

Land use change decreases soil carbon stocks in Tibetan grasslands

Na Qiao · Xingliang Xu · Guangmin Cao ·
Hua Ouyang · Yakov Kuzyakov

Received: 29 January 2015 / Accepted: 4 June 2015 / Published online: 16 June 2015
© Springer International Publishing Switzerland 2015

Abstract

Backgrounds and aims Land use is an important factor affecting soil organic carbon (SOC) dynamics and can produce positive C climate feedback, but its effects remain unknown for Tibetan ecosystems.

Methods Recent land use changes have converted the traditional winter *Kobresia* pastures of nomads in the northeastern Tibetan Plateau to *Elymus* pastures or even to cropland. Detailed SOC measurements up to 30-cm depth were combined with analysis of $\delta^{13}\text{C}$, $\delta^{15}\text{N}$, bulk density, microbial C, and N contents in three land use types. **Results** Bulk density was decreased by conversion from *Kobresia* pasture to cropland but increased by conversion to *Elymus* pasture. The loss of 1 % of SOC caused by land use change leads to $\delta^{13}\text{C}$ increase of 0.8‰. Conversion to cropland significantly decreased SOC stocks (10 %) and microbial biomass C, but the C loss

(1.6 %) was insignificant in *Elymus* pasture. Land use changes strongly increased soil $\delta^{15}\text{N}$ in the top 5 cm. **Conclusions** Conversion to *Elymus* pasture did not change the C stocks, but conversion to cropland decreased C stocks by 10 % within 10 years. Soil $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ data indicate acceleration of C and N cycling due to the replacement of *Kobresia* pasture by *Elymus* pasture and cropland.

Keywords Alpine meadow · Pasture · Cropland · Soil organic carbon · Total nitrogen · $\delta^{13}\text{C}$ · $\delta^{15}\text{N}$

Introduction

Soil carbon (C) is the largest terrestrial organic C pool, globally containing 3300 Pg C (Tarnocai et al. 2009;

Responsible Editor: Johan Six.

N. Qiao
Key Laboratory of Tropical Forest Ecology, Chinese Academy of Sciences, Xishuangbanna Tropical Botanical Garden, Menglun Mengla, Yunnan 666303, China

X. Xu (✉) · H. Ouyang · Y. Kuzyakov
Key Laboratory of Ecosystem Network Observation and Modeling, Chinese Academy of Sciences, Institute of Geographic Sciences and Natural Resources Research, 11A Datun Road, Chaoyang District, Beijing 100101, China
e-mail: xuxingl@hotmail.com

G. Cao
Northwest Institute of Plateau Biology, Chinese Academy of Sciences, NO. 23 Xinning Road, Xining 810008, China

N. Qiao
University of the Chinese Academy of Sciences, 19A Yuquan Road, Beijing 100049, China

Y. Kuzyakov
Department of Soil Science of Temperate Ecosystems and Department of Agricultural Soil Science, University of Göttingen, Göttingen, Germany

Y. Kuzyakov
Institute of Environmental Sciences, Kazan Federal University, Kazan, Russia

German et al. 2011), four times larger than the atmospheric C pool and five times larger than the vegetation C pool. Consequently, even small changes in the soil organic C (SOC) pool would have large effects on atmospheric CO₂ and produce potential feedbacks to climate (Kirschbaum 2004; Heimann and Reichstein 2008; Cotrufo et al. 2011; Stockmann et al. 2013). Land use change is one of the most important factors strongly affecting SOC stocks and dynamics on earth (Jendinson et al. 1991; Stockmann et al. 2013; Guillaume et al. 2015). Therefore, understanding how land use changes affect SOC dynamics is important to clarify feedbacks to climate (Stockmann et al. 2013).

Grasslands are one of the most important vegetation types on earth, covering approximately 40 % of the earth's land surface (LeCain et al. 2002; Wang and Fang 2009). Global grasslands store about 308 Pg C, with 92 % of that in soils (Houghton 1995), indicating that grasslands may have great potential to store a considerable fraction of atmospheric CO₂ as organic C in the soil (Reid et al. 2004). However, recent studies have suggested that large areas of grasslands have suffered soil C losses due to land use change to cropland or intensive pastures. Globally, approximately 6.60×10^8 ha of grasslands has been converted to cropland (Geist 2006). In the past 20 years (from 1990 to 2010), the grassland area used for pasture and cultivation in China was estimated to exceed 5.3×10^6 ha (Liu et al. 2014). These land use changes can strongly alter C cycling with consequences for C stocks (Hafner et al. 2012; Unteregelsbacher et al. 2012). Soil C is lost at the rate of 1–2 % of the C stock per year during decades after land use changes from grasslands to agriculture (Newton et al. 1945). This means that about 20–30 % of SOC can be lost due to grassland conversions to cropland within 2–3 decades (WBGU Special Report 1998). So far, a total of 77 Pg soil C has been lost due to grassland conversions to cropland worldwide (Geist 2006). There are three main mechanisms that could increase SOC decomposition after conversion: (1) plowing leading to better aeration, (2) removal of plant biomass by annual harvesting or grazing, and (3) decrease of belowground C input by roots and rhizodeposition. Additionally, other processes such as changes of water budget (Sanaullah et al. 2011), aggregate destruction (Chen et al. 2007), fertilization, and decreasing soil C/N ratio may be important for soil C losses.

The Tibetan Plateau covers about 2.6 million km² (Zhang et al. 2002). Alpine steppes cover an area of

800,000 km² in the northwest of the Tibetan Plateau (Zhang 1988; Miede et al. 2011), and *Kobresia* pastures cover an area of 450,000 km² in the southeast (Miede et al. 2008). Those *Kobresia* pastures are partly secondary grasslands after forests had been cleared since the mid-Holocene (Kaiser et al. 2007; Miede et al. 2009, 2014). About 7.4 Pg C is estimated to be stored in the upper 1 m of Tibetan grasslands (Yang et al. 2008). Because of recently enhanced human activities and various sedentarization programs, larger parts of the *Kobresia* pastures are classified as degraded, and, partly, they have been converted to cropland.

Compared with temperate grasslands, however, only a few studies assessed SOC stocks and C fluxes depending on land use systems in Tibetan Plateau (Li et al. 2006; Wang et al. 2011; Ingrisch et al. 2015) and their effects on SOC dynamics in these montane grasslands (Babel et al. 2014). Previous studies mostly explored SOC dynamics through measuring SOC contents, a technique that does not allow conclusions about the mechanisms of SOC decrease. Additionally, land use changes can induce shifts in plant functional diversity and community structure. Consequently, these shifts lead to differences in plant litter compounds and thus modify SOC decomposition and storage. During microbial decomposition, isotope discrimination occurs (Šantrůčková et al. 2000; Bowling et al. 2008). The light isotope (e.g., C and N) is respired, and the heavy isotope (e.g., C and N) is assimilated into biomass that is subsequently deposited in the soil organic matter. Consequently, isotopic enrichment occurs and reflects increased decomposition of soil organic matter. Therefore, we combined direct measurements of SOC with soil $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ as well as microbial biomass C and N contents to analyze the mechanisms of C and N losses (Guillaume et al. 2015). To achieve more detailed information regarding the effects of land use on SOC, we analyzed soil samples at 5-cm intervals up to 30-cm depth. The aim of the study was to clarify the effects and mechanisms of land use change on SOC dynamics and stocks in these *Kobresia* grasslands on the Tibetan Plateau.

