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Pasture degradation impact on soil carbon and nitrogen fractions of alpine meadow in a Tibetan permafrost region

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Abstract

Purpose Knowledge of the effects of pasture degradation on soil organic carbon (SOC) and nitrogen (N) fractions in permafrost soils on the Tibetan Plateau is limited. The aims of this study were (1) to evaluate the changes in SOC and N contents in density fractions under *Kobresia* pasture due to degradation and (2) to explore the contributions of the changes of SOC and N in density fractions to the changes of SOC and N in whole soil.

Materials and methods The impact of *Kobresia* pasture degradation on SOC and N fractions was investigated in the permafrost region of the Tibetan Plateau. A continuously degraded pasture was identified and classified into three categories of vegetation cover according to their degrees of degradation (i.e., vegetation cover decline from 90% ± 6.6% to 70% ± 8.3% and 45% ± 8.7%). The SOC and N fractions were separated by using the density separation method.

Results and discussion The *Kobresia* pasture degradation significantly decreases SOC and N contents and stocks in soils. The SOC and N contents in the whole soil were positively correlated with the SOC and N contents in the light and heavy fractions ($p < 0.001$, respectively). The SOC and N contents were significantly correlated with soil pH and the contents of soil moisture, clay, silt, and sand. The ratio of SOC to total N in the whole soil was positively correlated with the ratio of SOC to N in heavy fractions ($p < 0.001$) rather than the ratio of SOC to N in light factions ($p > 0.05$). When pasture degraded from vegetation covers 90% to 45%, SOC stock at 0–40-cm soil layer decreased by 28.7% and N stock decreased by 39.2% in the whole soil; 56.6% and 47.6%, respectively, in the light fractions and 14.3% and 40.6%, respectively, in the heavy fractions. The depletion rates of N were higher than those of SOC in the heavy fractions and whole soil. At all sites, more than 80% of the SOC and N stocks were protected in heavy fractions.

Conclusions These results indicate that a decoupling depletion of SOC and soil N appeared with the *Kobresia* pasture degradation in the permafrost region of the Tibetan Plateau. The *Kobresia* pasture degradation affects the SOC and N fractions differently and thus regulates soil carbon and N cycling in the permafrost soils on the Tibetan Plateau.

Keywords *Kobresia* pasture · Soil organic matter · Heavy fractions · Light fractions · Tibetan Plateau

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1 Introduction

The stocks and drivers of soil organic carbon (SOC) and nitrogen (N) in the permafrost region have attracted widespread interests because of climate change and the potential of permafrost thaw (Dutta et al. 2006; Evgrafova et al. 2018; Hugelius et al. 2014; Mueller et al. 2015; Natali et al. 2014; Ping et al. 2015; Tarnocai et al. 2009; Vogel et al. 2009). In the Northern Hemisphere, SOC stored in the 0–3 m is estimated at 1035 ± 150 Pg (Hugelius et al. 2014). In the Tibetan Plateau, SOC stored in the permafrost-affected soils is estimated at 15.31 Pg in 0–3 m (Ding et al. 2016). During the past three decades, the mean annual temperature of high-latitude and -

altitude regions has significantly increased (IPCC 2013; Schuur et al. 2015), and such increase has strongly affected SOC decomposition in these regions (Ding et al. 2017; Gentsch et al. 2015; Schadel et al. 2016; Schuur et al. 2015). The corresponding release of greenhouse gases CO_2 and CH_4 may instigate a positive feedback on climate warming (Koven et al. 2015; Natali et al. 2014; Schuur et al. 2011; Whiteman et al. 2013). SOC decomposition depends not only on the changes in soil environmental conditions but also on the contribution of different SOC fractions (Gentsch et al. 2015; Mueller et al. 2015; Schmidt et al. 2011; Yeasmin et al. 2017). Thus, studies on the stocks and site characteristics of SOC and N fractions in the permafrost region are of great importance (Dinakaran et al. 2018; Dorfer et al. 2013; Gentsch et al. 2015).

Functional SOC pools, such as labile and stable pools, have different turnover rates and protective mechanisms (Dinakaran et al. 2018; Eze et al. 2018; Ramnarine et al. 2018; Whalen et al. 2000). SOC can be separated into light fraction organic carbon (LFOC) and heavy fraction organic carbon (HFOC) through physical density separation method (Six et al. 2002; Tan et al. 2007; Whalen et al. 2000). LFOC is considered to be more sensitive to change in soil environment than total SOC (Gong et al. 2009; Leifeld and Kogel-Knabner 2005; Li et al. 2018a). Labile LFOC in permafrost soils have been studied in many researches (Dorfer et al. 2013; Gentsch et al. 2015; Shang et al. 2016; Wu et al. 2018), whereas HFOC is rarely examined in these soils (Dong et al. 2018; Gao et al. 2017; Ramnarine et al. 2018). The HFOC also play an important role in SOC synthesis and decomposition. Basing on 28 pedons across the Siberian Arctic, Gentsch et al. (2015) suggest that HFOC represent the vast majority of subsoil SOC and are affected by the changes in soil conditions.

Soil N is highly interdependent with SOC as both are derived from soil organic matter (Calazans et al. 2018; Liu et al. 2019). However, it has received less attention for the N fraction dynamic in permafrost soils (Bingham and Cotrufo 2016; Giannetta et al. 2018; Song et al. 2014). Soil organic matter fractions vary in terms of their response to environmental change because of their different protective mechanisms (Giannetta et al. 2018; Song et al. 2014). Several studies showed that different soil organic matter fractions have different soil N contents and C/N ratios (Giannetta et al. 2018; Huo et al. 2013; Ramnarine et al. 2018). Thus, not only the response of total N to environmental change but also N content in various fractions should be given attention (Bingham and Cotrufo 2016; Giannetta et al. 2018). Doing so can improve our understanding for the effect of environmental change on soil carbon and N cycles, especially under the condition of climate warming (Eze et al. 2018; Song et al. 2014; Zhong et al. 2015).

