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Distribution of Black Carbon in Topsoils of the Northeastern Qinghai-Tibet Plateau Under Natural and Anthropogenic Influences

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Abstract

Black carbon (BC), ubiquitous in soils, plays an important role in global carbon cycles, the radiative heat balance of the Earth, pollutant fate, emissions of greenhouse gas, soil fertility, soil microbial community, and ecosystem stability. However, information on BC in topsoils of the northeastern Qinghai-Tibet Plateau is limited. Therefore, this study performed field sampling and analyzed contents of total BC and soot BC in topsoils. The results indicated that the contents of total BC in all soil samples ranged from 0.504 to 74.381 g kg^{-1} with an average value of 5.152 g kg^{-1}, whereas those of soot BC were in the range of 0.400–15.200 g kg^{-1} with a mean value of 1.719 g kg^{-1}. Contents of BC were significantly correlated with those of total carbon and total organic carbon. Soil types affected the distribution of soil BC. The contents of total BC in the loam soils were larger than those in the clay soils, whereas soot BC was more easily enriched in the clay soils. Total BC was negatively correlated with Ca, and soot BC was negatively correlated with Ti. The contents of soil BC in functional areas, such as agricultural and pastoral areas, industrial areas, and mining areas, were significantly higher than those in other areas, illustrating that anthropogenic activities drastically affected the distribution of soil BC. This study exhibits the fundamental information on soil BC in the northeastern Qinghai-Tibet Plateau to provide important knowledge on global soil carbon sink.

Existing as the form of a carbonaceous-compound continuum, black carbon (BC) is composed of diverse carbonaceous residues originating from graphitic carbon as well as incomplete combustion of fossil fuels, vegetation, biofuel, and biomass, with size ranging from nano- to macroscopic scale (Schmidt and Noack 2000; Dickens et al. 2004; Hammes et al. 2007; Agarwal and Bucheli 2011a, b). BC is ubiquitous in various matrices, including soils, sediments, atmosphere, and ice (Kuhlbusch 1998), and exhibit unique physicochemical features, such as optical properties, variable particle size, high specific surface area, and a three-dimensional structure (Koelmans et al. 2006). BC has shown multiple geochemical and environmental behaviors to affect climate change, the global carbon and oxygen cycles, heat balance of the Earth, fate of pollutants, microbial community, and soil ecosystem (Crutzen and Andreae 1990; Schmidt and Noack 2000; Simpson and Hatcher 2004; Wang et al. 2014a, b; Patel et al. 2016). Annual yield of BC is approximately 0.062–0.294 Gt, with 80–90% of BC directly depositing in soils and the rest being released into the atmosphere (Druffel 2004; Wang et al. 2014a, b). BC contents in soils range from 0.06 to 13.6 g kg^{-1}, significantly varying in different countries (Bird et al. 1999; Schmidt et al. 1999, 2002; Ribes et al. 2003; Nam et al. 2008; Agarwal and Bucheli 2011a; Zhan et al. 2013; Liu et al. 2013, 2016).

Soil is an important BC sink to investigate geochemical behaviors of BC. A large portion of BC remains in the site where it is formed, and then it is combined into soil where it can exist at relatively stable forms for a long time. BC can be transported into marine sediments via fluvial and

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atmospheric pathways (Schmidt and Noack 2000; Mitra et al. 2002; Mannino and Harvey 2004; Chaplot et al. 2005; Rumpel et al. 2006). Physicochemical properties of soil that serves as the largest carbon pool in the Earth are critical to influence soil carbon sequestration and the distribution of BC (Six et al. 1999; Lal 2004; Bronick and Lal 2005). Accordingly, BC might significantly affect soil physicochemical properties and soil ecosystem (Schmidt and Noack 2000; Lehmann et al. 2003; Deenik et al. 2010). Some studies have shown that the human activities also have a significant influence on the distribution of BC (He et al. 2007; He and Zhang 2009; Gao et al. 2018).

The Qinghai-Tibet Plateau, a critical and unique region in the world, has attracted wide attention due to its high elevation, fragile ecosystem, severe natural conditions, and relatively weak anthropogenic disturbance (Wang et al. 2008; Song et al. 2009; Guo et al. 2016). However, unexpected pollution especially soil pollution occurred in this plateau, exerting potential risks to the ecosystem and humans (Wu et al. 2016a, b; Wu et al. 2018). Previous studies have shown that BC might affect the transport and fate of pollutants in soils (Liu et al. 2011; Eckmeier et al. 2013; Patel et al. 2016). Scarce information on distribution of BC in soils of the Qinghai-Tibet Plateau makes it unthorough to understand the pollution process of this important area. Moreover, information on soil BC of the Qinghai-Tibet Plateau will provide study basis for regional environmental management and planning. Therefore, the objectives of this study are to investigate the occurrence and distribution of BC in topsoils of the northeastern Qinghai-Tibet Plateau and discuss the impacts of natural and anthropogenic factors on soil BC of this area.

Materials and Methods

Study Area and Soil Sampling

Compared with the other regions of the Qinghai-Tibet Plateau, the northeastern area is more disturbed by anthropogenic activities (Wu et al. 2018) and thus selected as the study area (Fig. 1). The study area with the average elevation more than 3100 m is rainless with annual precipitation less than 100–300 mm, cold with the annual temperature of approximately −5 °C, and arid with the annual evaporation up to 1200 mm (Xie et al. 2010; Chen et al. 2011). The study area covers the background area, salt-lake area, urban area, agricultural and pastoral area, industrial area, and mining area. The background area, mainly including Har Lake, Gyaring Lake, and Ngoring Lake, represented the region with the least anthropogenic activities. The salt-lake area covered the main salt lakes in the northeastern Qinghai-Tibet Plateau, such as Chaka Salt Lake, Qarhan Salt Lake, Gahai Salt Lake, Da Qaidam Salt Lake, Xiao Qaidam Salt Lake, Dongtaijinaier Salt Lake, Xitaijinaier Salt Lake, and Gasikule Salt Lake. The urban area mainly included Delingha City and Golmud City. The agricultural and pastoral area mainly covered the regions with relatively frequent agricultural and pastoral activities. The industrial area included regions with the chemical and petrochemical plants. The mining area mainly included coal and iron mining areas.

