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Soil Organic Carbon and Nutrients along an Alpine Grassland Transect across Northern Tibet

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Abstract: Soil carbon and nutrient contents and their importance in advancing our understanding of biogeochemical cycling in terrestrial ecosystem, has motivated ecologists to find their spatial patterns in various geographical area. Few studies have focused on changes in the physical and chemical properties of soils at high altitudes. Our aim was to identify the spatial distribution of soil physical and chemical properties in cold and arid climatic region. We also tried to explore relationship between soil organic carbon (SOC) and total nitrogen (TN), total phosphorus (TP), available nitrogen (AN), available phosphorus (AP), soil particle size distribution (PSD). Samples were collected at 44 sites along a 300 km transect across the alpine grassland of northern Tibet. The study results showed that grassland type was the main factor influencing SOC, TN and TP distribution along the Gangdise Mountain-Shenzha-Shuanghu Transect. SOC, TN and TP contents were significantly higher in alpine meadow than alpine steppe ecosystems. SOC, TN, TP and AN contents in two soil layers (0-15 cm and 15-30 cm) showed no significant differences, while AP content in top soil (0-15 cm) was significantly higher than that in sub-top soil (15-30 cm). SOC content was correlated positively with TN and TP content (r = 0.901 and 0.510, respectively). No correlations were detected for clay content and fractal dimension of particle size distribution (D). Our study results indicated the effects of vegetation on soil C, N and P seem to be more important than that of rocks itself along latitude gradient on the northern Tibetan Plateau. However, we did not found similar impacts of vegetation on soil properties in depth. In addition, this study also provided an interesting contribution to the global data pool on soil carbon stocks.

Keywords: Soil organic carbon; Total nitrogen; Total phosphorus; Particle size distribution; Alpine grassland; Tibet

Introduction

The terrestrial ecosystem C pool is about twice that in the atmosphere and nearly three times that in aboveground biomass (Eswaran et al. 1993; Heimann and Reichstein 2008), which plays an important role in global carbon cycle. Small changes in terrestrial ecosystem C pools will have significant effects on global C balance and climate change. The complicated nature of the sub-surface layer and disturbance by human activities make the terrestrial ecosystem one of the most unstable ecosystems (Piao et al. 2011). Alpine steppe and meadow are the dominant grassland types in northern Tibet, which cover a combined 94.4% of the total land area in this region(Gao et al. 2009a). The alpine grassland ecosystem is extremely sensitive to environmental changes on the northern Tibetan Plateau due to arid and cool climate.

Soil C storage in grasslands is affected by many factors, including land management(Batlle-Bayer et al. 2010; Preger et al. 2010; Wang et al. 2011) and climate change (Johnson et al. 2011; Xu et al. 2011). N deposition can affect significantly C

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cycle by directly enhancing plant growth and net primary productivity (Bai et al. 2008; Magill et al. 1997) and reduces the rates of organic matter decomposition in sediment (Hobbie 2008). Varying responses of soil C stocks to N addition have been reported. For example, in a grassland field experiment, high N input (4 g m^{-2} yr^{-1}) promoted some plant species produced lignin-rich litter and increased stabilisation of soil C (Dijkstra et al. 2004). A study in a prairie ecosystem showed that N fertilisation (10 g m^{-2} yr^{-1}) can significantly increase soil C sequestration (Wilson et al. 2009). However, other studies have shown that the effect of N deposition on C sequestration in grasslands is negligible and that other factors, such as water availability, may be more important (Lu et al. 2011; Mack et al. 2004; Wamelink et al. 2009). Therefore, the effects of nitrogen deposition on grassland ecosystem carbon storage remain controversial.

Previous studies have shown that the P release from rock weathering is a major factor governing the accumulation of organic matter and plays an important role in soil C turnover (Hamdan et al. 2012). When P availability is limited, C turnover is inhibited because microbial biomass becomes less efficient in utilising substrates (Saggar et al. 2000). Immobilisation of P by microbes provides a P conservation mechanism in soils with fluctuating redox potential and may ultimately stimulate more C cycling in ecosystems (Liptzin and Silver 2009). Soil C will also affect the storage of P in some soils. In soil erosion by water, soil carbohydrates play a role in determining how extensively P is exposed to overland flow (McDowell and Sharpley 2003). However, the exact relationship between P deposition and soil organic carbon (SOC) storage in alpine grassland ecosystems is still unknown.

