Atmospheric Environment 43 (2009) 2464–2470

Contents lists available at ScienceDirect

Atmospheric Environment

journal homepage: www.elsevier.com/locate/atmosenv

Elemental carbon in urban soils and road dusts in Xi'an, China and its implication for air pollution

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ARTICLE INFO

Article history:
Received 5 July 2008
Received in revised form
28 January 2009
Accepted 29 January 2009

Keywords:
Elemental carbon (EC)
Road dusts
Carbonaceous particles
Thermal/optical reflectance (TOR) method
Char
Soot

ABSTRACT

Increasing evidence confirms that elemental carbon (EC) is not only a light-absorbing constituent that warms the atmosphere but also a significant environmental pollutant. Investigations were conducted to identify carbonaceous pollution signatures in road dusts and urban soils and to evaluate potential sources in Xi'an. Average concentrations of EC, char-EC, and soot-EC in soils were 0.90, 0.51, and 0.39 mg g^{-1}, respectively, a little higher than or comparable to prior studies on the Loess Plateau. Vertical profiles in soils revealed soot-EC concentrations from pre-industrialized samples close to ~0.20 mg g^{-1}, while EC and char-EC varied widely, with no distinct pattern. Enrichment factor analysis indicated that EC, char-EC, and soot-EC in road dusts were all elevated by an order of magnitude. The spatial distribution of total EC, char-EC, and soot-EC in road dusts revealed close correspondence with human activities such as coal combustion and vehicle emissions. The average char-EC/soot-EC ratio was 1.66 for road dusts, suggesting that the main sources of carbonaceous particles are local coal combustion and vehicle emissions. The study demonstrated that EC, char-EC, and soot-EC levels in road dusts are effective indicators of anthropogenic pollution.

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1. Introduction

The increasing use of coal and petroleum products in China has resulted in elevated emissions of carbonaceous aerosols, including organic carbon (OC) and elemental carbon (EC, or black carbon, BC). EC originates primarily from the incomplete combustion of fossil fuels and biomass burning. It can be subdivided into two classes: char and soot, of which both can be produced in different ways from all combustion processes (Goldberg, 1985; Kuhlbusch, 1997; Masiello, 2004; Koelmans et al., 2006). Char is generally black-colored material left as combustion residues derived from solid or liquid organic matter at relatively low combustion temperatures (<600 °C), retaining recognizable morphological features similar to its source material. Soot normally comprises those carbon particles that form via gas-to-particle conversion at high temperatures (generally >600 °C). The global annual emission of EC is (for the year 1996) ~8 Tg (Bond et al., 2004), with about 20% from bio-fuels, 38% from fossil fuels and 42% from open biomass burning. The annual EC emission in China is ~1.2–1.5 Tg (Streets et al., 2001; Chameides and Bergin, 2002; Cao et al., 2006a).

EC is usually considered as the only particulate-phase light-absorbing species in the earth radiation balance (Ackerman et al., 2000; Jacobson, 2001). The contribution of EC to global warming may be substantial, perhaps second only to that of CO_2 (Jacobson, 2001). In addition, EC is an important pollutant related to public health. Ultra-fine soot globules can migrate deep into the lungs and carry very toxic, often carcinogenic compounds such as polycyclic aromatic hydrocarbons (PAHs) (Avakian et al., 2002; Koelmans et al., 2006). High lung cancer mortality and high esophageal cancer rates have been reported to be associated with inhalation of PAH-coated soot particles deposited on food and food-preparation surfaces in homes (Chuang et al., 1992; Ramanakumar et al., 2007).

EC is ubiquitous in the environment. It is an aerosol component derived from continents, and has been deposited in soils, and lacustrine and marine sediments (Masiello, 2004). Although carbonaceous aerosols have been extensively investigated in urban areas (e.g. Cao et al., 2005; Chow et al., 2005), little progress has been made on carbonaceous particles deposited on urban ground. Previous environmental investigations concerning urban road dusts and soils focused mainly on heavy metals and PAHs, where they were used them as indicators of air pollution (e.g. Tokalioglu and Kartal, 2006; Han et al., 2006, 2008a; Ran et al., 2007). EC in urban road dusts may also contribute to local air pollution when being re-suspended (e.g. Ho et al., 2003). Significant amounts of EC

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doi:10.1016/j.atmosenv.2009.01.040

have been found in coarse particles in urban aerosols (Huang et al., 2006). The behavior of EC in road dusts may provide insights on a better understanding of the interaction of EC between the atmosphere and the road dusts. This study aims to (1) assess the levels of EC, char-EC, and soot-EC in road dusts and soils in Xi'an, China; (2) examine the spatial distributions of these carbonaceous particles in road dusts and identify major factors controlling their distributions; and (3) examine the effect of anthropogenic activities on carbonaceous contamination and evaluate the possibility of using carbonaceous particles in dusts as indicators of air pollution.

