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Full Length Research Paper

Relationship between carbon and nitrogen in degraded alpine meadow soil

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The distribution of soil organic carbon (SOC), labile organic carbon (LOC), and available nitrogen, as well as, the corresponding relationships between carbon and nitrogen were analyzed among meadows with varying degrees of degradation (normal, slight and severe) in Dangxiong, Tibet. The increasing severity of meadow degradation corresponded with decreasing soil organic carbon, LOC and available nitrogen. The SOC distributions in the 0 to 10 cm soil layer of the slightly degraded and severely degraded meadows were lower than that of the normal meadow by 13.2 to 27.5% and 39.5 to 78.6%, respectively. The LOC distribution in the two areas decreased by 11.1 to 50.9% and by 31.2 to 77.2%. The corresponding available nitrogen decreased by 25.6 to 38.2% and 48.8 to 68.0%, whereas the SOC decreased by 6.0 to 29.7% and 53.2 to 73.2%. The degradation of soil carbon and nitrogen occurred first in the 0 to 10 cm layer. In the 0 to 10 cm and the 10 to 20 cm layers, the relationship between soil available nitrogen and LOC was more significant than that between soil available nitrogen and SOC. Grassland degradation caused a decrease in the ratio of soil LOC to available nitrogen. The average proportions of LOC and available nitrogen in the normal, slightly degraded, and severely degraded meadows were 24, 19, and 17. These values showed that the nitrogen loss caused by grassland degradation is faster than LOC loss. During degradation, organic carbon was more stable than soil available nitrogen.

Key words: Alpine meadow, soil organic carbon, labile organic carbon, available nitrogen.

INTRODUCTION

Grassland degradation is the reduction of grassland coverage and soil degradation caused by overgrazing and global climate change (Wang et al., 2007; Shang and Long, 2007). Climatic changes lead to considerable degradation of meadows and steppes, and grassland degradation leads to the loss of soil organic carbon (SOC) and total nitrogen (Wang et al., 2007; Peng et al., 2010). Moreover, grassland degradation leads to the deterioration of the soil structure and fertility as well as, to the decline, oxidation, and decomposition of organic matter. These processes reduce the carbon and nitrogen sequestration capacity of the soil, thereby, accelerating carbon and nitrogen loss and increasing the CO_2 concentration in the air. SOC is an active constituent of the soil, and it plays an important role in soil productivity and the global carbon cycle (Biederbeck and Janzen, 1994). The soil carbon pool is directly related to the atmospheric carbon pool, and small changes in the soil carbon pool cause marked changes in the atmospheric CO_2 (Schimel et al., 1994). Land use and management measures destroy the SOC balance, thus, exposing a large amount of SOC, which is oxidized into CO_2 and passes to the atmosphere. Consequently, the SOC was significantly lower (Follett, 2001) and soil degradation is accelerated. Nitrogen is another important factor that influences the primary productivity of grasslands (Wedin and Tilman, 1990). Nitrogen affects the coupling effect of carbon emission and absorption in terrestrial ecosystems (Gruber and James, 2008). In many ecosystems,

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nitrogen supply is an important environmental factor because it determines plant growth and species composition (Fremstad et al., 2005). Soil nitrogen efficiency directly affects the terrestrial carbon budget (Ashagrie et al., 2007) and terrestrial ecosystem carbon turnover (Vestgarden, 2001). One of the realistic medium- to long-term strategies for soil management is the regulation of soil nitrogen fixation to maximize soil carbon fixation from atmospheric carbon (Metting et al., 2001).

The dynamic characteristics of soil carbon and nitrogen reflect the soil quality response to changes in external environmental conditions and management practices. However, changes in the SOC are slow and difficult to measure over short intervals (Bandick et al., 1999; Kätterer et al., 2004). Nevertheless, different SOC components are sensitive to external environmental conditions and reflect soil, climate, and management changes (Marriott and Wander, 2006; Shao et al., 2009). LOC has the highest activity with fast turnover rates, which affect the soil heterotrophic respiration (Gu et al., 2004). LOC is sensitive to changes in soil management practices (Cambaredlella, 1998), and rapidly responds to changes in carbon supply. Thus, it is as an important indicator of soil quality (Zhang et al., 2006a). LOC content is influenced by soil use (Zhang, 2010) and management practices (Marriott and Wander, 2006). Soil LOC content directly affects the activity of soil microbes, soil carbon sequestration, and greenhouse gas emissions (Yagi and Minami, 1990).