Materials and methods

Research site

The study was conducted at the Haibei Alpine Meadow Ecosystem Station of the Chinese Academy of Sciences,

Qinghai Province (37° 36' N, 101° 19' E, 3215 m above sea level). At the site, the 25-year mean for precipitation is 600 mm per year. The growing season starts from around April 22 and ends around October 12, with approximately 143 growing days (Li et al. 2004). Dominant plant species in *Kobresia* pastures include *Kobresia humilis* Serg., *Stipa aliena* Keng., *Poa* sp., *Festuca ovina* Linn., *Gentiana aristata* Maxim., *Gentiana straminea* Maxim., *Saussurea superba* Anth., and *Gueldenstaedtia diversifolia* Maxim. (Zhou 2001). The soil is classified as Mat-Cryic Cambisol (Chinese Soil Taxonomy Research Group 1995), corresponding to Gelic Cambisol (WRB 1998).

Land use types

At the Haibei research station, *Kobresia* pastures are often changed to *Elymus* pastures and croplands. To explore the effects of land use change on montane SOC dynamics, we chose three most common land use types: *Kobresia* pasture, *Elymus* pasture, and cropland. These three land uses are in similar positions within the flat landscape and on the same soil type.

Kobresia pasture was in general not used for grazing and not fertilized in the past decade. Ten years ago, both *Elymus* pasture and cropland had been converted from the *Kobresia* pasture. Cropland was cropped with oat (*Avena sativa*). The seeds of *A. sativa* were scattered each May after plowing (approximately 20-cm depth). Organic manure was used in the cropland at a rate less than 50 kg N ha⁻¹. Aboveground biomass of *A. sativa* was harvested every year, and thereafter, the cropland was left bare in winter. The *Elymus* pasture was established with *Elymus nutans*. The seeds of *E. nutans* were scattered only once at the beginning of its establishment. There was no any fertilization during the whole growing period, and this type of pasture was used as winter grazing.

Three plots (30 m × 30 m) for each land use type were randomly selected, with the distance of over 100 m between them that assured independence of replicates. The manure had a $\delta^{13}\text{C}$ of -25.8‰ and a $\delta^{15}\text{N}$ of 0.5‰. *K. humilis* showed a $\delta^{13}\text{C}$ of -26.4‰, *E. nutans* with -26.8‰ and *A. sativa* with -27.1‰.

Soil sampling

To collect soil, three subplots (5 m × 5 m) were randomly placed in each replicate plot. Soil samples were taken

from a pit (50 cm × 50 cm) located at the center of each subplot, at 5-cm intervals up to 30 cm in depth. Soil from each layer of the three subplots in a replicate plot was mixed together. After collection, soil samples were immediately transferred to the laboratory. Living roots were carefully removed from the soil and were sieved to <2 mm. A subsample of 20-g fresh soil was dried at 75 °C for 48 h and was ground to a fine powder using a ball mill (MM200, Retsch, Haan, Germany). The remaining soil was stored at -20 °C for microbial biomass measurements.

Analyses

Soil bulk density was determined by core cutter method. Ground soil was weighed into tin capsules and analyzed for total C, N, $\delta^{13}\text{C}$, and $\delta^{15}\text{N}$ by continuous-flow isotope ratio mass spectrometry coupled with an elemental analyzer (EA 1110; CE Instruments, Milan, Italy) (EA-IRMS) and a ConFlo II device connected to IRMS (FinniganMAT 253, Bremen, Germany). The $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ abundance in soil is expressed in δ units as related to V_{PDB} standard.

Microbial biomass C was measured after chloroform fumigation and extraction of dissolved organic C (Vance et al. 1987). Microbial biomass C was estimated from the difference between total organic C in the extracts from fumigated and non-fumigated soils, with a k_{EC} factor of 0.45 (Wu et al. 1990). Microbial biomass N was estimated from the difference in total N from the extracts of fumigated and non-fumigated soils, with a k_{EN} factor of 0.54 (Brookes et al. 1985).

Calculations and statistics

Soil organic C stock (kg C m⁻²) was calculated as a sum of SOC amounts (SOC content multiplied by bulk density and the thickness of soil layer) in each layer up to 30 cm (Wu et al. 2003). The standard errors of means are presented in figures. Two-way analysis of variance (ANOVA) was used to estimate the effect of land use and soil depth on SOC, total N, microbial biomass C and N, as well as soil $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$. One-way ANOVA was used to estimate the effect of land use on stocks of SOC and microbial biomass C. Linear regression was used to correlate SOC and total N, microbial biomass N or soil $\delta^{13}\text{C}$. Linear regression was also used to correlate log SOC% and soil $\delta^{13}\text{C}$ for each land use type for

estimation of SOC turnover (Garten 2006; Guillaume et al. 2015), as well as to assess the increase of $\delta^{13}\text{C}$ ($\Delta\delta^{13}\text{C}$) and the decrease of SOC (ΔSOC) caused by land use changes from grassland to cropland or *Elymus* pasture. All statistical analyses were performed with SPSS 16.0 software (SPSS Inc., Chicago, IL, USA). All differences were tested for significance at $P=0.05$.

Results

Effects of land use change on soil bulk density, SOC, and total N

Land use change affected bulk density, SOC, and total N, and these effects were dependent on land use and soil depth (Fig. 1, Table 1). The bulk density ranged between 0.69 and 1.19 g cm^{-3} for *Kobresia* pasture, between 1.02 and 1.20 g cm^{-3} for *Elymus* pasture and between 0.81 and 1.12 g cm^{-3} for cropland. In the upper 5 cm, conversion from *Kobresia* pasture to *Elymus* pasture and cropland significantly increased bulk density. Below the 5-cm depth, the conversion to *Elymus* pasture increased density while the conversion to cropland decreased density. In *Kobresia* pasture, bulk density increased with depth from $0.69\pm 0.04 \text{ g cm}^{-3}$ at the upper 5-cm depth to $1.19\pm 0.02 \text{ g cm}^{-3}$ at the 30-cm depth. A steep increase was observed from the top 5-cm depth to the 10-cm depth (Fig. 1).