The *Kobresia* pasture, often named alpine meadow, is vegetation dominated by sedge plants, such as *Kobresia pygmaea*, in the Tibetan Plateau and forms a tight root turf (Babel et al. 2014; Kaiser et al. 2008; Miehe et al. 2008). The *Kobresia* pasture plays a vital role in the provision of ecology, environment, and social services in this region (Hopping et al. 2018; Liu et al. 2018; Yang et al. 2018). However, owing to natural and human factors, the *Kobresia* pasture is rapidly degrading (Babel et al. 2014; Hopping et al. 2016; Hopping et al. 2018; Lehnert et al. 2016). The process has distinct characteristics; that is, the dominated sedge plants can be gradually replaced by other functional plants, such as grasses and forbs (Wu et al. 2014). The *Kobresia* pasture degradation decreases vegetation productivity and SOC and soil nutrient stocks (Dong et al. 2012; Li et al. 2014; Liu et al. 2017; Liu et al. 2018; Peng et al. 2018; Wang et al. 2009a, b). Basing on 44 studies, Liu et al. (2018) summarized that 42% of SOC and 33% of N stocks are lost due to the pasture degradation on the Tibetan Plateau. Recently, climate change has been identified as one of the potential causes of pasture degradation (Hopping et al. 2018; Lehnert et al. 2016). In this context, studying carbon and N dynamics under pasture degradation in permafrost ecosystems has become urgent and important.

Many studies on the *Kobresia* pasture degradation focused on vegetation characteristics, soil carbon pools, soil hydraulic properties, greenhouse gas emissions, and soil microbial communities. These studies provided important information about the responses of vegetation and soil to grassland degradation and promoted the restoration and protection of alpine grasslands. However, how SOC and N fractions respond to the *Kobresia* pasture degradation is still unclear, especially in permafrost soils. The Tibetan Plateau has a high altitude and highly sensitive permafrost ecosystem (Yang et al. 2010). Characterizing SOC and N fractions dynamics in the *Kobresia* pasture is crucial for understanding the physical protection mechanisms of soil organic matter in the permafrost region. Meanwhile, some studies about pasture degradation were based on the method of 'site represent time,' that is, sites with different microtopography, soil texture, vegetation type, and even climatic characteristics were selected to indicate the degradation gradient (Liu et al. 2018; Peng et al. 2018; Yuan et al. 2019). The impact of pasture degradation can be better explored in a relatively homogeneous microenvironment (Dlamini et al. 2014; McHunu and Chaplot 2012; Yuan et al. 2019).

In this study, we investigate the effects of the *Kobresia* pasture degradation on SOC and N fractions in homogeneous soils in the permafrost region of the Tibetan Plateau. Our aims were to (1) evaluate the changes in SOC and N contents and stocks in light and heavy fractions with the *Kobresia* pasture degradation and (2) explore the contributions of the changes of SOC and N in light and heavy fractions to the changes of SOC and N in whole soil.

2 Materials and methods

2.1 Study area

The study was carried out at Kaixinlin basin (92.35°E, 33.96°N, 4627 m a.s.l.) near the Qinghai-Tibet Railway on the Tibetan Plateau, Qinghai Province, China (Fig. 1). This area is located at the permafrost region of the Tibetan Plateau (Wu et al. 2012). The mean annual temperature in this area is − 3.8 °C. The mean annual precipitation is 347 mm, 90% of which occurs from April to October. The active layer thickness is about 2.4–3.4 m and has obvious increasing trend (Wu et al. 2012). The vegetation type in the experimental site is alpine meadow and is dominated by the sedge species (*Kobresia pygmaea* C.B. Clarke). The other plant species are *Elymus nutans*, *Festuca ovina*, *Polygonum* L., *Oxytropis glacialis*, and *Astragalus polycladus* (Yuan et al. 2019).

At the Kaixinling site, the Tibetan Plateau railway runs parallel to the highway, with an interval of about 800 m. Near the railway or highway, the vegetation of *Kobresia* pasture has gradually degenerated because of construction activity, such as vehicle driving and construction trampling. Vegetation degradation can change from nearly intact root mat to highly degraded root mat due to the strength of construction activity (Fig. 1), which is a common degradation gradient of the *Kobresia* pasture along the railway or highway in the Tibetan Plateau.

