EFFECTS OF CONVERSION OF NATURAL AND DEGRADED GRASSLAND TO CROPLAND ON SOIL ORGANIC CARBON FRACTIONS IN NORTHEAST CHINA

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ABSTRACT

Although the dynamics of soil organic carbon (SOC) during the conversion of grassland to cropland has received much attention, relatively little is known of the effects of grassland conversion to paddy soil on SOC and its fractions. This study examined eight systems: 1) natural grassland (NG); 2) NG conversion to maize for 5 years (NGM5); 3–4) NG to paddy land for 22 and 55 years (NGP22 and NGP55); 5) degraded grassland (DG) and; 6–8) DG conversion to paddy land for 4, 22, 55 years (DGP4, DGP22 and DGP55). Results showed the contents of SOC, labile organic C (LOC), recalcitrant organic C (ROC), light fraction of organic carbon (LFOC), dissolved organic carbon (DOC) and microbial biomass carbon (MBC) at 0–60 cm in NGM5 were 32.43–52.30%, 44.58–66.07%, 25.33–34.24%, 11.33–19.02%, 31.02–47.16% and 20.10–50.44%, respectively, lower than those of NG, indicating LOC was more sensitive than SOC to the conversion. NGP22 and NGP55 maintained higher SOC, ROC and LOC than that NG, with the highest content in NGP55. The SOC, ROC and LOC in 0–80 cm soil layer followed the order: DGP55 > DGP22 > DGP4.

KEYWORDS:
Grassland conversion, Maize land, Paddy land, Soil organic carbon, Labile organic carbon fractions

INTRODUCTION

The grassland biome is widely distributed, covering approximately 40% of Earth's surface and storing at least one-third of the global terrestrial ecosystem carbon (C) [1,2]. However, approximately 25% of grasslands have been degraded or destroyed by conversion to agricultural land [3], resulting in alterations to the chemical, physical and biological properties of soil, and thus impacting soil organic carbon (SOC) stocks [4]. The SOC pool is the largest C pool of the global terrestrial ecosystem and is closely related to atmospheric greenhouse gas concentrations [5]. Therefore, understanding the dynamics of the SOC pool during the conversion of grassland into agricultural land is of vital importance.

The SOC pool mainly comprises the labile organic C (LOC) and recalcitrant organic C (ROC) pools [5]. ROC is characterized as stable and unsusceptible to short-term tillage [6], thereby constituting long-term C storage [7]. Due to its higher activity and faster turnover rate, LOC is more sensitive and susceptible to plants [8] and short-term land use changes compared to SOC [9]. Therefore, LOC can act as an early indicator of changes in the carbon stock [10]. However, LOC fractions, such as light fraction organic carbon (LFOC), dissolved organic carbon (DOC) and microbial biomass carbon (MBC), have different turnover times, chemical compositions and function [11]; thus, they may respond differently to land use change.

Changes in SOC with the conversion of grassland into cropland has received much attention, however, less has been paid to changes in ROC. Most investigations reported a decrease in SOC with the conversion of grassland into cropland [12-14], some found an opposite result [15]. Several studies showed decreases in LFOC [16], MBC [17], and DOC [18] due to the conversion of grassland into cropland, whereas other studies reported an increase in MBC [15]. Aslam et al. [19] found that conversion of grassland to different agricultural farming affected MBC difficulty. Most previous studies have focused on the effects of conversion of grassland to dryland farming, such as maize, potato, wheat and soybean within the topsoil (≤ 40 cm), and few studies have considered irrigated farming and deeper soil. Furthermore, the inconsistent results of these studies indicate that different tillage practices may lead to contradictory effects on SOC and its fractions. Management and tillage practices differ greatly between dryland farming and irrigated farming. Therefore, there is a need for further analysis of the changes in

TABLE 1
Soil properties at a depth of 0–20 cm in all systems

Treatment	Conversion age by 2017 / yr	pH	Bulk density ($g \cdot cm^{-3}$)	Total N ($g \cdot kg^{-1}$)	Electrical conductivity ($mS \cdot cm^{-1}$)	Moisture (%)
NG		8.1	1.26	1.46	0.38	16.68
DG		9.4	1.55	0.27	0.68	9.08
NGM5	15	8.5	1.37	1.23	0.43	11.95
NGP22	22	7.6	1.19	1.95	0.41	43.21
NGP55	55±3	7.5	1.17	2.01	0.39	43.75
DGP4	4	9	1.34	0.58	0.59	40.32
DGP22	22	8.2	1.22	0.94	0.50	41.23
DGP55	55±3	7.7	1.19	1.79	0.42	43.64

SOC and its fractions due to the conversion of grassland to irrigated farming to better understand soil C storage.

