

Effects of wetland recovery on soil labile carbon and nitrogen in the Sanjiang Plain

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Abstract Soil management significantly affects the soil labile organic factors. Understanding carbon and nitrogen dynamics is extremely helpful in conducting research on active carbon and nitrogen components for different kinds of soil management. In this paper, we examined the changes in microbial biomass carbon (MBC), microbial biomass nitrogen (MBN), dissolved organic carbon (DOC), and dissolved organic nitrogen (DON) to assess the effect and mechanisms of land types, organic input, soil respiration, microbial species, and vegetation recovery under *Deyeuxia angustifolia* freshwater marshes (DAMs) and recovered freshwater marsh (RFM) in the Sanjiang Plain, Northeast China. Identifying the relationship among the dynamics of

labile carbon, nitrogen, and soil qualification mechanism using different land management practices is therefore important. Cultivation and land use affect intensely the DOC, DON, MBC, and MBN in the soil. After DAM soil tillage, the DOC, DON, MBC, and MBN at the surface of the agricultural soil layer declined significantly. In contrast, their recovery was significant in the RFM surface soil. A long time was needed for the concentration of cultivated soil total organic carbon and total nitrogen to be restored to the wetland level. The labile carbon and nitrogen fractions can reach a level similar to that of the wetland within a short time. Typical wetland ecosystem signs, such as vegetation, microbes, and animals, can be recovered by soil labile carbon and nitrogen fraction restoration. In this paper, the *D. angustifolia* biomass attained natural wetland level after 8 years, indicating that wetland soil labile fractions can support wetland eco-function in a short period of time (4 to 8 years) for reconstructed wetland under suitable environmental conditions.

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Introduction

Overdevelopment and irresponsible use of soil by humans have reduced organic materials, resulting in lower soil fertility and capacity to hold water (Shi et al.

2000). Thus, effective utilization of land, which is closely related to soil nutrient cycling, is the utmost concern of land management. Land use management can influence plant litter and residue (Dalal and Mayer 1988) and can affect soil microbes and relocation of nutrients in the soil system (Kennedy and Papendick 1995). Land management can have a positive effect on the accumulation of organic carbon. Numerous plantations can lower organic carbon in soil and increase fine particles (Burdige and Gardner 1998). Generally speaking, 16–17 % of soil organic material can be lost because of agricultural activity, with an average loss of up to 29–30 %. The lighter the soil is, the larger the loss of organic matter. The same is also true for organic nitrogen (Knops and Tilman 2000). Earth biomass will decrease because of clearing of natural plantations, which increases soil ventilation, leading to mineralization of organic materials. Consequently, soil will be lost, resulting in soil degradation (Post and Kwon 2000). Lal (2002) showed that 60–70 % of lost carbon can be recovered using effective land management. Many research studies have shown that restoring agricultural land to natural plantation can increase soil organic material and total nitrogen (TN) contents (Ma and Jiao 2005), but only on the soil surface (An et al. 2003; Song et al. 2004; Zhang et al. 2005). After conducting a research on carbon and nitrogen dynamics of restored agricultural land, Landgraf (2001) showed that organic carbon within 0–10 cm of the soil increased gradually, but that in 10–30 cm of the soil decreased with the time during the restoration process. The result for TN was almost the same. Restoration speed was related to organic background, solid management, soil hydrological condition, and microbes (Saggar et al. 2001; Post and Kwon 2000). For the same type of soil, the longer the cultivation period, the longer the time for restoration of the eco-function. Restoration to 95 % of their natural use was estimated to take 180 years for nitrogen and 230 years for carbon (Knops and Tilman 2000). The active components, however, will be restored within a short period of time. Hughes et al. (2002) discovered that dissolved organic carbon (DOC) will increase after restoring the land to a forest due to the increase in organic A1 compounds and chelating organic acid. Zhou and Jiang (2004) conducted research on red-soil carbon pool and observed that total organic carbon (TOC) and different kinds of active carbon significantly increased after plantation restoration. The microbe carbon in the 0–20 cm soil after 17 years of restoration was 2.95 times that of the soil after 9 years of restoration only.

The Sanjiang Plain is located in the eastern part of Heilongjiang Province, Northeast China, and is bordered by Russia. It covers an area of 10.89 Mha, mostly dominated by marshes in 1893, and is presently the second largest marsh in China (Zhao 1999; Liu and Ma 2000). Draining wetlands for agricultural purposes is significant in this area especially in the last 50 years, and this activity causes wetland loss. According to the US EPA (2001), destroying wetlands can lead to serious consequences that include increased flooding and extinction of species. In the Sanjiang Plain, this occurrence has resulted in the degradation of the ecological attributes of the natural wetlands and also significantly affected the TOC and TN of the wetlands.