SOC ranged between 3.84 and 7.37 % for *Kobresia* pasture, between 4.30 and 5.52 % for *Elymus* pasture, and between 4.46 and 5.21 % for cropland. Land use

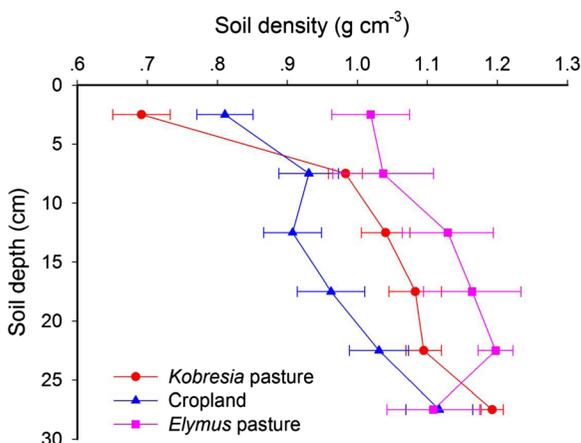


Fig. 1 Soil density in the upper 30 cm after the conversion from *Kobresia* grassland to *Elymus* pasture and cropland (*Avena sativa*) for 10 years. Each value is means \pm SE of three replicates

change from *Kobresia* pasture to *Elymus* pasture, and cropland decreased SOC contents in all depths, except the lowest depth (Fig. 2a). In the upper 5 cm, land use change strongly decreased SOC by about 30 %. SOC in pasture from the surface to 20-cm depth was

Table 1 Results of two-way analysis of variance (ANOVA) for the effects of land use types and soil depth on soil bulk density, soil organic carbon (SOC), total nitrogen (N), microbial biomass C and N, as well as soil $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$

Factors	Sum of squares	d.f.	F	Significance
Bulk density				
Land use type	0.206	2	0.103	<0.001
Soil depth	0.519	5	0.104	<0.001
Land use type \times soil depth	0.168	10	0.017	0.019
Errors	0.235	36	0.007	
SOC				
Land use type	4.16	2	16.7	<0.001
Soil depth	16.4	5	26.4	<0.001
Land use type \times soil depth	8.93	10	7.18	<0.001
Errors	4.48	36		
Total N				
Land use type	0.122	2	26.1	<0.001
Soil depth	0.136	5	11.7	<0.001
Land use type \times soil depth	0.068	10	2.91	0.009
Errors	0.084	36		
Microbial biomass C				
Land use type	141839	2	5.39	0.009
Soil depth	1721974	5	26.2	<0.001
Land use type \times soil depth	518583	10	3.943	0.001
Errors	473428	36		
Microbial biomass N				
Land use type	2585	2	1.73	0.191
Soil depth	88574	5	23.8	<0.001
Land use type \times soil depth	19236	10	2.58	0.018
Errors	26835	36		
Soil $\delta^{13}\text{C}$				
Land use type	26.8	2	58.6	<0.001
Soil depth	34.7	5	30.3	<0.001
Land use type \times soil depth	11.5	10	5.04	<0.001
Errors	8.23	36		
Soil $\delta^{15}\text{N}$				
Land use type	7.50	2	12.7	<0.001
Soil depth	3.67	5	2.48	0.050
Land use type \times soil depth	4.81	10	1.62	0.139
Errors	10.7	36		

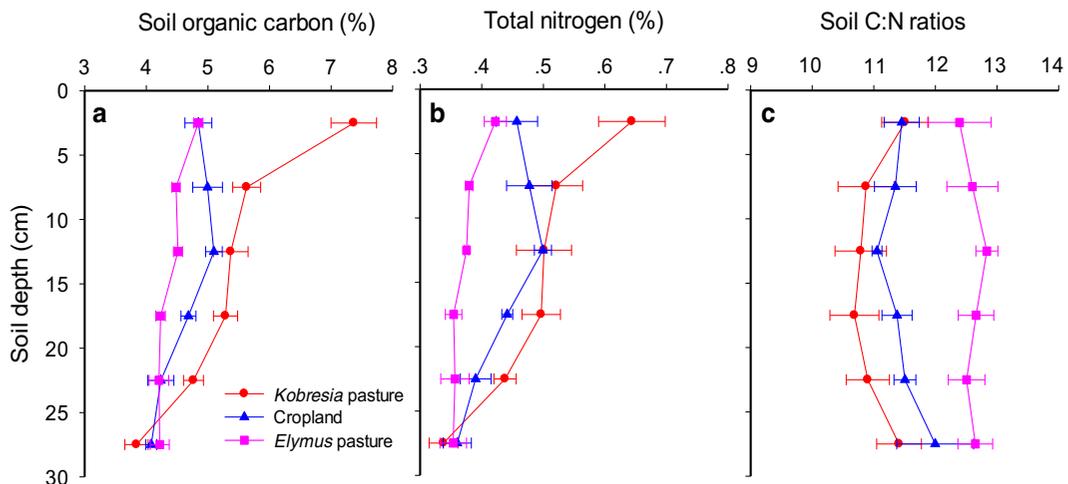


Fig. 2 Soil organic carbon (a), total nitrogen (b), and soil C:N ratios (c) in the upper 30-cm soils after the conversion from *Kobresia* pasture to *Elymus* pasture and cropland (*Avena sativa*) for 10 years. Values are means \pm SE of three replicates

significantly lower than in *Kobresia* pasture (Fig. 2a). Along the profile, SOC in *Kobresia* pasture strongly decreased with depth due to lower C input by roots below 5 cm. Compared to *Kobresia* pasture and cropland, SOC in *Elymus* pasture varied slightly by depth (Fig. 2a). Total N showed similar patterns as those of SOC among three land use types (Fig. 2b). Land use changes increased soil C:N ratios, with the highest values in *Elymus* pasture and the smallest in *Kobresia* pasture. Soil C:N ratios in cropland were close to those in *Elymus* pasture (Fig. 2c).

Effects of land use change on microbial biomass C and N

Microbial biomass C ranged between 264 and 1041 $\mu\text{g C g}^{-1}$ d.w. soil for *Kobresia* pasture, between 298 and 913 $\mu\text{g C g}^{-1}$ d.w. soil for *Elymus* pasture, and between 235 and 506 $\mu\text{g C g}^{-1}$ d.w. soil for cropland. Land use change showed significant effects on microbial biomass C, but no strong effects on microbial N (Table 1). Soil depth significantly affected microbial C and N (Table 1). An especially clear pattern was that the conversion from *Kobresia* pasture to cropland significantly decreased microbial biomass C by 50 % in the surface soil, while the conversion to pasture significantly decreased microbial biomass C in the 5–10-cm layer due to mixture by tillage (Fig. 3a). Along the profile, microbial biomass C strongly decreased with depth, except the upper 5 cm for cropland (Fig. 3a). Microbial N in the three land use types showed similar patterns to

those of microbial C (Fig. 3b). Land use changes had no effects on microbial C:N (Fig. 3c).

Effects of land use change on soil $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$

Soil $\delta^{13}\text{C}$ ranged between -25.6 and -21.3‰ for *Kobresia* pasture, between -22.8 and -21.4‰ for *Elymus* pasture, and between -23.7 and -21.1‰ for cropland. Land use and soil depth significantly affected soil $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ (Table 1, Fig. 4). The conversion from *Kobresia* pasture to *Elymus* pasture strongly increased $\delta^{13}\text{C}$ in SOC (Fig. 4a). With increasing depth, $\delta^{13}\text{C}$ in SOC increased, while cropland showed a slight decrease in the upper 15 cm due to mixture by tillage (Fig. 4a). In the upper 5 cm, $\delta^{13}\text{C}$ was lowest ($-25.6 \pm 0.3\text{‰}$) in grassland, 2.5‰ lower than those in *Elymus* pasture and cropland. The $\delta^{13}\text{C}$ of all three land use types converged to -21‰ at the 30-cm point showing that there were no significant effects of land use changes on SOC below this depth during the 10 years.