Western Jilin Province in Northeast China has historically retained a large area of green steppe. However, the conversion of grassland to cropland to boost grain production potential in this region has dominated land use change in recent decades [20]. Grassland in this region has mostly been converted to paddy and maize land, the dynamics of SOC and its fractions remain poorly understood. The overall objectives of the present study were to: 1) determine the responses of SOC and its fractions to the conversion of grassland to paddy and maize land; 2) evaluate the sensitivity of LOC fractions as early indicators of SOC variations due to the conversion. The result may provide reference to the C pool management in this region.

MATERIALS AND METHODS

Site description. The study site is located in Qianguo County (43°59′N–46°18′N, 121°38′E–126°12′E), Western Jilin Province, Northeast China. The site marks the convergence of land used for agriculture and stock farming. The climate is classified as temperate and semi-humid, with a frost-free period of approximately 180 d a^{-1} and an annual average temperature of 5.8 °C. Annual evaporation is 1 500 mm–1 900 mm, 4–5 times that of mean annual precipitation. The crop growing period begins in the middle of May and ends in the late September. From 1976–2013 in Western Jilin Province, the conversion of grassland to farmland and alkali-land, and alkali-land to farmland have totaled 145 100 ha, 146 400 ha, and 16 200 ha, respectively.

Experimental design and sampling. A space-for-time substitution methodology with the assumption of equivalent spatial and temporal variations [21] was adopted.

This study examined eight systems (Table 1) :1) natural grassland (NG); 2) NG conversion to maize for 5 years (NGM5); 3–4) NG to paddy land for 22 and 55 years (NGP22 and NGP55, respectively); 5) degraded grassland (DG) and; 6–8) DG conversion to paddy land for 4, 22 and 55 years (DGP4, DGP22 and DGP55, respectively). Soil within NG free of grazing was classified as chernozem. DG allowed almost no plant growth. After the conversion from grassland to agricultural land in this region, maize and rice were the only vegetation, and fallow farming was not practiced for either. Cultivation of the developed croplands was by conventional practices with plant roots maintained in the soil. Aboveground residues were removed from the field. Developed paddy land experienced additional irrigation and drainage; no fertilizer was applied in the initial years due to the excessive salinity. Once the salinity decreased, the applied fertilizer amount gradually increased until equal to that applied to paddy land converted from NG. All paddy soil experienced flooded conditions from early May to early September.

The aboveground biomass and litter were removed before soil sampling. Eighteen soil cores were collected randomly from each system using a soil borer with a diameter of 38 mm in late August 2017. Soil samples were obtained from depths of 0–20 cm (L1), 20–40 cm (L2), 40–60 cm (L3) and 60–80 cm (L4). For each layer, soil samples from every six cores were combined to form one subsample, and three subsamples were collected for each system. Visible roots, litter, residue, stones and gravel > 2 mm in diameter were removed after sampling.

Laboratory analysis. SOC was measured using a TOC analyzer (Elementar vario TOC, Germany).

LOC was measured according to the method described by Lefroy et al. [22]. Briefly, 25 mL 333 mmol L^{-1} $KMnO_4$ was added to soil containing the equivalent of 15 mg C, after which the samples were shaken and centrifuged. The liquid supernatant was diluted using deionized water. Absorbance values were determined using a spectrophotometer (Analytik Jena Specord 200plus, Germany) at 565 nm to calculate the quantity of oxidized $KMnO_4$. LOC content was measured by the change in $KMnO_4$ concentration by assuming 1 mmol $KMnO_4$ oxidizes 9 mg C. ROC was the difference between SOC and LOC.

DOC measurement. Distilled water was added to 10 g fresh soil. The mixed sample was shaken, centrifuged, and filtered. The extract was processed using a TOC analyzer (Elementar vario TOC, Germany) to determine DOC.