Converting native marshland to agricultural soil resulted in distinct changes in soil water content and temperature (Song et al. 2004), increase in the amount of microaggregate, and a rapid decrease in labile organic C concentration and amount of macroaggregate, as well as that of soil organic C (SOC) (Zhang et al. 2006).

From the 1990s, overuse and reclamation of the Sanjiang Plain have changed in some ways. In particular, in recent years, many ecological engineering have taken place in Heilongjiang Province. In the Sanjiang Plain, restoring plants to wetland and forest helps control wetland degradation and changes carbon storage and formation. Zhang and Song (2003) conducted a related research, but extensive field studies are still needed. In the present paper, we conducted research on dissolved organic matter, microbe carbon, nitrogen, and plantation and evaluated the eco-functions after restoring the agricultural land into wetland.

Materials and methods

Study area

The study site was set up at the Sanjiang Mire Wetland Experimental Station, Chinese Academy of Sciences, Sanjiang Plain, China, approximately 47°35' N, 133° 31' E (Fig. 1). Boreal climate conditions and low slope grade have led to the largest area of mire wetlands in North China. The average altitude is between 55.4 and 57.9 m, the annual mean temperature is 1.9 °C, and the non-frost period is 125 days (Song et al. 2004). The study site is in the seasonal frozen zone (Song et al. 2004) with annual precipitation between 550 and



Fig. 1 Location of Sanjiang Mire Wetland Experimental Station

600 mm, mainly in July and August, accounting for more than 65 % of the annual precipitation.

The study area which was a natural wetland was converted to a farmland and subsequently restored into a wetland. The study area was originally dominated by *Deyeuxia angustifolia*. *D. angustifolia* wetland is a seasonal flooded wetland and submerged only in May. This natural wetland was subjected to human interferences which resulted in significant changes in the TOC and TN of the wetland. The drainage and use of wetlands for agricultural fields occurred in the past 50 years with the population growth, resulting in the increase in cultivated land from about 0.79×10^6 ha in 1949 to 4.57×10^6 ha in 1994 (Liu and Ma 2000). Now, the Sanjiang Plain has become an intensive area of land use/cover change in China. The soils at all sites were classified as Albaquic Paleudalfs with silty clay texture (Zhang et al. 2008).

The Honghe and Qianjin farmlands have plantations existing for 20 and 40 years, respectively. The area is approximately 105 hm², composed mainly of different natural wetlands, in addition to 6.6 hm² of swampy area and 7.0 hm² of dry land. In the study area, the plantation time is short, the plantation history is clear, and the structure is simple. In this area, natural wetland, artificial forest, agricultural land, and restored wetland exist, providing better conditions for research on different soil management practices.

Experimental design

The study area considered was a natural mire wetland with *D. angustifolia*. This natural mire wetland was converted to agricultural land. The agricultural land was subsequently restored to wetland. During the period when the area was used as an agricultural land, soy was planted for more than 10 years, which was a typical mired meadow. Data were collected over a period of 10 years at 2-year interval during the restoration period of the agricultural soil to wetland (R2, R4, R6, R8, and R10 denote data collected on the second, fourth, sixth, eighth, and tenth years, respectively). Also, a nearby soy plantation (S) and a natural *D. angustifolia* wetland (M) within the Sanjiang Plain were considered. In each type of soil management, a 40×40-m study area was chosen, and three sampling areas and ten soil volumes (20 mm in diameter) were obtained. The samples were sent to the laboratory where they were treated by removing the litter, dead roots, and small animals and preserved in refrigerator at 4 °C.

Plant biomass measurements

The harvesting method involved obtaining the biomass from the ground. Three to four samplings of a 50×50-cm area were chosen randomly. Plants above

the ground were brought to the laboratory and identified. They were dried at 80 °C for 48 h and weighed. The cutting ring method was employed to obtain the underground biomass. Two to three areas were chosen, and ten soil volumes at soil depths of 0–40 cm were obtained by using cutting ring of 4 cm in diameter and 10 cm in height.

DOC and DON measurements

Field moist soil samples (equivalent to 10 g oven dry weight) were weighed into 40-mL polypropylene centrifuge tubes. The samples were extracted using 30 mL of distilled water for 30 min on an end-over-end shaker at 30 rpm and centrifuged for 20 min at 8,000 rpm. The entire supernate was filtered through a 0.45- μm filter into separate vials for C analysis (Ghani et al. 2003). The extracts were analyzed for C using high-temperature combustion (TOC- V_{CPH} C analyzer, Shimadzu, Kyoto, Japan). The concentrations of the total dissolved N, NH_4^+ , and NO_3^- were determined using a continuous-flow analyzer (Skalar, Breda, Netherlands). The dissolved organic nitrogen (DON) in the extracts was calculated by subtracting NH_4^+ and NO_3^- from the total dissolved N in the extracts [i.e., $\text{DON} = \text{total dissolved N} - (\text{NH}_4^+ - \text{N} + \text{NO}_3^- - \text{N})$].