The field work was performed from June 14–29, 2017. A total of 147 topsoil (0–20 cm) samples were collected using stainless steel shovels, in situ homogenized, stored in the sample bags, and transported back to the laboratory. All soil samples were air-dried at room temperature before analysis. Soil samples were passed through a 2-mm sieve for analyzing pH, electrical conductivity (EC), and soil texture while they were passed through a 0.074-mm sieve for elemental analysis.

Physicochemical Properties of Soil Samples

The pH and EC were determined by measuring these parameters in supernatants with a water-soil ratio of 2.5:1 (volume:weight) using a pH meter (Shanghai INESA Scientific Instrument Co., China) and Myron L 6PII (Myron L Company, Carlsbad, USA), respectively. The soil texture was determined by Bouycous hydrometer method (Shirazi and Boersma 1984). The contents of major elements in soil samples were determined by X-ray fluorescence spectrometry (Axios, PANalytical, Netherlands).

The total carbon (TC), total nitrogen (TN), and total organic carbon (TOC) of soil samples were determined by a CHN elemental analyzer (Elementar micro cube, Germany). Before TOC analysis, all soil samples were preprocessed with 1 M HCl for 24 h to remove the inorganic carbon, filtered through a 47-mm quartz filter (Whatman International Ltd., Maidstone, England), washed until neutral using deionized (DI) water, and dried in drying oven at 60 °C for 12 h. All analyses were performed in duplicate and the average values were used in this study.

Black Carbon Analysis

The chemo-thermal oxidation (CTO-375) (Gustafsson et al. 1997; Schmidt and Noack 2000; Hammes et al. 2007; Poot et al. 2009; Agarwal and Bucheli 2011b;) and dichromate oxidation ($K_2Cr_2O_7/H_2SO_4$) (Lim and Cachier 1996; Song et al. 2002) were used to determine contents of BC in soils.

The soil BC determined by the chemo-thermal oxidation method was abbreviated as BCT in this study and the analysis procedure was the following. Approximately 20–25 mg of soil sample was weighed and put in the pre-tired Ag-capsules (5 × 9 mm, Santis, Switzerland). The Ag-capsules were placed in a stainless steel wagon and then put into a

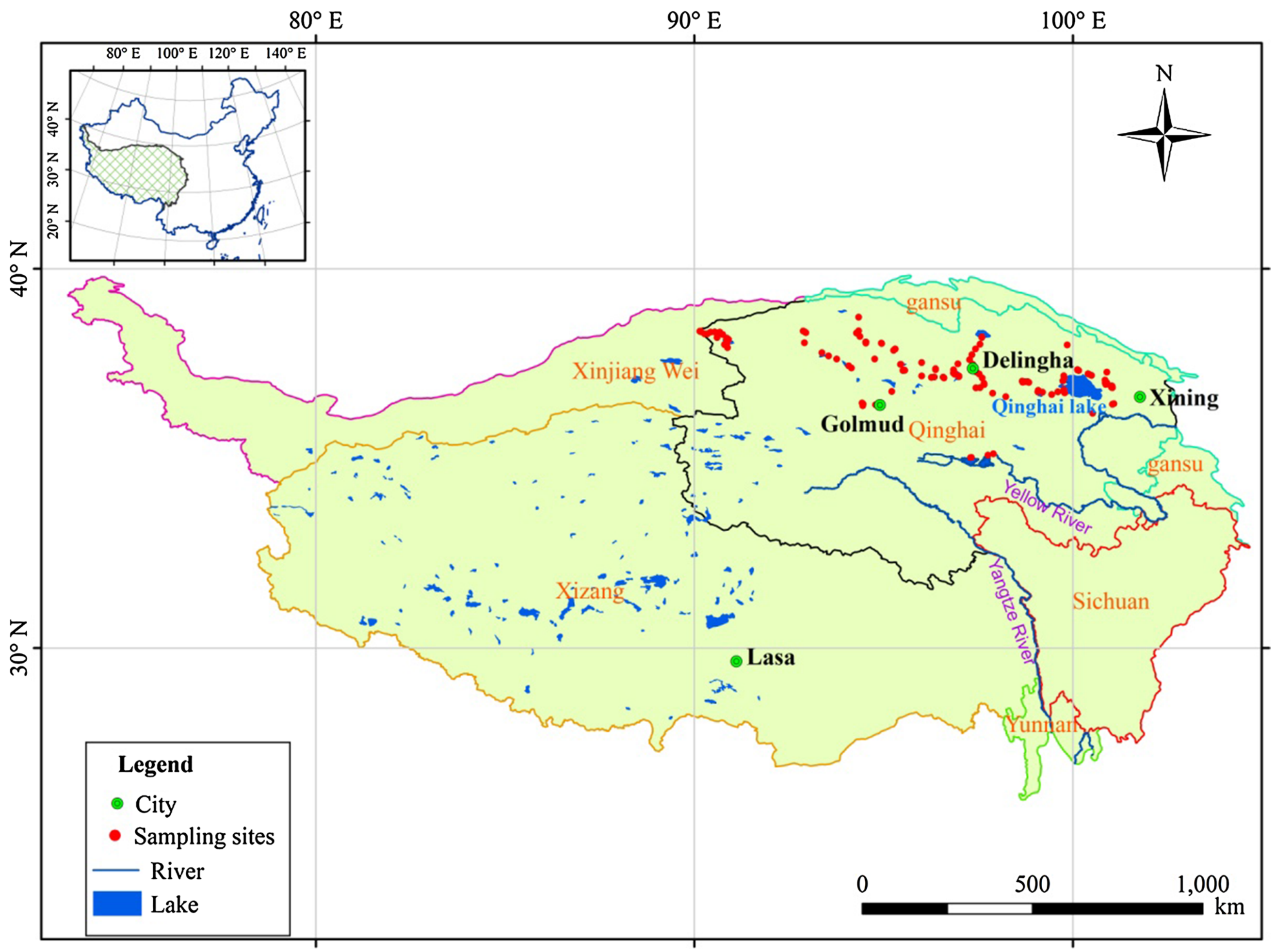

Fig. 1 Study area and the sampling sites

tube furnace OTF-1200X with quartz tube 75 × 10,000 mm (Hefei Ke Jing Materials Technology Co. Ltd, China) for combustion. The temperature was raised to 350 °C at a rate of 10 °C min^{-1} to prevent the samples from being charred, then to 375 °C at 1 °C min^{-1}, and held for 24 h at a constant airflow of 250 mL min^{-1}. After cooling down, carbonates were removed by adding 1 M HCl until effervescence ceased, and then the samples were placed at air for 4 h. The samples were completely dried at 60 °C for 12 h after 50 μL of DI water was added. Finally, the BCT contents of soil samples were determined with the CHN analyzer (Elementar micro cube, Germany). Each sample was analyzed in duplicate and the average BC content (BCT) was used in this study.