MBC was determined using a fumigation extraction method [23]. In brief, soil sample (equivalent to 20.0 g dry soil) was fumigated with $CHCl_3$ vapor for 24 h in a vacuum desiccator. The fumigated soil was extracted using 80 mL 0.5 mol L^{-1} K_2SO_4 at 25 °C for 0.5 h after removal of residual $CHCl_3$. The C extracts from the fumigated and unfumigated samples were analysed by a TOC analyser (Elementar vario TOC, Germany). MBC content was calculated according to equation (1):

$$\text{MBC content} = (\text{fumigated C} - \text{unfumigated C})/0.45 \quad (1)$$

LFOC was measured by density fractionation [24]. Briefly, 50 mL1.7 g cm^{-3} NaI solution was added to 10.0 g air-dried soil. The solution was filtered through a 2 mm mesh and shaken for 5 min. The filtrate was centrifuged for 10 min at 4,200 rpm after ultrasonic separation for 10 min, and filtered through a 0.45 mm filter. The fraction on the filter was first rinsed with 200 mL 0.01 mol L^{-1} $CaCl_2$ and then with 400 mL distilled water to remove the NaI and $CaCl_2$. The procedures were repeated twice. The three subfractions were mixed, oven-dried at 50 °C and then used to analyze LFOC content using a TOC analyzer (Elementar vario TOC, Germany).

The sensitivity index (SI) was defined as the variations in SOC and its fractions after land use change and was calculated according to the following equation (2) [25]:

Note: NG was defined as the control for NGM5, NGP22 and NGP55, and DG was defined as the control for the DGP4, DGP22 and DGP55.

Statistical analyses. All statistical analyses were conducted in the software SPSS 22.0 (International Business Machines Corporation, New York, USA). All figures were drawn using Sigmaplot 12.5 software (Systat Software, Inc., San Jose, CA, USA).

RESULTS

Changes in SOC and its fractions with the conversion of NG. Besides for a significant increase in ROC at L4 with the conversion of NG to maize land, significant decreases in SOC, LOC and ROC at L1–L4 were observed (Figure 1). Decreases in LOC were mainly observed at L1, L2 and L3 by 3.3, 2.7 and 3.6 g kg^{-1}, respectively and in SOC by 50.7%, 59.2% and 71.7%, respectively. SOC contents in L1, L2 and L3 decreased by 32.43%, 40.48% and 52.30%, respectively, whereas LOC decreased by 44.58%, 54.04% and 66.07%, respectively, thereby indicating that LOC could be considered as a sensitive indicator of SOC variation (Figure 2).

SOC, LOC and ROC at L1–L4 in NGP22 and NGP55 were significantly higher than those in NG. More SOC, LOC and ROC in the two paddy fields were sequestered at L1–L2 than those at L3–L4. ROC at L1–L3 in NGP22 and NGP55 increased by 1.83–7.11 g kg^{-1}, accounting for 54.65%–87.92% of the increase in SOC and implying that ROC dominated the increase in SOC with the conversion of NG to paddy land. The NGP55 treatment retained more SOC, LOC and ROC than NGP22 treatment.

Significant decreases in DOC and MBC at L1–L4 were observed with the conversion of NG to maize land (Figure 1). DOC decreased by 31.20%, 32.40% and 47.16% and MBC decreased by 41.61%, 20.10% and 25.90% at L1, L2 and L3, respectively, suggesting that DOC and MBC were less sensitive than SOC to the conversion of NG to maize land (Figure 2). However, a maximum decrease in MBC at L4 was observed, implying that MBC was more sensitive than SOC to the conversion. There was no significant difference between LFOC for grassland and maize land at L1 and L3–L4, indicating that LFOC was relatively insensitive to the conversion.

LFOC and DOC at all depths were significantly enhanced with the conversion of grassland to paddy land (Figure 1). LFOC at L1–L4 increased by 117.90–230.61% and 155.70–323.86% in NGP22

$$\text{SI} = (\text{C fraction in treatment} - \text{C fraction in control})/\text{C fraction in control} \quad (2)$$

LFOC and DOC at L1–L4 appeared to be more sensitive to the conversion of grassland to paddy land than SOC (Figure 2). Significant increases in MBC were observed at L1–L4 after the conversion and NGP55, respectively. DOC in NGP55 increased by 476.41 g kg^{-1}, 398.05 g kg^{-1}, 293.40 g kg^{-1} and 161.98 g kg^{-1} at L1, L2, L3 and L4, which were 136.12 g kg^{-1}, 172.82 g kg^{-1}, 219.91 g kg^{-1} and 35.48 g kg^{-1} greater than those in NGP22, respectively. of NG to paddy land, whereas a significant decrease was observed in L4.