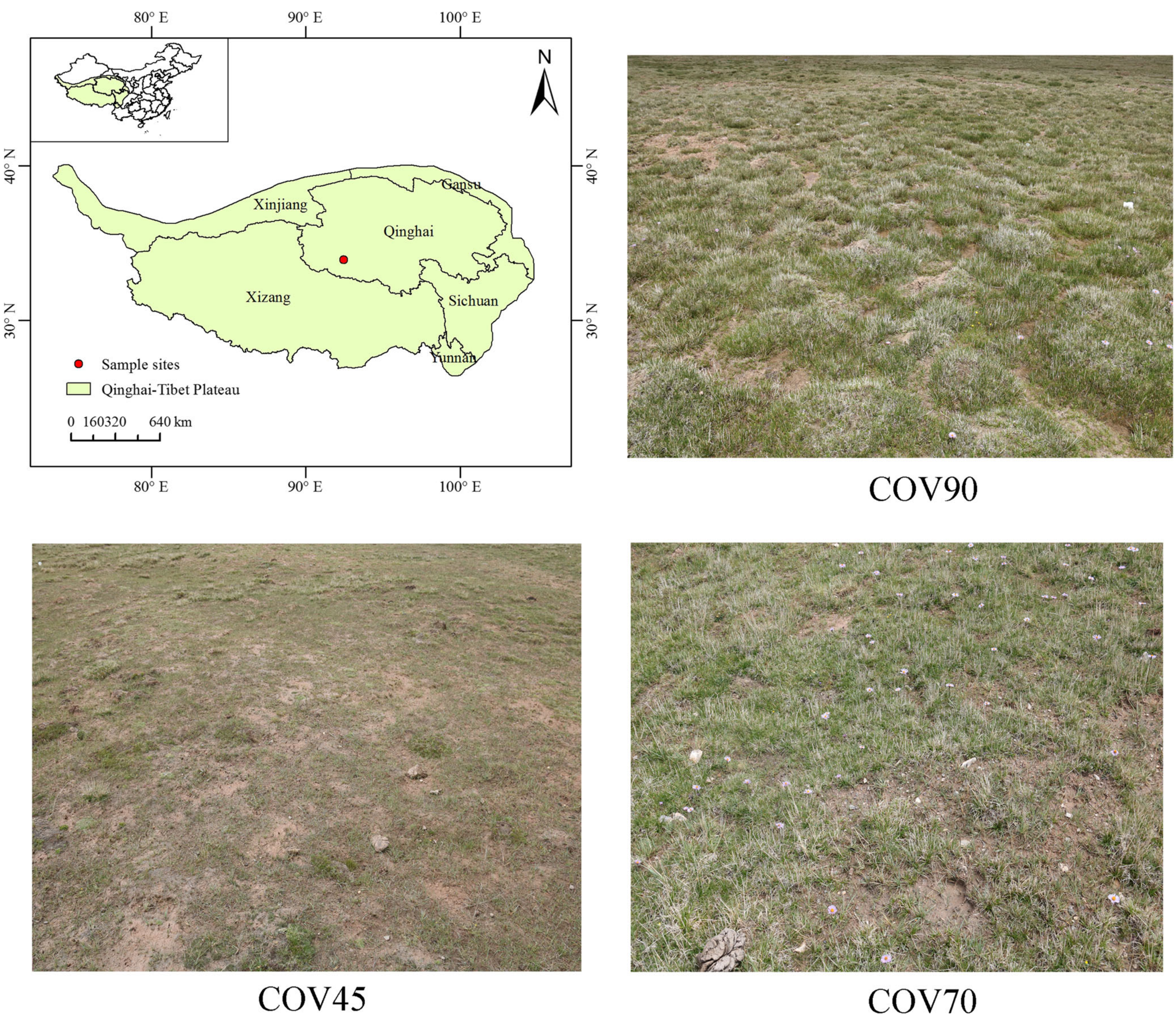

Fig. 1 The location and vegetation condition for the experimental site on the Tibetan Plateau, China. COV90 represents the site with vegetation cover by 90% (± 6.6%); COV70 represents the site with vegetation cover by 70% (± 8.3%); COV45 represents the site with vegetation cover by 45% (± 8.7%)

2.2 Experimental design

At the end of July 2016, we selected a relatively flat (slope gradient ≤ 4°) and continuously degraded pasture that has a surface area of more than 100 m × 500 m (Fig. 1). In this area, we identified and classified three categories of vegetation cover according to their degrees of degradation, that is, COV90 (90% ± 6.6%), COV70 (70% ± 8.3%), and COV45 (45% ± 8.7%; Fig. 1). These categories represent a continuous gradient of pasture degradation that allow us to explore the effects of pasture degradation in a relatively homogeneous environment. The area has normal grazing by livestock (yaks and sheep) and wild animals (such as wild ass, Tibetan antelope, and Mongolian gazelle). The grazing intensity is low in this area as the Chinese government strengthens its efforts to protect the ecological environment. The grazing intensity is lower than that in the wetter areas in the southeastern of the Tibetan Plateau (such as the Zoigê area) based on the number of grazing sheep and yaks, and the situations of plant aboveground biomass and excrements (Shi et al. 2013; Yang et al. 2018). These areas have been long used as grasslands and have never been used for other land utilization such as farmland. No additional disturbance, such as mowing, fertilization, and soil digging, has been recorded in the experimental sites since the Qinghai-Tibet Railway has been opened in 2006, except for herders grazing and wild animals eating.

In each vegetation cover category, three sampling plots (10 m × 10 m) were set up at least five meters from one another. At each plot, ten randomly quadrats with an area of 0.5 m × 0.5 m were placed to determine vegetation cover and total aboveground biomass of plants. Vegetation cover was determined by using the grid method. Total aboveground biomass was determined through the oven-drying method. Soil samples for soil layers of 0–20 cm and 20–40 cm were collected at each quadrat with a tube auger (5.0 cm in diameter). Soil bulk densities were determined by using the cut ring method. The diameter of the ring is 50.46 mm and the volume is 100 cm^3. Triplicate soil samples at each plot were used.

2.3 Soil analysis

The density fractionation method was used to separate light and heavy soil organic matter fractions (Gregorich and Ellert 1993; Yuan et al. 2016). Before the density fractionation, the soil samples were air-dried and passed through a 2-mm steel sieve. After sifting, 10 g of soils was transferred to a centrifuge tube and dispersed in 50 mL of NaI solution (1.8 g cm^{-3}). After being shaken for 10 min on a horizontal shaker (300 rpm), the centrifuge tubes were centrifuged for 30 min (3000 rpm). The supernatant was collected with a Whatman membrane filter after NaI was removed by $CaCl_2$ solution and distilled water. The fraction in the supernatant was as the light fraction organic matter. The additional light fractions in the centrifuge tube were collected again. The residue of soil samples was centrifuged for 15 min (5000 rpm) with 100 mL distilled water three times. After the centrifugation, the heavy fraction organic matter was collected from the residue of soil samples. The light and heavy fractions were finely ground for the analysis of SOC and N contents after being dried at 60 °C.

The SOC contents in light fractions (LFOC), heavy fractions (HFOC), and whole soil (SOC) and the N contents in light fractions (LFN), heavy fractions (HFN), and whole soil (total N) were analyzed through dry combustion method. Before measurements, samples were acidified with 0.5 M HCl to remove carbonates and washed thrice with distilled water. An elemental analyzer (Elementar Analy sensysteme GmbH, German) was used. The ratios of SOC to N in the light fractions (LFOC/LFN), in the heavy fractions (HFOC/HFN), and in whole soil (SOC/TN) were calculated for each soil sample. A laser diffraction instrument was used to measure soil particle distribution. Selected soil physical properties and SOC and N contents are shown in Table 1.

2.4 Calculation of SOC and N stocks

The SOC and N stocks (kg m^{-2}) in light fractions, heavy fractions, and whole soil were calculated using Eq. (1) (Yang et al. 2008):

$$S = C \times BD \times T \times (1{-}P) \times 0.01 \tag{1}$$

where S is the SOC and N stocks in light fractions, heavy fractions, and whole soil (kg m^{-2}); C is the SOC and N contents in light fractions, heavy fractions, and whole soil (g kg^{-1}); BD is the bulk density (g cm^{-3}); T is the soil thickness (cm); and P is the percentage (%) of the fraction > 2 mm.

Changes in SOC stocks under degraded sites relative to the SOC stock under a non-degraded site were calculated and used to represent the changes in SOC stocks along the pasture degradation gradient (Dlamini et al. 2014; Yuan et al. 2019). Changes in SOC stocks were calculated using Eq. (2) (Dlamini et al. 2014):

$$\mathrm{SOC_{sc}} = \frac{\mathrm{SOC_n}{-}\mathrm{SOC_d}}{\mathrm{SOC_n}} \times 100 \tag{2}$$

where SOC_{sc}, SOC_n, and SOC_d are the changes in SOC stocks (%), SOC stock in the non-degraded soils (COV90), and SOC stock in degraded soils (COV45 and COV70), respectively. The changes in SOC and N stocks in light fractions, heavy fractions, and whole soil were calculated by using this equation.