MBC and MBN measurements

The soil microbial biomass carbon (MBC) and microbial biomass nitrogen (MBN) were determined using a fumigation–extraction method. Fumigated and non-fumigated soils were extracted with 0.5 M K_2SO_4 for 30 min (soil/extractant ratio=1:5), and the extracts were analyzed for C using a TOC analyzer (TOC V_{CPH} , Shimadzu). The total dissolved N concentrations were determined using a continuous-flow analyzer (Skalar, Breda, Netherlands). The C/N obtained from the fumigated samples minus that from the non-fumigated samples was assumed to represent the microbial–C/N flush and converted to microbial biomass C/N by using the following relationships: microbial biomass C=microbial–C flush/0.38, and microbial biomass N=microbial–N flush/0.45 (Lu 2000).

SOC and TN analyses

Air-dried samples were used for the soil organic carbon (SOC) and TN analyses. SOC was analyzed by

wet digestion method using H_2SO_4 – $\text{K}_2\text{Cr}_2\text{O}_7$, and TN was determined by semi-micro Kjeldahl digestion method using Se, CuSO_4 , and K_2SO_4 as catalysts (Lu 2000).

Statistical analysis

Statistical analysis was done using the SPSS software package for Windows (SPSS 17). One-way ANOVA was used to test for significance. For all analyses where $p < 0.05$, the factors tested and the relationships were considered to be statistically significant.

Results

Changes in physicochemical properties of the restored wetland

The bulk density of the surface soil decreased with the restoration time (Fig. 2c). After 4 years, the bulk density at the surface reduced from 1.15 to 0.95 g/cm^3 . After 10 years, it decreased to 0.72 g/cm^3 . From the results, the change in *D. angustifolia* will take 25.7 years in order to be totally restored to the same state as the species in the natural wetland. After the agricultural land was restored, the porosity increased (Fig. 2a). According to the formula, the recovery process will take 29.2 years. The field capacity also increased with the restoration time (Fig. 2b), and it can be noted that it will take approximately 24.8 years to fully recover to equivalent levels of the natural wetlands.

Characteristic changes of soil TOC and TN under different restoration times

TOC and TN changed after the recovery process (Fig. 3). After 10 years of recovery, the TOC in the 0–10-cm soil was 87.91 ± 1.02 g/kg , whereas that in the 10–20-cm soil was 46.32 ± 0.51 g/kg . TN gradually increased after 10 years. The TN in the 0–10-cm soil was 5.10 ± 0.03 g/kg , whereas that in the 10–20 cm was 3.14 ± 0.38 g/kg . The total organic matter and the TN in the topsoil were higher ($p < 0.0001$) than those at lower soil depth (10–20 cm). Accumulation of the TOC and TN was more significant at the upper layer relative to the lower layer.

