Carbon and nitrogen storage in particle-size fractions of topsoil along a 3000 km aridity gradient in northern China

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Number of text pages, number of tables, figures:
The manuscript contains 30 pages and 5 figures. There are no tables.

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Abstract.

Climate factors such as aridity significantly influence soil carbon (C) and nitrogen (N) storage dynamics in terrestrial ecosystems. Further, soil composition plays an important role in driving changes of soil C and N storage at regional scale. However, it remains uncertain whether such changes result from the variation of different soil particle-size factions or the C and N concentrations in those fractions. We examined the distribution of total C and N in both bulk soil and different soil particle-size fractions, including sand (53-2000 μm), silt (2-53 μm) and clay (<2 μm), along a 3000 km transect in arid and semi-arid grasslands of northern China. Across the whole transect, sand content was positively and silt content was negatively correlated with increasing aridity. The total C and N concentrations and storage in bulk soils as well as in the three particle-size fractions tended to be negatively correlated with aridity. The concentrations and storage of total C and N in bulk soils were positively correlated with silt and clay contents and negatively correlated with sand content. There were positive correlations between the concentrations and storage of C or N in bulk soils and the C or N concentrations in the three soil particle-size fractions. By characterizing such a large scale aridity gradient, our results highlight that aridity would decrease soil C and N storage both by favoring increased sand content and by decreasing C and N concentrations in all the three soil fractions. These patterns thus have significant implications for understanding soil C and N sequestration under scenarios of increasing aridity in global drylands that are predicted to occur this century.

Keywords soil particle-size fractionation, soil organic matter, temperate steppe, carbon sequestration, precipitation to evapotranspiration, drought

1 Introduction

Grasslands, which cover nearly 40% of the world's land area, store approximately one-third of the total C in terrestrial ecosystems (He et al., 2012; White et al., 2000). Consequently, C turnover in grassland soils is considered to be a critical component of the global C cycle (Fisher et al., 1994; Wang et al., 2009). In China, grasslands account for 41.7% of terrestrial land area and are mainly distributed in arid and semi-arid regions (NSBC, 2002). Carbon and N cycling in the grasslands of northern China are relatively sensitive to global change factors, such as increases in drought, more extreme precipitation regimes, and global warming (Wang et al., 2014; Song et al., 2012). However, this sensitivity may show regional variations due to variability in both climate and soil characteristics. Greater understanding of the controls on regional variation of soil C and N stocks in Chinese grasslands would facilitate projections of regional C and N cycling under global change scenarios.

Soil C and N storage in grassland ecosystems are closely correlated with climatic conditions. In arid and semi-arid ecosystems, soil C and N storage are positively correlated with mean annual precipitation (MAP) at the regional scale (He et al., 2014; Nichols, 1984). This positive relationship is driven by the fact that water availability is the dominant limiting factor for plant growth (and thus soil organic matter inputs) in these ecosystems. In contrast, mean annual temperature (MAT) is negatively correlated with soil C and N storage, as higher temperature generally enhances microbial decomposition more than detrital production (Homann et al., 2007; Miller et al., 2004; Schimel et al., 1994). Previous studies found that soil C and N tends to decrease with increasing aridity (that is the degree of dryness of the climate at a given location) largely due to decreased primary productivity (Carrera and Bertiller, 2010; Delgado-Baquerizo et al., 2013; Sanaullah et al., 2014).

Variation in soil particle-size fractions also exerts significant controls on the storage and turnover of soil organic matter (SOM) (Chen et al., 2010; Christensen, 2001; Qin et al., 2010) and increasing attention has focused upon the responses of C and N pools in different soil particle-size fractions to climate change (Amelung et al., 1998; He et al., 2014). Clay and silt fractions in soil usually have higher C and N concentrations and storage than that of sand fraction, so soils with higher clay and silt contents generally have higher soil organic C (SOC) and N storage (Amelung et al., 1998; Feller and Beare, 1997; Follett et al., 2012; Hassink, 1997). This pattern reflects that organic materials are preferably decayed from pools of coarse soil particles; these relatively C- and N-rich decomposition products tend to accumulate in finer clay and silt particles (Amelung et al., 1998). Moreover, clay and silt may physically protect organic materials from decomposition and promote the accumulation of recalcitrant material in the fine particle-size fractions of soils (Hassink, 1997; Zhao et al., 2006; Chen and Chiu, 2003).

Aridity, which is intensified by decreasing MAP and increasing MAT, is projected to increase in drylands worldwide during this century (Dai, 2013; Delgado-Baquerizo et al., 2013); this change may significantly diminish soil C and N storage in those regions (Delgado-Baquerizo et al., 2013; Sanaullah et al., 2014). Variation in soil fraction composition and the C and N concentrations in different soil particle sizes may significantly influence the pattern of decreasing bulk soil C and N pools observed with increasing aridity (Amelung et al., 1998; He et al., 2014). However, compared with these well-described patterns of variation in soil C and N storage along climate and soil particle size gradients, the relative influence of these factors on terrestrial C and N pools under climate change scenarios such as increasing aridity is less clear (Delgado-Baquerizo et al., 2013).

