Controlling factors of soil nitrogen and carbon contents across the Tibetan Plateau: soil formation, permafrost, and soil moisture

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Abstract
The Tibetan Plateau is the largest high-altitude and low-latitude permafrost area of the world. We assume that permafrost dynamics are mainly controlled by topography, precipitation and temperature having a central impact on soil degradation, carbon sources and sinks. We investigated the main parameters (e.g. mean annual air (MAT) and soil temperature (MAST), mean annual precipitation (MAP), soil moisture (SM), soil chemistry and physics) influencing organic carbon (C_{org}), total nitrogen (N_t) and mineralised nitrogen (N_{min})at 47 sites along a 1,200 km transect of the central-eastern Tibetan Plateau. This large-scale survey allows testing the hypothesis that diversity of pedogenesis is another major component for assessing C and N cycling. We demonstrate that SM is the dominant parameter explaining 64% of C_{org} and 60% of N variation. The extent of the effect of SM is determined by permafrost, aeolian sedimentation and pedogenesis. Thus, the explanatory power for C and N concentrations is significantly improved by adding $CaCO_3$ content ($P = 0.012$ for C_{org}; $P = 0.006$ for N_t) and soil texture ($P = 0.077$ for C_{org}; $P = 0.015$ for N_t) to the model. SM overrides soil temperature as the main driving parameter at landscape scale. Our study shows that degradation of permafrost and corresponding changes in soil hydrology combined with a shift from mature stages of pedogenesis to initial stages, have severe impact on soil C and N cycles.

Key Words
Soil formation, permafrost degradation, alpine grassland, C and N stocks, global warming

Introduction
The Tibetan Plateau represents a key area for environmental evolution of the earth at regional and global scales proving particularly sensitivity to global warming (Yao *et al*. 1995; Liu and Chen 2000). It is the largest high-altitude and low-latitude permafrost area of the world with 54.3% of its total surface affected by permafrost (Cheng 2005), characterised by strong diurnal patterns, high radiation on the surface as well as a distinct geothermal gradient (Wang and French 1994). Further, the proposed decay of the Tibetan permafrost (Böhner and Lehmkuhl 2005) will have a strong impact on soil hydrology, leading to severe changes in soil moisture–temperature regimes (Zhang *et al. 200*3). Thus, there is a direct link to soils, which are the basic resources life in terrestrial ecosystems depends on and of particular importance for the global C cycle (Schimel 1995; Sudgen *et al*. 2004). Global environmental change, largely caused by human activities, affects climate as well as soils, and consequently reassigns their role in ecosystem functioning (Vitousek *et al. 199*7; Chapin *et al*. 2000).
The main objective of our study was to investigate, on a landscape scale, the influence of pedogenesis on C and N stocks supplementary to the generally used ecological parameters like climate, temperature, moisture conditions, vegetation, topography, and hydrology. We hypothesize that diversity patterns of pedological features across a changing landscape are crucial to assess C and N dynamics more precisely (cf. Baumann *et al. 200*9).

Study sites and methods
During an expedition in summer 2006 (cooperation of Peking University, China and University of Tübingen, Germany) along a transect of about 1,200 km length and 200 km width in the central-eastern part of the Tibetan Plateau from Xining to Lhasa, botanical, ecological and pedological settings have been investigated at 47 sites. The transect was situated between 91 and 101°E latitude and 30 to 36°N longitude with an eastern section from Xining to Yushu and a western part from Golmud to Lhasa (Figure 1).