2. Experimental

2.1. Study area

Xi'an is the capital city of Shaanxi, a province that covers a large part of the Loess Plateau in China. It had a population of over 3.8 million and an estimated 433,000 motor vehicles at the end of 2006. The city is situated in a semi-arid zone, with a mean temperature of 13.0–13.4 °C and annual rainfall of 558–750 mm (Han et al., 2006, 2008a). The prevailing wind direction is northeasterly, especially in winter. As the city is surrounded by mountains, frequent inversions prevent pollutants from migrating, leading to an adverse influence on the local environment.

The main energy consumption in Xi'an is coal (3.5 Tg in 2000), accounting for 81% of the total energy consumption, followed by oil (12%) and natural gas (4%) (Xi'an Clean Energy Office, 2002). Recently the government has taken measures to use clean energy to reduce coal consumption. Since 1997 the government has closed most small boilers and used natural gas to replace the traditional energy (Xi'an Clean Energy Office, 2002). In addition, the city is expanding and some previously agricultural areas are being replaced with factories and residential areas (e.g. the high-tech zone in the southwest of Xi'an). In these newly expanding areas such as the high-tech zone and the relaxation sites such as the park of Dayanta Square (Fig. 1), the individual use of coal has been banned. Meanwhile the previous dispersed heating (from many small boilers) is being replaced by concentrated heating (generated in central facilities and distributed as a public utility) all over the city. Further re-construction of some old residential and industrial areas is also being planned and carried out by the government.

2.2. Sampling

A total of sixty road dust samples were collected from 240 km^2 in Xi'an city during September 2006, following a systematic sampling scheme using a clean polypropylene dustpan and brush. As shown in Fig. 1, each sample was acquired from a 1×1 m^2 grid (Han et al., 2006) from the paved ground surface at the roadside, representing a study area of 2×2 km^2.

To assess the environmental pollution of carbonaceous particles from human activities in dusts, the anthropogenic EC sources should be distinguished from the natural ones. In the Loess Plateau, loess–paleosol sequences (successive layers of loess and paleosol), originating mainly from wind dust accumulation, form the base, with the top 1–3 m generally representing the total deposition of the whole Holocene (Wang et al., 2005). Soils not disturbed by human activities can be used as reference material to evaluate the pollution degree from human-induced EC. Thus, 10 surface soil samples (from the top 5 cm, sites 1–10, Fig. 1) and 24 samples from 4 vertical soil profiles (from sites 1, 2, 5, and 6) were collected using a stainless steel shovel in the southwest of Xi'an, where there have been previously agricultural areas before the end of 1990s and thus relatively less industrially polluted. The 4 vertical soil profiles were selected from exposed soil sections along new building sites. These soil profiles were sampled to depths of 70 cm (with one exception of 30 cm, Fig. 2D) after scraping away the open wall of the existing soil pits. Samples were collected from the wall of the pits, starting from the top at 10 cm depth increments, up to 70 cm. Since all the fresh sections are easily distinguished from the surface soils, the vertical soil samples were primarily divided into "disturbed" and "non-disturbed" groups during the sampling, based on the homogeneity of the soil characteristics such as sand and clay, and of the variation of soil colors from the profiles (see description in Fig. 2).

2.3. Sample pretreatment and carbon analysis

The thermal/optical reflectance (TOR) method was employed to determine carbon concentration in road dusts and soils after acid pretreatment (Han et al., 2007a, 2009) following the IMPROVE-A protocol (Chow et al., 2007). This method can compare EC between soils and aerosols since the two matrices use the same protocol (Han et al., 2007a). All dust and soil samples were dried in an oven at 40 °C for 2 days. The dried samples were passed though a 1-mm