Soil $\delta^{15}\text{N}$ ranged between 4.3 and 5.7‰ for *Kobresia* pasture, between 5.8 and 6.8‰ for *Elymus* pasture, and between 5.5 and 6.5‰ for cropland. Land use change from *Kobresia* pasture to *Elymus* pasture and cropland increased $\delta^{15}\text{N}$, except at the 5–10-cm layer. The $\delta^{15}\text{N}$ values in the surface soil were significantly higher in both *Elymus* pasture and cropland than those in *Kobresia* pasture, indicating accelerated N cycling caused by the two land use changes. Along soil depth, the $\delta^{15}\text{N}$ in *Kobresia* pasture showed an opposite pattern to that in *Elymus* pasture (Fig. 4b).

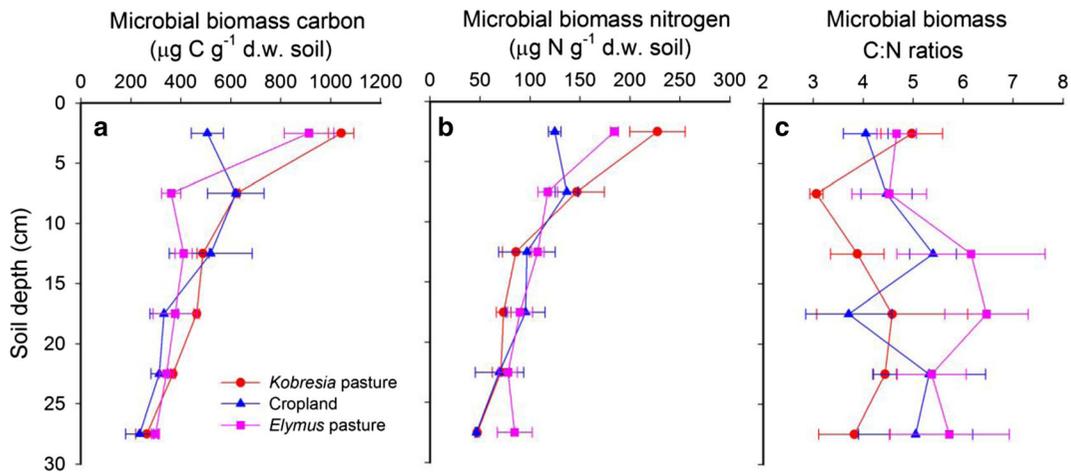


Fig. 3 Microbial biomass carbon (a), microbial biomass nitrogen (b), and C:N ratios in microbial biomass (c) in the upper 30-cm soils after the conversion from *Kobresia* grassland to *Elymus*

pasture and cropland (*Avena sativa*) for 10 years. Each value is means \pm SE of three replicates

Correlations between soil organic C, microbial biomass C, and $\delta^{13}\text{C}$

Across the three land use types, SOC was strongly correlated with total N ($y=0.10x-835$, $R^2=0.88$, Fig. 5a) and microbial biomass C ($y=222x+646$, $R^2=0.59$, Fig. 5b). Soil $\delta^{13}\text{C}$ significantly decreased with SOC contents ($y=-0.0001x-15.9$, $R^2=0.77$, Fig. 5c). Soil $\delta^{13}\text{C}$ significantly decreased with log SOC% for each land use type in the upper 15-cm depth, with a marginally significant effect between cropland/*Elymus* pasture and *Kobresia* pasture ($P=0.058$, Fig. 5d). We calculated the difference in SOC (ΔSOC) and in $\delta^{13}\text{C}$ ($\Delta\text{soil } \delta^{13}\text{C}$) between *Kobresia* pasture and *Elymus* pasture/cropland along the profile,

showing that $\Delta \delta^{13}\text{C}$ was strongly positively correlated with ΔSOC ($y=0.80x+0.50$, $R^2=0.82$, Fig. 6). This means that a decrease of 1 % of SOC led to an increase in $\delta^{13}\text{C}$ of 0.8‰. No strong correlations were observed between these variables and soil $\delta^{15}\text{N}$ (data not shown).

Effects of land use change on C stocks and the size of microbial biomass C

According to soil bulk density and SOC content in each soil layer, we found the C stock decreased compared to *Kobresia* pasture for cropland until 25-cm depth. By comparison, *Elymus* pasture did not lose C in the top 5-cm soil but decreased its C stock from 5- to 20-cm

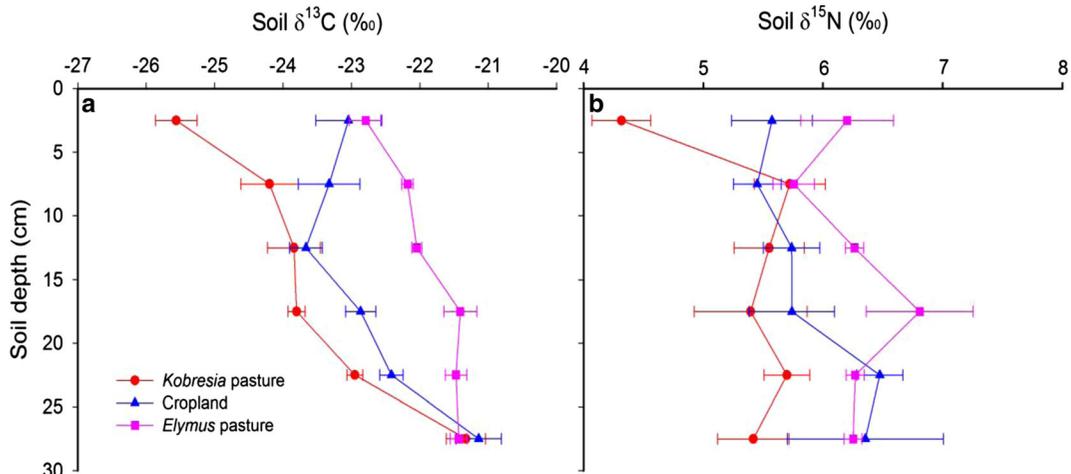


Fig. 4 Soil $\delta^{13}\text{C}$ (a) and $\delta^{15}\text{N}$ (b) in the upper 30-cm depth after the conversion from *Kobresia* grassland to *Elymus* pasture and cropland (*Avena sativa*) for 10 years. Each value is means \pm SE of three replicates