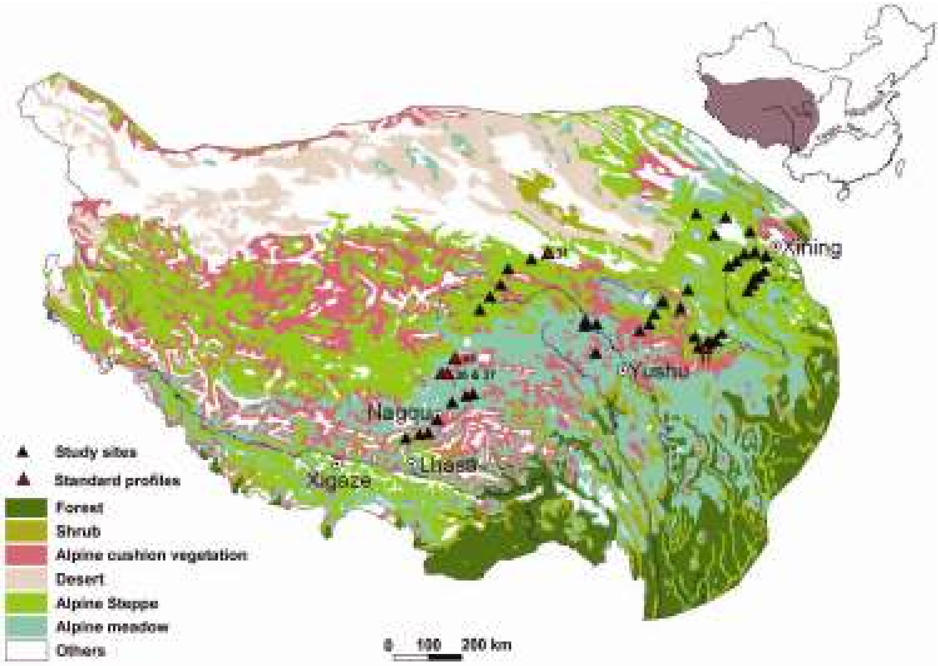

Figure 1. Vegetation map of the Tibetan Plateau, adapted from the Vegetation Map of China (Hou 1982), showing study sites and standard soil profiles representing the most important soil groups (Baumann *et al.* 2009).

Detailed field investigations included soil profile description according to FAO (2006). N_{min} was extracted on-site. At each site four schematic samples of each depth-increment (0–5, 5–10, and 10–20 cm) were mixed. Macroscopic root material and other organic compounds were removed. An aliquot of 10 g of homogenised soil was used for extraction with 50mL 1M KCl for 60 minutes immediately after sampling, stirred with a glass stirrer every 10 minutes, and then filtered into 100mL PE-vials. SM was determined directly in the field by TDR-probes (Delta-T Devices Ltd.) for all soil horizons as well as for the depth increments. Above- and below-ground biomass was investigated at a $1m^2$ sampling square at each site by clipping and digging out the roots. The same method was used to describe plant species composition. Soil temperature was measured with buried temperature data loggers (Hobo U12, Onset Computer Corporation, Pocasset, MA, USA) at an interval of 1 h starting in July 2006 for 1 year. Grain size analysis was done by combined pipette and sieving method. EC was determined in distilled H_2O, pH was measured in both 0.01M $CaCl_2$ and distilled H_2O potentiometrically. $CaCO_3$ was analyzed volumetrically. N_t and C_{org} were measured with heat combustion (VARIO EL III). C bound in $CaCO_3$ was subtracted from C_t quantified with CN analysis to get the proportion of C_{org}. KCl-extractions for N_{min} analysis were measured photometrically (CFA SAN Plus). Water content was determined gravimetrically by subtracting the coarse size fraction (>2mm). Climate data for each site was calculated based on linear models using latitude, longitude, and altitude as variables from 50-year averaged temperature and precipitation records (1951–2000) at 680 well-distributed climate stations across China (He *et al.* 2006). For statistics the results of the schematic sampling series was utilized (sample size n=141), split into the depth increments (0–5, 5–10, 10–20 cm). To examine dependencies, correlation, and regression analyses were conducted for SM, MAST, MAT, MAP, soil texture, $CaCO_3$ content, and pH. To address multi-colinearity, out of these predictors only variables with $R^2<0.5$ were used for regression analysis in the same model.