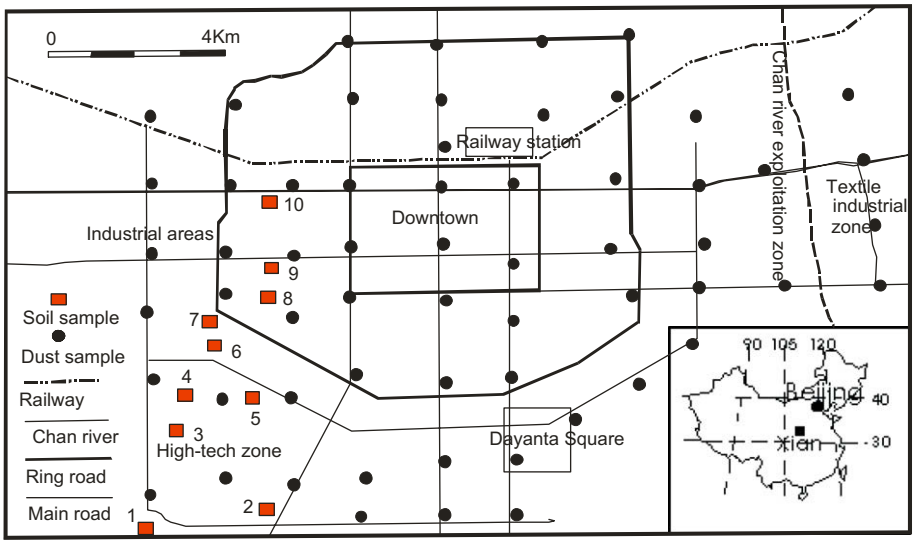

Fig. 1. The sampling locations of paved road dusts and soils in Xi'an (soil sample locations were numbered and vertical profile samples were collected from sites 1, 2, 5, and 6).

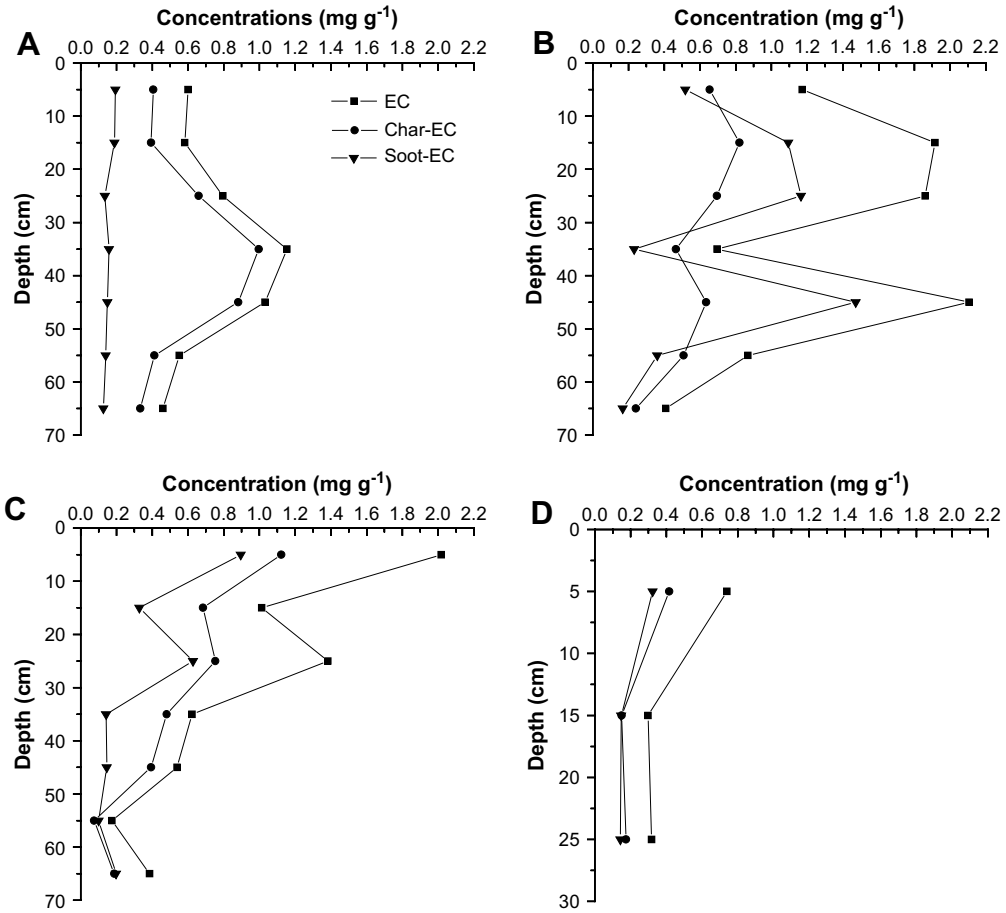

Fig. 2. Vertical profile characteristics of EC, char-EC, and soot-EC in Xi'an soils. (A) From location 1 with little human disturbance (earth yellow clay); (B) from location 2 with human disturbance (brown clay containing some gravels); (C) from location 6 with human disturbance in the top 30 cm (gray silver sand containing black conglomeration in the upper part and earth yellow clay in the lower part); and (D) from location 5 with human disturbance in the top 10 cm (earth yellow clay, containing brown silver sand in the upper part.