Northern Tibet is located between the Gangdise and the northern part of the Nyainqentanglha mountain ranges. The average elevation of this region is over 4,500 m a.s.l. (Gao et al. 2009a; 2009b). Most studies on the effect of increasing available N on C sequestration have been carried out in low latitude ecosystems. A few studies have documented the relationships of soil total nitrogen (TN) and soil total phosphorus (TP) with C storage in alpine grassland ecosystems. Therefore, we established a 300 km latitudinal transect through northern Tibet and used this transect to compare SOC, TN, TP and fractal dimension of PSD along latitude gradients. In this paper, our aims are to (i) characterize the spatial distribution of soil physical and chemical properties along the latitude gradient; (ii) explore relationship between soil characteristics and SOC content; and (iii) identify key factors determining SOC content in alpine grassland ecosystems.

1 Material and Methods

1.1 Study area

The study area focuses on a 300 km south to north transect in northern Tibet. The Gangdise Mountains-Shenzha-Shuanghu Transect (GSST) extends from 30.42° N to 33.15° N and 88.68° E to 89.45° E (Figure 1). The average elevation of the region is more than 4,500 m a.s.l. with high altitudes in both the south and north and a low altitude in the middle. The climate of northern Tibet is predominantly cold and dry, with an annual average temperature of −2.8-1.6°C (Liu et al. 2003). Under the influences of atmospheric circulation and terrain, rainfall along the transect varies from nearly 300 mm in the south to less than 200 mm in the north. The high-altitude western wind currents are strong in the winter and spring, and gales above Grade 7 are frequent (sometimes, the wind force is as high as Grade 10–12), which results in dry weather and low soil temperature (Liu et al. 2003). Vegetation varies gradually from alpine meadows in the south to alpine steppes in the north (Figure 2). The distribution of grassland types is almost completely determined by the climatic gradients, especially by precipitation(Ni and Zhang 2000). The alpine meadows are mostly in the Gangdise Mountains and are dominated by *Koresia pygmaea* C. B. Clarke. Alpine steppes occupy the northern portion of the GSST and are dominated by *Stipa purpurea* Griseb (Li 2000; Yang et al. 2010). Grassland degradation due to historic overgrazing is one of main eco-environmental problems in this area (Wang et al. 2012).

1.2 Soil sampling

Field work took place at the end of August and early September 2010 along the 300-km transect.

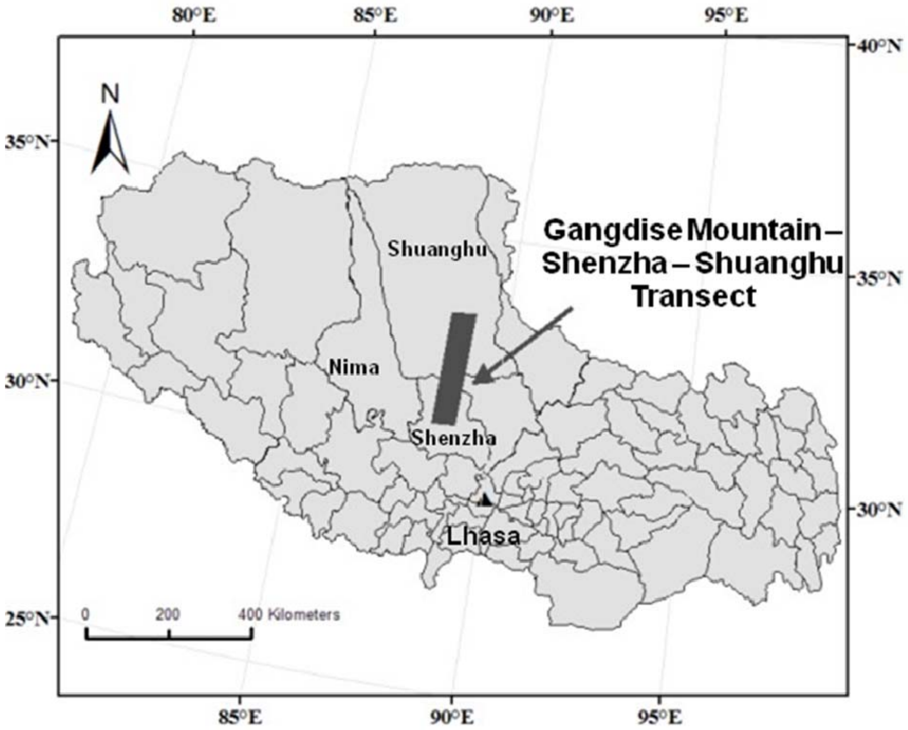


Figure 1 The geographical location of the Gangdise Mountain-Shenzha-Shuanghu Transect in Tibet, China

Figure 2 Alpine meadow grassland (left) and alpine steppe grassland (right) in the Gangdise Mountain-Shenzha-Shuanghu Transect in Tibet, China.