During meadow degradation, wherein plant coverage is reduced, the surface soil is eroded by wind and water, which leads to the oxidative decomposition of SOC and soil nitrogen, which results in soil carbon and nitrogen loss. The SOC and total nitrogen in severely degraded grazing areas were lower by 33 and 28%, respectively, (Wu and Tiessen, 2002). Wang et al. (2006) found that the 0 to 20 cm layer of soil in severely degraded grasslands lost 50.9% organic carbon. Given the increasing severity of meadow degradation, the nitrogen in the soil can be leached by water, oxidized, or volatilized into the atmosphere. Soil nitrogen influences the carbon sequestration functions of terrestrial ecosystems (Wu et al., 2007), wherein the turnover of soil carbon (Vestgarden, 2001) affects plant growth and the decomposition of soil vegetation litter.

Tibet, which is a part of the Qinghai–Tibetan Plateau, is located at the Southwestern border of China. It has alpine meadows and grasslands with varying degrees of degradation (Zhou et al., 2005). Plateau grasslands account for 33.2% of the total Chinese grasslands and play an important role in animal husbandry development and environmental protection. The grassland resources in Tibet are mainly located in the Northwest desert and semi-desert areas with sandy soils, which creates an ecologically fragile area. From 1990 to 2005, the degraded area of the Tibetan grassland expanded at a rate of 5 to10% annually, and has become an important factor in restricting the economic and ecological security of Tibet. At present, research on carbon and nitrogen in the alpine meadow soil of Qinghai–Tibetan Plateau is mainly focused on the distribution of total organic carbon and total nitrogen, whereas research on the carbon and nitrogen distribution in grassland soils with varying degrees of degradation is minimal.

The purpose of this study is to determine i) the variability of alpine meadow soil carbon (total organic carbon and LOC) and the available nitrogen in areas with varying degrees of degradation; ii) the relationships between soil carbon and nitrogen among different soil layers (0 to 10 cm and 10 to 20 cm layers); and iii) the degradation rates and stability of the soil carbon and nitrogen during grassland degradation. This research will provide a scientific basis for determining the variations in the soil carbon and nitrogen content of alpine meadows in the Qinghai–Tibetan Plateau. The results would be a useful benchmark for charting the recovery of grasslands subject to global climate change and intense human activity.

MATERIALS AND METHODS

Study site and description

The Dangxiong Grassland is located at 90° 45′–91° 31′ E, 29° 31′–31° 04′ N in central Tibet (Figure 1). It is a uniquely pure animal husbandry county near Lhasa city, with an average elevation of 4,200 m above sea level and a plateau landform. The area of available grassland is 624,000 hm^2, which accounts for 91.5% of the total land area. The area is a high-altitude cold temperate zone with a semi-arid monsoon climate and an annual rainfall of 456.8 mm. Rainfall mainly occurs from June to August, with an annual average evaporation of 1,725 mm. The grass-growing period is 90 to 120 days, and land is frozen from November to March every year. The dominant plant species is *Kobresia tibetica*, the roots of which are mainly distributed in the soil layer 0 to 20 cm deep (Liu et al., 2008). The soil in Dangxiong is mainly alpine meadow, which accounts for 51.9% of the total soil area. The soil texture is sandy loam, with a thickness of 50 to 70 cm (Zhang et al., 2006b). Low temperatures, drought, and poor soil are the main factors that limit grass growth and recovery.

Soil sampling and preparation

Geda town (29° 54.075′ N, 90° 21.585′ E, altitude = 4383 m), Ningzhong town (30° 29.926′ N, 90° 52.696′ E, altitude = 4247 m) and Dangxiong County (30° 29.9 09′ N, 091° 08.584′ E, altitude = 4290 m), which are located in the alpine meadow area of Dangxiong along the Nyainqentanglha mountains were selected as research regions. Geda town represents higher ground whereas Ningzhong town and Dangxiong County are located in lower basins with relatively good water conditions. Based on the meadow coverage and soil conditions of the three tested areas (Table 1), normal, slightly degraded, and severely degraded meadow areas were selected. Three samples from each type of meadow were collected from the 0 to 10 cm and the 10 to 20 cm layers. Each degraded soil sample had three replicates. A total of 54 soil samples were collected from each region.