To increase our understanding of the variation in both the components of different soil particle-size fractions and their C and N concentrations with increasing aridity at the regional scale, we collected soil samples from 58 sites along a 3000 km aridity transect across arid and semi-arid grasslands in northern China. The distinctive features of this transect include a continuum of xeric to mesic grassland types, ascending MAP and descending MAT from the west to the east, complete meteorological records, relatively gentle geographical relief, and light human disturbances (Luo et al., 2015). The objectives of this study were to: (1) examine the distribution of C and N in various particle-size fractions of soils across the aridity gradient, and (2) evaluate the relative contributions of soil fraction components and their element concentrations to the changes of soil C and N storage across the aridity gradient. We hypothesized that: (1) concentrations and storage of C and N in soil particle-size fractions would be negatively correlated with increasing aridity; and (2) soil C and N storage would decline with increasing aridity due to both an increase in the relative proportion of sand to silt and clay and a decrease of C and N concentrations in the three soil fractions.

2 Materials and methods

2.1 Study site and soil sampling

This study was carried out along a 3000 km west-east transect of arid and semi-arid grasslands across Xinjiang, Gansu, and Inner Mongolian in northern China. The longitude of the transect ranged from 87°22′E to 123°23′E and the latitude ranged from 39°51′N to 50°3′N. Along the transect, the MAP increased from 34 mm in west region to 436 mm in east region, whereas the MAT ranged from -5 to 11℃. The aridity (calculated as "1－precipitation / evapotranspiration") of this transect ranged from 0.43 to 0.97 and derived from the WorldClim data set (http://www.worldclim.org/) (Hijmans et al., 2005). The main vegetation types were desert steppe, typical steppe, and meadow steppe from the west to east across the transect, with the primary productivity ranging from <10 g m^{-2} yr^{-1} in the desert steppe to >400 g m^{-2} yr^{-1} in the meadow steppe, and showing a negative relationship with aridity (Wang et al. 2014). The species richness per square meter ranged from 0 (no plants) in the west of the transect to >30 in the east parts (Lü et al. unpublished data). The soil types were arid, sandy, calcium-rich brown loess, and belonged to Kastanozem soil group in the Food and Agriculture Organization (FAO) classification system (Cheng et al., 2009).

Fifty-eight sites were set up along the transect at an interval of 50-100 km. The location and elevation of the sampling sites were measured by GPS (eTrex Venture, Garmin, USA). For each site, one large plot (50 m×50 m) was selected and five subplots (1 m×1 m) were designated within the large plot (the four corners and the center of the large plot). In each subplot, five soil samples (0-10 cm) were randomly collected by a 3.0 cm diameter soil corer and then totally mixed them together as one composite sample which was then sieved through a 2.0 mm sieve. All of the soil samples were returned to the lab and then air dried for further analysis. Soil bulk density (BD) was calculated as the ratio of dry soil mass per unit volume of the sampling core and expressed as g cm^{-3} (Grossman and Reinsch, 2002).

2.2 Particle-size fractionation

Particle-size fractionation was completed by disrupting soil aggregates of bulk soil samples using ultrasonic energy and separating the particle-size fractions by a combination of wet sieving and continuous flow centrifugation (Chen and Chiu, 2003; He et al., 2009). Briefly, 40 g of sieved soil (< 2 mm) following removal of visible debris was dispersed in 200 ml of deionized water using a probe-type ultrasonic cell disrupter system (scientz-IID) operating for 15 min in the continuous mode at 361 W. We used a sieve to separate sand (particle size, 53-2000 μm) by manual wet sieving method with deionized water. Particles which consisted of silt (2-53 μm) and clay (< 2 μm) passing through the sieve during the wet sieving process were collected. In order to separate slit from clay, the mixture of particles and water was poured into a 500 ml centrifuge bottles and centrifuged at 682 rpm for 5 min. During this procedure, only the silt fraction sinks to the bottom while the clay fraction remains suspended. The silt fraction was then re-suspended in 200 ml deionized water and re-centrifuged at 476 rpm; this procedure was repeated 5 times. The clay fraction was obtained by transferring the suspensions into new centrifuge bottles and centrifuging them at 4000 rpm for 30 minutes. All the fractions were dried at 50 ℃ and then ground for further chemical analysis. The concentrations of total C and N in the bulk soil and soil particle-size fractions were determined using an automatic element analyzer (Vario MACRO cube, Elementar Analysensysteme GmbH).