Changes in SOC and its fractions with the conversion of DG. SOC, LOC and ROC throughout all soil layers were markedly enhanced after the conversion of DG to paddy land, particularly in DGP22 and DGP55 (Figure 3). The contents of SOC, LOC and ROC followed the order: L1 > L2 > L3 > L4. LOC at L1–L4 in DGP22 and DGP55 increased by 0.96–12.21 g kg^{-1}, accounting for 44.49–56.00% of the increase in SOC after the conversion, thereby indicating that LOC and ROC contributed equally to the sequestered SOC.

LFOC, DOC and MBC at L1–L4 significantly increased after the conversion of DG to paddy land, with longer durations of conversion resulting in higher content (Figure 3). SOC, LOC, LFOC, DOC and MBC throughout the soil profile increased by 86.3–272.1%, 62.4–227.0%, 210.6–569.0%, 67.7–196.2% 121.1–977.7% in DGP22, and by 204.0–561.0%, 175.8–541.4%, 455.3–1109.9%, 289.8–509.7%, 168.7–1840.2% in DGP55, respectively. This suggests that LFOC and MBC were more sensitive to the conversion than SOC (Figure 4).

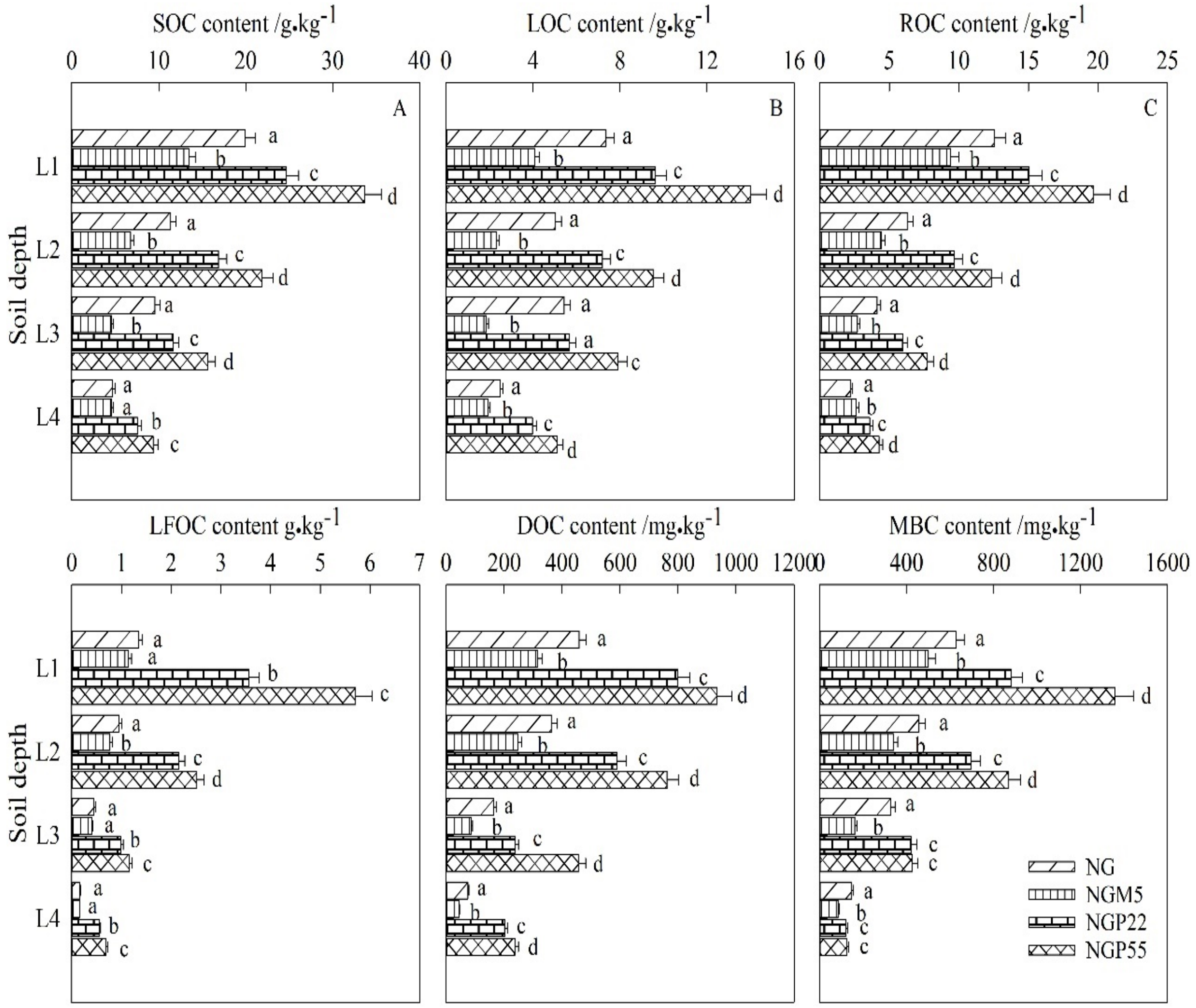

FIGURE 1
SOC, LOC, ROC, LFOC, DOC and MBC contents of the soil profile resulting from the conversion of NG to maize and paddy land. Different lowercase letters indicate significant differences among treatments at the same soil depth.

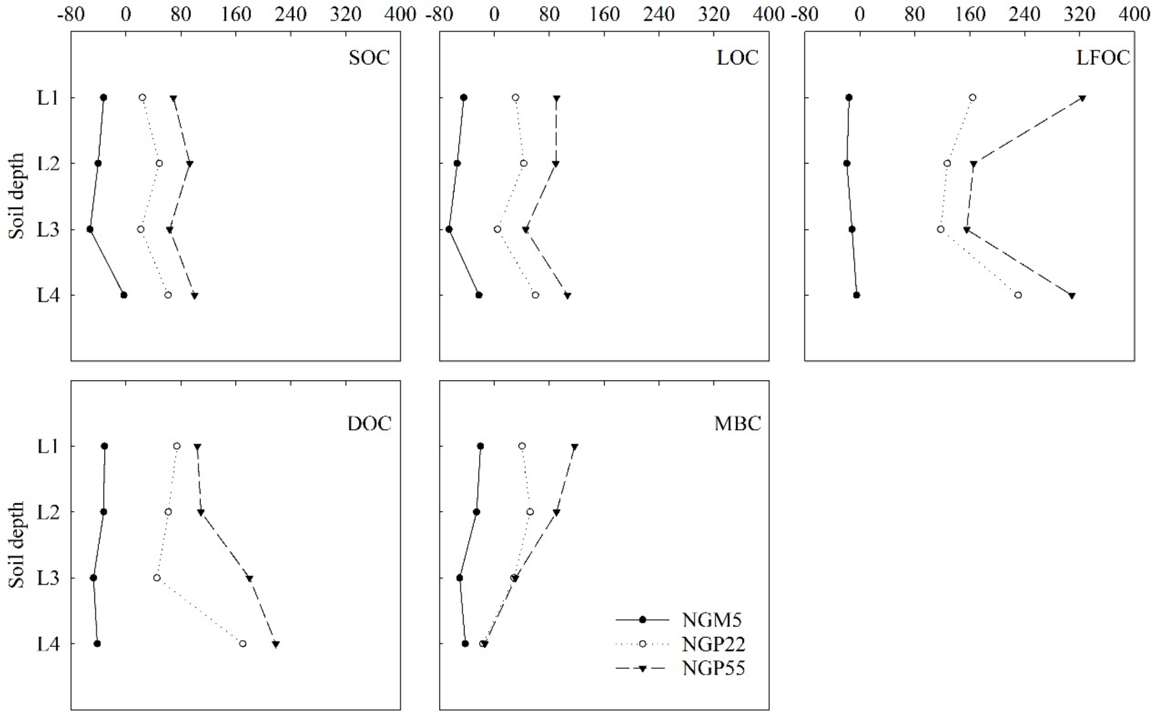

FIGURE 2
Sensitivity index of SOC and its labile fractions with the conversion of NG to maize and paddy land