The black carbon measured by the dichromate oxidation method (K_2Cr2O7/H_2SO_4) was abbreviated as BCD and the analysis referred to the following procedures. Soil samples with weight of 1 g were put into the 50-mL centrifugal tube, decarbonated using 10 mL of 3 M HCl for 24 h, and centrifuged at 4000 rpm for 10 min. After decanting the supernatant, the residues were treated by 10 mL of mixture solution of 10 M HF and 1 M HCl (1:1) for 24 h to remove silicates. Thereafter, the mixtures were centrifuged and the residues were treated by 10 mL of 10 M HCl for 24 h to remove fluorites. Finally, the residues were oxidized with 15 mL of mixture solution (0.1 M $K_2Cr_2O_7$ and 2 M H_2SO_4, 1:1) at 55 °C for 60 h. The mixtures were centrifuged and rinsed by using DI water until neutral. The BC contents of the samples were determined by the CHN analyzer (Elementar micro cube, Germany). Each sample was analyzed in duplicate and the average BCD content was used in this study.

It is generally accepted that CTO-375 method could determine the most refractory fractions (e.g., soot) of BC while the acid dichromate method could detect main part of BC continuum (Schmidt and Noack 2000; Schmidt et al. 2001; Hammes et al. 2007; Poot et al. 2009; Wang et al. 2014a, b). Different BC portions might play different roles in the soil ecosystem. Therefore, this study investigated soot BC and total BC using different methods to provide more comprehensive information on soil BC of the study area.

All data were processed using Origin 9.0 (OriginLab Corporation, Northampton, MA). Correlation analysis was performed using SPSS 22.0 (IBM, New York, USA).

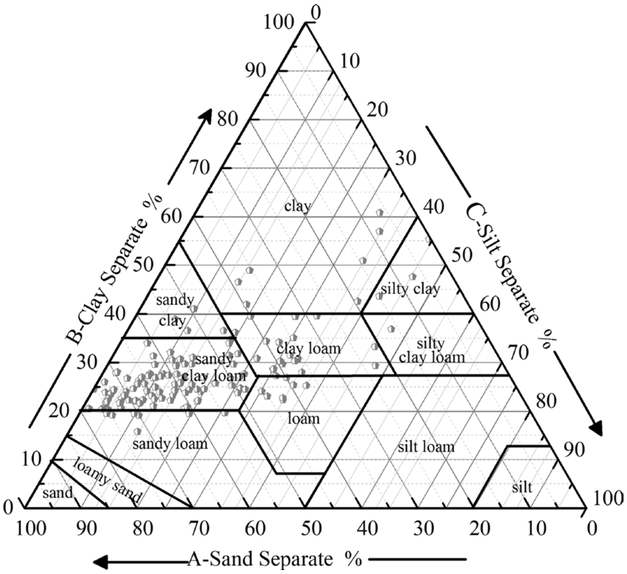

Fig. 2 The soil texture in the study area

Results and Discussion

Physicochemical Properties of Soil Samples

The soil texture triangle was used to classify the soil types in the study area (Fig. 2). The major types of soil samples were loam including sandy clay loam, clay loam, loam, and sandy loam according to soil taxonomy of the United States Department of Agriculture (Minasny and Mcbratney 2001). Approximately 98, 20, 8, 7, and 7 samples belonged to sandy clay loam, clay loam, loam, sandy loam, and clay, respectively.

Soil pH ranged from 6.1 to 10.3 with an average value of 8.47, indicating that the soil samples were mainly alkaline (Fig. 3). Soil EC values were in the range of 70.29–195,800 μS/cm with an average value of 14.13 mS/cm, illustrating significant spatial variation (Fig. 3). The TN content of soils ranged from 0.02 to 0.85% with an average value of 0.12%, exhibiting that the soils of the northeastern Qinghai-Tibet Plateau were relatively infertile. TN was positively related with K and negatively related with Ca at significance level of $p < 0.01$ (Table 1).

The major elements are important components in soils, generally affect the deposition, migration, and aggregation of different compounds in soils (Bronick and Lal 2005). Si was the dominant major element in soil samples, ranging from 12.98 to 30.30% with mean value of 24.74% (Fig. 3). Si was positively related with Al, K, and Ti at significance level of $p < 0.01$, whereas it was negatively related with Na,