sieve to remove large plant roots and gravel. Next, each ~5 g sample was ground with an agate mortar and passed through a 63-μm sieve. ~0.125 ± 0.025 g of each sample was weighed (1/10,000 balance) and pretreated with HCl and HF acids to remove carbonates, minerals and metal oxides (Han et al., 2007a, 2009). The residues were then filtered onto pre-fired (850 °C, 3 h) 47-mm quartz filters for carbon analysis using a DRI Model 2001 Thermal/Optical Carbon Analyzer. Carbon was made to evolve through programmed, progressive heating to produce eight carbon fractions: four organic carbons (OC, comprising OC1, OC2, OC3 and OC4 at 140, 280, 480 and 580 °C in pure helium), one pyrolyzed organic carbon (POC, produced in the heating process, and monitored using a laser when the laser reflectance returns its initial value) and three EC (EC1, EC2, and EC3 at 580, 740, and 840 °C in 2% oxygen and 98% helium). OC is defined as OC1 + OC2 + OC3 + OC4 + POC and EC as EC1 + EC2 + EC3 − POC. Since some hydrolysable OC can be lost in acid pretreatment, the acid pretreated OC is called non-hydrolysable OC (NHOC). The sum of NHOC and EC is non-hydrolysable total carbon (NHTC).

Previous studies have found that abundances of EC1 and EC2 varied between sources (e.g. Chow et al., 2004; Cao et al., 2005). For example, EC1 was more abundant in biomass burning, while EC2 was abundant in diesel vehicle emissions. Han et al. (2007a) compared the TOR and chemothermal (CTO-375) methods and found that soot-EC defined by the CTO-375 method (Nguyen et al., 2004; Hammes et al., 2007), corresponded to EC2 and EC3 defined by TOR method. Further studies (Han et al., 2007b) revealed that pure char material always peaked at EC1, while pure soot samples peaked at EC2 and EC3. Thus Han et al. (2007b) defined char-EC as EC1 minus POC and soot-EC as the sum of EC2 and EC3. This differentiation facilitates the interpretation of carbon fractions reported in the IMPROVE-TOR temperature protocol and has been used in a recent aerosol study (Han et al., 2008b).

The carbon analyzer was calibrated daily with known quantities of methane (Chow et al., 1993). Replicate analyses were performed at the rate of one per group of 10 samples. The difference in comparison with the average values from replicate analyses was <8% for NHTC and <10% for NHOC, EC, char-EC and soot-EC.

3. Results and discussion

3.1. Composition of carbonaceous particles in soils

Carbon concentrations in Xi'an soils are summarized in Table 1. The EC concentrations were 0.3–2.11 mg g^{-1}, with 0.19–1.12 mg g^{-1} of char-EC and 0.10–1.47 mg g^{-1} of soot-EC. These levels are generally higher than, or comparable with, the soil EC concentrations on the Loess Plateau in China determined using the same method (Han et al., 2007a), consistent with the central mega-city status of Xi'an on the Loess Plateau. The results are also comparable with the EC concentrations of the country park soils from non-urban areas (0.33 mg g^{-1}) and urban soils (4.81 mg g^{-1}) in Hong Kong measured with the TOR method using the re-suspension technique (Ho et al., 2003). Since previous methods measured EC as

Table 1
Carbonaceous particle concentrations (mg g^{-1}) and background values (mg g^{-1}) of Xi'an soils. Background values are the average concentrations of non-industrialized samples from the three vertical profiles (Fig. 2A, C, and D).

Types	Range	Average[a]	Median	VC[b]	Number
NHTC[c]	0.74–13.38	2.83 ± 2.47	2.03	1.22	30
NHOC[c]	0.43–11.36	1.93 ± 2.07	1.23	1.68	
EC	0.17–2.11	0.90 ± 0.58	0.74	0.78	
Char-EC	0.07–1.12	0.51 ± 0.28	0.47	0.60	
Soot-EC	0.10–1.47	0.39 ± 0.37	0.20	1.85	
EC/NHTC (%)	15.1–54.5	34.1	33.7		
Background of urban soils					
NHOC	NHOC	EC	Char-EC	Soot-EC	Number
1.70	1.12	0.58	0.43	0.15	13[d]

[a] Averages are expressed as average ± standard deviation (SD).
[b] VC is variation coefficient, which is SD/average (Han et al., 2006).
[c] Because some hydrolysable organic carbon (OC) would be lost in acid pretreatment, the acid pretreated OC is defined as non-hydrolysable OC (NHOC) and NHTC is the sum of NHOC and EC.
[d] The 13 samples are from the non-industrialized ones of the three vertical profiles, including 7 samples from Fig. 2A (0–70 cm), 4 samples from Fig. 2C (30–70 cm), and 2 samples from Fig. 2D (10–30 cm). Samples from the vertical profile of Fig. 2B are not included in the calculation of background values as they are human influenced.