2.3 Statistical analysis

All of the relationships between variables were explored by using simple linear regression analyses (58 sites with five subplots as replications in each site). We observed that the relationships were best-fitted by either a first-order equation or a second-order equation. As the contents of sand, silt and clay in soils are not independent of each other, stepwise multiple regression analyses, which are highly conservative (Fornara and Tilman, 2008), were used to determine the simultaneous effects of soil fraction composition and C and N concentrations in soil particle-size fractions on soil C and N storage. All analyses were performed using SPSS V13.0 (SPSS, Chicago, IL, USA).

3 Results

3.1 Soil particle-size fractions and BD across the aridity transect

Sand was the most abundant fraction for most sites, accounting for 21.62-90.65% of the total soil weight along the transect. The content of sand was positively correlated with increasing aridity (Fig. 1). The silt content, which accounted for 4.19-49.29% of the total soil weight, decreased with increasing aridity (Fig. 1). The content of clay was relatively low across the transect, ranging from 1.36-33.7%. There were no significant relationships between clay content and aridity (Fig. 1). Bulk density ranged from 0.90 to 1.72 g cm^{-3} and was positively correlated with aridity.

3.2 C and N concentrations in bulk soil and different soil particle-size fractions

Total C (Fig. 2a) and N concentrations (Fig. 2b) in the bulk soil significantly decreased with increasing aridity. Soil C concentrations ranged from 2.71 to 50.33 g C kg^{-1}, while the N concentrations ranged from 0.14 to 4.75 g N kg^{-1}. Across the transect, C and N concentrations in all of the three particle-size fractions were negatively correlated with increasing aridity (Fig. 2). The total C and N concentrations in the soil particle-size fractions varied greatly among the three soil fractions, with the highest concentrations in clay (36.06 ± 1.49 g C kg^{-1}, 3.90 ± 0.17 g N kg^{-1}) and the lowest in sand (5.19 ± 0.56 g C kg^{-1}, 0.37 ± 0.04 g N kg^{-1}) ($p < 0.001$ in both cases).

3.3 C and N storage in bulk soil and different soil particle-size fractions

We found negative correlations between C and N storage in each soil particle-size fraction and aridity, with the exception of C storage in sand (y=57.12-161.29x+114.70x^2, R^2=0.48, p<0.0001), which first decreased and then increased with increasing aridity (Fig. 3a). Paralleling this pattern, C storage in bulk soils first decreased and then slightly increased with increasing aridity, with the lowest value presented in sites with aridity of ~0.8 (y=160.49-371.88x+228.73x^2, R^2=0.73, p<0.0001, Fig. 3a). Nitrogen storage in bulk soils was negatively correlated with aridity (Fig. 3b).

3.4 Relationships between soil fraction composition, C and N concentrations in soil particle-size fractions and bulk soil C and N storage

Across the transect, the concentrations and storage of C and N in bulk soils were negatively correlated with the content of sand and positively correlated with the contents of silt and clay (Fig. 4). The concentrations and storage of C and N in bulk soils were positively correlated with their concentrations in sand, silt, and clay (Fig. 5).

Stepwise multiple regression analyses allowed us to quantify the simultaneous effects of soil fraction composition, element concentrations in soil particle-size fractions, and BD on bulk soil C and N storage. The multiple regression model for C storage in bulk soils included the variables: clay C concentration (with the value of normalized regression coefficient for this variable = 0.70), clay content (0.45), silt content (0.21) and silt C concentration (-0.12), while sand content, sand C concentration and BD were excluded from the model. These variables together accounted for 93.8% of the total variation of bulk soil C storage. In contrast, the multiple regression model that best predicted soil N storage included: clay N concentration (0.61), sand content (-0.30), clay content (0.27), BD (-0.10), and sand N concentration (-0.05), while silt content and silt N concentration were excluded from the model. These variables accounted for 93.6% of the total variation of bulk soil N storage. Inconsistent with the results of simple linear regressions, the stepwise multiple regression analyses showed that C concentration in silt had a negative correlation with soil C storage, and that sand N concentration had a negative correlation with soil N storage.

4 Discussion

Across this 3000 km aridity gradient, sand was the most abundant fraction and the contents of silt and clay were much lower, especially in soils from the extremely arid sites. We suspect that this pattern is partly caused by the wind erosion and dust storms which can be exacerbated by increasing aridity and frequently occur in higher aridity areas of northern China (Wang et al., 2013; Yan et al., 2013; Zhang and Liu, 2010). Wind erosion favors losses of fine soil particles and consequently leads to changes of the soil texture (Feng et al., 2001; Wang et al., 2006; Yan et al., 2013). In arid and semi-arid ecosystems experiencing increasing aridity, soils become more vulnerable to wind erosion because vegetation coverage declines (Zhang and Liu, 2010). Increased aridity is negatively correlated with aboveground net primary productivity across this transect (Wang et al. 2014), which, could further decrease soil C and N storage through diminishing litter input (Yang et al., 2011). Similar to our results, Liu et al. (2008) found that sand fractions in soils of steppe and meadow was negatively correlated with MAP and positively correlated with MAT due to drought-driven vegetation cover decline in the semi-arid East Asian steppe.