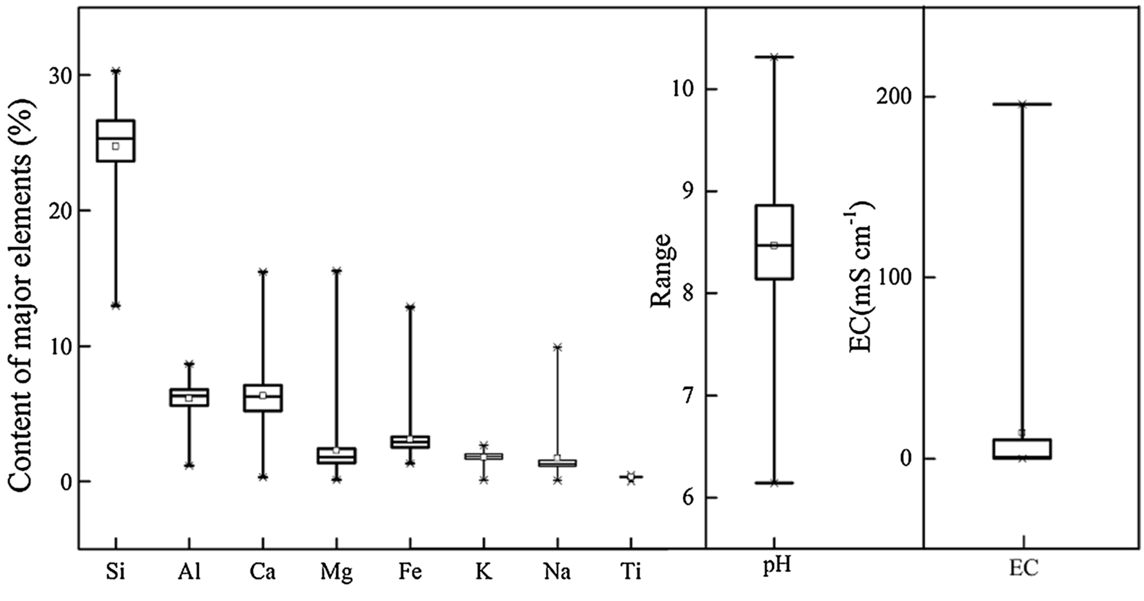

Fig. 3 The box plots diagram of the major element contents, pH, and electrical conductivity (EC) in soils. In each box, the bottom and top of the box illustrate the 25th and 75th percentiles; the mid-line of the box means the median value; the small square represents the average value; the bottom and top of the whiskers refers to the minimal and the maximal values

Table 1 Pearson correlation coefficient matrix for major elements, total nitrogen (TN), total carbon (TC), total organic carbon (TOC), total black carbon (BCD), and soot black carbon (BCT) in soils of the northeastern of Qinghai-Tibet Plateau

	Si	Al	K	Na	Ca	Mg	Fe	Ti	TN	TC	TOC	BCD	BCT
Si	1												
Al	0.378**	1											
K	0.356**	0.911**	1										
Na	−0.406**	−0.319**	−0.139	1									
Ca	−0.760**	−0.185*	−0.236**	0.227**	1								
Mg	0.040	−0.511**	−0.526**	0.087	−0.220**	1							
Fe	−0.329**	−0.224**	−0.157	0.274**	−0.065	0.010	1						
Ti	0.338**	0.688**	0.638**	−0.102	−0.104	−0.665**	−0.006	1					
TN	0.145	0.096	0.217**	−0.170*	−0.355**	−0.105	0.086	0.074	1				
TC	−0.135	0.075	0.026	−0.211*	0.005	−0.094	−0.021	−0.035	0.646**	1			
TOC	−0.006	0.042	0.027	−0.195*	−0.252**	−0.064	0.079	−0.047	0.716**	0.920**	1		
BCD	−0.009	0.051	−0.006	−0.114	−0.220**	−0.042	0.040	−0.037	0.428**	0.820**	0.871**	1	
BCT	−0.257**	−0.193*	−0.364**	−0.106	0.145	0.204*	0.047	−0.319**	0.103	0.647**	0.571**	0.676**	1

**$p < 0.01$; *$p < 0.05$

Ca, and Fe at $p < 0.01$ (Table 1). Concentrations of Ti, significantly less than those of other major elements, were in the range of 0.01 to 0.48% with the average value of 0.34% (Fig. 3). The average concentrations of Al and Ca were similar, whereas distribution of these two elements showed significant variations (Fig. 3). Other major elements, including Fe, Mg, K, and Na, also showed fluctuant contents in soils of different sites with the mean concentrations of 3.12%, 2.29%, 1.80%, and 1.73%, respectively (Fig. 3). Positive correlation in Al–K, Al–Ti, K–Ti, Na–Ca, and Na–Fe occurred at significance level of $p < 0.01$, while significantly negative correlation in Al–Na, Al–Ca, Al–Fe, K–Ca, K–Mg, Ca–Mg, and Mg–Ti existed at $p < 0.01$ or $p < 0.05$ (Table 1). The concentrations of major elements in soils of the study area well corresponded with those reported by the previous study (Li et al. 2009).

Occurrence and Distribution of BC in Soils

The contents of BC, TC, and TOC in soils drastically varied at different sampling sites (Fig. 4). The contents of TC in all soil samples ranged from 5.700 to 145.350 g kg^{-1} with an average value of 29.753 g kg^{-1} (Fig. 4a). TC contents of 140 soil samples were in the range of 10.000–60.000 g kg^{-1}, corresponding with those of the previous studies (Chen et al. 2015; Zhao et al. 2018). The highest TC concentration occurred at Dameigou coal mining region, whereas the lowest TC concentration occurred at the adjacent region of Toson Lake. The concentrations of TOC in all soil samples ranged from 1.000 to 144.350 g kg^{-1} with an average value of 15.071 g kg^{-1} (Fig. 4b). The TOC concentrations of 141 soil samples were in the range of 1.000–45.000 g kg^{-1}, similar with those reported by other scientists (Wang et al. 2002). The highest contents of TC and TOC occurred at Dameigou coal mining region while the lowest contents of them occurred at the adjacent region of Toson Lake. TOC was significantly related with TC at $p < 0.01$ (Table 1; Fig. 5a), accounting for approximately 5.16–99.37% of TC.

BCD and BCT showed significant difference in concentrations (Fig. 4c, d). The contents of BCD in all soil samples ranged from 0.504 to 74.381 g kg^{-1} with an average value of 5.152 g kg^{-1} while those of BCT were in the range of 0.400–15.200 g kg^{-1} with a mean value of 1.719 g kg^{-1}. Contents of BCD in 95% of soil samples ranged from 5.000 to 20.000 g kg^{-1}, whereas those of BCT in 97% of soil samples varied from 1.000 and 8.000 g kg^{-1}. The highest contents of BCD and BCT respectively occurred at Dameigou coal mining region and Tiantian coal mining region while the lowest contents of BCD and BCT occurred at the areas near Gahai Lake and Gasikule Salt Lake, respectively. BCT was significantly related with BCD at $p < 0.01$ (Table 1; Fig. 5b) and generally accounted for about 4.66–100% of BCD, illustrating that the other forms of BC besides refractory BC also might have important impact on carbon functions in soil. The contents of BC especially BCD in topsoils of the study area were similar with those in urban soils of Germany (Lorenz et al. 2006) but lower than those in the urban topsoils of Anshan and Xuzhou, China (Wang 2010; Zong et al. 2016). Interestingly, the contents of BC in topsoils of the northeastern Qinghai-Tibet Plateau were relatively higher than those in soils of the mountainous and pristine regions in the world (Ali et al. 2017). The relatively high BC contents in soils of the study area might be caused by the incomplete combustion due to “plateau effects”, such as relatively low pressure, low oxygen content, and high elevation. Moreover, combustion of abundant biomass and yak