2.5 Statistical analysis

Two-way ANOVAs were applied to assess the effects of pasture vegetation coverage and soil sampling depth on soil

Table 1 Selected soil physical properties and soil organic carbon and nitrogen contents in experimental sites on the Tibetan Plateau (mean ± SD)

	Depth (cm)	BD (g cm^{-3})	pH	SMC (%)	Clay (%)	Silt (%)	Sand (%)	SOC (g kg^{-1})	TN (g kg^{-1})	LFOC (g kg^{-1})	LFN (g kg^{-1})	HFOC (g kg^{-1})	HFN (g kg^{-1})
COV90	0–20	1.28 (0.08)	8.4 (0.1)	23 (6)	1.7 (0.4)	35.1 (4.3)	63.2 (4.6)	28.9 (2.8)	2.7 (0.5)	4.81 (1.7)	0.53 (0.09)	24.09 (2.2)	2.17 (0.26)
	20–40	1.37 (0.09)	8.5 (0.1)	18 (3)	2.7 (0.6)	42.6 (4.5)	54.7 (5)	22.5 (1.9)	1.7 (0.2)	2.78 (0.8)	0.41 (0.04)	19.72 (2.7)	1.29 (0.33)
COV70	0–20	1.33 (0.08)	8.9 (0.2)	16 (2)	2.0 (0.5)	31.8 (6.1)	66.2 (6.6)	20.4 (1.1)	1.9 (0.2)	2.58 (0.8)	0.55 (0.07)	17.82 (0.9)	1.35 (0.16)
	20–40	1.45 (0.07)	8.9 (0.1)	13 (4)	3.1 (0.9)	37.3 (5.7)	59.6 (6.4)	16.4 (1.2)	1.1 (0.1)	0.46 (0.3)	0.35 (0.02)	15.94 (1.1)	0.75 (0.22)
COV45	0–20	1.43 (0.09)	9.1 (0.2)	12 (3)	2.6 (0.7)	39.8 (4.1)	57.6 (4.6)	17.9 (2.6)	1.5 (0.3)	1.26 (0.7)	0.4 (0.07)	16.64 (1.1)	1.1 (0.09)
	20–40	1.47 (0.06)	9.2 (0.2)	13 (4)	3.6 (0.5)	46.4 (2.2)	49.9 (2.5)	15.3 (0.5)	1.0 (0.1)	0.79 (0.2)	0.2 (0.02)	14.51 (1.3)	0.8 (0.13)
Summary of ANONA (*p* values)													
Vegetation cover		< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
Soil sampling depth		0.059	0.091	0.012	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
Cover × depth		0.632	0.784	0.027	0.886	0.563	0.662	0.007	0.014	0.58	0.783	< 0.001	0.001

COV90 represents the site with vegetation cover by 90% (± 6.6%); COV70 represents the site with vegetation cover by 70% (± 8.3%); COV45 represents the site with vegetation cover by 45% (± 8.7%)

BD soil bulk density, *SMC* soil moisture content, *SOC* soil organic carbon content in whole soil, *TN* total N content in whole soil, *LFOC* SOC content in light fractions, *HFOC* SOC content in heavy fractions, *LFN* soil N content in light fractions, *HFN* soil N content in heavy fractions

physical properties and SOC and N contents and stocks. One-way ANOVAs were performed to evaluate the differences among different pasture degradation degrees at the same soil layer on (1) SOC and N contents and stocks and (2) the portions of SOC and N stocks in different fractions relative to whole soil. Linear regressions were used to relate SOC and N contents in the light and heavy fractions to SOC and N contents in whole soil, respectively. Linear regressions were also used to relate SOC and N contents to soil pH, moisture, clay, site, and sand contents. The SPSS 20.0 statistical package was used to perform these analyses (SPSS Inc., Chicago, IL, USA).

The relationships among the SOC and N fraction contents were investigated through principal component analysis with CANOCO 4.5 software (ter Braak and Smilauer 2002). Correlations among SOC and N fractions in the principal component analysis were adjusted by multiple correlations via using the SPSS software.

3 Results

3.1 Changes of SOC and N contents

Pasture degradation and soil sampling depth had significant effects on SOC and N contents in whole soil, light fractions, and heavy fractions (Table 1). The contents of SOC and N had significantly decreased trends with the decline of vegetation cover (Fig. 2). They were significantly higher at the COV90 site than at the other two sites (Fig. 2). The SOC/TN and HFOC/HFN at both soil layers increased with vegetation cover reduction and were significantly higher at the COV45 site than at the other two sites (Fig. 2g and i). LFOC/LFN represented an opposite trend with SOC/TN (Fig. 2h). SOC/TN was positively correlated with HFOC/HFN ($r = 0.82$, $p < 0.001$) and was not statistically significantly correlated with LFOC/LFN ($p > 0.05$; Fig. 3).

3.2 Relations of SOC and N contents with selected soil properties

SOC and total N had positive correlations with LFOC, LFN, HFOC, HFN, and LFOC/SOC (Fig. 4). They were negatively correlated with SOC/TN and HFOC/HFN (Fig. 4). They did not have statistically significant correlation with LFOC/LFN (Fig. 4). Soil pH and clay and silt contents were negatively correlated with SOC and N contents ($p < 0.001$, respectively; Fig. 5). Soil moisture and sand contents were positively correlated with SOC and N contents ($p < 0.05$, respectively; Fig. 5).

