaggregate formation due to increased residue biomass input (Yu et al., 2012). Fertilizer N could also negatively influence SOM accumulation via increased SOC mineralization primed by N fertilizer addition (Khan et al., 2007). There is evidence in previous research that N-fertilised, and unfertilised, treatments do not differ in terms of aggregate size fractions or associated SOC and TSN stocks (Tripathi et al., 2014). Considering these results, the application effects of fertilizer N on soil aggregation, N, and C probably change with agronomic production practices such as different crop rotation strategies.

Mineralization of manure provides the same chemical forms of nutrients as chemical fertilizers (Eghball et al., 2002). However, manure application, especially from compost, directly adds organic carbon or residue to soil, which are reported to positively influence soil structure and aggregate stability (Olchin et al., 2008). Soil organic matter can be the nucleus for aggregate formation and act as a soil binding agent (Tisdall and Oades, 1982).

Total soil nitrogen and SOC sequestration are closely associated with the stability and structure of soil aggregates (Six et al., 2004). Aggregates are important reservoirs of TSN and SOC that remain unaffected by microbial access and are thus less affected by microbial, physical, chemical, and enzymatic degradation (Six et al., 2000a, 2000b). Aggregate-SOM models are a significant, classical approach for studying the stabilization of TSN and SOC (Tisdall and Oades, 1982; Six et al., 2004). By providing physico-chemical protection in hierarchical soil aggregates, such stabilization is significant for establishing and maintaining TSN and SOC stocks (O'Brien and Jastrow, 2013). According to previous reports, the proportion of macroaggregates (> 250 μm) among the aggregate size fractions provide an early indicator of SOM dynamics as affected by agronomic practices (Six et al., 1999; Veum et al., 2012). Hence, applying physical approaches to separate aggregates and determine the associated SOC and TSN stocks can be a systematic method with which to measure the effects of N fertilization management and rotation on SOC, soil structure, and TSN sequestration in production systems used for flue-cured tobacco.

Conventional flue-cured tobacco production in China can be considered agronomically unsustainable due to the negative effects on aggregation, SOC stocks, and TSN stocks. However, the effects of rotation, manure amendment, and N fertilization management practices on these properties are not well understood. It is hypothesized that: i) compared with monoculture at low N fertilization rates, and without manure application, tobacco rotation with rice, high N fertilization rates, and manure application can promote a larger proportion of macroaggregates and improvements in soil structure; ii) practices including rotation with rice, high mineral N input, and manure application enlarge bulk SOC and TSN stocks by raising the concentration of macroaggregate-associated SOC and TSN. To test our hypothesis, we investigated soil water aggregate stability and SOC and TSN stocks as affected by agronomic management. The samples were collected from 0 to 10 cm and 10–20 cm depths in an 18-year, long-term study site, which was located in a representative soil type and climate for raising tobacco in Yunnan China. The primary objective was to understand the mechanism by which agronomic practices influence soil quality and sustainable agronomic activity.

2. Materials and methods

2.1. Study site description

This study was conducted at the Yunnan Academy of Tobacco Agricultural Sciences' Yanhe Research Farm near Yuxi, Yunnan, China (24°14′N 102°30′W). The soil was classed as a red soil according to the traditional Chinese soil taxonomy, which is the dominant type soil for flue-tobacco production in Yunnan. Based on the USDA (2014) soil taxonomy, this soil belongs to the Typic Plinthudults. The topographical features and soil nutrient levels of the experiment site are representative for most of the most tobacco growing region. When the study was initially established in 1998, the baseline soil water pH (1:1, w/v) was 6.4, and basic soil chemical properties were: organic matter, 10.70 g/kg; total N, 0.54 g/kg; total P 0.11 g/kg; total K, 6.43 g/kg. Mehlich (1984) extractable nutrient levels were 90 and 160 mg/kg for P and K, respectively. The soil alkali-hydrolyzable N before transplanting was in the range of 70–90 mg/kg across years. The initial soil texture was 28% sand, 50% silt, and 22% clay based on the hydrometer method (Gee and Bauder, 1986). The location is characterized by wide variation in mean monthly precipitation, and the rainy season (April–September) accounts for 79.5% of annual rainfall, with annual average total precipitation of 1160 mm. This research site has an altitude of 1680 m, with annual average temperature of 15.9 °C and 2072 h of annual average sunshine.

2.2. Field experiment design

The experiment was a randomized complete block design with three replicates. This study included two factors: rotation style and N fertilizer management. Rotation styles included tobacco monocropping (M) and tobacco rotated with rice (R) every two years. Nitrogen fertilizer application had four levels: 0, 75, 112 kg N/ha, and a treatment with 60 kg N/ha with manure application. The manure was comprised of humified swine compost and its application rate was 15,000 kg/ha. The OM, N, P_2O_5, and K_2O contents of manure in this study were approximately 15%, 0.5%, 0.5% and 0.35%, respectively. Therefore, the current study had eight treatments: M-0, M-75, M-112, M-M-60 (Monocropping-Manure-60), R-0, R-75, R-112, and R-M-60 (Rotation-Manure-60). These treatments were randomly assigned in the plots (2 m wide by 14 m long) within each block. From 1998 to 2016, flue-cured tobacco was mono-cropped for 18 seasons, and tobacco rotations with rice were completed with 9 years of tobacco and rice. The cultivar for flue-cured tobacco was K326. For flue-cured tobacco production, the biomass residue of tobacco was completely removed; including root systems. For rice, the N fertilizer rate was 240 N kg/ha (N:P_2O_5:K_2O = 1.0:0.5:1.0) for all the plots, and the average biomass residue left in the field was around 2000 kg/ha every season. Agronomic management practices followed the guidelines recommended by the Integrated Technology Promotion Center at the Yunnan Academy of Tobacco Agricultural Sciences.

2.3. Collecting soil samples and sample preparation

Soil samples were collected for this study on 10 March 2016. An aluminium cutting ring (54 mm high and 60 mm in diameter) was used to measure the bulk density of the soil in soil layers at depths of 0 to 10 cm and 10 to 20 cm (Kemper and Rosenau, 1986). To measure the distribution of wet aggregate size and concentrations of TSN and SOC, 20 soil cores were randomly obtained from 0 to 10 cm and 10 to 20 cm in each plot using a hand probe and composited. The sample was placed onto an 8 mm-aperture sieve and those particles finer than 8 mm were used. After removing visible rocks and root residues, the field-moist samples were taken to the laboratory and sealed in plastic bags at 4 °C for subsequent wet sieving. Wet sieving fractionation was carried out within a week of sampling.