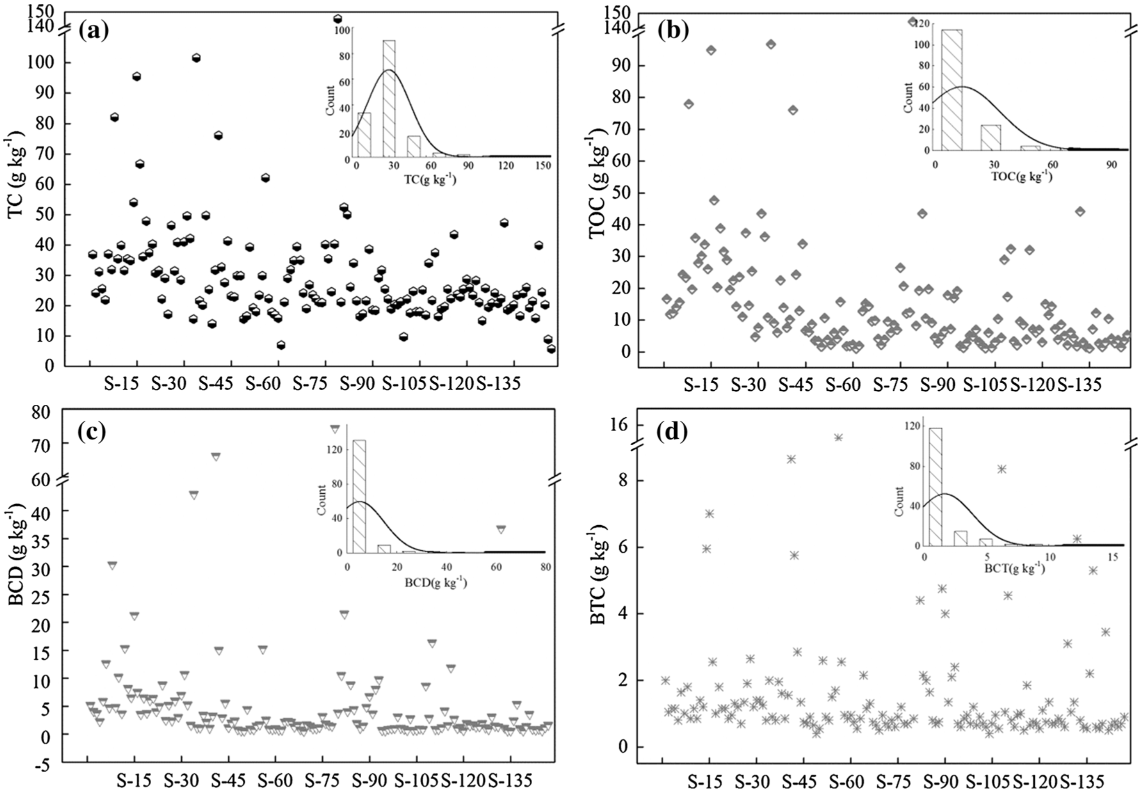

Fig. 4 The contents and normal distributions of TC (**a**), TOC (**b**), BCD (**c**), and BCT (**d**) in soils

dung in this area might be an important BC source. Other anthropogenic activities, such as mining, industry, and transportation, also contributed to soil BC.

Two forms of BC were significantly related with TOC at $p < 0.01$ (Table 1). BCD and BCT accounted for 9.15–97.31% (mean: 33.94%) and 2.07–96.82% (mean: 19.99%) of TOC, respectively. The previous studies demonstrated that the BC/TOC values ranged from 0.24 to 45% in different soils (Skjemstad et al. 1996, 2002; Schmidt et al. 1999, 2002; Rumpel et al. 2006; Nam et al. 2008; Agarwal and Bucheli 2011a) and ranged from 6 to 50% in sediments (Gustafsson and Gschwend 1998; Masiello and Druffel 1998; Middelburg et al. 1999; Guo et al. 2004). The BC/TOC values of this study were comparable with those of Phoenix, which were in the range of 1–89% with an average value of 31% (Hamilton and Hartnett 2013) but higher than those in soils of other regions/countries (Zhan et al. 2013), illustrating that distribution of BC might be dependent on multiple factors. BC has shown multiple geochemical and environmental behaviors in soil ecosystem, such as contributing to soil organic carbon (Eckmeier et al. 2013), modifying soil fertility and structure (El-Naggar et al. 2019), adsorbing organic pollutants or heavy metals, persisting in the environment (Nam et al. 2008; Patel et al. 2016), and influencing the microbial community (Ding et al. 2016). BC averagely accounted for 33% of TOC in soils of this study, which suggested that BC might play an important role in the functions of ecosystems and behaviors of pollutants in soils of the northeastern Qinghai-Tibet Plateau.

Impact of Natural Conditions on Distribution of Soil BC

Soil texture plays an important role in carbon storage and aggregation (Silver et al. 2000; Bronick and Lal 2005). It generally reflects the soil characteristics, such as nutrient, fertility, productivity, desertification, and erodibility (Bronick and Lal 2005). The main nutrients in soil are reported to decrease as soil particles increase (Hassink et al. 1993; Silver et al. 2000). Generally, increased clay concentration is associated with increased soil organic carbon stabilization and content (Burke et al. 1989; Sollins et al. 1996). The content of carbonaceous substances in clay soils is generally three times that in sandy soils (Zhan et al. 2013). Fine particles in the clay soils are more than those in sandy soils. The fine particles possess greater surface area than coarse particles, thus providing more binding sites for the organics (Liu 1985). Therefore, soils texture might have important impact on BC contents.