Visible plant roots and other non-soil components were removed from the collected soil samples. The samples were sequentially

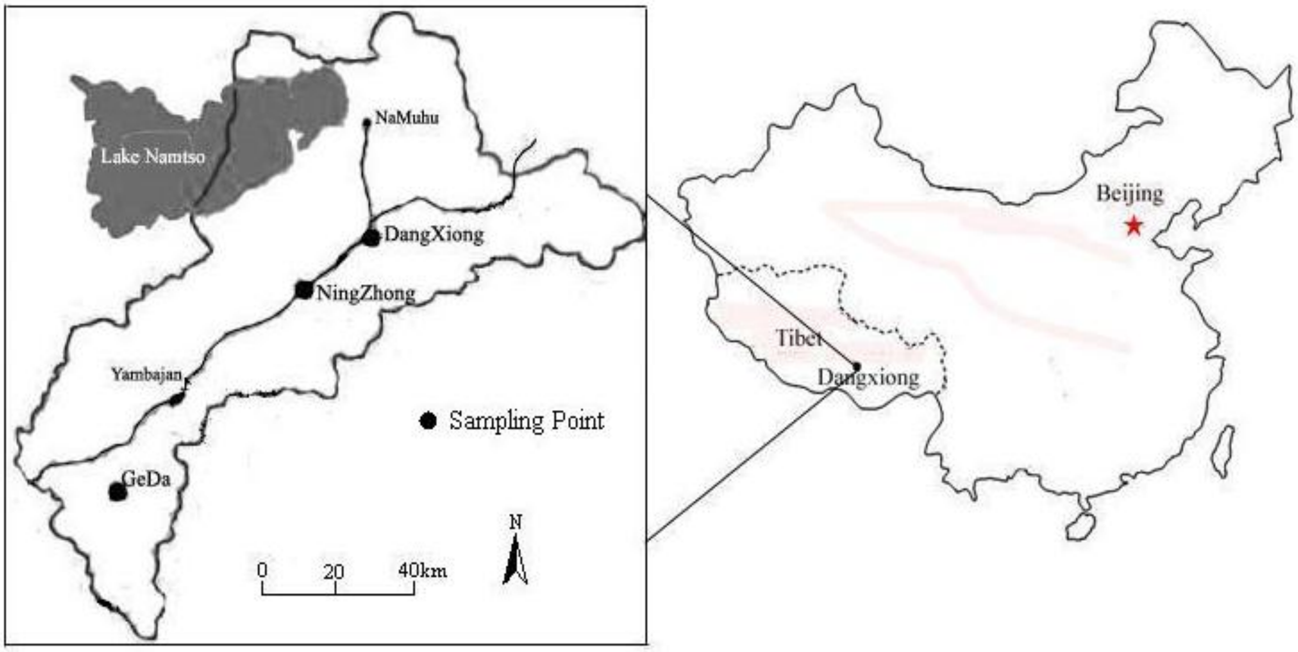

Figure 1. Sampling site.

Table 1. Vegetated fraction of different degraded meadows.

Grassland condition	Vegetated fraction (%)	Soil condition
Normal meadow	Vegetated fraction>95%	No desertification
slightly degraded	Decline in plant growth by 20-35%, Obvious reduction of cover plants	Light desertification
Severely degraded	Decline in plant growth by 60-85%, bare soil dominant	Serious desertification

ground and sieved through 1 and 0.25 mm mesh. The $K_2Cr_2O_7$ outside heating method was adopted for the determination of total SOC and 333 mmol L^{-1} $KMnO_7$ was used in the oxidation process to determine the LOC (Blair et al., 2001). A 2.5 g soil sample and 25 mL of the 333 mmol/L $KMnO_4$ solution were mixed in a 100 mL plastic centrifuge tube, shaken for 1 h, and centrifuged for 5 min at 4000 rpm. The absorbance of the supernatant liquid was recorded with a spectrophotometer. The LOC content was calculated using the differences in absorbance between the $KMnO_4$-treated soil samples and the corresponding blank samples. Alkaline hydrolysis was used to determine the available nitrogen (Lu, 1999).