Other factors may also contribute to the pattern observed here. Parent materials, land use (e.g. grazing), and topography, can largely influence soil formation process and the contents of soil fractions (Barthold et al., 2013; Deng et al., 2015). For example, soils derived from limestone and quartzite have a lower content of sand fractions and a higher content of silt, compared to soils derived from granite (Belnap et al., 2014). In the grasslands of Inner Mongolia, climate and land use are of greater importance than parent material and topography in controlling soil type distribution (Barthold et al., 2013). Therefore, we suspect that those factors associated with climate would be more important than other factors in structuring the pattern of soil particle-size distribution in our study sites.

Our results showed that C and N concentrations were highest in clay, followed by silt, and much lower in sand across a 3000 km aridity gradient. This pattern, which may be caused because fine fractions in soil have high surface area which can enhance formation of organo-mineral complexes that protect SOM from microbial degradation (Hassink, 1997; Zhang and Liu, 2010), supports previous findings that soil fractionation is a useful tool for examining different C and N pools in soil (Amelung et al., 1998; Gerzabek et al., 2001; Stemmer et al., 1999). Across the transect, we observed that C and N concentrations and storage in bulk soils were negatively correlated with sand content and positively correlated with silt and clay contents. Similarly, Bai et al. (2007) demonstrated that there was a negative correlation between SOC content and sand content, and there were positive correlations between SOC content and clay and silt contents based in wetland soils in northeastern China. Positive correlations between soil C and N concentrations and silt and clay contents were also found in Inner Mongolian grasslands (He et al., 2014).

Supporting our first hypothesis, we found that C and N concentrations and storage in soil particle-size fractions tended to be negatively correlated with increasing aridity. The higher aridity sites have lower primary productivity (Wang et al., 2014) and thus a lower input of plant detritus into soil. Lower litter input is correlated with lower C and N concentrations and storage in soil fractions (Yang et al., 2011; He et al., 2014). Paralleling our results, He et al. (2014) found that C and N concentrations in soil particle-size fractions were positively correlated with MAP; moreover, they considered that MAP was better than MAT to model the variation of soil C storage in an Inner Mongolia grassland. In the present study, we quantified the relationship between soil C and N storage and aridity, which combines MAP and MAT, across different sampling sites. Our results suggest that aridity is a robust predictor for the regional variation of C and N storage in soil fractions.

We found that C storage in sand was first decreased and then increased along the aridity gradient, which seems paradoxical given the results that the C concentrations in sand linearly declined with increasing aridity while the content of sand linearly increased with increasing aridity across the transect. The observed variation of C storage in sand across the transect may be due to the shifts of dominant controller for the C storage in sand across the aridity transect. Sand C concentration appears to be more important than sand content in driving the variation of sand C storage in the ecosystem with aridity value is less than 0.8 (where the C concentration in sand was relatively higher and sand content was relatively lower). In contrast, sand content appears to be more important than C concentration in determining sand C storage when the aridity value exceeds 0.8. Our results highlight the importance of looking at both soil particle size and the C concentration of different particles in order to better understand the influence of aridity on soil C pools.

We found that total C and N concentrations and storage in bulk soils generally decreased with increasing aridity across the whole transect. Previous studies have reported that soil C and N storage in the upper soil layers were positively correlated with MAP and negatively correlated with MAT; these findings are similar to our observations along a large aridity gradient (Follett et al., 2012; He et al., 2014; Liu et al., 2012; Miller et al., 2004). The depletion of fine soil particles due to the intensified wind erosion with increasing aridity could further deplete C and nutrients in arid systems because these particles have disproportionately greater amounts of C and nutrients than larger particles (Yan et al., 2013).

Our results suggest that the decreases of bulk soil C and N storage along the aridity gradient resulted not only from the changes of composition of different soil fractions but also from the decreases of C and N concentrations in each of those fractions. While both soil C and N storage decreased with increasing aridity, the stepwise multiple regression analyses indicated that the simultaneous influences of variation of different soil fractions and the element concentrations were different for C and N. For bulk soil C storage, the most robust regression model did not include sand content, sand C concentration, and BD, whereas for bulk soil N storage, silt content and silt N concentration were excluded from the model. Our results thus demonstrate that sand content is less important than silt content for controlling variation of soil C storage, whereas silt is less important for the variation of soil N storage at regional scale in the arid and semi-arid grasslands of northern China.

These findings are somewhat in agreement with previous findings that C is readily mineralized from un-complexed organic matter in sand-sized aggregates whereas N is not, while silt tends to be more enriched in C than N (Christensen, 2001). We found that clay content and clay element concentrations were the most important factors for predicting the variation of both the soil C and N storage across this aridity gradient. Similarly, Burke et al. (1989) observed that clay was an important predictor of soil C for American grassland soils. Together, these results indicate differences in the relative importance of different soil particle-size fractions in driving soil C and N storage, although it is generally accepted that the dynamics of those two elements in soils are closely correlated (Finzi et al., 2011).