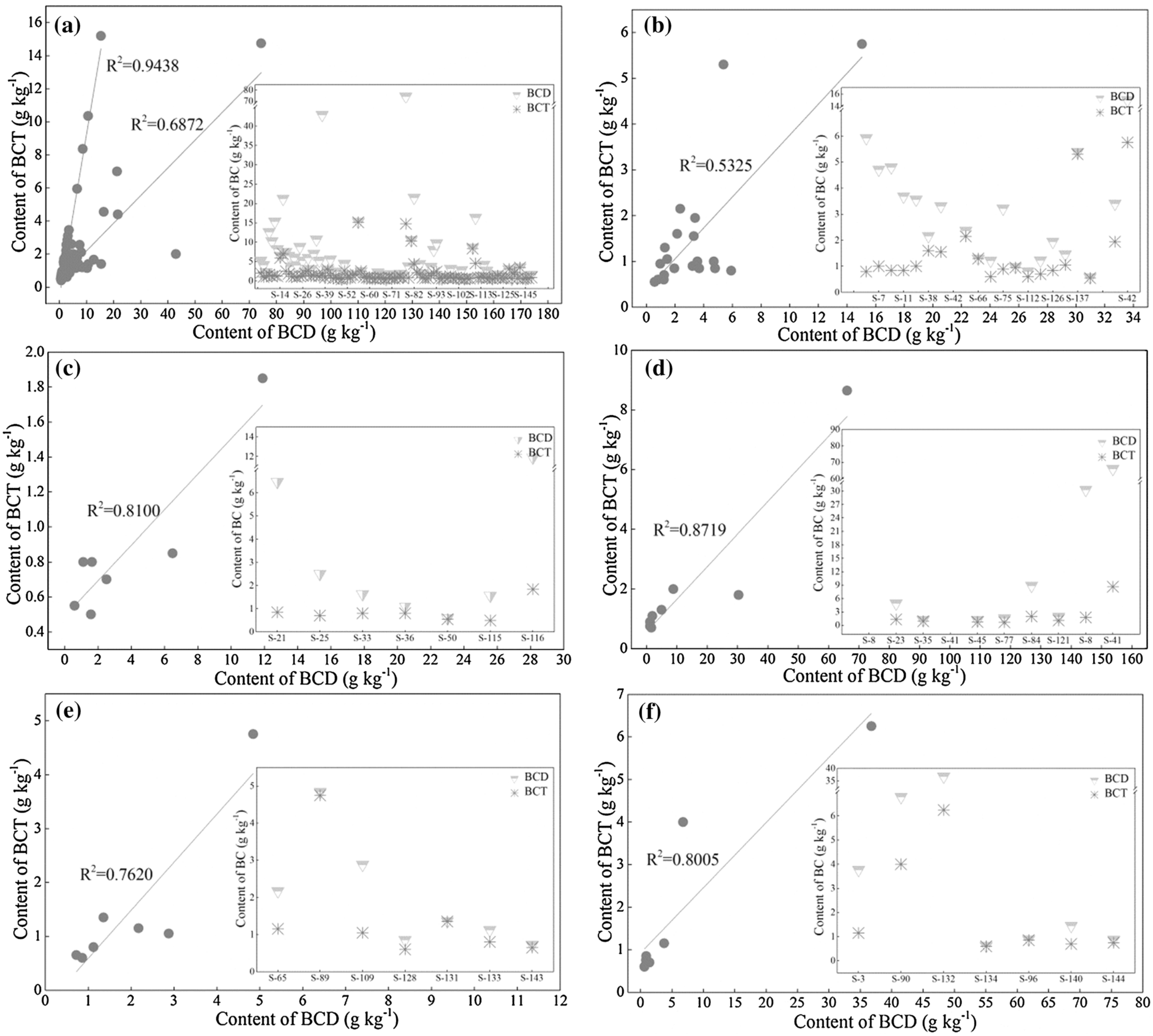

Fig. 5 Relationship between BCD and BCT in the different types of soils, including sandy clay loam (**a**), clay loam (**b**), sandy loam (**c**), loam (**d**), clay (**e**), and sandy clay ans silty clay (**f**)

The soils in the study area could be divided into two main categories, including loam and clay. The loam soils covered sandy clay loam, clay loam, sandy loam, and loam, whereas the clay soils included clay, sandy clay, and silty clay (Fig. 5). The contents of BCD in the loam soils ranged from 0.504 to 74.381 g kg^{-1} with an average value of 5.218 g kg^{-1}. Those of BCT were in the range of 0.400 to 15.200 g kg^{-1} with an average value of 1.713 g kg^{-1}. BCT in the loam soils accounted for 0.50 to 100.00% with a mean value of 55.98% of BCD. The highest contents of BCD and BCT in the loam soils respectively occurred at Dameigou coal mining region and Tiantian coal mining region. The lowest contents of BCD and BCT occurred at the areas near Gahai Lake and Gasikule Salt Lake, respectively. Sandy clay loam was the dominant soil subtype of the study area. BCD and BCT in different soils showed the similar variation trends (Fig. 5). The contents of BCD and BCT in sandy clay loam soils were in the ranges of 0.504–74.381 and 0.400–15.200 g kg^{-1}, respectively (Fig. 5a). Contents of BCD and BCT in approximately 75% of sandy clay loam soil samples showed a strong linear correlation ($R^2 = 0.9438$). The maximal contents of BCD and BCT in clay loam soils reached 15.061 g kg^{-1} at the area near Qinghua coal mining area and 5.750 g kg^{-1} at a highway roadside, respectively (Fig. 5b). No significant linear relationship between BCD and BCT in clay loam soil sample occurred. The contents of BCD and BCT in sandy loam soils ranged from 0.594 to 11.894 g kg^{-1} with an average value of 3.685 g kg^{-1} and from 0.500 to 1.850 g kg^{-1} with an average value of 0.864 g kg^{-1}, respectively (Fig. 5c). The linear correlation coefficient (R^2) between BCD and BCT in sandy loam soil samples was 0.8100. The average contents of BCD and BCT in loam soils were 14.527 and 2.150 g kg^{-1}, respectively (Fig. 5d). The significant linear correlation existed between BCD and BCT in sandy loam soil samples.