Samples were collected every 5 km. Because the sampling route was interrupted by a lake, we sampled along the coastline of the lake every 10 km. In each sampling site, about 95% of the total root distribution was concentrated in the 0-15 cm soil layer while 5% of the roots were found in the 15-30 cm layer. Soil samples were obtained for each site and collected from two depths: 0-15 cm and 15-30 cm. Forty-four samples were taken in total. For the determination of soil bulk density, soil cores (5.4 cm in diameter) were also taken from each layer using a stainless-steel cylinder. In addition, soil type, colour, temperature, and moisture were also recorded. The location and elevation of each site were measured using GPS (Garmin MAP60CSX made in Garmin Ltd, <10 meters accuracy).

1.3 Soil physical and chemical analysis

Prior to analysis, all soil samples were air-dried and then hand-sieved through a 2-mm mesh to remove roots and other debris (Li et al. 2006).

Soil bulk density was determined as the moisture-corrected (oven-dried at 105°C) mass of each sample divided by the measured excavation volume (Zarin et al. 1998). SOC content was measured by potassium dichromate oxidation with external heating (Nelson et al. 1982). TN was determined by the semi-micro-Kjeldahl method. TP was determined by the sodium bicarbonate alkali digestion method and by molybdenum antimony colorimetry (Institute of Soil Academia Sinica 1978). Available N was determined by a micro-diffusion technique after alkaline hydrolysis (Fu et al. 2000). Available P was extracted with 0.5 mol.L^{-1} $NaHCO_3$ solution (pH 8.5). Soil particle-size distribution was determined using a Malvern Mastersizer 2000 particle size analyser (Worcs UK)

1.4 Calculations of SOC, TN, and TP stocks and fractal dimension of particle size distribution (PSD)

SOC stocks for each sample depth were calculated using the following equations:

$$\text{SOC (g m}^{-2}\text{)} = z \times BD \times SOC_s \times 10 \qquad (1)$$

where z is the thickness of each sample depth (cm), BD is bulk density (g cm $^{-3}$) of each sample depth and SOC_s is the SOC concentration (g C kg $^{-1}$ soil) of each sample depth. The numerical value 10 is used for units exchange. TN and TP stocks (g m^{-2}) were also computed with a similar formula.

The fractal dimension of PSD (D) was estimated using the following equation(Tyler and Wheatcraft 1992, Su et al 2004):

$$\frac{V(r < R_i)}{V_T} = \left(\frac{R_i}{\lambda_v}\right)^{3-D} \qquad (2)$$

where r is soil particle size, V (r < R_i) is the cumulative volume of a particle of the ith size r less than R_i, V_T is the total volume, R_i is the mean particle volume of the ith size class, and λ_V is the mean volume of the largest particle; the mean particle volume was taken as the arithmetic mean of the upper and lower sieve sizes, and the mean diameter of particles < 2 μm was calculated as 1 μm.

1.5 Data analysis

Classical statistical descriptors such as minimum, maximum mean and standard deviation (SD) were determined. An analysis of variance (ANOVA) test was performed to analyse differences between soil characteristics (SOC, TN, TP, AN, AP, sand, silt and clay content) and SOC/TN and SOC/TP ratios between the two sample depths within grassland types or in the entire transect as well as between the two types of grassland. Significant differences for all statistical tests were determined at the level of $P \le 0.05$. Correlation analysis was used to determine the relationship between edaphic factors (sand, silt and clay) and SOC content in the different soil layers. A simple regression analysis was applied to establish relationships between the fractal dimension and soil characteristics (sand, silt, clay, SOC, TN and TP contents). All statistical analyses were performed using the SPSS ver. 17.0 software package (SPSS Inc. USA).