Results and Discussion

Pedogenesis

All investigated soil profiles were allocated to five main soil groups, covering most soil types of the Tibetan Plateau (Initially formed soils IS = 13, Regosols RG = 7, Cambisols CM = 11, Groundwater influenced GL = 4, Permafrost influenced PF = 12). These main soil groups represent different stages of maturity, from initial soil formation to long developed soils underlain by stable permafrost conditions. Soil development is often young and has been frequently disturbed over time. Therefore, relict, mostly humic horizons can be observed in some profiles, representing phases of stability. The most important factor controlling these processes is recent active aeolian sedimentation, diluting the topsoil's chemical composition or burying the developed

soils completely. This explains the strong trend to accumulate carbonates and bases often relocated to deeper horizons, recognizable by carbonate pseudo-mycelic structures. In the southern and eastern part, distinct weathering and enrichment of secondary Fe oxides in Bw horizons can be found disappearing to the north of the continuous permafrost zone. Strong gleyic or stagnic properties were evident towards the southern and eastern margin of the permafrost-affected area with increasing precipitation, although the permafrost table was deeper.
The main differences between sites are substantially related to the permafrost regime. Figure 2 shows profile 37 and 36 situated in the discontinuous permafrost zone south of Amduo (4900m ASL). The vegetation was dominated by *Kobresia tibetica* and *Carex spp*. community developing in a hummocky area. The distribution of the hummocks was inhomogeneous. Permafrost could be detected at this site in 190cm depth. At a distance of only 150m away (site 36, colluvic Regosol) no permafrost was evident to a depth of 240 cm with correspondingly different C and N contents as well as soil parameters.