The contents of BCD in the clay soils ranged from 0.618 to 36.773 g kg^{-1} with an average value of 4.652 g kg^{-1}, whereas those of BCT varied from 0.600 to 6.251 g kg^{-1} with a mean value of 1.761 g kg^{-1} (Fig. 5e, f). Ratios of BCT/BCD ranged from 17.00 to 99.48% with an average value of 67.93%. The highest contents of BCD and BCT in the clay soils occurred at the areas near Da Qaidam chemical plant. The lowest contents of BCD and BCT occurred at Eboliang Yardang scenic area. The linear correlation coefficients of BCD and BCT in the clay soils were relatively high.

The average content of BCD in loam was greater than that in clay while the average content of BCT in loam was lower than that in clay. Moreover, the average value of BCT/BCD in loam was lower than that in clay. These phenomena were consistent with previous results (Zong et al. 2016). The distribution of soil BC in different soil types possibly was influenced by the natural conditions. Previous study showed that the content of carbonaceous substances in clay was higher than that in sandy soils and increased content of clay could affect stabilization of soil organic carbon (Sollins et al. 1996; Zhan et al. 2013). Another recent study reported that larger size fractions could enrich more BC than the fine fractions in soils and the fine soil particles more easily contributed to the atmosphere aerosol BC (Zong et al. 2016). Furthermore, BCT (soot-BC) was less than 1 μm in size and smaller than other portions of BC (Hamilton and Hartnett 2013), and it could be easier to enrich in the clay soils and more stable. These studies probably explained that the fine soot-BC might be easy to accumulate in the fine particle soils and be transported by wind. Therefore, the clay soils in the study area possessed more BCT, whereas the loam soils had higher total BC. Moreover, fine particle clay minerals might enhance the preservation of soot-BC. In summary, soil texture had complex influence on distribution of BC in soil.

Major elements in soils might affect distribution of soil BC. Therefore, Pearson correlation analysis was used to clarify the possible relationship among major elements and soil BC. Na was negatively related with TC and TOC at $p < 0.05$, whereas Ca was negatively related with TOC at $p < 0.01$ (Table 1). Similar with TOC, BCD was negatively related with Ca at $p < 0.01$ (Table 1). BCT, the highly condensed BC (Hammes et al. 2007; Poot et al. 2009), was negatively correlated with Si, Al, K, and Ti but positively correlated with Mg (Table 1), suggesting that the refractory BC might be more susceptible to the effects of the major elements in soil. Previous studies reported that different BC feedstock sources had different contents of major elements and the high contents of element K associated with the soot-BC were attributed to the fossil fuel burning and forest fires (Andreae 1983; Polissar et al. 1998; Singh et al. 2010). Moreover, contents of BC in soil might cause the change in contents of the major elements in soils (Lehmann et al. 2003; Laird et al. 2010; Van Zwieten et al. 2010).

Impact of Anthropogenic Activities on Distribution of Soil BC

The contents of BCD in soils of the background area ranged from 0.963 to 1.919 g kg^{-1} with an average value of 1.421 g kg^{-1}. Those of BCT ranged from 0.600 to 1.350 g kg^{-1} with an average value of 0.858 g kg^{-1} (Fig. 6a), higher than those in soils of the Himalayan region (Ali et al. 2017). The values of BCD/TOC and BCT/TOC of this region were in the ranges of 11.90–18.12% and 6.49–9.92%, whereas BCT/BCD ranged from 47.43 to 79.05% with a mean value of 60.96%. Contents of BCD in soils of salt-lake area ranged from 0.504 to 6.794 g kg^{-1} with a mean value of 1.639 g kg^{-1}. Contents of soil BCT were in the range of 0.500–4.750 g kg^{-1} with an average value of 1.144 g kg^{-1} (Fig. 6b), higher than those of the background area. The average values of BCD/TOC and BCT/TOC in salt-lake areas were 34.02% and 27.77%; BCT averagely accounted for approximately 77.42% of BCD. The average/maximal contents of BCD and BCT in soils of the urban area were respectively 1.653/4.193 and 0.679/1.000 g kg^{-1} (Fig. 6c), similar with those of Xi'an (Han et al. 2009) but much lower than those of other cities in China, such as Beijing (Liu et al. 2011), Shanghai (Wang et al. 2014a, b), Nanjing (He and Zhang 2009), and Xuzhou (Wang 2010). Difference in soil BC contents of these regions/cities might be caused by urbanization and transport emissions. BCT/BCD values of this area ranged from 23.85 to 92.59% with the average value of 54.42%. Agricultural and pastoral area possessed relatively higher soil BC contents with average/maximal contents of BCD and BCT respectively reaching 4.466/42.939 and 1.110/2.650 g kg^{-1} (Fig. 6d), higher than those in the grassland and woodland soils of UK (Nam et al. 2008). The values of BCD/TOC and BCT/TOC of this region were in the ranges of 9.15–92.51% and 2.07–75.00%, whereas BCT/BCD ranged from 4.66 to 100% with a mean value of 50.59%. The contents of BCD and BCT in soils of the industrial area results were in the ranges of 0.581–66.166 and 0.400–8.650 mg kg^{-1} with average values of 8.158 and 2.567 g kg^{-1} (Fig. 6e), respectively. Compared with soil BC contents (1.86–246.46 g kg^{-1} with an average value of 33.86 g kg^{-1}) of Anshan that is the