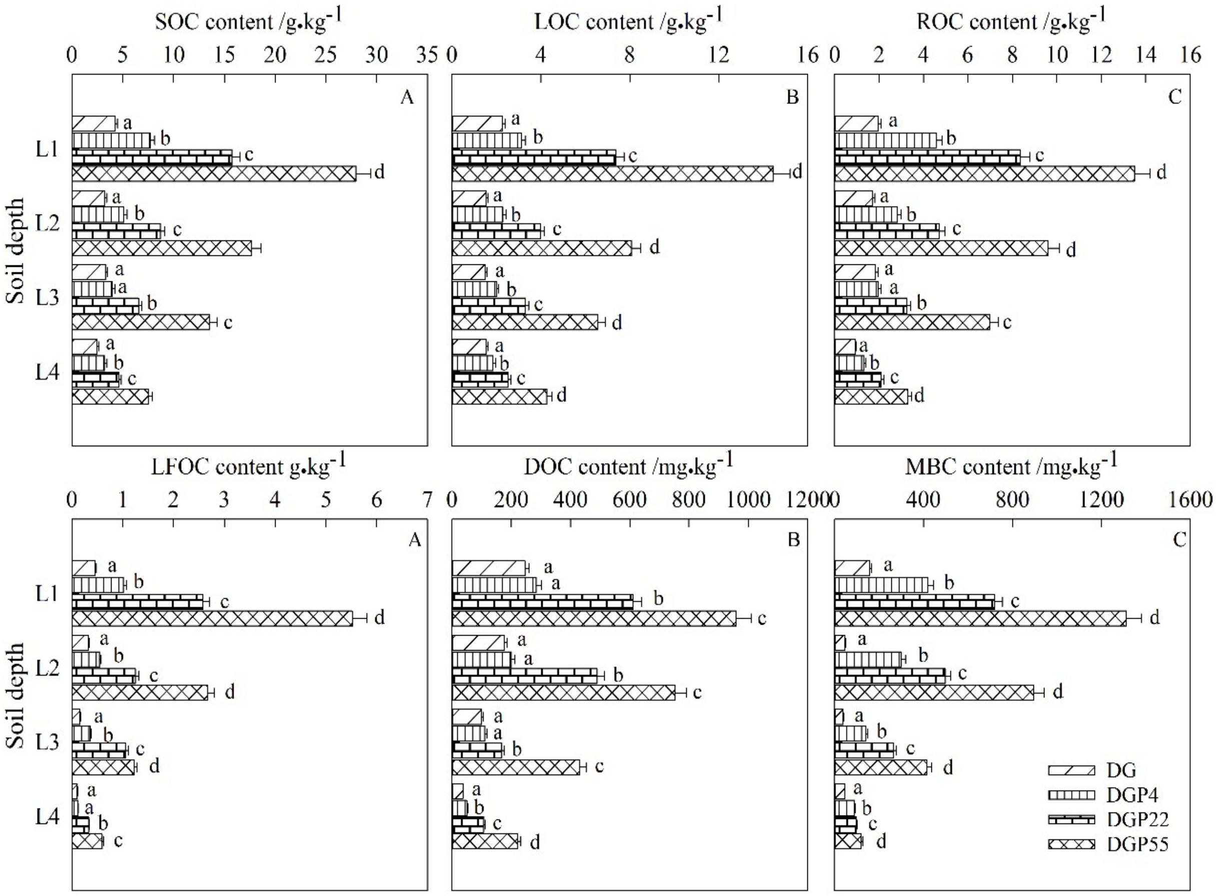

FIGURE 3
SOC, LOC, ROC, LFOC, DOC and MBC contents of the soil profile resulting from the conversion of DG to paddy land

