



Heavy metal enrichment in roadside soils in the eastern Tibetan Plateau

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Abstract

The effects of human activities on heavy metal pollution in soil have been less investigated on the Tibetan Plateau. The present study was designed to assess the effects of highway traffic on Cu, Zn, Pb, and Cd enrichments in the 0–60-cm soil profile in the eastern Tibetan Plateau. Soils were sampled at four transects (with an altitude range of 2643–2911 m) across the G212 highway and five transects (3163–3563 m) across the G213 highway. Background concentrations of Cu, Zn, Pb, and Cd to the 60-cm soil depth (measured at each transect 400 m away from highways) varied greatly among transects and between highways. However, this spatial variation in the heavy metal concentrations was not related to the altitude of the investigated areas. On each the left and right sides of G212 or G213, Cu, Zn, and Pb concentrations to the 60-cm depth, at 5, 10, 20, and 50 m away from the highway, were all generally greater than the respective metal background concentrations. Cd concentrations to the 20 cm on G212 or 60-cm soil depth on G213 increased prominently within a distance of 20 m away from the highways, compared to background values in different depths. From the curb to 400 m away from highways, concentrations of Cu, Zn, Pb, and Cd were generally higher in the upper than in the lower soil layers. This may suggest that other factors such as atmospheric deposition were also contributable to the accumulation of heavy metals in soil. The contamination factor (C_f) calculation showed that roadside soils to the 60-cm depth, within a distance of 50 m from the curbs of both G212 and G213, were moderately ($1 \leq C_f < 3$) contaminated with Cu, Zn, and Pb. The contamination from Cd mainly occurred ($1 \leq C_f < 8$) in the top 20 cm soil with a closer distance from the highways. Our results indicated that traffic effects in enriching heavy metals reached 60-cm depth in roadside soils on the eastern Tibetan Plateau. For assessment of heavy metal pollutions in soil in mountainous areas, it is necessary to in situ identify the background values.

Keywords Background concentrations · Heavy metals · Roadside soils · Qinghai–Tibetan Plateau · Soil pollution

Introduction

The Tibetan Plateau has been referred to as “the third pole of the Earth” and is considered one of the most vulnerable geoecosystems to rapid climate change and human activities. The Tibetan Plateau is of vital importance to the global hydrological cycle, carbon storage, biodiversity, and animal husbandry. Currently, the effects of accelerated climate warming and concurrent intensification in land use on carbon and nutrient cycling, landscape shaping, and water supply modification are

attracting increasing research attention (Qiu 2008; Cui and Graf 2009; Miehe et al. 2011; Su et al. 2011). However, the effects of economic activities on the behavior and accumulation of heavy metals in soil have been less investigated.

Because of the high altitude and mountainous terrain, the natural conditions of the Tibetan Plateau are harsh for human life. Traditionally, the Tibetan Plateau was set apart from the other areas within China. However, over the past several decades, the economy of the Tibetan Plateau has been accelerated alongside the overall growth of China’s economy. Among the economic spheres of the Tibetan Plateau, the growth of the transportation industry, particularly road transport, has been remarkable. Road transport offers numerous benefits to society, but it is also one of the most important sources of heavy metal pollution and plays an important role in the biogeochemical cycles of trace metals (Liu et al. 2009; Zehetner et al. 2009; Khan and Kathi 2014; Zhang et al. 2015). Components, fuels, and lubricating oils of vehicles and paving materials may contain heavy metals such as Cu,