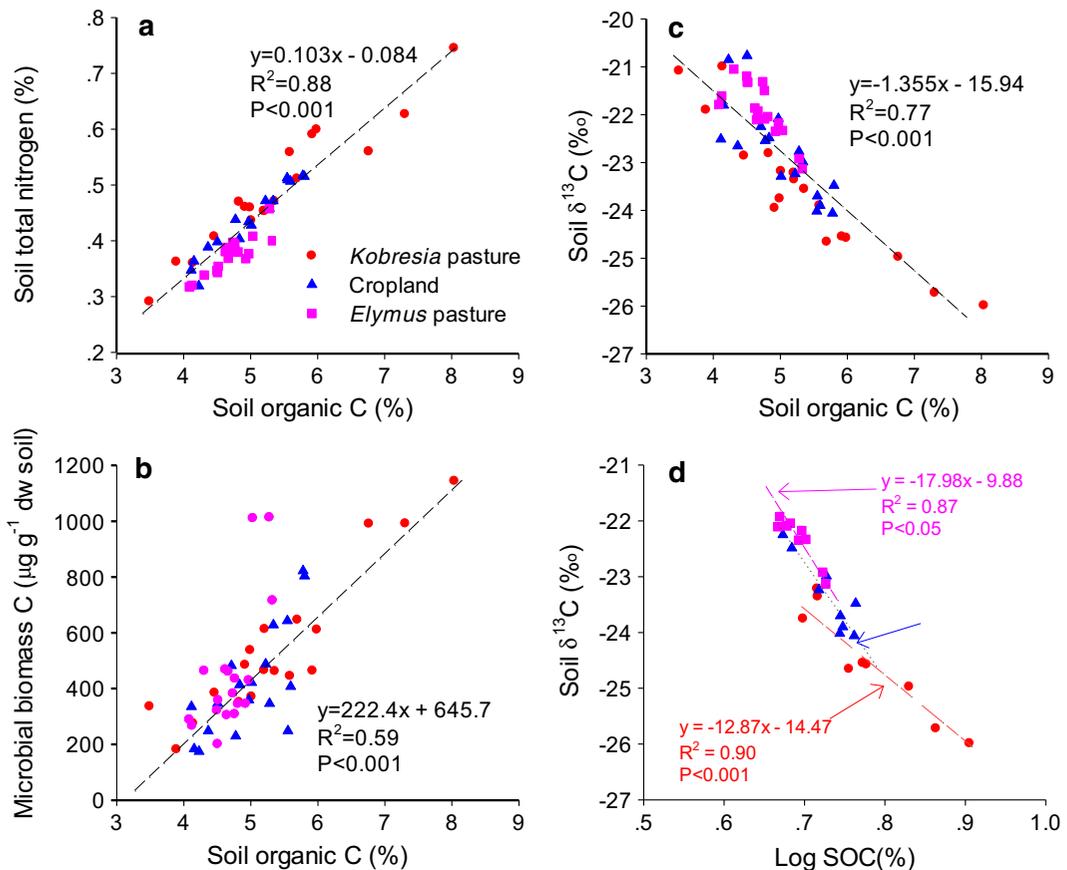


Fig. 5 Correlations between soil organic carbon with total nitrogen (a), microbial biomass carbon (b), and soil $\delta^{13}\text{C}$ (c) across three land use types as well as relation between logarithm of C content and soil $\delta^{13}\text{C}$ (d) in the top 15 cm for each land use type

depths (Fig. 7a). The C stock at the 30-cm depth was estimated to be $15.8 \pm 0.4 \text{ kg C m}^{-2}$ in *Kobresia* pasture,

$14.3 \pm 0.5 \text{ kg C m}^{-2}$ in cropland, and $15.6 \pm 1.1 \text{ kg C m}^{-2}$ in *Elymus* pasture (Fig. 7a). The microbial biomass C

Fig. 6 Correlation between the difference in SOC (ΔSOC) and soil $\delta^{13}\text{C}$ ($\Delta\text{soil } \delta^{13}\text{C}$) along the profile caused conversion from *Kobresia* grassland to *Elymus* pasture and cropland (*Avena sativa*)

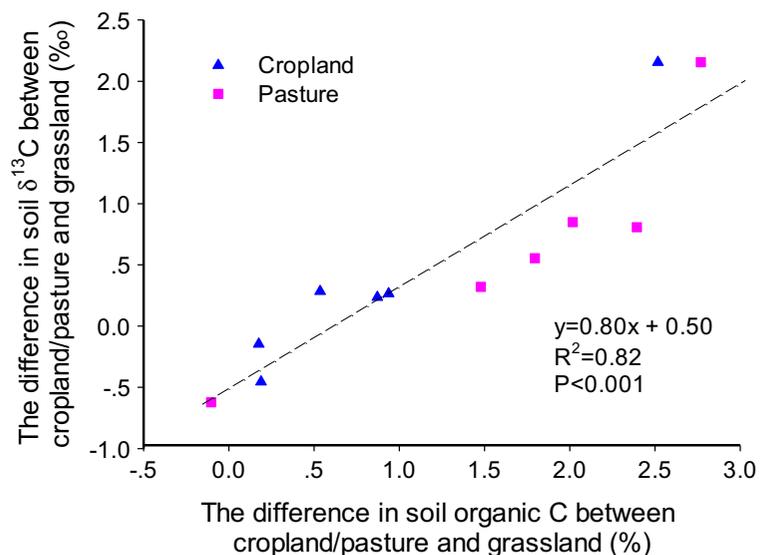
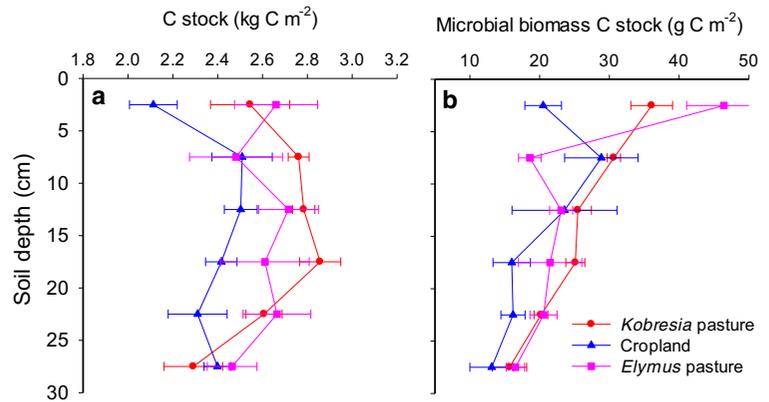


Fig. 7 The stocks of soil organic carbon (a) and microbial biomass carbon (b) in the upper 30-cm depth after the conversion from *Kobresia* pasture to *Elymus* pasture and cropland (*Avena sativa*) for 10 years. Each value is means \pm SE of three replicates



pool for *Elymus* pasture increased in the top 5-cm depth but strongly decreased in the second layer compared with *Kobresia* pasture (Fig. 7b). At the 30-cm depth, microbial biomass C was estimated to be 153 ± 8.4 g C m⁻² in *Kobresia* pasture, 118 ± 24 g C m⁻² in cropland, and 147 ± 12.6 g C m⁻² in *Elymus* pasture (Fig. 7b). Ten years after the conversion, a significant C loss (10.1 % of total SOC) was observed in cropland, while there were only insignificant C losses (1.6 % SOC) in pasture. However, microbial biomass C was strongly reduced by 22.8 % in cropland, compared to *Kobresia* pasture.