Calculations and statistical analysis

Correlation analysis was used to study the relationship among soil total organic carbon, LOC, and soil available nitrogen. A Turkey's test (95% confidence) was used for variance analysis to determine the soil carbon and nitrogen distribution across the meadow types. All statistical analysis was carried out with SPSS 17.0.

RESULTS AND DISCUSSION

SOC values of degraded grassland soils

Table 2 shows the SOC levels for the three alpine meadow types, which indicate that the values were within the following range: normal > slightly degraded > severely degraded meadow. In general, the SOC values were varied. For the Geda region, the SOC content of the 0 to 10 cm samples from the slightly degraded and severely degraded meadows were 13.2 and 63.8%, respectively, which are lower than those of normal meadows (Wang et al., 2007; Peng et al., 2010; Zhang et al., 2011). In the 10 to 20 cm samples, the values were lower by 22.9 and 66.1%, respectively. For the 0 to 10 cm samples from the slightly degraded and severely degraded meadows in the Dangxiong region, the SOC content were 22.2 and 39.5%, respectively, which are lower than that of the normal meadow. The values for the 10 to 20 cm samples were lower by 29.7 and 53.2%. For the Ningzhong region, the SOC contents of the 0 to 10 cm samples from the lightly degraded and severely degraded meadows were 27.5 and 78.6%, respectively, which are lower than that of the normal meadow. The values for the 10 to 20 cm samples were lower by 6.0 and 73.2%. Ningzhong region located in a warmer, low-lying valley with adequate soil water from springs is conducive to the growth of meadows. Given the warmer.

Table 2. Total organic carbon (g kg^{-1}) (mean ± SD) of three meadow soils with different degrees of degradation.

Sample area	Layer (cm)	Normal	Slightly degraded	Severely degraded	F- value	P- value
GeDa	0–10	33.26 (2.35)^a	28.88 (1.87)^b	12.04 (1.25)^c	102.35	<0.001
	10–20	30.21 (3.01)^a	23.29 (1.05)^b	10.24 (0.87)^c	82.26	<0.001
DangXiong	0–10	35.29 (2.33)^a	27.45 (2.09)^b	21.35 (1.03)^c	123.5	<0.001
	10–20	33.03 (1.20)^a	23.21 (0.97)^b	15.45 (0.88)^c	186.3	<0.001
NingZhong	0–10	56.00 (3.26)^a	40.59 (3.31)^b	11.96 (1.68)^c	96.3	<0.001
	10–20	22.76 (1.89)^a	21.40 (2.03)^a	6.09 (0.75)^b	10.36	0.018

*Different letters indicate significant differences in organic carbon content among layers at $p < 0.05$, according to the Turkey's test.

Table 3. Soil LOC (g·kg^{-1}) (mean ±SD) of three meadow soils with different degrees of degradation.

Sample area	Layer (cm)	Normal	Slightly degraded	Severely degraded	F- value	P- value
GeDa	0–10	2.35 (0.15)^a	1.45 (0.17)^b	0.84 (0.15)^c	102.3	<0.001
	10–20	1.86 (0.16)^a	1.02 (0.12)^b	0.70 (0.07)^c	17.89	<0.001
DangXiong	0–10	2.49 (0.11)^a	2.21 (0.21)^a	1.71 (0.05)^b	9.14	0.015
	10–20	2.30 (0.19)^a	1.96 (0.19)^b	1.15 (0.10)^c	45.59	<0.001
NingZhong	0–10	4.61 (0.21)^a	2.27 (0.04)^b	1.05 (0.10)^c	369.5	<0.001
	10–20	1.86 (0.06)^a	1.33 (0.02)^b	0.48 (0.11)^c	118.9	<0.001

Table 4. Soil available N (mg·kg^{-1}) (mean ± SD) of three meadow soils with different degrees of degradation.