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Zn, Pb, and Cd (Sutherland 2000; Al-Awadhi and Aldhafiri 2016). These heavy metals can be released to the environment around highways, through wearing and tearing of vehicle components and paving materials and emissions of exhausts. In high-altitude areas, the combustion of fuel is typically less complete than in low-altitude areas because of the reduced oxygen concentration in air, resulting in greater fuel consumption and thus greater pollutant emissions (Bishop et al. 2001). Goods (rubbers, metal wares, fertilizers, coals, oils, construction materials, etc.) transported by vehicles may contain heavy metals (Sutherland 2000; Al-Awadhi and Aldhafiri 2016). Scattering and rain washing of goods may also bring heavy metal to the environment. Soil around highways is known to be a major sink of polluting heavy metals (Liu et al. 2009; Zehetner et al. 2009; Khan and Kathi 2014; Zhang et al. 2015). The level of heavy metal contamination in roadside soils depends on many factors such as traffic density, age of site, site configuration, topography, climatic conditions, and soil properties (Pagotto et al. 2001). High levels of heavy metals in soil are a threat to human health and ecosystems (Rouillon et al. 2013; Shahid et al. 2016). The environmental effect of road traffic as a pollutant source is a crucial issue to address in the course of rapid economic growth.

Some studies (Zhang et al. 2015; Wang et al. 2017) have shown that traffic activities induce significant pollutions of Cu, Zn, Cd, and Pb to roadside soils on the northern plateau. However, the Tibetan Plateau is huge (2.4 million km²) with the most changeful topography and geomorphology in the world, accounting for about a quarter of China's land area. Traffic associated pollutions in other vast regions of the Tibetan Plateau are not investigated. In previous studies, the soil sampling depth was shallow, mostly within the top 20 cm of soil (Zhang et al. 2015; Yan et al. 2013; Alharahsheh 2015; Ahmed et al. 2016; Wang et al. 2017). These studies reflect the contamination sensitively because pollutants from traffic will firstly accumulate in the surface soil. However, shallow sampling cannot reveal the effect of heavy metal pollution at greater soil depths. Plant uptake can occur from depths lower than 20 cm in the soil profile, and pollutants in deeper soils are more likely to diffuse into groundwater than those in the upper levels of soil. In addition, the background content in soil is a reference standard for defining the degree of contamination of a heavy metal. However, reliable background values of soil heavy metal concentrations are lacking in the vast and mountainous Tibetan Plateau regions (Zhang et al. 2015).

The present study was designed to investigate the effects of highway transportation on Cu, Zn, Pb, and Cd contents at 0–60-cm soil depth in the soil profile of the eastern Tibetan Plateau. The background values of soil heavy metal concentrations were measured in situ to evaluate the degree of heavy metal contamination in roadside soils.

Materials and methods

Study area and soil sampling

The study was conducted in the Gannan Tibetan Autonomous Prefecture (33° 06' N–36° 10' N, 100° 46' E–104° 44' E), Gansu Province. Two highways pass through this mountainous area: G212 and G213 (Fig. 1a, b). The two highways both start from Lanzhou in the northwest but end in Chongqing and Mouhan, respectively, in the southwest of China. G212 and G213 were built in 1950s and 1980s, respectively. Afterwards, both highways were upgraded for several times in order to increase transport capacity. Since the end of the last century, the traffic flow of the two highways has increased with economic growth. According to data from local governments in the study area, the average traffic loads were about 4500 and 6600 vehicles per day in 2014, in each direction, for highways G212 and G213, respectively.

In the present study, soil sampling was conducted in sections between transect 1 (34° 55' N, 103° 59' E; 2643 m above sea level) and transect 4 (34° 58' N, 104° 5' E; 2911 m) on G212, and between transect 5 (34° 29' N, 104° 19' E; 3163 m) and transect 9 (34° 34' N, 104° 27' E; 3563 m) on G213 (Fig. 1b–d). The distances between adjacent transects were all about 5 km on each highway.

The annual daily mean air temperature and rainfall recorded at the nearest weather stations were 2.3 °C and 580 mm, respectively, in the sampling section on G212 and 4.6 °C and 704 mm on G213. Vegetation in the sampling section was alpine steppe on G212 and alpine meadow on G213. Soils were classified as sub-alpine steppe soil on G212 and alpine meadow soil on G213, according to the Chinese Soil Classification System. They were developed from loess on G212 and eluvial sediments on G213.