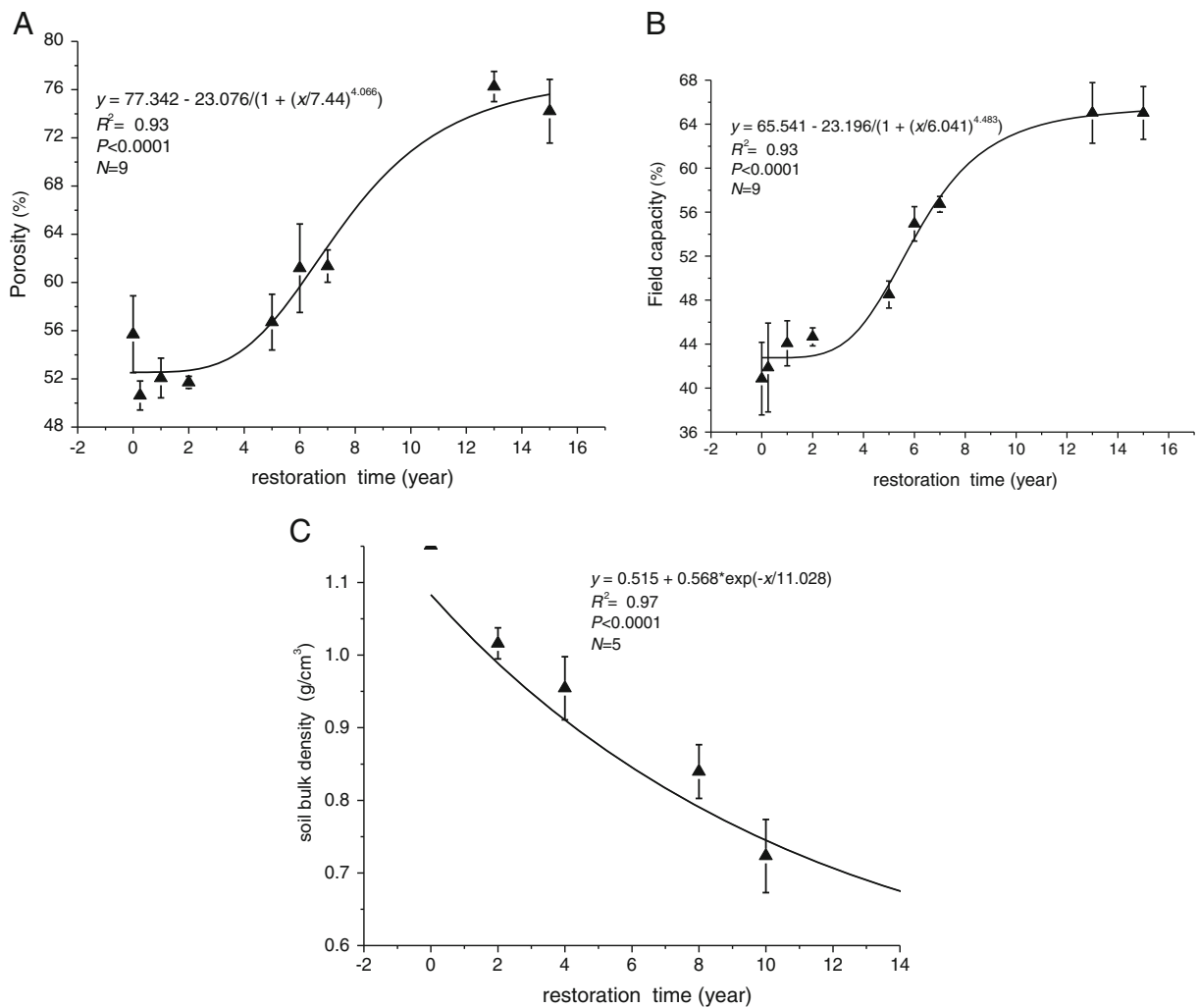


Fig. 2 Changes in physicochemical properties of the restored wetland

Characteristic changes of soil DOC and DON under different restoration times

DOC and DON increased significantly after the restoration of the agricultural land into wetland (Fig. 4). Compared with the reference soy field, the DOC of the recovered wetland was significant within a short period of time (2 years; $p < 0.001$). After 4 years of recovery, the soil DOC and that of natural *D. angustifolia* wetland were the same for the 4–10 years of recovery. No significant difference ($p > 0.5$) existed. After 4 years of recovery, no difference in the 0–10 and 10–20-cm soils was apparent.

After restoration of the agricultural land into wetland, the DON in the 10–20 cm soil was higher than that in the

0–10 cm ($p < 0.001$). The difference in DON in R2 and R4 was not significant ($p > 0.5$), but higher than that of R8 and R10. Compared with the 0–10-cm soil of *D. angustifolia* and in the 10–20 cm of the agricultural land, DON was higher in natural *D. angustifolia* wetland. After 2 years of recovery, the DON was almost the same as that of the agricultural land ($p > 0.5$). Between the fourth year and the tenth year of recovery, the DON increased, but the difference was negligible.

Dynamics of MBC and MBN

The MBC and MBN increased significantly and reached the level of natural *D. angustifolia* wetland ($p > 0.5$;

Fig. 3 Characteristic changes of soil TOC and TN under different restoration times