Sample area	Layer (cm)	Normal	Slightly degraded	Severely degraded	F- value	P- value
GeDa	0–10	98.81 (2.39)^a	61.10 (2.19)^b	50.63 (0.71)^c	513.6	<0.001
	10–20	60.04 (1.76)^a	42.69 (2.75)^b	37.53 (0.60)^c	113.3	<0.001
DangXiong	0–10	212.48 (8.61)^a	158.20 (2.21)^b	89.81 (1.24)^c	240.9	<0.001
	10–20	150.90 (7.10)^a	143.30 (1.20)^a	66.08 (1.42)^b	368.3	<0.001
NingZhong	0–10	171.96 (4.51)^a	116.70 (3.36)^b	54.96 (1.95)^c	869.1	<0.001
	10–20	71.09 (3.56)^a	62.39 (3.42)^a	34.47 (5.63)^b	58.8	<0.001

soil in the region, plant residues are easily decomposed and transformed, which increases the SOC content

Soil labile organic carbon (LOC) of degraded grassland soils

The comparison between the LOC pool and total organic carbon reflects the change in the SOC pool (Hua et al., 2009) during the initial stage of grassland vegetation restoration, and plays a vital role in indicating the changes in vegetation conditions. With the increasing severity of grassland degradation, the changes in LOC content become similar to those of the SOC, as shown by the following trend: normal > slightly degraded > severely degraded meadow (Table 3).

The differences in the soil LOC within the same layer were significant except for those from the 0 to 10 cm sample from Dangxiong. In the 0 to 10 cm from Geda, the soil LOC content of the slightly and severely degraded meadow was lower by 38.4 and 64.2%, respectively, compared with the normal meadows. In the 10 to 20 cm samples, the corresponding values were 45.1 and 62.6%. In the 0 to 10 cm samples from Dangxiong, the soil LOC content was lower by 11.1 and 31.2%, respectively, whereas for the 10 to 20 cm layer, the corresponding values were 14.8 and 50.0%, respectively. In Ningzhong, the soil LOC content of the degraded meadow was lower by 50.9 and 77.2% in the 0 to 10 cm samples and by 28.6 and 74.3% in the 10 to 20 cm samples.

Soil available nitrogen of degraded grassland soils

The available nitrogen content in the soil followed the following trend: normal > slightly degraded > severely degraded meadow (Table 4). The trend was most obvious in the 0 to 10 cm samples. Moreover, the difference among the degree of degradation in this layer has reached a significant level. In the 10 to 20 cm samples from Dangxiong and Ningzhong, the differences in available nitrogen content in the soil were not significant, which might be related to environmental conditions such as soil temperature and water content in the layer. The soil available nitrogen content in the 0 to 10 cm samples from the slightly degraded and severely degraded meadows was less than that of the normal meadow by 25.6 to 38.2% and 48.8 to 68.0%, respectively, whereas those in the 10 to 20 cm samples were lower by 5.0 to 28.9% and 37.5 to 56.2%, respectively. The soil available nitrogen content clearly decreased with increasing grass degradation (Li et al., 2009; Yang et al., 2011). The available nitrogen content in Dangxiong was the highest, followed by that in Ningzhong, with the lowest in Geda. The differences in soil available nitrogen content between the two layers within the three regions were 37.1, 38.2, and 59.2%. These values confirmed that Geda has the lowest variability, which indicates the effect of temperature.

Relationships among soil available nitrogen, organic carbon, and LOC

The soil carbon and nitrogen circulation and the atmospheric greenhouse gas concentrations in terrestrial ecosystems are closely related to carbon, and nitrogen fixation, and their accumulation in terrestrial ecosystems reduces the concentration of greenhouse gases (Liu et al., 2008). Soil C/N reflects the soil nitrogen mineralization capacity, which is a sensitive index of soil quality (Zhang et al., 2011). However, the changes in soil LOC and available nitrogen in degraded grassland cannot be determined clearly. A reduction in soil C/N enhances the microbial activity, accelerates the mineral decomposition of soil organic matter and organic nitrogen, reduces the carbon-fixing ability of the soil, facilitates the release of more inorganic nitrogen, and increases nitrogen loss, which negatively affects the environment (Qi et al., 2008). Soil nitrogen availability influences SOC storage through plant growth and litter quantity, as well as, stabilizes the soil carbon decomposition in forest ecosystems (Nave et al., 2009).