2 Results and Discussion

2.1 Spatial changes in SOC, N and P

As can be seen from Table 1, mean total SOC, TN and TP stocks in the upper 30 cm of soil varied from 8.54 kg C m^{-2}, 0.65 kg N m^{-2} and 0.24 kg P m^{-2}, respectively, in alpine meadow, to 4.18 kg C m^{-2}, 0.40 kg N m^{-2} and 0.19 kg P m^{-2}, respectively, in alpine steppe areas. SOC, TN, TP, AN and AP stocks in the upper 30 cm of soil in the alpine meadow are significantly higher ($P < 0.05$) than those in the alpine steppe. Compared to previous

Table 1 Statistical characteristics of SOC, total N, total P, available N and available P in alpine meadow and alpine steppe areas along the Gangdise Mountain–Shenzha–Shuanghu Transect in Tibet, China

Tested items	Min.	Max.	Mean	S.D.	CV
Alpine meadow					
SOC (kg.m^{-2})	5.69	12.40	8.54	2.48	0.29
Total N (kg.m^{-2})	0.47	0.93	0.65	0.17	0.26
Total P (kg.m^{-2})	0.21	0.30	0.24	0.03	0.13
Available N (g.m^{-2})	26.10	70.16	45.12	14.25	0.32
Available P (g.m^{-2})	1.81	2.93	2.24	0.46	0.21
Alpine steppe					
SOC (kg.m^{-2})	0.80	7.60	4.18	1.68	0.41
Total N (kg.m^{-2})	0.11	0.82	0.40	0.14	0.35
Total P (kg.m^{-2})	0.14	0.25	0.19	0.025	0.14
Available N (g.m^{-2})	9.71	52.22	23.47	8.51	0.36
Available P (g.m^{-2})	1.36	3.32	1.99	0.45	0.23

results, we found lower SOC stock in two alpine grasslands (Wang et al. 2002; Tao et al. 2007). The coefficient of variation (CV) was used to qualitatively describe the magnitude of spatial variability as weak when CV < 0.1, moderate if 0.1 < CV < 1, and strong when CV > 1 (Yang et al. 2011). The CV of both grassland types can be arranged in the order SOC > AN > TN > AP > TP, and all are moderately variable. SOC exhibits the largest spatial variability because many factors, such as land management(Conant et al. 2001), precipitation, air temperature, and grassland type (Jobbágy and Jackson 2000), can influence SOC content. The CV of TP was smaller because TP content is largely determined by the soil parent material (Liu et al. 2005).

A few authors proved that root distributions affect the vertical placement of C in the soil, and above- and below-ground allocation affects the relative amount of C that eventually falls to the soil surface from shoots (Jobbágy and Jackson 2000). However, no similar results were observed in the current study. The percentage of SOC in the top 15 cm averages 54.7% and 52.0% for alpine meadow and alpine steppe environments, respectively. SOC content is slightly higher in the upper layer, but the difference is not significant in soil depth. ANOVA showed no significant difference in TN, TP and AN contents between top soil (0-15 cm) and sub-top soil (15-30 cm). Available P content is significantly higher in the upper 15 cm of soil than in the 15-30 cm soil ($P < 0.05$). Surface enrichment of P may be due to return of residual organic matter to soil (Jobbágy and Jackson 2001).

Figure 3 shows that SOC and TN distribution are similar, while TP concentration varies with latitude along the GSST. On a larger scale, SOC and TN stocks decrease from southern to northern regions corresponding to precipitation patterns. However, the trends in total SOC, TN and TP stocks in the upper 30 cm of soil along the latitudinal transect did not always follow these patterns. For instance, despite decreasing precipitation along the transect, SOC and TN concentrations increased in the latitude range from 30.92°N to 31.42°N and 31.87°N to 32.48°N, respectively. The unusual trend in SOC and TN stocks in the upper 30cm of soil were in direct proportion to the amount of precipitation and inversely proportional to the mean annual temperature (Post et al. 1982; Trumbore et al. 1996). SOC and TN stocks increased from 30.92°N to 31.42°N latitude, but precipitation did not change significantly in this region; this trend is likely due to the joint interactions between precipitation, temperature and amount of primary production in controlling soil C and TN storage. However, increasing SOC and TN stocks from 31.87°N to 32.48°N latitude may reflect the role of precipitation in controlling SOC and TN storage. The primary mineral source of P in most soils is apatite in the parent material. Organisms and plant roots take up P from the surrounding soil and then return it to the soil in the form of organic P (Parton et al. 1988). Therefore, soil organic P increased with high soil organic matter content. Soil TP stocks are more affected by parent material and human disturbance, but northern Tibet is sparsely populated, so P distribution along the latitude gradient may reflect the joint interaction between soil parent material and organic matter. In addition, the lake located in the study area maybe have potential effects on the distribution of SOC, TN, TP. More studies will be needed in future.