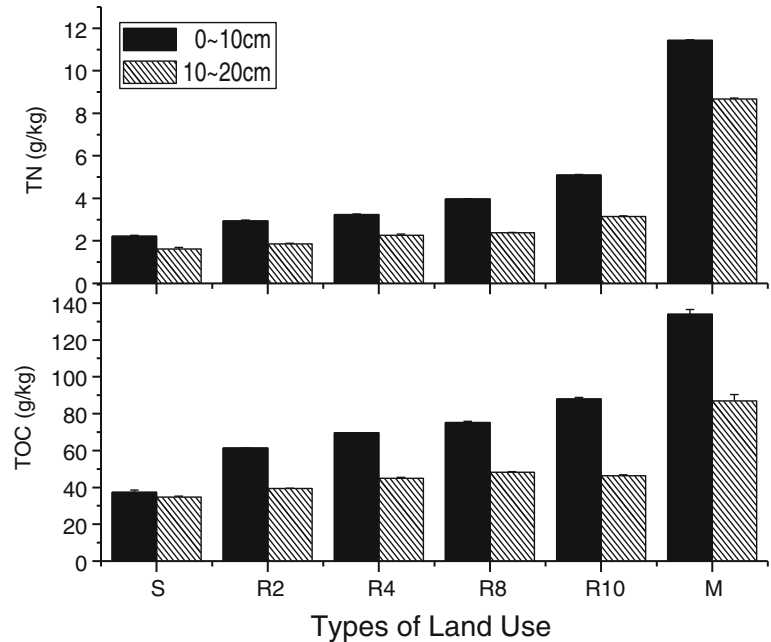


Fig. 5). Within 2 years of recovery, the MBC of the surface soil (0–10 cm) recovered in some manner, which was higher than the MBC of the cultivated agricultural land (481.72 ± 70.54 mg/kg). After 10 years of recovery, the MBC was almost the same as that of natural *D. angustifolia* wetland. The MBC in the 10–20-cm soil was similar to that of the 0–10-cm soil. However, the MBN in the 0–10-cm soil was higher than that of the 10–20-cm soil. After recovery, the MBN in the

0–10-cm soil for different years was almost the same as that of the 10–20-cm soil. In the 0–10-cm soil, a small difference in the natural *D. angustifolia* wetland (60.30 ± 12.00 mg/kg; $p > 0.5$) was observed after 4 years of recovery. In the 10–20-cm soil, the MBN of natural *D. angustifolia* wetland was 46.52 ± 1.85 mg/kg, with no significant difference after 2 years of recovery. The MBN of natural *D. angustifolia* wetland for all the years of recovery was higher than that of the soy soil.

Fig. 4 Characteristic changes of soil DOC and DON under different restoration times

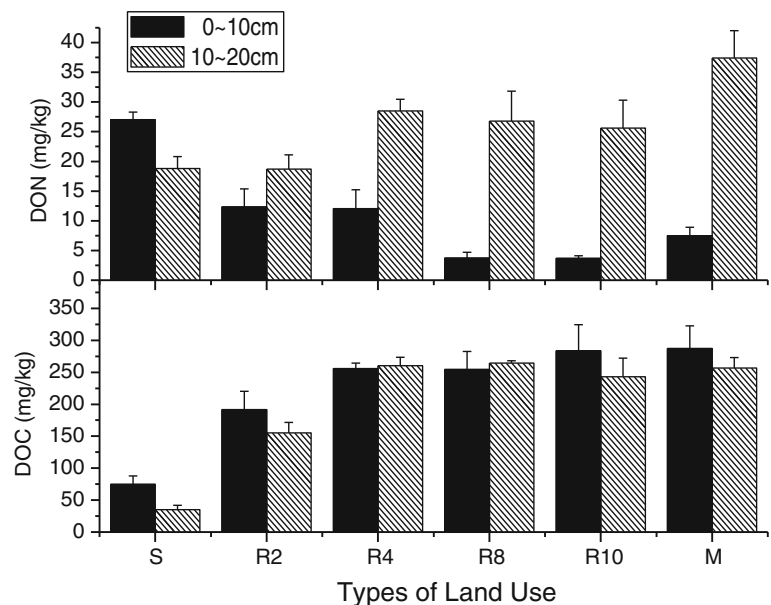
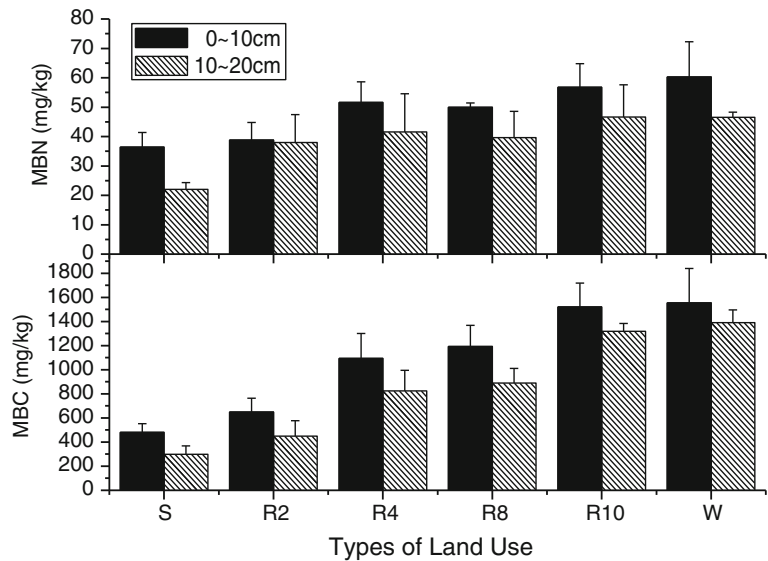


Fig. 5 Characteristic changes of soil MBC and MBN under different restoration times



The effects of soil depth on the TOC/TN and DOC/DON over the restoration period

The TOC/TN in the 0–10-cm soil increased with time within the initial 4-year restoration period but decreased afterwards. However, the TOC/TN in the 10–20-cm soil decreased with time over the entire restoration period except for the period between the fourth and the eighth year where there was a slight increment (Fig. 6a). The DOC/DON of the 0–10-cm soil increased with time over the entire restoration period. The DOC/DON in the 10–20-cm soil increased slightly after 2 years of recovery then remained almost the same for the rest of the restoration period (Fig. 6b). After recovery, the MBC/MBN of the 0–10- and 10–20-cm soils increased (Fig. 6c).