The relationships between soil available nitrogen and SOC are significant (Cao et al., 2011) ($F = 6.158$, $P = 0.0042$) in the 0 to 10 cm layer (Figure 2), but not in the 10 to 20 cm layer. The correlation coefficients for soil available nitrogen and the organic carbon contents were 0.6481 and 0.6264.

The relationships between soil available nitrogen and LOC among the different layers were determined by correlation analysis. As shown in Figure 2, the relationships are highly significant. After excluding two outliers (2.49 and 212.5), the correlation coefficients for the 0 to 10 cm layer and the 10 to 20 cm layer were $R = 0.8649$ and $R = 0.8191$, respectively. The correlation between the available nitrogen and the LOC was higher than that between available nitrogen and total organic carbon in alpine meadow soil.

Figure 3 presents the relative proportion of soil available nitrogen to those of SOC and LOC for all sites and depths. For the GeDa and NingZhong sites, the SOC ratios for the slightly degraded meadows were higher than those for the normal meadows and the severely degraded meadows.

This observation suggests that loss of available nitrogen occurs first and that the SOC becomes relatively stable. However, in severely degraded meadows, both organic carbon and available nitrogen were lost. For the GeDa and NingZhong sites, the ratios of the soil available nitrogen and LOC for the normal meadows were higher than those for the slightly degraded meadows, which were higher than those for the severely degraded meadows. The loss of LOC lags behind that of available nitrogen. Grassland degradation enhances soil nitrogen mineralization, which is easily lost to the environment. Thus, during grassland degradation, the available nitrogen is the first to decline.

The proportional relationship of soil available nitrogen with SOC (Figure 3a) shows the following trend: slightly degraded meadow > normal meadow > severely degraded meadow. During grassland degradation, the degradation of SOC and available nitrogen is first reflected in available nitrogen whereas SOC is relatively stable. In severely degraded meadows, both organic carbon and available nitrogen are lost significantly.

The ratio of soil available nitrogen and LOC (Figure 3b) shows the following trend: normal meadow > slightly degraded meadow > severely degraded meadow. Meadow degradation lowers the available nitrogen in the soil, that is, the loss of LOC lags behind that of available nitrogen. In other words, SOC is more stable than soil available nitrogen. The dynamics of soil nitrogen is closely related to that of carbon. Thus, during grassland degradation, degradation of soil LOC and available nitrogen causes the loss of available nitrogen. Subsequently, degradation indicates the decrease in LOC content. These indicate that nitrogen significantly affects the storage of organic carbon and the content of carbon in soil ecosystem.