a whole, there are few reports in the literature differentiating between char-EC and soot-EC. However, the CTO-375 method measures the specific type of EC, soot-EC, leading to a possibility of comparison of soot-EC between the two methods. Han et al. (2007a) found that soot-EC, as defined by the CTO-375 method (Nguyen et al., 2004; Hammes et al., 2007), corresponds to EC2 and EC3 measured by the TOR method, indicating that the two methods are comparable for the soot-EC fraction. Ran et al. (2007) showed that urban soil EC using the CTO-375 method (Gelinas et al., 2001) varied between 0.24 and 3.92 mg g^{-1} in Guangzhou, a developed city in the southeastern China with more extensive industrial and vehicle activities. These levels are comparable with the total EC concentrations, but much higher than soot-EC concentrations in Xi'an soils measured by the TOR method. Since the CTO-375 is thought to measure soot-EC (Nguyen et al., 2004; Han et al., 2007a), soot-EC levels in Guangzhou soils measured by the TOR method may be much higher than those in Xi'an soils, which is consistent with the more extensive industrial and vehicle activities in Guangzhou.

3.2. Background levels of carbonaceous particles in Xi'an soils

To evaluate the background level of carbonaceous particle concentrations in urban soils, the characteristics of carbonaceous particles in vertical profiles were studied. Fig. 2 demonstrates the variations of EC, char- and soot-EC with vertical depth. In the profile with little human disturbance (Fig. 2A), soot-EC remained constant, while EC and char-EC varied greatly and followed the same pattern. Contrary to our expectation, the highest EC and char-EC (>1.0 mg g^{-1}) were not found in the top section. However, the EC and char-EC patterns are similar to the natural paleosol–loess section (Wang et al., 2005). Pre-industrialized EC is mainly composed of char-EC from local fire events and thus varies greatly in vertical profile. EC in vertical profiles measured with the benzenepolycarboxylic acids (BPCA) in northern Siberia's permafrost soils also showed great variations and had no distinct pattern (Rodionow et al., 2006). However, soot-EC in the soil profile not disturbed by human activities varied only slightly, decreasing from 0.19 to 0.13 mg g^{-1} with increasing depth (Fig. 2A). Soot, present as submicron particles, generally experiences regional-to-global dispersion, remaining suspended for a week or more. Thus soot-EC can be used to indicate the atmospheric EC and would not vary greatly without human influence.

In the vertical profile with human disturbance (Fig. 2B), the EC, char-EC, and soot-EC were much higher than in profiles with little human disturbance (Fig. 2A). In particular, soot-EC increased by a factor of ~3 between the undisturbed (Fig. 2A) and the disturbed profiles (Fig. 2B). The profiles with human influence in their upper part (Fig. 2C and D) showed that EC, char-EC, and soot-EC concentrations decrease with depth. From all four profiles it is interesting to note that although EC and char-EC varied significantly and showed no consistent trend with depth, soot-EC concentrations from non-disturbed samples showed narrow variation and were approximately 0.2 mg g^{-1}, a value similar to that from the top soil of the paleosol–loess section in Lingtai (Y.M. Han, unpublished data). Although both biomass and fossil fuel burning can produce both char and soot, biomass burning tends to generate a much higher proportion of char in total EC emissions (sometimes even above 95%), while fossil fuel combustion tends to emit a relatively lower proportion of char (see Section 3.4). At present, due to the large consumption of fossil fuels, much more soot has been produced by human activities. Thus it can be seen that soot-EC concentration in soils disturbed by humans is generally far higher than that of soils undisturbed by humans (Fig. 2A–D). Meanwhile, the char-EC concentrations can also be much higher in undisturbed soils, due to natural biomass fire events (Fig. 2A).

In order to evaluate the anthropogenic pollution levels (see below), the average concentrations of EC, char-EC, and soot-EC of undisturbed samples from the three vertical profiles (Fig. 2A, C and D, and see the description in Table 1) were calculated to represent the background values of the Xi'an soils (Table 1). The averages are 0.58, 0.43, and 0.15 mg g^{-1} for EC, char-EC, and soot-EC, respectively. Compared with the corresponding EC, char-EC, and soot-EC concentrations in Xi'an soil, the background values are lower, especially for soot-EC, which is in agreement with the increasing fossil fuel use in modern times.