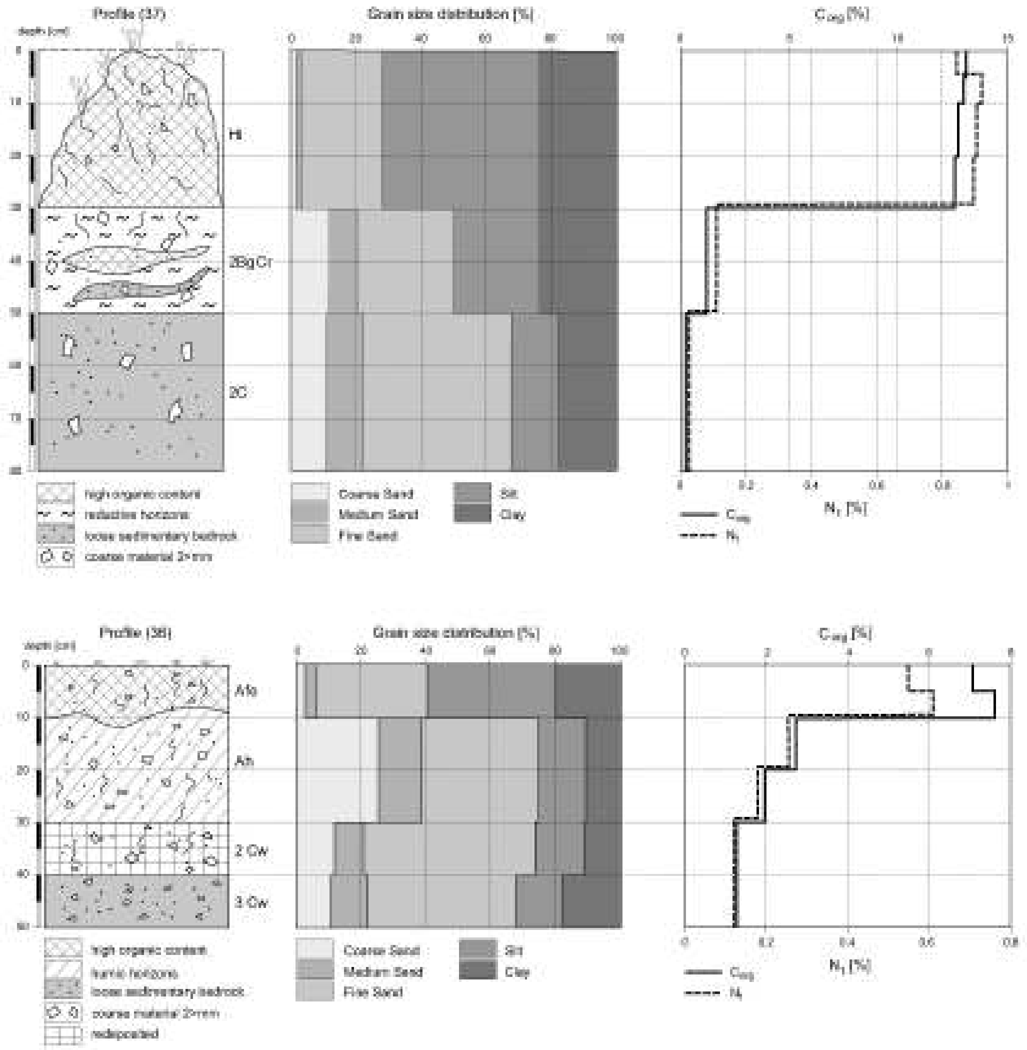

Figure 2. Sites 37 (Calcaric Gelic Histosol) and site 36 (Colluvic Regosol) (cf. Baumann *et al.* 2009).

C and N stocks: amount and distribution
Highly fluctuating C and N contents of topsoils were observed on small spatial scales, mainly controlled by relief position and in particular by related permafrost distribution in discontinuous permafrost areas (Figure 2). The mineralized fraction of N at the investigated sites can be found almost exclusively as NH_4^+, with the highest contents occurring at water saturated sites underlain by permafrost. Highest C and N contents occur in permafrost and groundwater influenced soils, whereas the lowest amounts appear in initially formed soils. There was a clear trend to higher C and N stocks with an advanced degree of maturity of soil development observable, with increasing soil acidity, decreasing carbonate content and grain size distribution showing more fine-rich textures.

C and N dynamics and General Linear Model (GLM)
Analyses of schematic soil samples show significant correlations for SM and C contents as well as for SM and N contents. Furthermore, significant, but relatively weak relationships are evident for MAP, whereas no significant correlations ($P<0.01$) were found concerning MAT and MAST. All three fractions of soil texture (sand, silt, and clay) also had significant relationships ($P<0.01$) with C and N contents, whereas only the sand fraction was negatively correlated. Both pH and $CaCO_3$ content had negative relationships to the dependent variables. Variables used as predictors for pedogenesis showed strong relationships within the independent parameter set. This was true for MAP and SM ($R^2=0.42$, $P<0.001$) as well as for pH and $CaCO_3$ ($R^2=0.50$, $P<0.001$). But also other parameters correlate, e.g. soil texture and soil moisture. The General Linear Model suggests SM as the most important parameter explaining 64% of C_{org} variation. Slightly lower values can be identified for N_t. Both C_{org} and N_t predictions can be significantly improved by adding $CaCO_3$ and sand contents to the model, explaining 65% and 64% of the variation. MAT as well as MAST has no influence on the model. Looking at the control parameters, SM explains 64%, MAP 20%, pH 38%, $CaCO_3$ 23%, and sand 29% for C_{org}. Concerning N_t, SM accounts for 60%, MAP 27%, pH 24%, $CaCO_3$ 26% and sand for 35% of the variation.

Conclusion
The soil development stage is an important predictor for C and N contents in soils on the Tibetan Plateau. This is emphasized by significant contributions of $CaCO_3$ and sand contents to the General Linear Model, which are used to describe pedogenesis. Our results imply that SM is the major controlling parameter of C and N stocks in high altitude grassland ecosystems influenced by permafrost, explaining 65% of C_{org} and 64% of N_t variations, respectively. As MAP and SM show only a moderate correlation compared with the very high relationship between MAT and MAST, it can be concluded that SM is closely linked to permafrost. Consequently, C and N stocks as well as ecosystem functioning are predominantly affected by permafrost, aeolian sedimentation and the stage of soil development. Permafrost and aeolian sedimentation triggered by permafrost degradation are also a function of relief position, parent material, human impact, and seasonal climatic fluctuations. Given a shift to drier and warmer climatic conditions, the Tibetan Plateau could change from a net C sink to a net source, implying significant C loss by respiration.

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