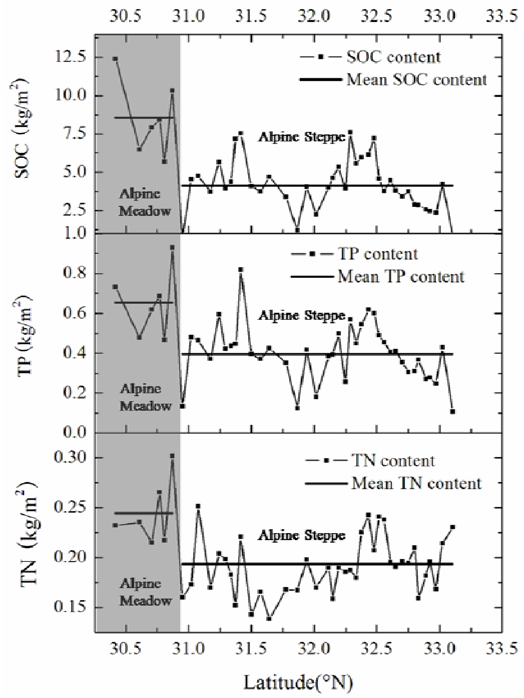
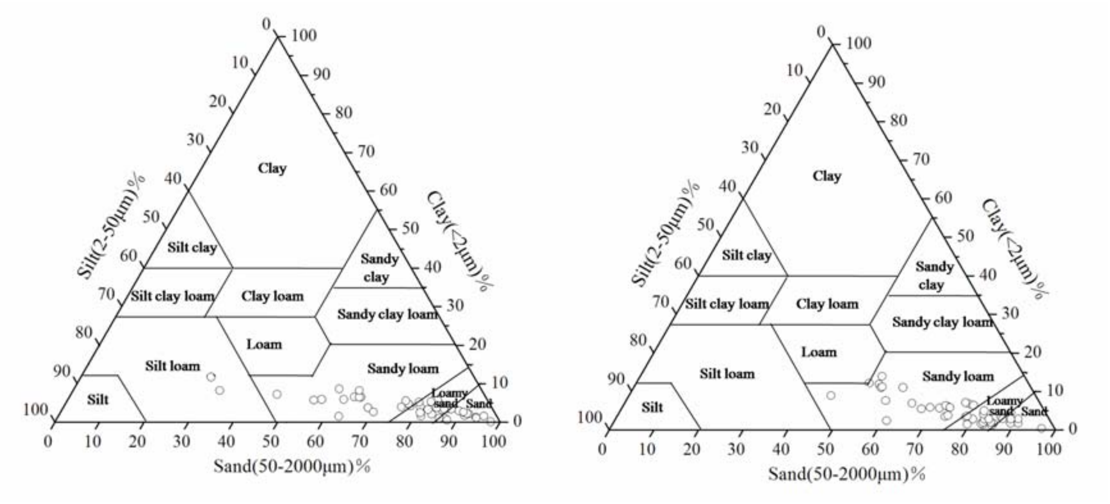


Figure 3 The distribution of SOC, TN and TP content in the upper 30 cm of soil along the latitude gradient of the Gangdise Mountain–Shenzha–Shuanghu Transect in Tibet, China (Dark grey shows the SOC, TN and TP variations in alpine meadow, and light gray shows the unusual distribution of SOC and TN)



(A) (B)

Figure 4 The distribution of 44 soil samples (A: 0-15 cm; B: 15-30 cm) within the USDA-SCS soil textural triangle.

2.2 Particle size spatial distribution

In Figure 4, soil sample texture is shown in the USDA soil texture triangle. There are four kinds of texture in the topsoil (0-15 cm) samples from the Gangdise Mountain-Shenzha-Shuanghu Transect. One is medium-textured (silt loam) and the others are coarse-textured (sand, loamy sand, and sandy loamy). The dominant soil textures are sand (31.81%), loamy sand (36.36%) and sandy loam (27.27%). Statistical results from soil depth showed the mean sand, silt, and clay contents are 77.65%, 18.2%, and 4.15% in the top soil and 75.47%, 19.55%, and 4.98%in the sub-top soil, respectively (Table 2). This pattern indicated that sand constitutes the largest proportion of soil in this region. Wind erosion sorts the soil material, with removal of fine particles (clays and silts) and leaving behind a more coarse–texture soil (Lobe et al. 2001). The CV of both soil depths can be placed in the order clay > silt > sand, and all are moderately variable. Clay and silt variability are higher than that of sand because wind erosion is prevalent along the transect, and fine-grained particles are easily moved by wind (Wang et al. 2010). A one-way analysis of variance showed no significant differences between sand, silt and clay contents between sample depths and grassland types (P < 0.05).