Discussions

Processes and mechanisms for soil C losses

The C stock is mainly determined by the balance between net C inputs to the soil as organic matter and net C losses from the soil as CO₂. Previous studies have suggested that C is lost due to increased SOC decomposition caused by various cultivation practices and removal of plant biomass by annual harvesting (Geist 2006; Braimoh and Vlek 2008). In this study, greater difference in SOC, microbial biomass, soil $\delta^{13}\text{C}$, and soil bulk density were mostly observed in the top 5-cm depth, reflecting land use changes strongly affecting the surface layer, where C and N cycling could be accelerated by tillage and grazing. Further, we confirm that land use change from grasslands to agricultural uses can cause soil C loss (Geist 2006; Piñeiro et al. 2010) and specify that the magnitude of the C loss depends on the land use types, e.g., conversion to cropland (10 %) led to more C losses than *Elymus* pasture (1.6 %).

Higher $\delta^{13}\text{C}$ of SOC generally suggests highly microbially processed and stronger SOC decomposition

(Garten et al. 2000; Poage and Feng 2004; Bowling et al. 2008). In this study, we found that a decrease of 1 % of SOC led to an increase in the $\delta^{13}\text{C}$ of 0.8‰ in montane soils. Therefore, higher $\delta^{13}\text{C}$ across the soil profile in *Elymus* pasture compared to both *Kobresia* pasture and cropland (Fig. 4a) indicates enhanced SOC decomposition in pasture. This is also reflected by decreased soil C:N ratios under *Elymus* pasture (Fig. 2c) due to C depletion by enhanced decomposition. The relationship between $\delta^{13}\text{C}$ and the logarithm of C content can reflect SOC turnover (Garten 2006; Guillaume et al. 2015). In this study, the steeper slope of cropland than that of *Kobresia* pasture in the top 15-cm depth demonstrates increased decomposition (Fig. 5d), but there was no significant difference between cropland and *Elymus* pasture. This indicates that SOC decomposition is similar in cropland and *Elymus* pasture, although *Elymus* pasture shows higher $\delta^{13}\text{C}$ values.

Higher $\delta^{13}\text{C}$ values across the soil profile do not reflect increased decomposition in *Elymus* pasture. This could be ascribed to some factors affecting soil $\delta^{13}\text{C}$. First, organic matter derived from C4 vegetation shows higher $\delta^{13}\text{C}$ values than C3 vegetation. However, no C4 plants are observed in these *Kobresia* pastures around the Haibei Research Station (Yi et al. 2003). Second, carbonates could contribute to higher $\delta^{13}\text{C}$ in SOC in lower soil layers due to high pH (around 8.0) at this site, but a previous study at the same site showed that $\delta^{13}\text{C}$ values in SOC after removal of carbonates with HCl solution are very close to ours at the corresponding soil layers (Yi 2004). This indicates that higher $\delta^{13}\text{C}$ in SOC at lower soil layers could not be ascribed to inorganic C. On the basis of $\delta^{13}\text{C}$ signature in soil organic matter, Yi (2004) suggests that it may be derived from ancient C4 vegetation. Third, trampling by grazers leads to soil compaction and causes vertical shifts in soil profile. This

also alters $\delta^{13}\text{C}$ signature along the soil profile. Finally, the remaining C stocks in these soils are too high, and the changes of the turnover may be not visible by this approach within 10 years.

Additionally, several studies have suggested that soil $\delta^{15}\text{N}$ can reflect SOC turnover, but no strong correlation was observed between SOC contents and $\delta^{15}\text{N}$ values. This is ascribed to the complexity of the N cycle in terrestrial soils (Schleuss et al. 2015). Soil $\delta^{15}\text{N}$ is a result of the isotopic compositions of N inputs, fractionations associated with N transformations and N losses (Hobbie and Ouimette 2009; Wang et al. 2013) and is often regarded as an integrator of the N cycle (Robinson 2001). Therefore, significantly higher $\delta^{15}\text{N}$ in the upper 5-cm soil depth in pasture than that in grassland (Fig. 4b) indicates accelerated N cycling in *Elymus* pasture, because grazers can increase $\delta^{15}\text{N}$ of soil by promoting N losses from the soil via NH_3 volatilization and denitrification (Frank and Evans 1997; Cheng et al. 2009). However, no C loss occurred in *Elymus* pasture compared to *Kobresia* pasture. This indicates that soil compaction caused by trampling of yaks and goats resulted in higher soil bulk density in *Elymus* pasture is another pathway controlling its SOC stocks, although numerous studies suggest that grazing in *Elymus* pasture alters SOC stocks simultaneously through changing net primary production, N stocks, and increased decomposition (Piñeiro et al. 2010; McSherry and Ritchie 2013). Further studies should investigate how grazing strongly decreases SOC content yet does not change its stocks.

Despite a small amount of manure inputs to cropland, a significant C loss occurred in cropland compared with *Kobresia* pasture. This is mainly ascribed to low C input to the soil in croplands due to harvest of aboveground biomass. Additional explanation is that tillage increases SOC loss by breaking open aggregates to expose protected organic C to microbial breakdown (Tian et al. 2015). This is reflected in decrease of microbial biomass C (Fig 3a) and increase of soil $\delta^{13}\text{C}$ (Fig 4a). The increased decomposition leads to rapid depletion of labile substrates (without strong input by plant residues and rhizodeposition) and thus limits microbial growth in *Elymus* pasture and cropland.

Relevance for C sequestration

Guo and Gifford (2002) highlighted the effects of land use changes on soil C stocks, showing land use changes

from pasture to cropland reduces total C stocks by 59 % over several decades. Our results showed a much smaller decrease of C stocks. Land use change from *Kobresia* pasture to *Elymus* pasture and cropland, 10 years ago, lead to a loss of 10 % of the C stock in cropland and 1.6 % in *Elymus* pasture within 30-cm depth. This corresponds to a loss of $160 \text{ g C m}^{-2} \text{ year}^{-1}$ and $25 \text{ g C m}^{-2} \text{ year}^{-1}$ in the upper 30-cm soil, offsetting C accumulation in *Kobresia* pasture soils (Tian et al. 2009). Compared to previous studies in the same area, $78.6 \text{ g C m}^{-2} \text{ year}^{-1}$ in the upper 40 cm was lost when *Kobresia* pasture was changed to cropland within 30 years (Li et al. 2006), half of our estimate in the 30-cm soil profile over 10 years. Greater C stock loss could be due to rapid depletion of labile organic C at early stages of land use change. Compared to other regions, low SOC loss caused by the conversion from *Kobresia* pastures to cropland could be ascribed to low temperature and short vegetation period, both limiting SOC decomposition in alpine regions (Song et al. 2010; He et al. 2014).

Half of the entire Tibetan Plateau is occupied by various montane grasslands, storing about 7.4 Pg C within the upper 1-m soil depth (Yang et al. 2008). If we assume that all montane grasslands will be converted to croplands, the total soil C loss can be estimated to be 0.74 Pg C within 10 years. The conversion from *Kobresia* pasture to *Elymus* pasture did not lead to significant C losses, but the soil fertility and properties decreased due to increased bulk density and reduced microbial biomass, both key parameters to maintain soil structure and functions. In the long run, net primary production could be reduced in pasture and thus affect the C stock.