3.3. Carbonaceous particles in road dusts and their enrichment

Table 2 summarizes carbonaceous particle concentrations in road dusts. The average concentrations of NHTC, NHOC, EC, char-EC, and soot-EC were 14.6, 7.4, 7.2, 4.4, and 2.8 mg g^{-1}, respectively. The EC concentrations ranged from 1.3 to 16.5 mg g^{-1}, which was comparable with that in the paved road dust from Hong Kong (12.9 mg g^{-1}) measured with the TOR method using the resuspension technique (Ho et al., 2003). Compared with those in Xi'an soils, the average concentrations of EC, char-EC, and soot-EC

Table 2
Carbonaceous particle concentrations (mg g^{-1}) and char-EC/soot-EC ratios in road dusts.

Types	Range	Average[a]	Median	VC[b]
NHTC	3.0–29.2	14.6 ± 5.8	13.8	0.39
NHOC	1.7–16.7	7.4 ± 3.1	7.1	0.42
EC	1.3–16.5	7.2 ± 3.4	6.6	0.47
Char-EC	0.56–9.40	4.4 ± 2.2	4.3	0.50
Soot-EC	0.52–8.09	2.80 ± 1.5	2.45	0.54
EC/NHTC (%)[c]	30.5–64.5	47.4	47.4	
Char-EC/soot-EC	0.35–3.0	1.66	1.65	
Char-EC/EC (%)	25.7–79.3	60.0	62.2	
Soot-EC/EC (%)	21.7–74.3	40.1	37.8	

[a] Averages are expressed as average ± standard deviation (SD).
[b] VC is variation coefficient, which is SD/average (Han et al., 2006).
[c] Because some hydrolysable organic carbon (OC) would be lost in acid pretreatment, the acid pretreated OC is defined as non-hydrolysable OC (NHOC) and NHTC is the sum of NHOC and EC.

in Xi'an road dusts were about 9.7, 9.4 and 14 times higher, respectively (Table 1), indicating modern traffic influence.

The correlation analyses of carbonaceous particles in road dusts (Table 3) showed that all the carbonaceous particles were strongly positively correlated with each other, suggesting common sources. This finding is in good agreement with the carbonaceous aerosol study in Xi'an city (Cao et al., 2005), conducted with the TOR method, which also showed good correlation between different carbonaceous particles. Compared with char-EC, soot-EC shows slightly weaker correlation with the other carbonaceous particles, which may be associated with difference formation mechanisms for char and soot. Generally char forms from the combustion residues, tending to keep its parent characteristics, while soot is formed from re-condensed volatiles via gas-to-particle conversion.

The background values of EC, char-EC, and soot-EC concentrations in soils (Table 1) allowed evaluation of carbonaceous contamination of urban road dusts. Enrichment factor (EF) is the most common method applied to assess the degree of human influence (e.g. Han et al., 2006). In this study, EF is defined as the carbonaceous particle concentration in road dusts divided by the corresponding background value in Xi'an soils. In trace element studies (e.g. Loska and Wiechuła, 2003; Han et al., 2006), it has been firmly established that an EF close to 1 points to a natural origin while EF values greater than 10 are considered highly enriched and originate from non-natural sources. EF was thus used to assist the determination of the degree of carbon contamination. Fig. 3 shows that average EF values in road dusts are about 12.4, 10.1, and 18.7 for EC, char-EC and soot-EC, respectively, and the highest soot-EC EF reaches 55, suggesting significant enrichment by human activities.

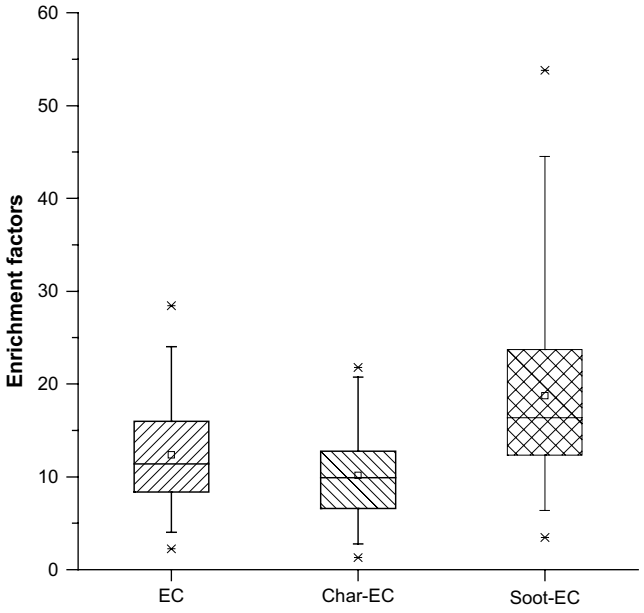

Fig. 3. Enrichment factors (EFs) of EC, char-EC, and soot-EC from paved road dusts. EFs were calculated from the carbonaceous particle concentrations divided by the corresponding background value of soils. The boxplot divides the normalized EFs into quartiles. The dark line inside the box represents the median; the boxes mark the 25th and 75th percentiles; the horizontal line outside the box marks the values that extend 1.5 times the width of the box).