This large-scale field investigation provides strong evidence that increasing aridity would reduce the soil C and N storage in arid and semi-arid ecosystems due both to the changes of particle-sized fractions in soils (i.e. relatively more coarse fraction content, but less fine fraction content with increasing aridity) and to the decline of C and N concentrations in each fraction. This study provides novel insights into the patterns underlying regional changes of soil C and N from a soil particle-size fractions perspective. Given the predicted increases in aridity in this century for the global drylands (Dai, 2013), this study indicates that the soil C and N pools in those arid ecosystems may decline in the future. Because wind erosion would lead to greater loss of relatively fine silt and clay particles (Yan et al., 2013), our results suggest that land use practices which reduce wind erosion (e.g. reducing the intensity of grazing) will play an important role in sustaining soil C sequestration in dryland regions globally.

Acknowledgements

We thank all the members in the Shenyang Sampling Campaign Team from the Institute of Applied Ecology, Chinese Academy of Sciences for their assistance in field sampling. This work was supported by National Natural Science Foundation of China (31470505), the National Basic Research Program of China (2015CB150802), Strategic Priority Research Program of the Chinese Academy of Sciences (XDB15010403 and XDB15010401), and Youth Innovation Promotion Association CAS (2014174).

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Figure legend

Fig. 1 Relationships of soil particle-size fractions contents with aridity. Data are presented as mean ± 1SE (n=5)

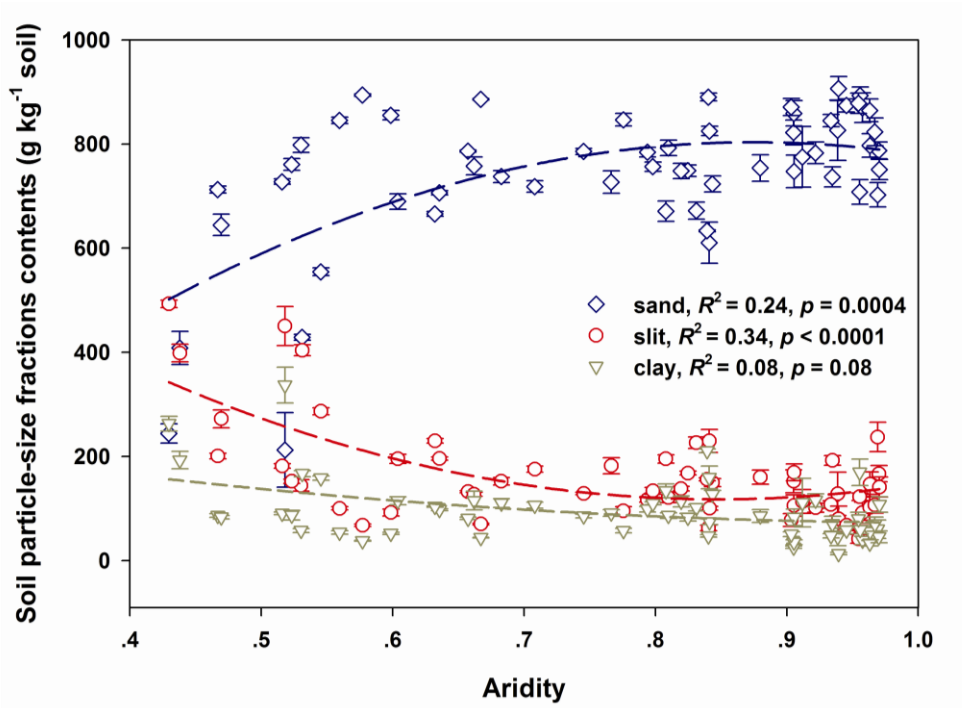
Fig. 2 Relationships of C and N concentrations in bulk soil and soil particle-size fractions with aridity (a: C concentration; b: N concentration). Data are presented as mean ± 1SE (n=5)

Fig. 3 Relationships of C and N storage in bulk soil and soil particle-size fractions with aridity (a: C storage; b: N storage). Data are presented as mean ± 1SE (n=5)

Fig. 4 Relationships of C and N concentrations and storage in bulk soil with the contents of soil particle-size fractions in bulk soil (a: C concentration; b: C storage; c: N concentration; d: N storage). Data are presented as mean ± 1SE (n=5)