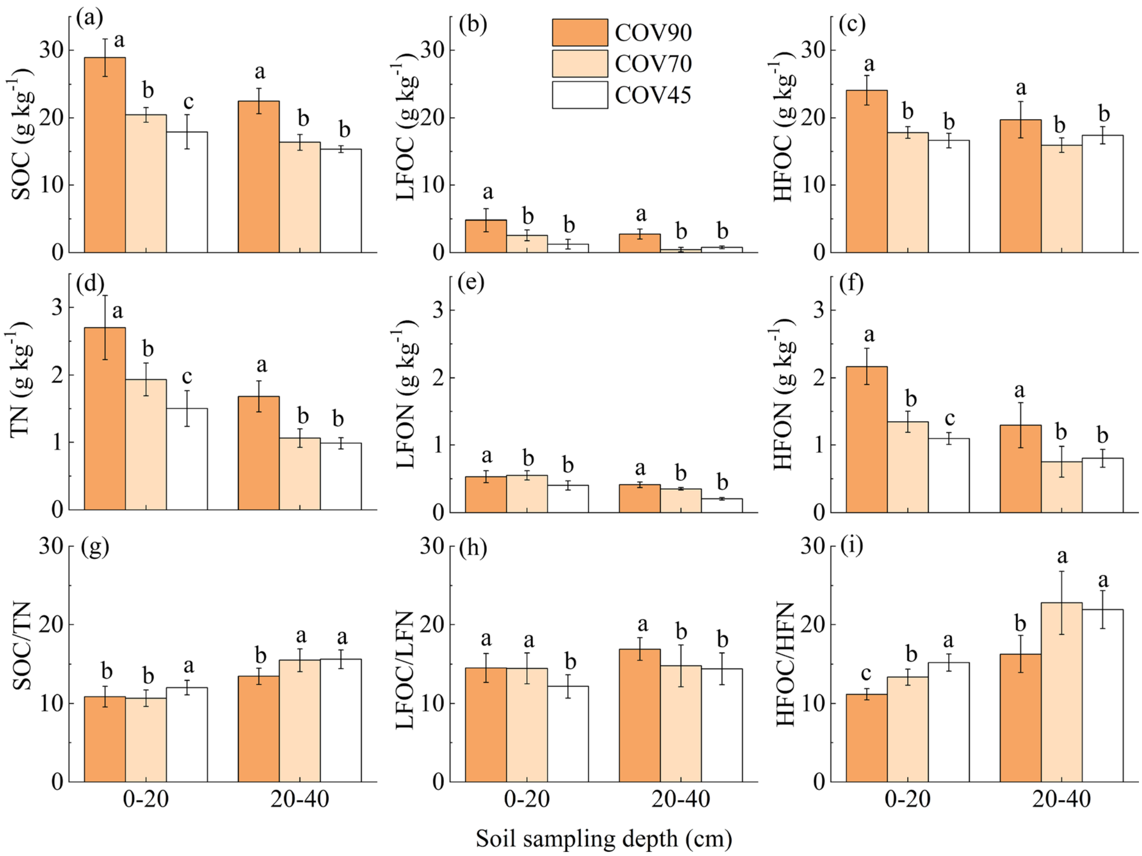

Fig. 2 Soil organic carbon and nitrogen contents (mean ± SD) in the *Kobresia* pasture with different degradation gradient. Means with different letters differ significantly among sites at each soil depth. For the abbreviations, please see Table 1

3.3 Changes in SOC and N fraction stocks

The stocks of SOC and N in whole soil, light fractions, and heavy fractions decreased with pasture degradation (Fig. 6). At soil depth of 0–40 cm, pasture degradation from 90 to 45% showed losses by as much as 3.89 kg m^{-2} for SOC, 1.3 kg m^{-2} for LFOC, and 2.18 kg m^{-2} for HFOC (Fig. 6), which corresponded to depletion rates of 28.7%, 56.6%, and 14.3%, respectively (Fig. 7). The pasture degradation from 90 to 45% showed losses by as much as 0.47 kg m^{-2} for total N, 0.07 kg m^{-2} for LFN, and 0.38 kg m^{-2} for HFN (Fig. 6), which corresponded to depletion rates of 39.2%, 47.6%, and 40.6%, respectively (Fig. 7).

In whole soil and heavy fractions, the depletion rates of N were significantly higher than those of SOC (Fig. 7). In the light fractions, the depletion rate of N was significantly lower than the depletion rate of SOC (Fig. 7). At each site, the HFC and HFN stocks contributed more than 80% to the SOC and total N stocks, respectively (Fig. 8). The proportion of LFOC stock decreased, and the proportion of HFOC stock increased

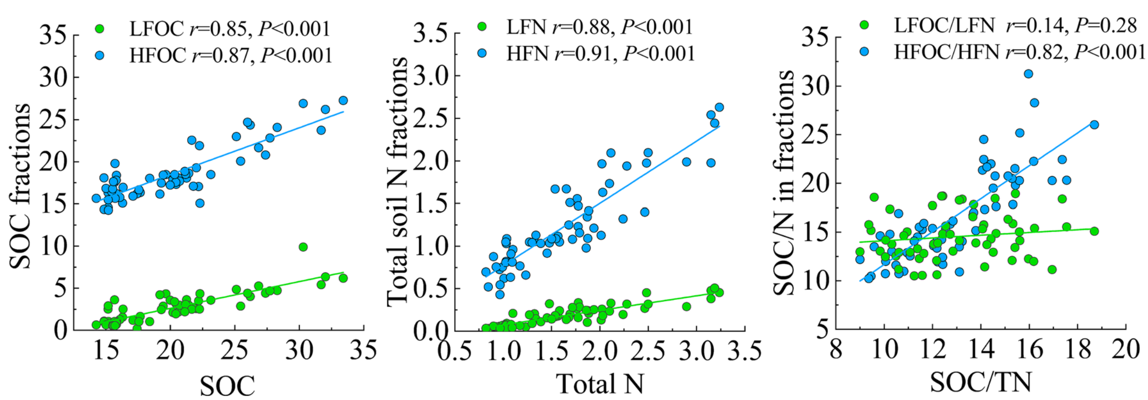

Fig. 3 The relationship between soil organic carbon (and nitrogen) content in whole soil and soil organic carbon (and nitrogen) content in density fractions. For the abbreviations, please see Table 1

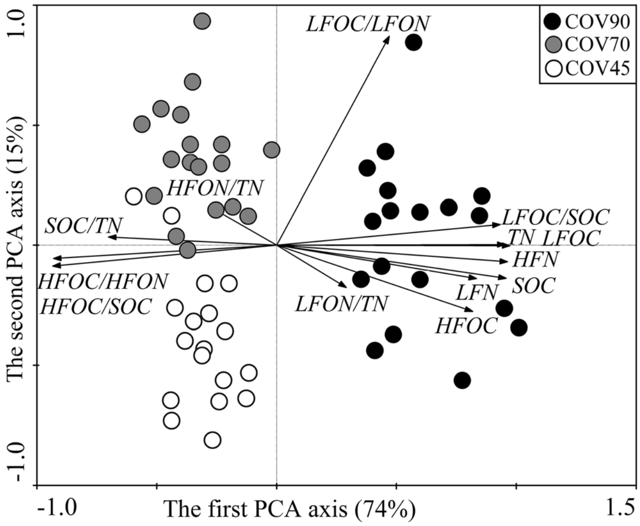

Fig. 4 Principal component analysis (PCA) showed the relations among SOC and N fractions contents. For the abbreviations, please see Table 1

with the decline of vegetation cover (Fig. 8). The proportions of LFN and HFN stocks had no significant difference among the sites (Fig. 8).