3.4. Spatial distribution of carbonaceous particles in road dusts and their source identification

The spatial distribution of EC, char-EC, soot-EC, and char-EC/soot-EC ratio in Xi'an dust is presented in Fig. 4. High-levels of EC (>9 mg g^{-1}) were found in the heavy-industrial zone in the western part of Xi'an where many coal-burning factories (e.g. Coal-Fired Power Plant, Thermoelectric Plant, Steel Plant, and Boil General Plant) are concentrated (Fig. 4). High EC concentrations were also observed around the Xi'an railway station (northeast of downtown, with about 200 trains per day) (Fig. 4), consistent with the use of diesel oil.

Although the heavy-industrial zone and railway station showed high EC levels (Fig. 4A), their char-EC/soot-EC ratios were different (Fig. 4D), at about 1.0 near the railway station, and about 1.8 in the heavily industrialized zone. Generally, char-EC/soot-EC ratios from primary emissions vary significantly between different sources. Char-EC/soot-EC ratios from biomass burning are larger than those from fossil fuel combustion, while ratios from coal combustion are larger than those from vehicle exhausts (Chow et al., 2004). Chow et al. (2004) reported a char-EC/soot-EC ratio of 22.6 for biomass burning and 0.60 for motor vehicle exhausts. The average source sample char-EC/soot-EC ratios in Xi'an were 11.6 for biomass burning and 1.9 for coal combustion (Cao et al., 2005). Hong Kong roadside samples showed char-EC/soot-EC ratios of 0.3 for diesel exhausts and 0.7 for gasoline emissions (Cao et al., 2006b). The difference in the char-EC/soot-EC ratios between the railway station and the heavily industrialized zone is in good agreement with the use of different fuels.

Low levels of EC were mainly found in places lacking coal combustion activities, such as the high-tech zone, Dayanta Square, and the Chan River development zone. The high-tech zone is a newly constructed area (previously agricultural) where coal combustion has been abandoned; Dayanta Square is a park without coal combustion, but with heavy vehicle emissions. Thus, char-EC was very low in Dayanta Square, but soot-EC was close to that in the downtown area, while the char-EC/soot-EC ratios were less than 1.0, close to the values from the direct emissions from motor vehicle exhausts.

The average char-EC/soot-EC ratio in Xi'an dusts was 1.66, a value that is a little lower than that of coal combustion in Xi'an (1.9 by Cao et al., 2005). This suggests that the main sources of EC in Xi'an are coal use and vehicle emissions. The distribution of dust sample locations (Fig. 4D) with high char-EC/soot-EC ratios (>2.6) appears to be mainly linked with agricultural open burning in the suburban area around Xi'an, with particles being transported to urban areas, and, to a lesser extent, associated with local biomass burning, since residential biomass burning still sometimes occurs. The char-EC/soot-EC ratios in dusts showed a northwest–southeast zonal distribution pattern, which corresponds to the prevailing wind direction that is northeasterly during winter and southwesterly during summer.

Table 3
Pearson's correlation matrix for the carbonaceous particle concentrations of road dusts.

	TC	NHOC	EC	Char-EC	Soot-EC
NHTC		0.000	0.000	0.000	0.000
NHOC	0.880**		0.000	0.000	0.001
EC	0.889**	0.582**		0.000	0.000
Char-EC	0.872**	0.596**	0.941**		0.000
Soot-EC	0.738**	0.431*	0.864**	0.642**	

**$p < 0.001$ (2-tailed); *$p < 0.005$ (2-tailed). The left lower part is correlation coefficient; the right upper part is significant level.