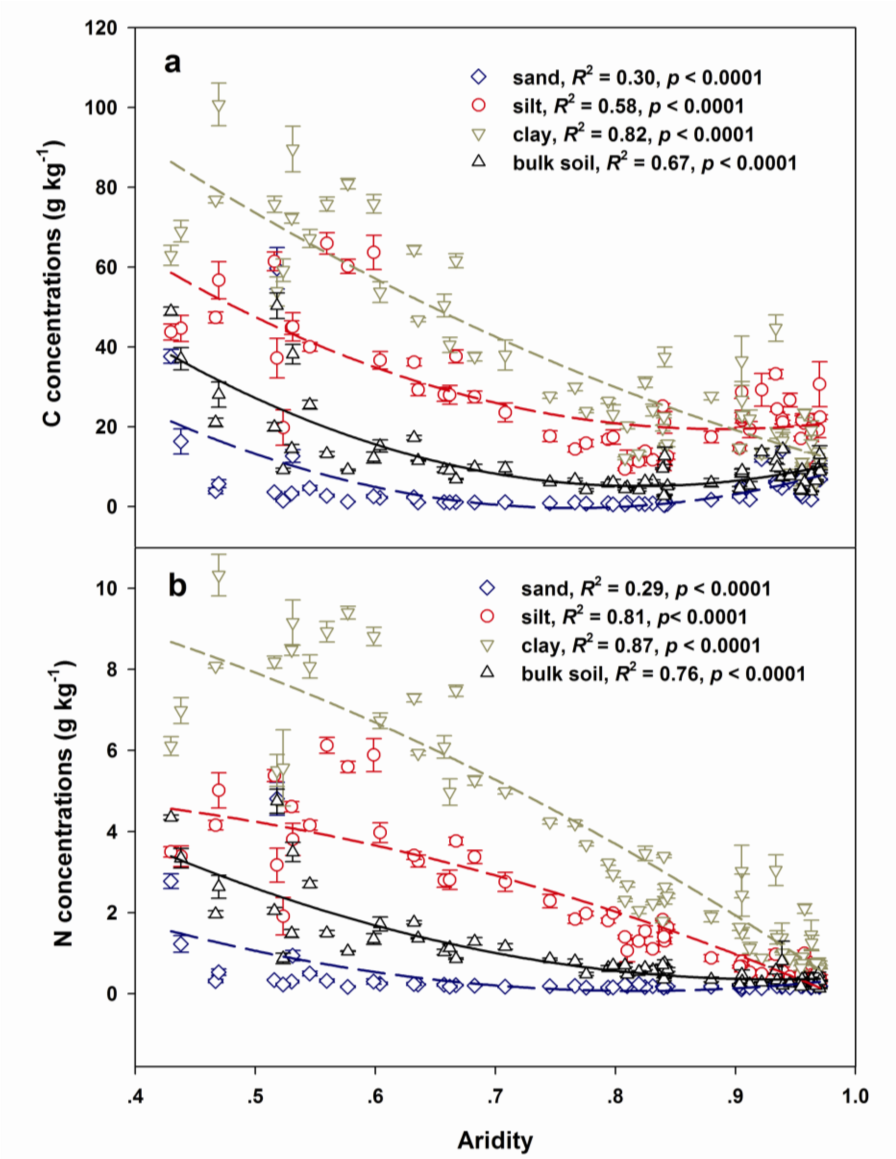
Fig. 5 The C and N concentrations and storage in bulk soil as affected by the concentrations of C and N in soil particle-size fractions (a: C concentration; b: C storage; c: N concentration; d: N storage). Data are presented as mean ± 1SE (n=5)

Figure 1



Soil particle-size fractions contents (g kg-1 soil)
1000
800
600
400
200
0
.4
.5
.6
.7
.8
.9
1.0
Aridity
sand, R2 = 0.24, p = 0.0004
slit, R2 = 0.34, p < 0.0001
clay, R2 = 0.08, p = 0.08