Table 2 Statistical features for sand, silt, clay and D of two soil layers along the Gandise Mountain – Shenzha – Shuanghu Transect in Tibet, China

	Min.	Max.	Mean	S.D.	CV
0-15 cm					
Sand (%)	36.12	97.82	77.65	13.84	0.18
Silt (%)	2.09	50.96	18.20	11.30	0.62
Clay (%)	0.09	14.44	4.15	2.85	0.69
D	1.98	2.74	2.49	0.13	0.05
15-30 cm					
Sand (%)	45.27	96.74	75.47	12.45	0.16
Silt (%)	2.88	45.78	19.55	9.71	0.50
Clay (%)	0.38	13.89	4.98	3.42	0.69
D	2.16	2.72	2.53	0.11	0.04

Note: "D" means "The fractal dimension of particle size distribution".

Table 3 Correlative analysis between edaphic factors and SOC content in different soil layers

Soil texture	0-15 cm	15-30 cm
Sand	-0.359*	0.235
Silt	0.406**	-0.131
Clay	0.132	-0.147
D	0.227	0.030
Total N	0.869**	0.875**
Total P	0.432**	0.448**
Available N	0.846**	0.841**
Available P	0.371*	0.240

Notes: * indicates significant level at P<0.05; ** indicates significant level at P < 0.01.

Table 3 shows the correlation between SOC content in the different soil layers with soil properties. SOC content in the upper 15 cm of soil showed a significant negative correlation with sand content and an extremely significant positive correlation with silt content, which shows that silt can contribute to SOC deposition. Previous studies have shown that clay content has a significant positive correlation with SOC content in grassland soil (Burke et al. 1989; Nichols 1984; Tian et al. 2008). This difference can be explained by the alpine ecosystem being dominated by sandy and silty compositions.

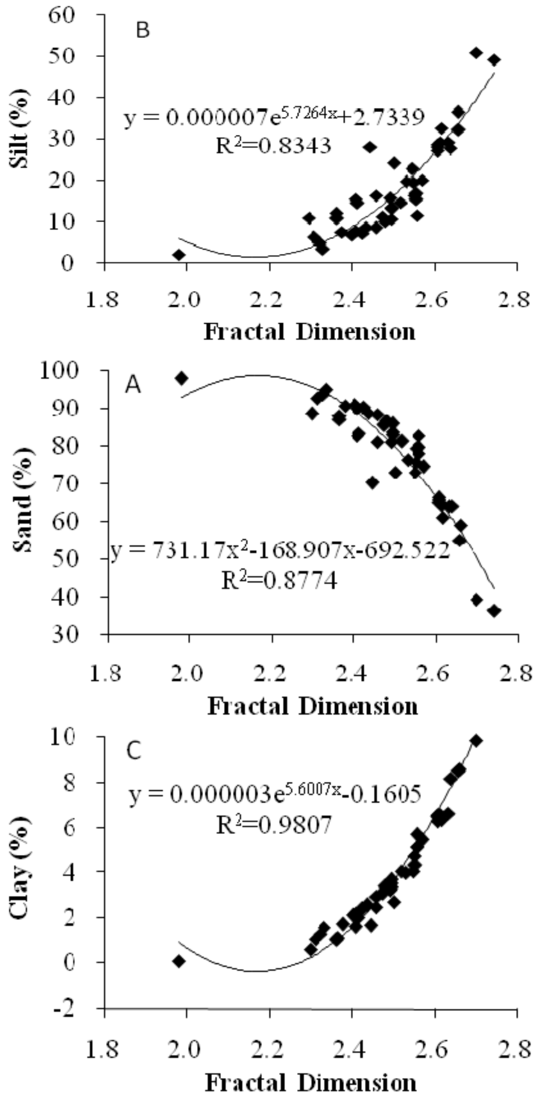


Figure 5 Relationship between fractal dimension of PSD and sand (A), silt (B) and clay (C) content