Vegetation changes after agricultural land restoration

After 2 years of recovery, the number of wetland *D. angustifolia* was 26.3 % of that of the reference natural wetland (Table 1). The higher proportion of the plant community was made up of Xerophytes. After 4 years of recovery, the number of wetland *D. angustifolia* was 80.3 % of that of the natural wetland. After 2 years of recovery, the number of *Pedicularis* L. (a typical Xerophyte) was lower than that before the 2-year recovery. Aquatic plants occupied the higher proportion of the plant community. After 8 years of recovery, the number of wetland *D. angustifolia* became the dominant community, which was 103.9 % of the

natural wetland. No significant difference was observed for the *D. angustifolia* between the eighth and tenth years of recovery.

D. angustifolia recovery characteristics under different recovery years

After 4 years of recovery, the *D. angustifolia* biomass recovered was 69.54 % of that of natural *D. angustifolia* (Fig. 7). After 8 and 10 years of recovery, little difference existed between the *D. angustifolia* biomass and that of the natural *D. angustifolia* ($p > 0.5$) biomass. The *D. angustifolia* biomass in 2 years of recovery was 12.79 %.

Discussion

Usually, when the recovery time is ongoing, the carbon and nitrogen components in the surface soil increase (Juo and Lal 2003; An et al. 2003), and the increase in organic components appears only in the surface (0–10 cm) soil (Wang et al. 2002). In this research, the TOC, TN, MBC, MBN, DOC, and DON changed after the recovery. They increased with recovery time, except for the DON in the 0–10-cm soil.

The balance between the input and dissolved components determines the composition of the soil organic content. After the restoration of the agricultural land into wetland, succession and recovery of plants occurred. The biomass on the ground and underground