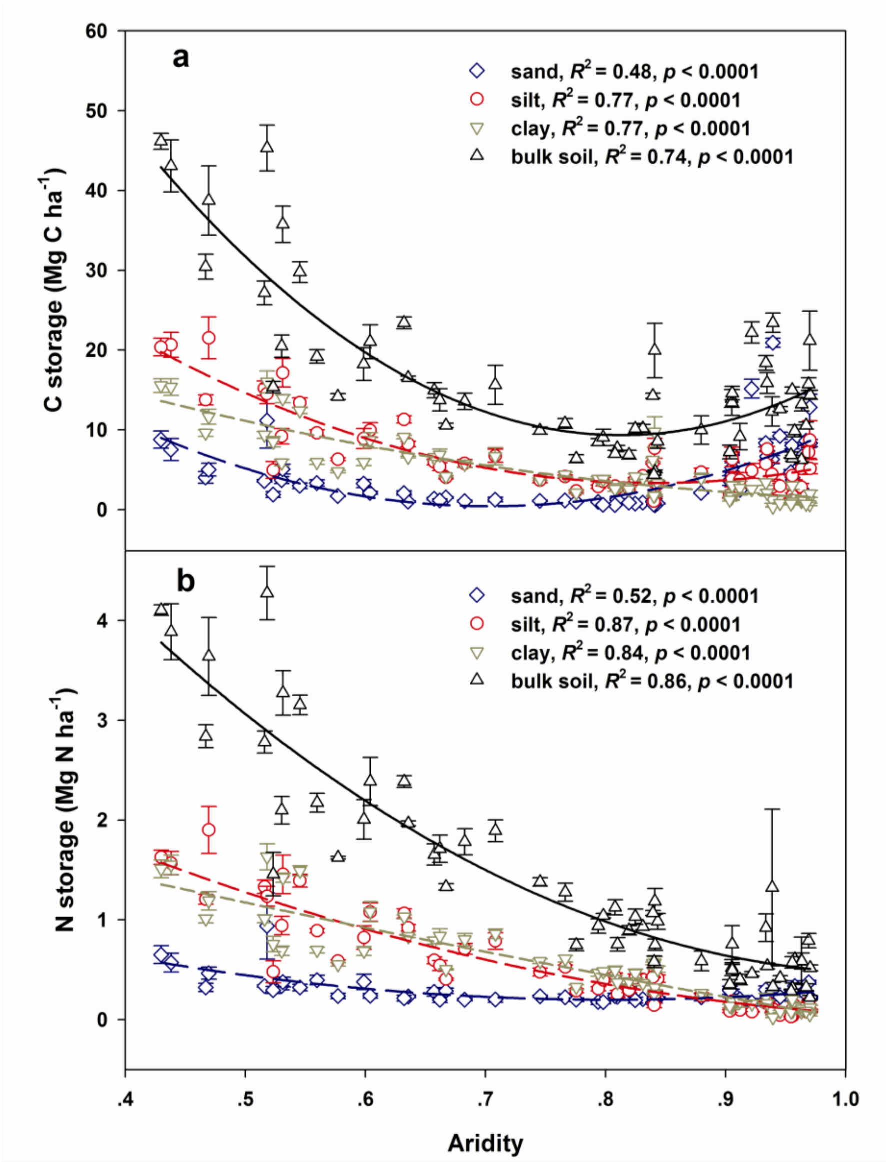
489 Figure 2



490

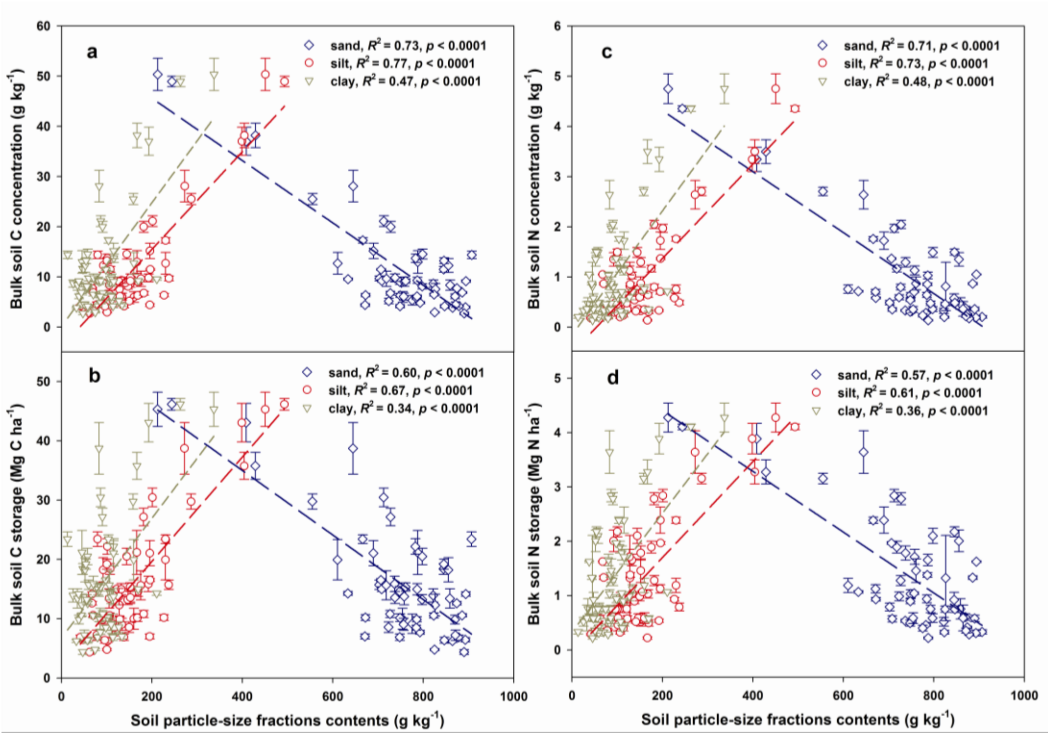
491

Figure 3



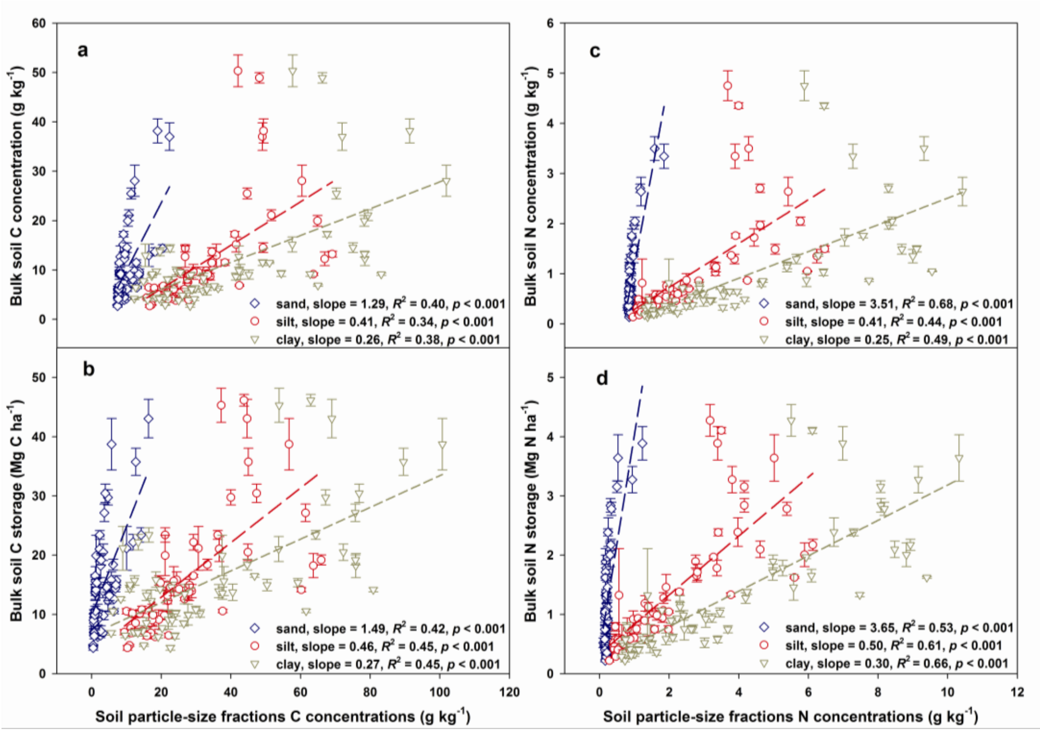
a
sand, R^2 = 0.48, p < 0.0001
silt, R^2 = 0.77, p < 0.0001
clay, R^2 = 0.77, p < 0.0001
bulk soil, R^2 = 0.74, p < 0.0001
C storage (Mg C ha^{-1})
b
sand, R^2 = 0.52, p < 0.0001
silt, R^2 = 0.87, p < 0.0001
clay, R^2 = 0.84, p < 0.0001
bulk soil, R^2 = 0.86, p < 0.0001
N storage (Mg N ha^{-1})
Aridity

Figure 4



a
b
c
d
sand, R^2 = 0.73, p < 0.0001
silt, R^2 = 0.77, p < 0.0001
clay, R^2 = 0.47, p < 0.0001
sand, R^2 = 0.60, p < 0.0001
silt, R^2 = 0.67, p < 0.0001
clay, R^2 = 0.34, p < 0.0001
sand, R^2 = 0.71, p < 0.0001
silt, R^2 = 0.73, p < 0.0001
clay, R^2 = 0.48, p < 0.0001
sand, R^2 = 0.57, p < 0.0001
silt, R^2 = 0.61, p < 0.0001
clay, R^2 = 0.36, p < 0.0001
Bulk soil C concentration (g kg^{-1})
Bulk soil C storage (Mg C ha^{-1})
Bulk soil N concentration (g kg^{-1})