In summary, we conclude that the conversion of montane *Kobresia* grasslands to cropland decreases C stocks, while the C stocks were unchanged after conversion to *Elymus* pasture. Low C input due to harvest of aboveground biomass is the major pathway for decreased SOC stock in croplands, while trampling caused by grazers is responsible for unchanged C stock in *Elymus* pasture. Soil $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ are useful to explore SOC dynamics caused by land use changes because they can reflect changes of C and N cycling. These findings suggest that it is essential to make a full evaluation before montane *Kobresia* grasslands will be converted to cropland, especially in sensitive ecosystems of the Tibet Plateau, where montane grasslands are more fragile to environmental changes and very hard to restore.

Acknowledgments We thank Dr. Eben Goodale for the language improvements. This study was supported by the National Natural Science Foundation of China (31470560), the Knowledge Innovation Foundation Program for Outstanding Young Scholar of the Chinese Academy of Sciences (KZCX2-YW-QN302), Key Laboratory of Tropical Forest Ecology of Chinese Academy of Sciences, and the German Science Foundation priority programme 1372 “Tibetan Plateau–Formation–Climate–Ecosystems (TiP)” with the contracts KU 1184/14-1,2.

References

- Babel W, Biermann T, Coners H, Falge E, Seeber E, Ingrisch J, Schleuß PM, Gerken T, Leonbacher J, Leopold T, Willinghöfer S, Schützenmeister K, Shibistova O, Becker L, Hafner S, Spielvogel S, Li X, Xu XL, Sun Y, Zhang L, Yang Y, Ma Y, Wesche K, Graf HF, Leuschner C, Guggenberger G, Kuzyakov Y, Miede G, Foken T (2014) Pasture degradation modifies the water and carbon cycles of the Tibetan highlands. *Biogeosciences* 11:6633–6656
- Bowling DR, Pataki DE, Randerson JT (2008) Carbon isotopes in terrestrial ecosystem pools and CO₂ fluxes. *New Phytol* 178:24–40
- Braimoh AK, Vlek PLG (2008) Land use and soil resources. Springer Science+Business Media B.V
- Brookes PC, Landman A, Pruden G, Jenkinson DS (1985) Chloroform fumigation and the release of soil nitrogen: a rapid extraction method to measure microbial biomass nitrogen in soil. *Soil Biol Biochem* 17:837–842
- Chen H, Billen N, Stahr K, Kuzyakov Y (2007) Effects of nitrogen and intensive mixing on decomposition of ¹⁴C-labelled maize (*Zea mays* L.) residue in soils of different land use types. *Soil Tillage Res* 96:114–123
- Cheng W, Chen Q, Xu Y, Han X, Li L (2009) Climate and ecosystem ¹⁵N natural abundance along a transect of Inner Mongolian grasslands: contrasting regional patterns and global patterns. *Glob Biogeochem Cyc* 23(2): GB2005, doi: 10.1029/2008GB003315
- Chinese Soil Taxonomy Research Group (1995) Chinese soil taxonomy. Science Press, Beijing, pp 58–147
- Cotrufo MF, Conant RT, Paustian K (2011) Soil organic matter dynamics: land use, management and global change. *Plant Soil* 338:1–3
- Frank DA, Evans RD (1997) Effects of native grazers on grassland N cycling in Yellowstone National Park. *Ecology* 78(7): 2238–2248
- Garten CT (2006) Relationships among forest soil C isotopic composition, partitioning, and turnover times. *Can J For Res* 36:2157–2167
- Garten CT, Cooper LW, Post WM III, Hanson PJ (2000) Climate controls on forest soil C isotope ratios in the Southern Appalachian Mountains. *Ecology* 81:1108–1119
- Geist H (2006) Our earth’s changing land: an encyclopedia of land-use and land-cover change. Greenwood Publishing Group
- German DP, Chacon SS, Allison SD (2011) Substrate concentration and enzyme allocation can affect rates of microbial decomposition. *Ecology* 92:1471–1480
- Guillaume T, Muhammad D, Kuzyakov Y (2015) Losses of soil carbon by converting tropical forest to plantations: erosion and decomposition estimated by δ ¹³C. *Glob Change Biol* doi:10.1111/gcb.12907
- Guo LB, Gifford RM (2002) Soil carbon stocks and land use change. *Glob Chang Biol* 8:345–360
- Hafner S, Unterregelsbacher S, Seeber E, Xu X, Li X, Guggenberger G, Miede G, Kuzyakov Y (2012) Effect of grazing on carbon stocks and assimilate partitioning in Tibetan montane pasture revealed by ¹³CO₂ pulse labeling. *Glob Chang Biol* 18:528–538
- He YT, Xu XL, Zhang XZ, Kueffer C, Shi PL (2014) Cushion plant litter shifts nitrogen mineralization to immobilization at high but not low temperature in an alpine meadow. *Plant Soil* 383:415–426
- Heimann M, Reichstein M (2008) Terrestrial ecosystem carbon dynamics and climate feedbacks. *Nature* 451:289–292
- Hobbie EA, Ouimette AP (2009) Controls of nitrogen isotope patterns in soil profiles. *Biogeochemistry* 95:355–371
- Houghton RA (1995) Changes in the storage of terrestrial carbon since 1850. In: Soils and global change. CRC Press, Inc, Boca Raton, pp 45–65
- Ingrisch J, Biermann T, Seeber E, Leopold E, Li M, Ma Y, Xu XL, Miede G, Guggenberger G, Foken T, Kuzyakov Y (2015) Carbon pools and fluxes in a Tibetan alpine Kobresia pygmaea pasture partitioned by coupled eddy-covariance measurements and ¹³CO₂ pulse labeling. *Sci Total Environ* 505:1213–1224
- Jendinson DS, Adamas DE, Wild A (1991) Model estimated of CO₂ emissions from soil in response to global warming. *Nature* 351:304–306
- Kaiser K, Schoch WH, Miede G (2007) Holocene paleosols and colluvial sediments in Northeast Tibet (Qinghai Province, China): properties, dating and paleoenvironmental implications. *Catena* 69(2):91–102
- Kirschbaum MUF (2004) Soil respiration under prolonged soil warming: are rate reductions caused by acclimation or substrate loss? *Glob Chang Biol* 10:1–8
- LeCain DR, Morgan JA, Schuman GE, Reeder JD, Hart RH (2002) Carbon exchange and species composition of grazed pastures and exclosures in the short grass steppe of Colorado. *Agric Ecosyst Environ* 93:421–435
- Li YN, Zhao XQ, Cao GM, Zhao L, Wang QX (2004) Analyses on climates and vegetation productivity background at Haibei Alpine Meadow Ecosystem Research Station. *Plateau Meteorology* 23:558–567
- Li YM, Cao GM, Wang YS (2006) Effects of reclamation on soil organic carbon in Haibei alpine meadow. *Chin J Ecol* 25: 911–915
- Liu JY, Kuang WJ, Zhang ZX, Xu XL, Chen YW, Jia N, Zhou WC, Zhang SW, Li RD, Yan CZ, Wu SX, Shi XZ, Jiang N, Yu DS, Pan XZ, Chi WF (2014) Spatiotemporal characteristics, patterns and causes of land use changes in China since the late 1980s. *Acta Geograph Sin* 69:3–14
- McSherry ME, Ritchie ME (2013) Effects of grazing on grassland soil carbon: a global review. *Glob Chang Biol* 19:1347–1357
- Miede G, Miede S, Kaiser K, Liu JQ, Zhao XQ (2008) Status and dynamics of the Kobresia pygmaea ecosystem on the Tibetan plateau. *Ambio* 37:272–279
- Miede G, Miede S, Kaiser K, Reudenbach C, Behrendes L, La D, Schlütz F (2009) How old is pastoralism in Tibet? an