4 Discussion

The SOC and total N contents had significantly decreased trends with vegetation cover reduction in this study (Table 1, Figs. 2, 3, and 4) and which were consistent with some previous studies (Cao et al. 2016; Dlamini et al. 2014; Dong et al. 2012; Gao et al. 2013; Li et al. 2014, Li et al. 2018a, b; Wang et al. 2009a, b). The SOC is mainly determined by the balance between carbon input and output in the soils in a given period (Kuzyakov 2010; Piñeiro et al. 2010). Therefore, factors linked to this balance may affect SOC dynamics (Piñeiro et al. 2010; Stockmann et al. 2013; Wiesmeier et al. 2019). Vegetation traits and soil properties (Table 1) can be noticeably changed with pasture degradation (Dong et al. 2012; Hopping et al. 2018; Peng et al. 2018; You et al. 2014; Yuan et al. 2019). First, decline in biomass and vegetation cover with pasture degradation leads to the decrease in soil organic matter input to soils (You et al. 2014; Peng et al. 2018; Wang et al. 2014). Second, the variations in species composition in plant communities with pasture degradation potentially affect the level of soil carbon fixation, particularly during the replacement of sedges by grasses (Mou et al. 2018; Wu et al. 2014; Yuan et al. 2019). Third, the decomposition of soil organic matter can be accelerated owing to the changes in soil microenvironment, especially in soil temperature, moisture, and pH (Li et al. 2018b; Liu et al. 2017; Peng et al. 2018; Wang et al. 2008; Yuan et al. 2019). In this study, soil pH, clay, and silt contents were negatively and soil moisture and sand contents were positively correlated with SOC and N fractions (Fig. 5), suggesting that SOC and N stocks in the alpine meadow can be significantly affected by soil physical properties. The increasing degradation of the *Kobresia* pasture considerably reduces carbon uptake and increases carbon loss (Babel et al. 2014; Liu et al. 2017; Peng et al. 2018). Furthermore, the reduced ability of soil aggregates to protect organic matter and the aggravated runoff and erosion due to vegetation reduction can cause soil organic matter transfer and erosion (Mchunu and Chaplot 2012; Zhu et al. 2011). Therefore, the SOC and N stocks can suffer losses due to the synthesis effects of the changes in vegetation and soils with pasture degradation (e.g., Peng et al. 2018; Yuan et al. 2019).

The results indicate that vegetation degradation in the *Kobresia* pasture leads to SOC and N losses not only in light fractions but also in heavy fractions (Figs. 2, 3, and 4). The conversion of grassland to farmland has suggested reducing the proportion of light fractions and increasing the proportion of heavy fractions to total organic matter (Jin et al. 2008; Ramnarine et al. 2018; Singh and Benbi 2018; Tan et al. 2007). Wang et al. (2009a, b) suggested that about 57% SOC and 43% N in heavy fractions and 84% SOC and 79% N in light fractions were lost from originally alpine meadow to degraded sites in the Tibetan Plateau. The light fractions had higher SOC and N depletion rates but lower absolute mass loss than the heavy fractions in this study (Fig. 4). The principal component analysis also suggests that SOC and total N contents had positive correlations with LFOC, LFN, HFOC, and HFN (Fig. 4). Therefore, not only the light fractions but also the heavy fractions contribute to SOC and N losses during the *Kobresia* pasture degradation.

Some studies showed that change in land use alters SOC and total N but does not alter soil C/N ratio (Liu et al. 2018; Xu et al. 2016). However, other studies showed that change in land use alter soil C/N ratio (Li et al. 2014; Liu et al. 2019; Groppo et al. 2015). In this study, the C/N ratios in whole soil and heavy fractions significantly increased with vegetation cover reduction (Fig. 2g–i). This result is in line with the results of some previous studies (Dlamini et al. 2014; Dong et al. 2012). Song et al. (2012) indicated that experimental warming decreased C/N ratios in whole soil and heavy fractions in a temperate steppe of China. Liu et al. (2019) indicated that there was a decoupling of SOC and N accumulation and the soil C/N ratio increased in the initial stage of revegetation in a karst region of China. The C/N ratio in whole soil was significantly correlated with the C/N ratios in the heavy fractions rather than the C/N ratios in the light fractions (Figs. 3 and 4), indicating that the change in C/N ratio in whole soil was mainly caused by the change in C/N ratios in the heavy fractions. This result can be also confirmed by the fact that the depletion ratio of N is higher than the depletion ratio of SOC in heavy fractions with pasture degradation (Fig. 7). The SOC and N depletion rates can be similar and were nearly at 1:1 ratio in many pasture studies (Liu et al. 2018).