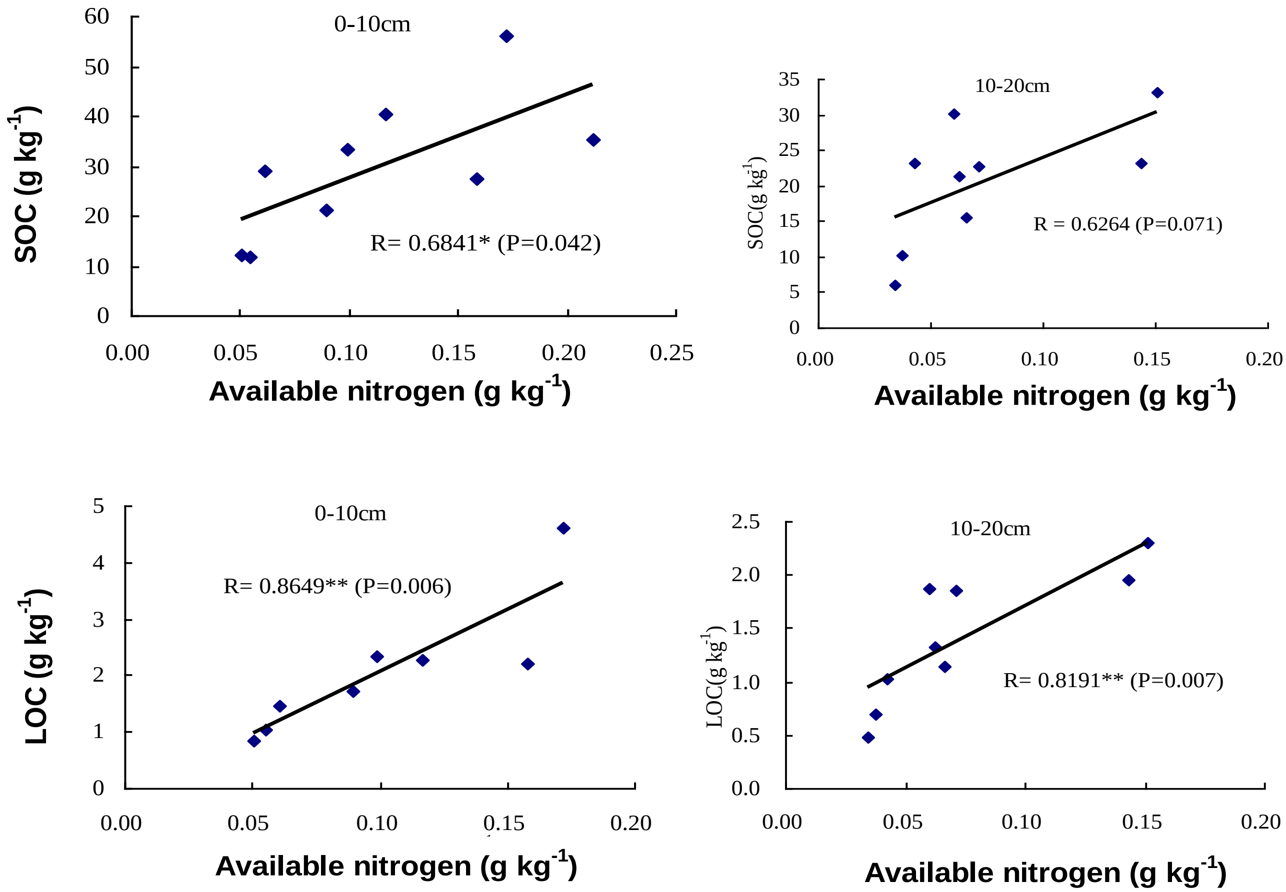

Figure 2. Correlation analysis of available N with soil organic carbon and with labile organic carbon.

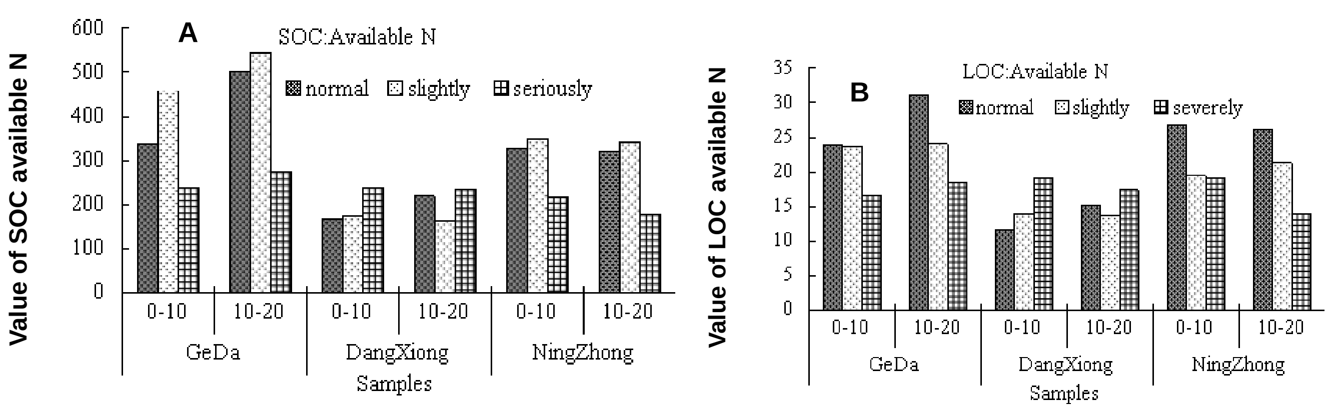

Figure 3. Relative proportions of SOC and available N.

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