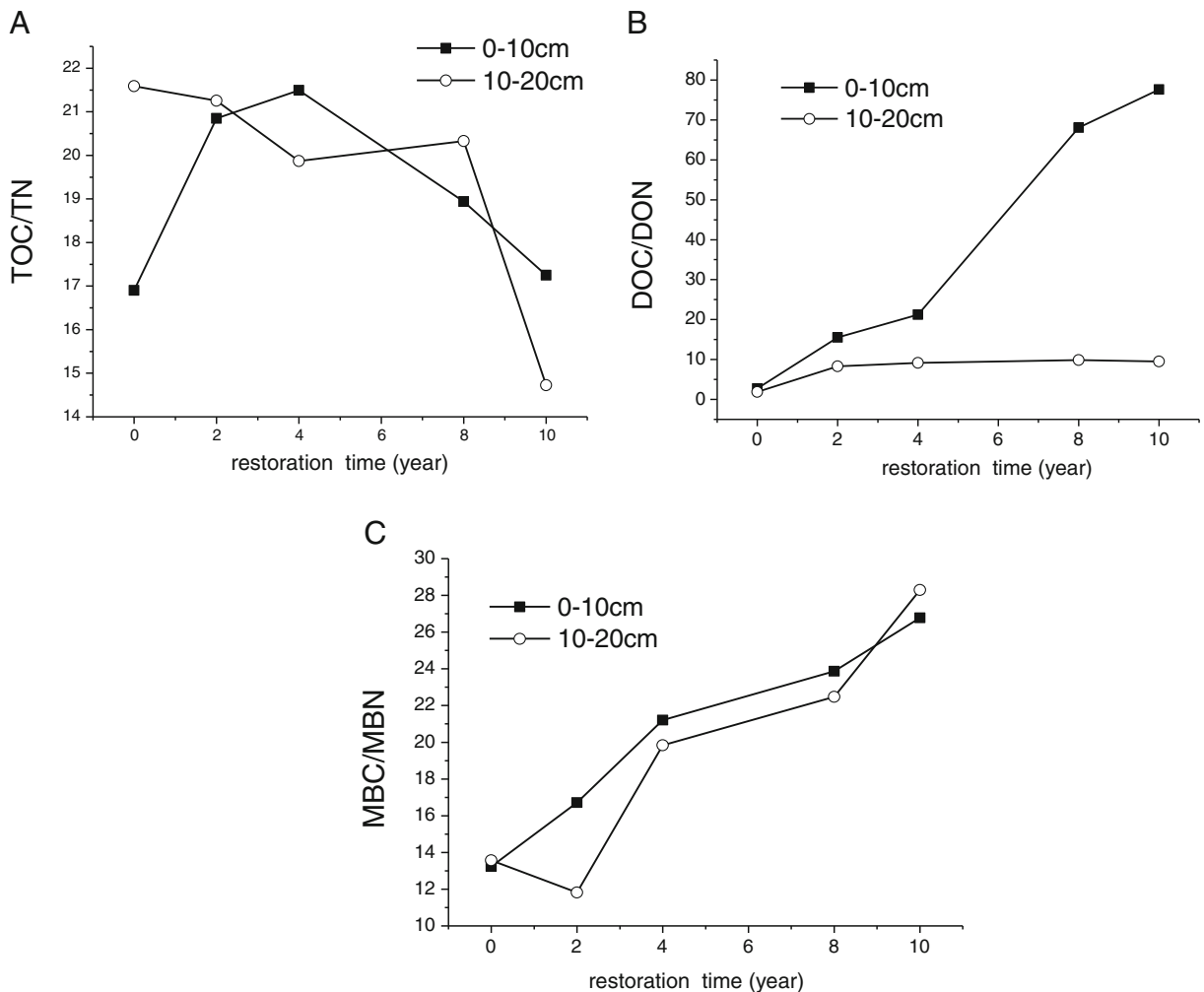


Fig. 6 C/N of soil carbon and nitrogen fractions after farmland restoration

both increased, and soil microbes developed well. Organic residue, such as the roots, increased slightly. Thus, recovery of soil physical properties occurred, which was suitable for organic accumulation. DOC and DON come from the organic residue of plants and microbes, mainly those easily decomposed by photosynthate. After restoration into wetland, the photosynthate increased with time, providing a base for DOC and DON, enabling them to increase and reach a balance between composition and degradation (Kalbitz 2001). In the current paper, after the recovery, the DON in the 10–20-cm soil was higher than that in the 0–10-cm soil, which might be due to the DON biomass usage by soil microbes and the plant roots of the surface soil (0–10 cm). After the recovery, the plant biomass increased, enabling larger nitrogen absorption in the 0–10-cm soil than in the 10–20-cm soil because nitrogen mineralization is

low in natural ecosystem; thus, meeting the need of the plant was difficult. Further, the DON might have been the main nutrient absorbed by the plants (Kieland 1994; Jonasson et al. 1999).

In addition, during seasonal flooding environment, microbe activity is active in the surface soil. In the biological process in surface soil, microbe and soil animals have higher biomass usage than the ground microbes, resulting in more usage of surface soil DON, which makes the underground DON higher than that in the surface.

In the process of ecosystem recovery, more litter results in more organic matter. Microbes can use more energy, leading to more microbe biomass (Jenkinson 1976). Therefore, microbe biomass and activity indicate the ecosystem condition through interference and recovery. Zhou and Jiang (2004) showed that TOC

Table 1 Aquicolous vegetation changes after farmland restoration

S	<i>Glycine max</i>	<i>Cirsium setosum</i>	<i>Chenopodium album</i>	<i>Commelina communis</i> L						
Plant/m ²	58	4	5	3						
R2	<i>Deyeuxia angustifolia</i>	<i>Artemisia selengensis Turcz</i>	<i>Cirsium setosum</i>	<i>Carex tristachya</i>	<i>Artemisia tanacetifolia</i>	<i>Pedicularis resupinata</i> L	<i>Salix L.</i>	<i>Salicaceae</i>	<i>Galium aparine</i>	<i>Galium aparine</i> var. <i>tenerum</i>
Plant/m ²	68	26	7	5	5	161	19	11	9	2
R4	<i>Deyeuxia angustifolia</i>	<i>Glycine soja</i>	<i>Pedicularis resupinata</i> L	<i>Artemisia tanacetifolia</i>	<i>Galium aparine</i> var. <i>tenerum</i>	<i>Salicaceae</i>			<i>Salixmagnifica</i> Hensl	
Plant/m ²	208	57	25	2	5	7			1	
R8	<i>Deyeuxia angustifolia</i>	<i>Lythrum salicaria</i> L.	<i>Glycine soja</i>	<i>Carex tristachya</i>	<i>Scutellaria baicalensis</i> Georgi	<i>Stachys baicalensis</i> Fisch. ex Benth.				
Plant/m ²	269	2	4	35	13	2				
R10	<i>Deyeuxia angustifolia</i>	<i>Equisetum arvense</i>	<i>Glycine soja</i>	<i>Pedicularis resupinata</i> L	<i>Fragaria ananassa</i> Duch	<i>Gentianaceae</i>				
Plant/m ²	234	3	1	5	2	1				
M	<i>Deyeuxia angustifolia</i>	<i>Equisetum ramosissimum</i> Desf.	<i>Carex lasiocarpa</i>	<i>Carex meyeriana</i>	<i>Carex schmidtii</i>	<i>Glyceria acutiflora</i>				
Plant/m ²	259	4	39	5	2	38				