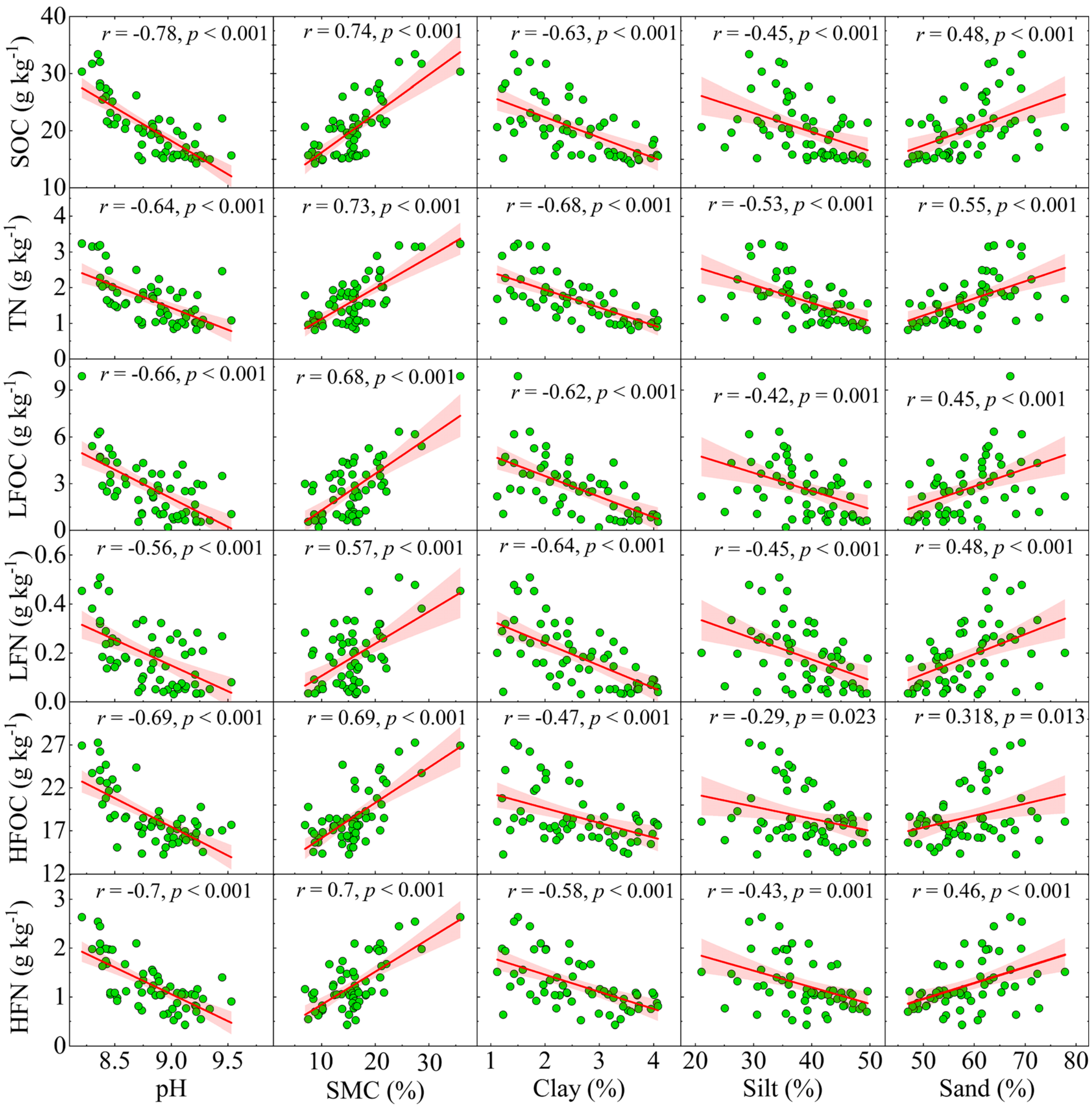

Fig. 5 Relationships of soil organic carbon and nitrogen fractions with selected soil physical properties. For the abbreviations of SOC and N fractions, please see Table 1

However, SOC and N had different loss pathways particularly during decomposition and leaching (Liu et al. 2018; Piñeiro et al. 2010). The differences in SOC and N losses in whole soil and the heavy fractions reflect the differences in the physical protective mechanisms and the possible loss pathways of SOC and N. Therefore, our results suggest that a decoupling of SOC and N losses occurs in the degradation process of the *Kobresia* pasture and is mainly related to the disproportionate losses of SOC and N in the heavy fractions.

The C/N ratio in soils can be used to indicate the mineralization of organic matter and the supply of available N (Schipper and Sparling 2011). The decomposition of soil organic matter can be accelerated and the mineralization of soil N can be increased when soil C/N ratio is low (< 15) and the activities of soil microorganisms can be limited and the decomposition rate of soil organic matter can be reduced when soil C/N ratio is high (> 15; Springob and Kirchmann 2003). In this study, the C/N ratio significantly increased (Fig. 2) and the stocks of SOC and N fractions significantly decreased with vegetation cover reduction (Fig. 6), indicating that the degraded site (COV45) had relative lower organic matter decomposition rate and available N supply capacity than the relative intact site (COV90). In the initial stage of vegetation degradation, high soil organic matter stock (such as light fractions) provides a large amount of nutrients needed by plants and microorganisms. During degradation, the mass of light fractions in soils decreases, the decomposition rate of soil organic matter slows down, soil available N supply decreases, and C/N ratio increases. Additionally, soil microorganisms and plants compete for available N. The competition further

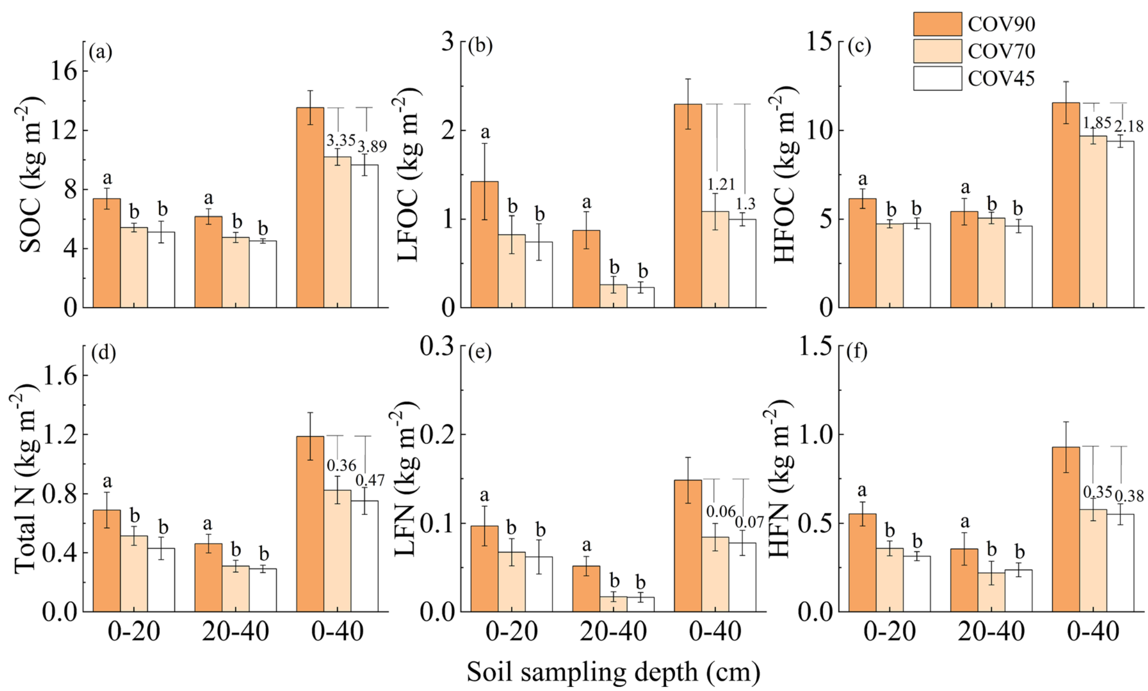

Fig. 6 Soil organic carbon and nitrogen stocks (mean ± SD) in the *Kobresia* pasture with different degradation gradient. Means with different letters differ significantly among sites at each soil depth. For the abbreviations, please see Table 1

decreases soil available N and increases soil C/N ratio. These changes lead to a feedback pathway in which soil C/N ratio regulates the decomposition rate of organic matter by soil available N and microorganisms in the N-limited *Kobresia* pasture. The decreased microbial biomass carbon and inorganic N contents with vegetation degradation further support the finding mentioned above (Yuan et al. 2019). The change in C/N ratio in this study can also be supported by some previous studies, which suggested that the C/N ratio can be increased by the N limitation increases in soils (de Graaff et al. 2006; Liu et al. 2019).