Soil sampling was conducted in July 2015 on G213 and in July 2016 on G212, respectively. At each of the nine sites (on two highways), an 800-m transect was established, running perpendicular through each highway (400 m on the left and 400 m on the right side of the highway). On each side along the transect, five pits were dug at 5, 10, 20, 50, and 400 m, respectively, away from the highway. Each pit measured 50 cm long × 50 cm wide × 60 cm deep. Because the sampling sections of both highways were in mountainous areas, the sampling transects and soil pits were appropriately positioned to avoid some special terrains (such as deep gullies, sudden bulges, and sites affected by construction activities). Soils were taken using a plastic shovel at 0–2-, 2–20-, 20–40-, and 40–60-cm depths, from the bottom to the top layer. Samples at the same depth from four sides of each pit were pooled to form a composite soil sample. A total of 80 composite soil samples (4 transects × 5 pits × 4 soil layers) were collected in an area of about 6 km² (15 km × 0.4 km) on each side of G212, and 100 composite samples (5 transects × 5 pits

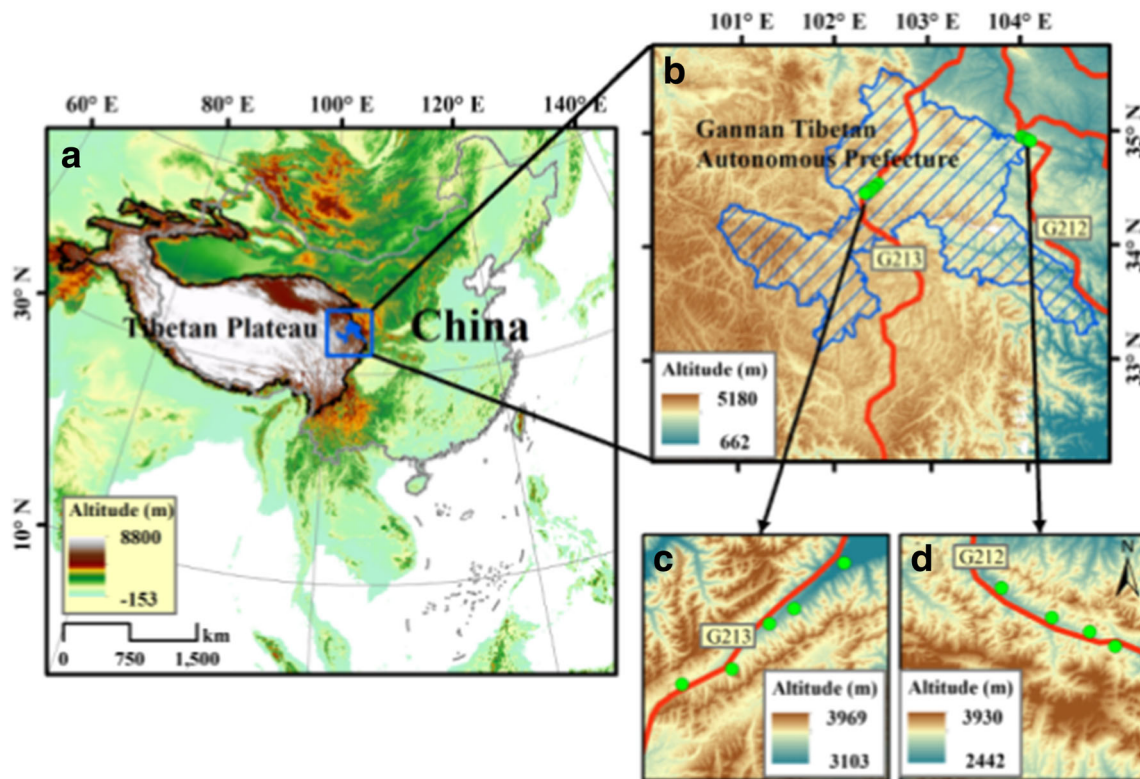


Fig. 1 Study area (a, b) and sampling transects (c, d) on highways of G212 and G213 in the eastern Tibetan Plateau, China. Green dots represent locations of sampling transects

× 4 soil layers) were taken in an area of about 8 km² (20 km × 0.4 km) on each side of G213.