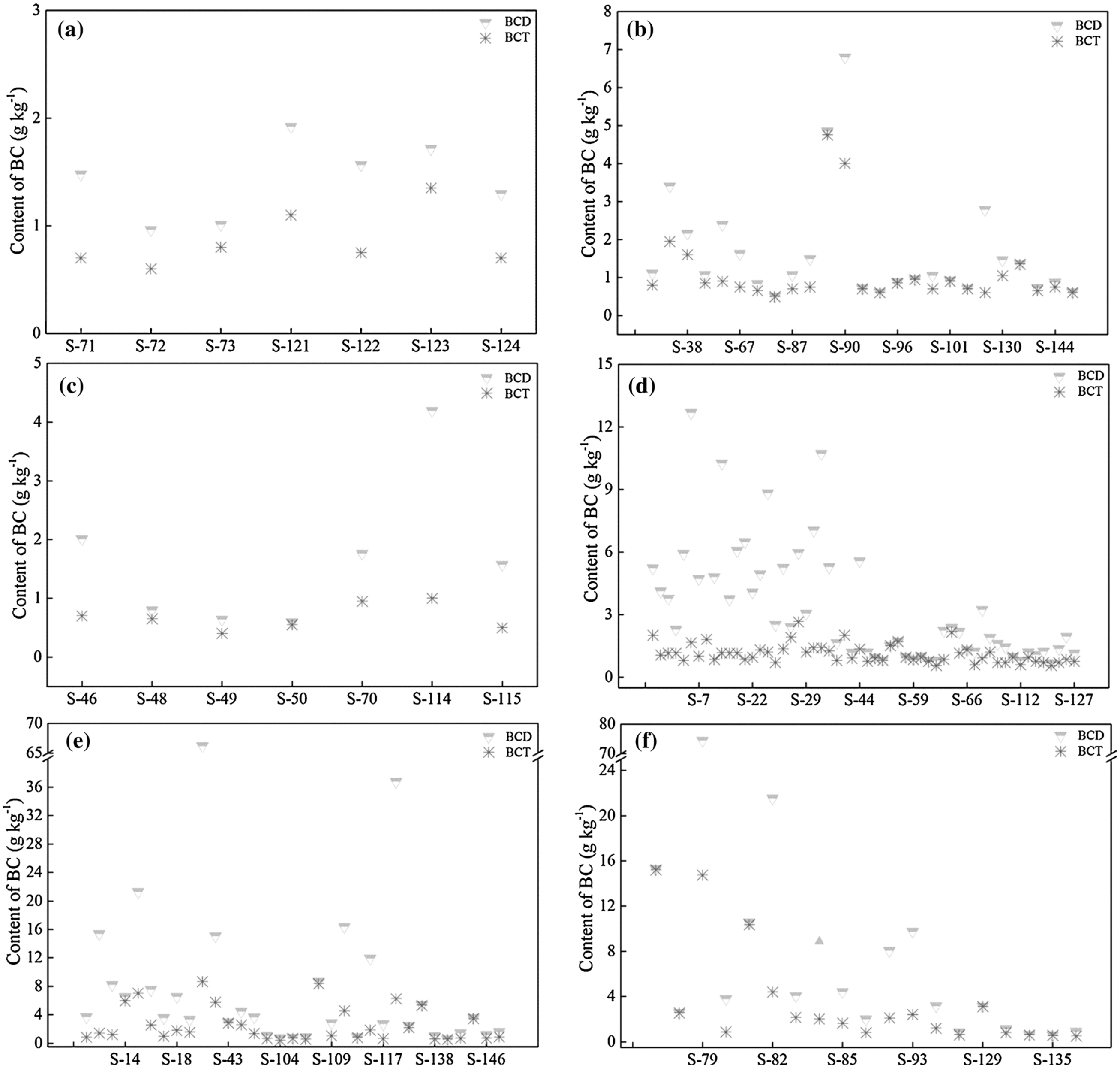

Fig. 6 Contents of BCD and BCT in soils of different functional areas, including the background area (**a**), salt-lake area (**b**), urban area (**c**), agricultural and pastoral area (**d**), industrial area (**e**), and mining area (**f**)

biggest steel industrial city in China (Zong et al. 2016), the BC contents in soils of the industrial area were relatively low. The maximal/average values of BCD/TOC, BCT/TOC, and BCT/BCD were 86.95%/36.66%, 42.27%/17.93%, and 98.28%/52.43%, respectively. The contents of BCD and BCT in soils of the mining area were the highest among all functional areas, ranging from 0.582 to 74.381 and from 0.500 to 15.200 g kg^{-1} with average values of 9.239 and 3.503 g kg^{-1} (Fig. 6f), respectively. The values of BCD/TOC and BCT/TOC of this region were in the ranges of 21.27–97.31 and 10.13–96.82%, whereas BCT/BCD ranged from 19.83 to 100% with a mean value of 57.42%. Agricultural, pastoral, industrial, and mining areas of this study possessed higher soil BC contents, exhibiting that the anthropogenic activities might be important factors affecting the distribution of soil BC. A large amount of previous studies also have shown that anthropogenic activities including traffic, indoor, and outdoor biomass burning, energy production, and fossil fuel burning have a significant influence on soil BC (Miguel et al. 1998; Posfai et al. 2004; Fullerton et al. 2008; He and Zhang 2009; Xiao et al. 2015; Gao et al. 2018).

Conclusions

Two methods, including the chemothermal oxidation and dichromate oxidation, were used to determine the contents of soot BC (BCT) and total BC (BCD) in soils of the northeastern Qinghai-Tibet Plateau, respectively. The contents of BCD and BCT in the study area were in the range of 0.504–74.381 g kg^{-1} with a mean value of 5.152 g kg^{-1} and 0.400–15.200 g kg^{-1} with a mean value of 1.719 g kg^{-1}, respectively. The BCD and BCT were significantly related with TC and TOC at $p < 0.01$. The soil physicochemical properties affected the distribution of soil BC in the study area. The contents of BCD in loam soils samples were higher than those in clay soils, which possessed higher-proportion BCT. The contents of BC significantly varied in different functional areas. The contents of BCD and BCT in soils of the mining area were the highest among all functional areas, ranging from 0.582 to 74.381 g kg^{-1} and from 0.500 to 15.200 g kg^{-1}, respectively. The contents of BCD and BCT were the lowest in the background area and the urban area, ranging from 0.963 to 1.919 g kg^{-1} and from 0.400 to 1.000 g kg^{-1}, respectively. The contents of BC in soils of mining area, industrial area, and agricultural and pastoral areas were approximately 5–7 times, 3–5 times, and 1–3 times those in the background area, respectively. The results indicate that anthropogenic activities might exert a significant impact on soil BC in the northeastern Qinghai-Tibet Plateau.

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