- ecological approach to the making of a Tibetan landscape. *Palaeogeogr Palaeoclimatol Palaeoecol* 276(1):130–147
- Miehe G, Bach K, Miehe S, Kluge J, Yang Y, La D, Co S, Wesche K (2011) Alpine steppe plant communities of the Tibetan highlands. *Appl Veg Sci* 14:547–560
- Miehe G, Miehe S, Böhner J, Kaiser K, Hensen I, Madsen D, Liu JQ, Opgenoorth L (2014) How old is the human footprint in the world's largest alpine ecosystem? A review of multiproxy records from the Tibetan plateau from the ecologists' viewpoint. *Quat Sci Rev* 86:190–209
- Newton JD, Wyatt FA, Brown AL (1945) Effects of cultivation and cropping on the chemical composition of some western Canadian prairie province soils. *Sci Agric* 25:718–737
- Piñeiro G, Paruelo JM, Oesterheld M, Jobbágy EG (2010) Pathways of grazing effects on soil organic carbon and nitrogen. *Rangel Ecol Manag* 63:109–119
- Poage MA, Feng XH (2004) A theoretical analysis of steady $\delta^{13}\text{C}$ profiles of soil organic matter. *Glob Biogeochem Cyc* 18:GB2016, doi:10.1029/2003GB002195
- Reid RS, Thornton PK, McCrabb GJ, Kruska RL, Atieno F, Jones PG (2004) Is it possible to mitigate greenhouse gas emissions in pastoral ecosystems of the tropics? *Environ Dev Sustain* 6:91–109
- Robinson D (2001) $\delta^{15}\text{N}$ as an integrator of the nitrogen cycle. *Trends Ecol Evol* 16(3):153–162
- Sanaullah M, Blagodatskaya E, Chabbi A, Rumpel C, Kuzyakov Y (2011) Drought effects on microbial biomass and enzyme activities in the rhizosphere of grasses depending on plant community composition. *Appl Soil Ecol* 48:38–44
- Šantrůčková H, Bird MI, Lloyd J (2000) Microbial processes and carbon-isotope fractionation in tropical and temperate grassland soils. *Funct Ecol* 14:108–114
- Schleuss P, Heitkamp F, Sun Y, Miehe G, Xu XL, Kuzyakov Y (2015) Nitrogen uptake in an alpine *Kobresia* pasture on the Tibetan Plateau: localisation by ^{15}N labelling and implications for a vulnerable ecosystem. *Ecosystems*. doi:10.1007/s10021-015-9874-9
- Song MH, Jiang J, Cao GM, Xu XL (2010) Effects of temperature, glucose and inorganic nitrogen inputs on carbon mineralization in a Tibetan alpine meadow soil. *Eur J Soil Biol* 46:375–380
- Stockmann U, Adams MA, Crawford JW, Field DJ, Henakaarchchi N, Jenkins M, Minasny B, McBratney AB, de Remy de Courcelles V, Singh K, Wheeler I, Abbott L, Angers DA, Baldock J, Bird M, Brookes PC, Chenu C, Jastrow JD, Lal R, Lehmann J, O'Donnell AG, Parton WJ, Whitehead D, Zimmermann M (2013) The knowns, known unknowns and unknowns of sequestration of soil organic carbon. *Agric Ecosyst Environ* 164:80–99
- Tamocai C, Canadell JG, Schuur EAG, Kuhry P, Mazhitova G, Zimov S (2009) Soil organic carbon pools in the northern circumpolar permafrost region. *Global Biogeochem Cycles* 23:GB2023, doi:10.1029/2008GB003327
- Tian YQ, Xu XL, Song MH, Zhou CP, Gao Q, Ouyang H (2009) Carbon sequestration in two alpine soils on the Tibetan plateau. *J Integr Plant Biol* 51(9):900–905
- Tian J, Pausch J, Yu G, Blagodatskaya E, Gao Y, Kuzyakov Y (2015) Aggregate size and their disruption affect ^{14}C -labeled glucose mineralization and priming effect. *Appl Soil Ecol* 90:1–10
- Unteregelsbacher S, Hafner S, Guggenberger G, Miehe G, Xu XL, Liu J, Kuzyakov Y (2012) Response of long-, medium- and short-term turnover processes of the carbon budget to overgrazing on the Tibetan plateau. *Biogeochemistry* 111:187–201
- Vance ED, Brookes PC, Jenkinson DS (1987) An extraction method for measuring soil microbial biomass C. *Soil Biol Biochem* 19(6):703–707
- Wang W, Fang JY (2009) Soil respiration and human effects on global grasslands. *Glob Planet Chang* 67(1–2):20–28
- Wang SP, Wilkes A, Zhang ZC, Chang XF, Lang R, Wang YF, Niu HS (2011) Management and land use change effects on soil carbon in northern China's grasslands: a synthesis. *Agric Ecosyst Environ* 142:329–340
- Wang LX, Okin GS, D'Odorico P, Caylor KK, Macko SA (2013) Ecosystem-scale spatial heterogeneity of stable isotopes of soil nitrogen in African savannas. *Landsc Ecol* 28(4):685–698
- WBGU Special Report (1998) The accounting of biological sinks and sources under the Kyoto Protocol. WBGU, Bremerhaven
- WRB (1998) World reference base for soil resources. FAO/ISRIC/ISSS, Rome
- Wu J, Jörgensen RG, Pommerening B, Chaussod R, Brookes PC (1990) Measurement of soil microbial biomass-C by fumigation-extraction—an automated procedure. *Soil Biol Biochem* 22:1167–1169
- Wu HB, Guo ZT, Peng CH (2003) Distribution and storage of soil organic carbon in China. *Global Biogeochem Cycles* 17:1–11
- Yang YH, Fang JY, Tang YH, Ji CJ, Zheng CY, He JS, Zhu B (2008) Storage, patterns and controls of soil organic carbon in the Tibetan grasslands. *Glob Chang Biol* 14:1592–1599
- Yi X (2004) Stable carbon isotopic composition in soil organic carbon and C3/C4 source variations at the Haibei Alpine Meadow. *Acta Bot Boreal* 25(2):336–342
- Yi X, Yang Y, Zhang X, Li L, Zhang L (2003) No C4 plants found at the Haibei Alpine Meadow Ecosystem Research station in Qinghai, China: evidence from stable carbon isotope studies. *Acta Bot Sin* 45(11):1291–1296
- Zhang JW (1988) *Vegetation of Xizang* Science Press, Beijing
- Zhang YL, Li BY, Zheng D (2002) A discussion on the boundary and area of the Tibetan plateau in China. *Geogr Res* 21:1–8
- Zhou XM (2001) *Alpine Kobresia meadows in China*. Science Press, Beijing