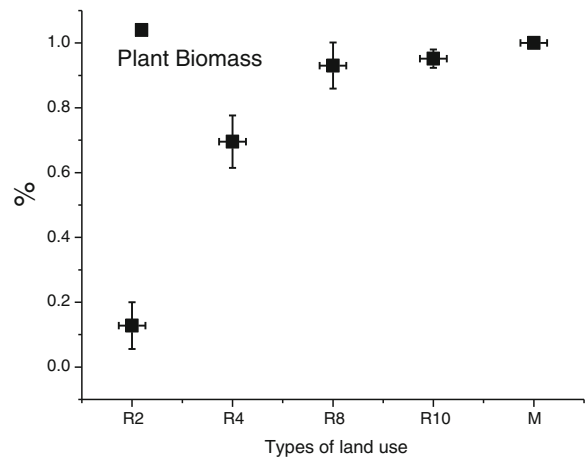


Fig. 7 Biomass of *D. angustifolia* under different restoration times

and MBN increased significantly after red-soil plantation recovery in Fir forest. The MBN after 17 years of recovery (0–20 cm) was 2.95 times that after 9 years of recovery. In this research, the soil microbe biomass significantly increased after recovery. Such environmental factors such as soil nutrients, water condition, and plantation affected the soil microbe biomass and population. Microbe biomass has a positive relationship with soil total nutrients. During the early stages of recovery, soil nutrients and plantation did not recover much, so the soil microbe biomass was small. After a period of nutrient accumulation, nutrient condition reached the highest community density, and the soil microbe biomass attained balance, which was almost the same as that of the natural wetland. The microbe biomass reached the level of that of natural wetland.

It was observed that the recovery of the *D. angustifolia* biomass significantly increased during the restoration process. It must be noted that the TOC, TN, MBC, MBN, DOC, and DON also increased during the recovery process. The changes in these chemical parameters influenced the recovery of the vegetation biomass. The recovery of the vegetation biomass was probably enhanced by these parameters directly through physiological and nutritional effects (FAO 2005).

It is also worthy to note that the sharp increase in the TOC/TN in the surface layer at the initial stages can be attributed to the effects of living roots and the soil microbial community within this layer. The absorption of TN by plant and microbes at the initial stages within the surface layer was very high. This activity, however, reduces with time leading to increases in the soil TN.

Therefore, the TOC/TN decreased after the eighth year. In addition, within the lower layer of the soil (10–20 cm), the transformation of the TOC occurs at a slower rate relative to the nitrogen content of the soil. As a result, the TOC/TN decreases within this depth.

Furthermore, the increases in the DOC/DON can be ascribed to the effects of the plants and the soil microbial community. Microbes and plants biomass utilize DON, whereas DOC does not change with time. Hence, DOC/DON increased over the entire restoration period. The increment was more pronounced in the surface layers owing to the active nature of the activities of plants and the soil microbial community within this region. The increases in the MBC/MBN could be attributed to the changes in the composition of the microbes.

It was found out that the labile fractions of the organic matter responded rapidly during the restoration process. This occurrence might be due to the rapid turnover rate of the labile fractions. These easily decomposed organic fractions are released directly from cells of fresh residues. As a result, they serve as early indicators of land use on soil quality (Gregorich et al. 1994) as well as important indicators of soil quality. Unlike the labile fractions of the organic matter, the TOC and TN took a long time before they were recovered during the restoration process. This observation might be due to the slower turnover rate of the TOC and TN. This may be explained by the fact that the sources of these organic matter fractions cannot be decomposed readily because they are more difficult for soil organisms to break down (FAO 2005).

It must also be pointed out that the restoration process is influenced strongly by weather conditions. In the Sanjian Plain, air temperature changes very smoothly, increasing from January to August, and then declining until December. Nearly half of the annual rainfall occurs in July and August. From May to June, the time period for plant rejuvenescence and growth, the precipitation usually is sufficient (Xu 2004). These climatic conditions provide suitable environment for the restoration of the vegetation biomass.

Conclusion

Draining wetlands for agricultural purposes is significant in the Sanjian Plain especially in the last 50 years, and this activity causes wetland loss. This occurrence has significantly affected the TOC and TN of the wetland.

It was observed that the duration for the TOC and TN to restore to the level at which they occur naturally in the ecosystem was very long. Meanwhile, the soil active components reached the uncultivated level within a short time. The active components supplied and recycled the soil nutrients, co-working and interacting with wetland plants, microbes, and animals. Thus, the soil active components can be one of the key factors that determine eco-function recovery after restoring the agricultural land into wetland. In conclusion, this study can be used as an effective evaluation in analyzing the dynamics of plant recovery and the active carbon and nitrogen components of a wetland ecosystem undergoing significant land use changes.

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