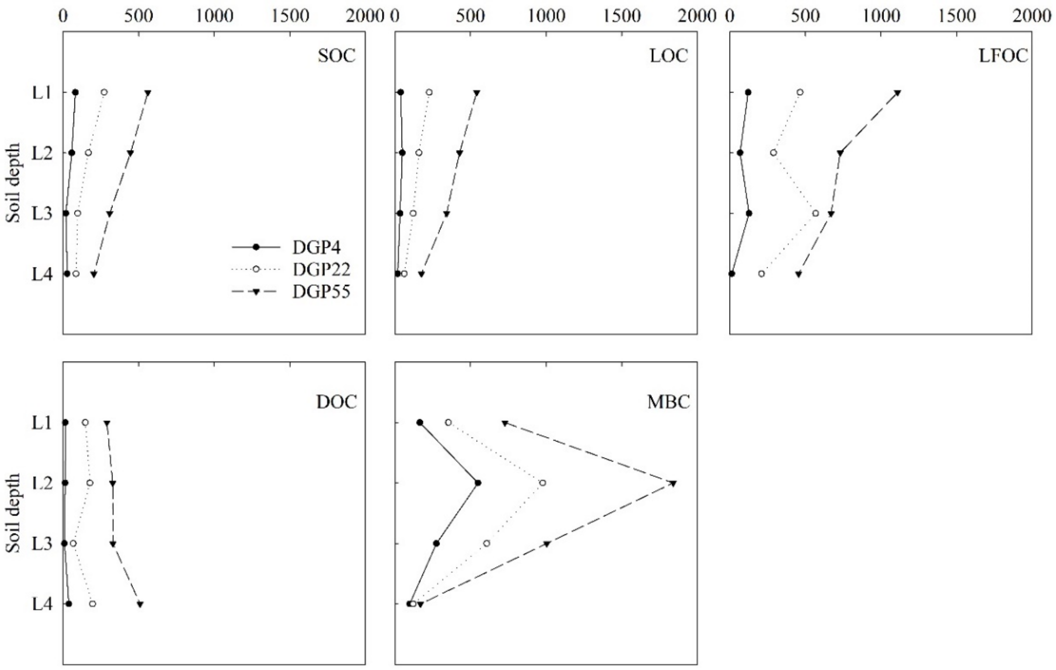

FIGURE 4
Sensitivity index of SOC and its labile fractions with the conversion of DG to paddy land

DISCUSSION

Changes in SOC fractions following the conversion of grassland to maize. The conversion of NG into maize land markedly reduced SOC, LFOC, DOC, and MBC at L1–L3, L2, L1–L4 and L1–L4, respectively, which were consistent with most previous observations [16,17]. However, the direction and magnitude of changes to SOC, DOC and MBC following conversion could significantly differ in vegetation types, conversion ages and regions. For example, Guan et al. [16] found that SOC and LFOC decreased by 27% and 47–72%, respectively at L1 after the conversion of grassland to barley-rape rotation for above 50 years in Tibet. Qiu et al. [26] recorded losses of SOC and MBC at L1 by 57–61% and 18–73%, respectively, following the conversion of grassland to maize land for 27 year on Loess Plateau. SOC, DOC and MBC at L1–L2 decreased by 14.9–28.2%, 66.7–77.1% and 36.5–42.4%, respectively, with the conversion of grassland to wheat over 36 years in Inner Mongolia [27]. These differences may possibly be explained by differences in cultivation practices, soil properties and climate. The loss of SOC and its labile fractions were generally attributed to decreased C inputs and the accelerated C mineralization rate in cropland under traditional tillage [27]. Reported evidence included significantly larger root biomass in grasslands compared to croplands [28], and roots plays a crucial role in carbon input [29]. In previous decades, aboveground crop residue was burned or removed from cropland, thereby contributing little to C input, whereas plant litter is retained in grassland. In addition, agricultural practices exert a negative impact on soil C store, as shown by Wang et al. [30] who found that conversion of grassland to agricultural land significantly reduced total soil C by 26% in the 0–30 cm soil layer. Zingore et al. [31] also found that agricultural practices accelerated the decomposition of SOC in cropland. However, inverse results were obtained by Nautiyal et al. [15] and Aslam et al. [19] who reported that SOC and MBC were significantly increased following the conversion of grassland to cropland. This could be ascribed to the high C inputs (large annual inputs of farmyard manure and maintenance of crop residues) and no tillage [15].

SOC and its labile fractions also decreased at L3–L4 following the conversion. This shows that subsoil SOC could be mobilized and decomposed as a result of land conversion. The insignificant decreases in SOC and LFOC at L4 in maize land can likely be attributed to the short conversion age and lower bioactivity and utilizability of these carbon fractions compared to DOC and MBC.