4. Conclusions

Carbonaceous particle concentrations in vertical soil profiles demonstrated that the samples with little human disturbance had soot-EC concentrations lower than ~0.2 mg g^{-1}, similar to those

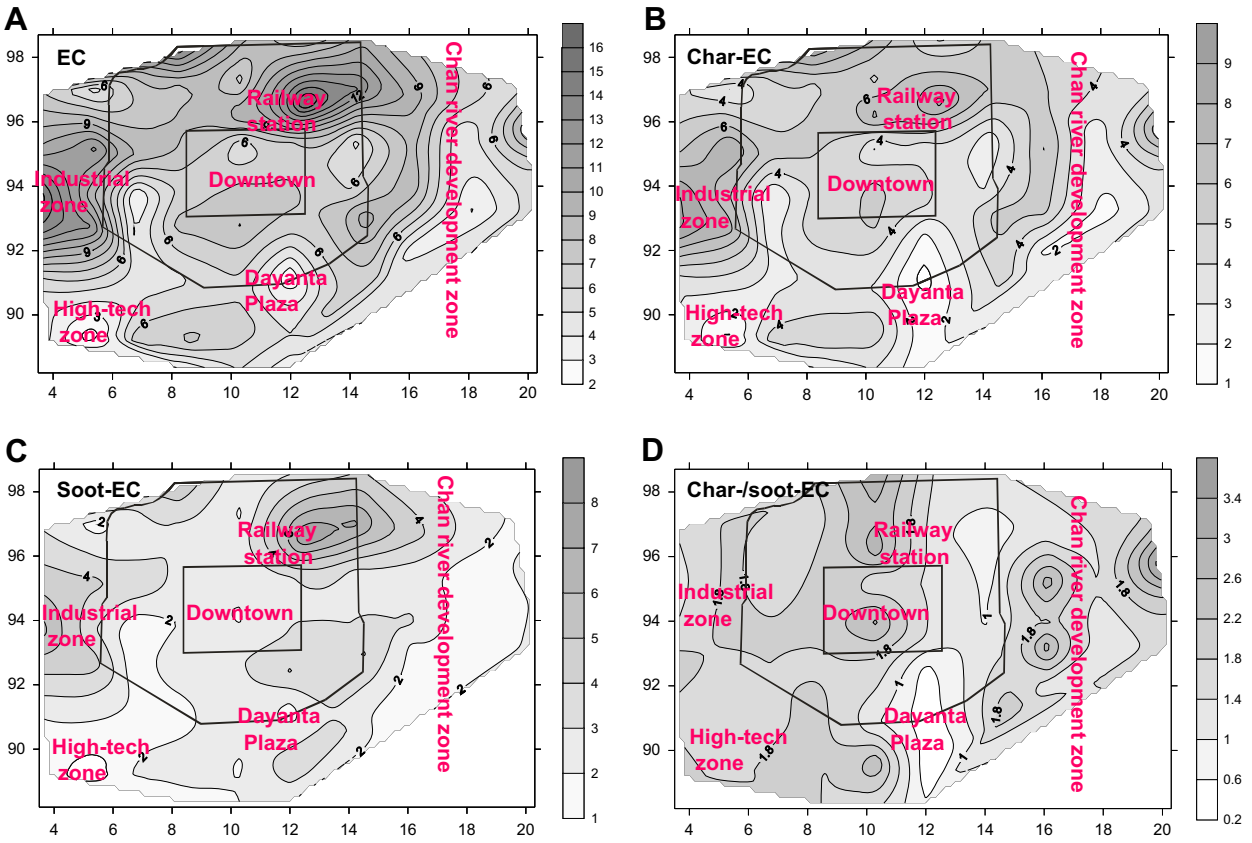

Fig. 4. Spatial distribution of EC, char-EC, soot-EC, and char-EC/soot-EC from road dusts.

measured from the top part of the loess–paleosols in the Lingtai section, while EC and char-EC concentrations varied greatly in the vertical profile, showing no distinct pattern. Thus, soot-EC concentrations can be used as a reference to discriminate between non-industrialized and industrialized soils, which can be expanded to other studies of carbonaceous pollution. The enrichment factors of EC, char-EC, and soot-EC in road dusts showed that the contamination from soot-EC was the most significant one. The spatial distributions of EC, char-EC, and soot-EC in road dusts corresponded well with the human emission sources, showing high EC levels in the heavy-industrial zones and at the railway station. Low levels of EC, char-EC, and soot-EC were found in newly constructed areas. The results indicate that the measures taken by the government to reduce energy emissions have been effective. The average char-EC/soot-EC ratio in road dusts was 1.66, suggesting that the main sources of EC were coal burning and vehicle emissions. The char-EC/soot-EC ratios in road dusts corresponded well with the different human emission sources, confirming that the TOR method is useful for the discrimination between char-EC and soot-EC. Also the findings provide information useful to the local government when evaluating the effectiveness of measures such as the redevelopment of old residential and industrial areas to reduce energy emissions.

Acknowledgements

This study was supported by the National Natural Science Foundation of China (40675081, 40599420), the National Basic Research Program of China (2004CB720203), the State Key Laboratory of Loess & Quaternary Geology (SKLLQG0718), and the MOST Special Fund for State Key Laboratory of Loess and Quaternary Geology (LQ0701).

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