At all the sites, more than 80% of SOC and N in soils were stored in the heavy fractions (Fig. 8). The results are similar with those in some studies in the Tibetan Plateau (Dorfer et al. 2013; Huo et al. 2013; Shang et al. 2015; Wang et al. 2009a, b; Wu et al. 2018) and in other regions (Eze et al. 2018; Gentsch et al. 2015; Giannetta et al. 2018). For instance, previous studies found that 30% of SOC can be associated with the light fractions whereas 70% of the SOC can be associated in the heavy fractions in a swamp meadow on the Tibetan Plateau (Huo et al. 2013; Shang et al. 2015). Gentsch et al. (2015) suggested that the SOC in heavy fractions constitute 55% of the overall SOC stocks in the Siberian Arctic region. Compared with the light fraction, the heavy fraction is a stable organic matter form and has a long mean residence time (Eze et al. 2018; Leifeld and Fuhrer 2009). In this study, the SOC stock reaches 10 kg m^{-2} at 0–40-cm soil layer and is mainly stored in the form of heavy fractions. Such high HFOC stock

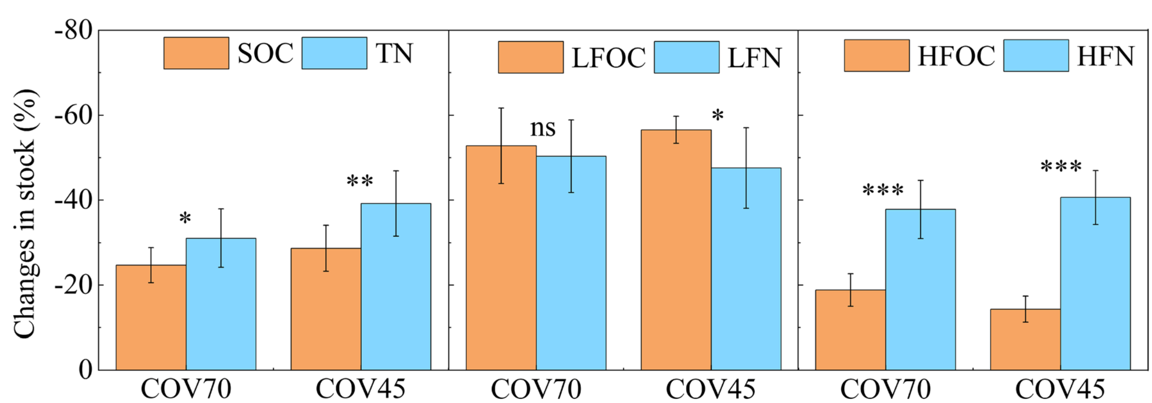

Fig. 7 The changes (mean ± SD) of soil carbon and nitrogen stocks in whole soil and density fractions at soil depth of 0–40 cm with *Kobresia* pasture degradation. *, **, and *** respective indicate significant at the 0.05, 0.01, and 0.001 level between the changes of SOC and N stocks at that site. For the abbreviations, please see Table 1

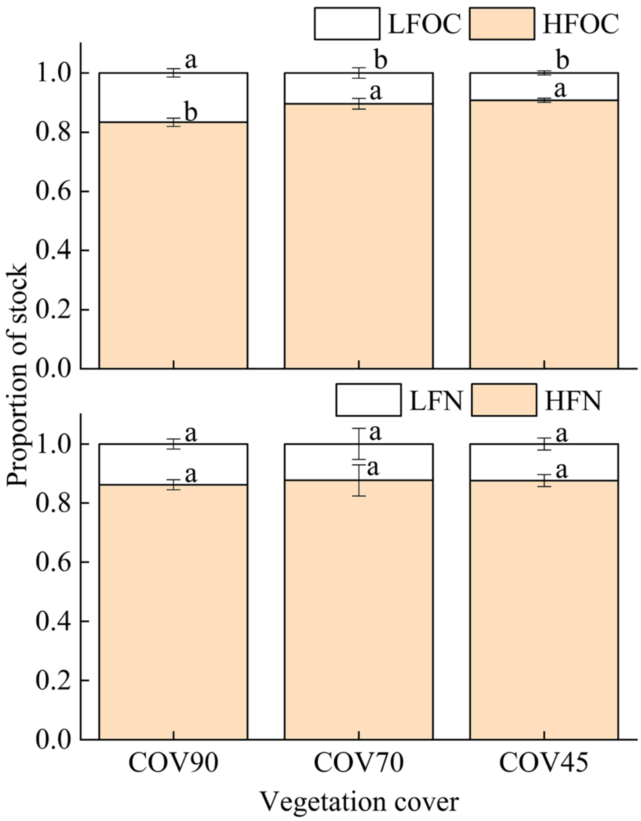

Fig. 8 The portions of SOC and N stocks in light and heavy fractions on SOC and N stocks in whole soil at soil layer of 0–40 cm. Means with different letters differ significantly among sites. For the abbreviations, please see Table 1

in the *Kobresia* pasture can play an important role in mitigating climate change in this permafrost region.

5 Conclusions

The effects of *Kobresia* pasture degradation on SOC and N fractions were investigated in the permafrost region on the Tibetan Plateau. This study demonstrated that SOC and N respond differently to the *Kobresia* pasture degradation. The data presented supports the following conclusions: (1) the SOC and TN losses caused by pasture degradation are found in both the light and heavy fractions, (2) soil N had significantly higher depletion rate than SOC in whole soil and heavy fractions, and (3) the SOC and N stocks in these soils were mainly protected in heavy fractions. The results suggest that a decoupling of SOC and N depletion occurs during pasture degradation, and the depletion is strongly related to the losses of them in heavy fractions. The results will help clarify how SOC and N respond to environmental change in the fragile and sensitive permafrost ecosystem on the Tibetan Plateau.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Research involving human participants and/or animals This research does not include human participants and/or animals.

Informed consent All the authors have read and approved the manuscript.

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