ROC, as a stable and insensitive fraction of SOC, was significantly reduced at L1–L3, probably due to the over-consumption of LOC pool. Guo et al. [32] indicated that decomposition of ROC would start after the LOC pool is exhausted. The noticeable later increase in ROC at L4 in maize land may have resulted from maize roots at L4 [33] and leaching of C from the upper soil. The increase in ROC at L4 could also be explained by the low C mineralization rate and temporarily abundant LOC for microbial activity, which led to temporary sequestration of ROC.

However, the remarkable decrease in LOC at L4 suggested that LOC could be exhausted with increasing conversion age, consequently leading to the mobilization and decomposition of ROC.

Changes in SOC fractions following the conversion of grassland to paddy. Conversion of DG and NG to paddy land resulted in significant increases in SOC and its fractions. After the conversion of DG to paddy land, ploughing, irrigation and drainage reduced salt and decreased pH, which gradually increased the suitability of the soil for the growth of rice plants. The root of rice plants played a vital role in C input. The preservation of SOC was ascribed to prevailing cold weather during the non-growing period [34] and anaerobic conditions during the growing period [35], which greatly inhibited the decomposition of SOC. In addition, the utilization of fertilizer contributed to increasing SOC and its fractions [36]. Since almost 100% of the rice root mass was distributed within L1–L2 [37], SOC and its fractions within L3–L4 may originate from leaching of C from upper soil. Ouyang et al. [38] similarly found that paddy soil had high SOC content in northeast China. These results indicate that paddy soil is easier to sequester SOC compared to grassland. The MBC contents at L4 in NGP22 and NGP55 decreased significantly following the conversion from NG. This could be attributed to MBC contents at L4 in the NGP22, and NGP55 being close to the threshold value limited by the soil environment. However, the physicochemical mechanisms responsible remain unclear.

Sensitive indicators of SOC alterations following land use change. Although LOC fractions are regarded as early indicators of SOC response to land use change [9], their sensitivities differed according to soil depth. In NGM, only LOC at L1–L3 was sensitive to the conversion of NG into maize land, whereas LOC, LFOC, DOC and MBC were more sensitive than SOC at L4 (Figure 2). After the conversion of NG to paddy land, LOC at L1 was more sensitive than SOC; however, the opposite was true at L2–L3. LOC and DOC at L1 were less sensitive to the conversion of DG to paddy land, whereas LFOC and MBC were more sensitive than SOC to the conversion (Figure 4). These results were similar to those observed by Sheng et al. [39] who reported that LFOC, DOC and MBC at L1 were more sensitive to land use change compared to SOC, but only LFOC and DOC were more sensitive than SOC following the change from native frost to sloping tillage. Consequently, the effects of conversion of grassland to cropland on LOC fractions were different throughout the soil profile.

In addition, the response of LOC fractions to the conversion of grassland to cropland also depends on the type of conversion. For example, LFOC at L1–L3 was less sensitive following the conversion of NG to maize land, but was more sensitive than SOC following the conversion of NG to paddy land (Figure 4). DOC at L1 was more sensitive to the conversion of NG to paddy land compared to SOC, but was less sensitive than SOC with the conversion of DG to paddy land. Sheng et al. [39] also found that LFOC at L1–L2 was less sensitive to the conversion of natural forest to plantations or orchards compared to SOC, but was more sensitive than SOC with the conversion of natural forest to sloping tillage. Therefore, the conversion of natural vegetation to different land types has variable impacts on LOC fraction.

CONCLUSION

The conversion of NG to maize land decreased SOC, LOC, ROC, LFOC, DOC and MBC fractions. ROC and LOC fractions were enhanced following the conversion of NG and DG to paddy land, and the degree of enhancement was positively related to conversion age. In general, LFOC and DOC were more sensitive to the conversion of NG to paddy land compared to SOC, whereas LFOC and MBC were more sensitive to the conversion of DG to paddy land compared to SOC. Paddy soil had higher and the maize soil had lower carbon sequestration capacities under traditional cultivation practices compared to grassland in this region.

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Conflict of Interest. The authors declare that there is no conflict of interest regarding the publication of this article.

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