Bulk soil N storage (Mg N ha^{-1})
Soil particle-size fractions contents (g kg^{-1})
Soil particle-size fractions contents (g kg^{-1})

Figure 5



a
Bulk soil C concentration (g kg^{-1})
sand, slope = 1.29, R^2 = 0.40, p < 0.001
silt, slope = 0.41, R^2 = 0.34, p < 0.001
clay, slope = 0.26, R^2 = 0.38, p < 0.001
b
Bulk soil C storage (Mg C ha^{-1})
sand, slope = 1.49, R^2 = 0.42, p < 0.001
silt, slope = 0.46, R^2 = 0.45, p < 0.001
clay, slope = 0.27, R^2 = 0.45, p < 0.001
Soil particle-size fractions C concentrations (g kg^{-1})
c
Bulk soil N concentration (g kg^{-1})
sand, slope = 3.51, R^2 = 0.68, p < 0.001
silt, slope = 0.41, R^2 = 0.44, p < 0.001
clay, slope = 0.25, R^2 = 0.49, p < 0.001
d
Bulk soil N storage (Mg N ha^{-1})
sand, slope = 3.65, R^2 = 0.53, p < 0.001
silt, slope = 0.50, R^2 = 0.61, p < 0.001
clay, slope = 0.30, R^2 = 0.66, p < 0.001
Soil particle-size fractions N concentrations (g kg^{-1})