As seen in Table 2, the lowest value of D (1.98 for the top 15 cm of soil and 2.16 for 15-30 cm soil) coincides with the lowest clay and silt content (2.18 % and 3.26%, respectively) but highest sand contents (97.82% and 96.74%, respectively). The highest D values (2.74 for the top 15 cm of soil and 2.72 for 15-30 cm soil) coincides with the largest combined clay and silt content (63.88% and 45.77%, respectively) and the lowest sand content (36.12% and 54.23%, respectively). Results from regression analysis indicate that D values are negatively correlated to sand content and positively correlated with the silt and clay contents. The relationship between D values and soil texture are expressed by sigmoid curves (Figure 5). Other authors also reported that sigmoid regression models can describe this relationship more effectively than a simple linear model (Wang et al. 2010; Zhao et al. 2009).

2.3 Relationship between SOC and N, P

SOC in the alpine steppe area is about 50% lower than that in the alpine meadow regions, while TN levels in the alpine steppe are approximately 38% lower than those in alpine meadows (Table 1). Regression analysis indicated that SOC increased with TN and TP (Figure 6).

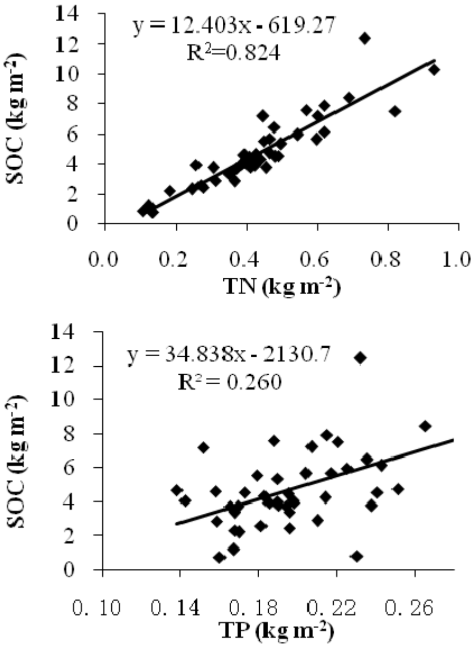


Figure 6 The relationship between SOC and TN (upper) and TP (lower) content along the Gangdise Mountain – Shenzha – Shuanghu Transect in Tibet, China

There is a significant positive correlation between SOC and TN along the latitude gradient (R^2 = 0.824, P < 0.05). SOC and TP also are positively correlated in the studied soils (R^2 = 0.260; P < 0.05). Linear equations provides good fits for SOC and TN and TP in 0-30 cm soil layers, with standardised regression equations as follows :

SOC = 12.403TN – 0.619 and SOC = 34.837TP – 2.131.

In this study, the linear models suggest that TN is the most important parameter and explains 82.45% of SOC variation. However, the influence of nutrient availability on SOC concentration is still controversial. With elevating atmospheric carbon dioxide (CO_2), SOC sequestration is constrained by nutrient availability (Luo et al. 2004; Su & Zhao 2002; van Groenigen et al. 2006). Other studies have shown that allocation to roots is reduced when nutrient availability is high (Craine et al. 2002). Concomitantly, low root activity can result in a reduction in CO_2 effluxes (Keith et al. 1997). Although microbial activity is the main factor influencing carbon stored in substrates, evidence from other studies suggests that increased nutrient availability results in higher respiration rates (McCulley et al. 2004; Adair et al. 2011).

3 Conclusions

This study revealed a set of data that quantified spatial changes of soil properties along an alpine grassland transect on the northern Tibetan Plateau. Fractal approaches and statistic analysis were applied to detect relationship between soil texture and carbon, nitrogen, phosphorus the in different soil depth. We found that the overall SOC, TN and TP contents are relatively low with a south to north decreasing spatial distribution pattern. Grassland type is a main factor influencing SOC and TN content, while TP is more affected by parental materials. Vertical distribution of SOC and TN were similar, with no differences found in soil depth, while TP content in the top 15 cm of soil is significantly higher than that in the sub-top soil. SOC content is correlated negatively with sand content and extremely positively correlated with silt content, while no significant correlation with clay content. The application of the fractal method to describe soil texture, soil dynamics, and physical processes within the soil allows for a better understanding of the performance of the soil systems under different grazing intensities. Our study also provides an interesting contribution to the global data pool on soil carbon stocks due to limited knowledge in high altitude regions.

Acknowledgements

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