In these areas, the major production sector is herding livestock, without large-scale agricultural cultivation and manufacturing industries. Therefore, the pollutant source is relatively easy to identify. According to studies by Wheeler and Rolfe (1979), Yan et al. (2013), and Zhang et al. (2015), the effects of traffic activities on pollutant depositions in soil are more intensive closer to roads and decrease with the distance from roads. Therefore, we considered soil samples taken from pits at 400 m away from highways as reference soils (presumably unaffected by traffic activities), from which background values of heavy metal contents in soil were analyzed.

Samples were air-dried under room temperature after visible plant roots and gravel had been removed. Soils were sieved through a 2-mm mesh for soil particle-size composition and pH determinations. A small portion of each sample (< 2 mm) was further ground to pass a 0.15 mm mesh for measuring soil organic carbon and heavy metal concentrations. During all operations of sampling and preparation, any potential metal contamination of soils was avoided.

Soil analyses

All analyses were made on soil samples from the depths of 0–2, 2–20, 20–40 and 40–60 cm. Soil particle size composition was

determined via the pipette method following the procedure described by the Institute of Soil Science, Academia Sinica (1978). Soil pH was measured using a glass electrode, with a soil to water ratio of 1:5. Soil organic carbon content was determined by the Walkley and Black dichromate oxidation method (Nelson and Sommers 1982). To measure four heavy metal (Cu, Zn, Pb, and Cd) contents, about 0.2 g of air-dried soil (< 0.15 mm) was digested in a mixture of HNO₃–HCl–HF–HClO₄ in a Teflon tube (SEPAC 1997a, b). Heavy metal contents in the digest were determined using atomic absorption spectroscopy (FAAS, ZEE nit700P, Analytik Jena, Germany). Each soil sample was analyzed for three times. When a standard deviation of three measurements was ≤ 5% of the mean value, results were accepted. Standard reference soil samples (Geochemical Standard Soil GSS-8) were included in all measurements of heavy metals. Recovery was 105–123, 95–109, 98–116, and 91–117% for Cu, Zn, Pb, and Cd, respectively.

All parameters in the 0–20-cm soil layer were calculated by weighting the data from 0–2- and 2–20-cm depths using respective soil thicknesses (2 and 18 cm).

Statistical analysis

We used two-way analysis of variance (ANOVA) on each side of a highway, with the distance from the curb (5, 10, 20, 50, and 400 m) and soil depth (0–20, 20–40, and 40–60 cm) as

two fixed factors to evaluate their effects on heavy metal concentrations. One-way ANOVA was used to assess the effects of sampling distance from the curb on heavy metal concentrations in the 0–2-cm surface soil layer. The block-structured sampling design (each sampling transect was taken as a block) was applied in all ANOVA, which permitted more powerful tests of treatments by distinguishing the variation among blocks (transects) from those among treatments (Quinn and Keough 2002). Significant differences between the means were identified by the least significant difference at $P < 0.05$. Prior to analysis, all data pools were tested for normality. If the distribution was non-normal, a reciprocal transformation was conducted (Quinn and Keough 2002). Significant correlations between parameters were expressed as Pearson correlation coefficients. All statistical analyses were performed using SPSS 13.0 (SPSS, Chicago, IL).

Soil pollution evaluation

The contamination factor (C_f) (Hakanson 1980) and the Nemerow synthetic pollution index (PN) (Chen et al. 1999; Cheng et al. 2007; Zheng et al. 2006) were applied to assess the degree of metal pollution in the soil at 5, 10, 20, and 50 m, respectively, relative to 400 m away from highways, on each side of a transect. The C_f was calculated as

$$C_f = \frac{C_i}{S_i},$$

where C_i is the content of the heavy metal i in a soil sample of different depths (0–2, 2–20, 20–40, or 40–60 cm) at 5, 10, 20, and 50 m away from a highway. S_i is the background content of the heavy metal i in the corresponding soil sample of different depths (0–2, 2–20, 20–40, or 40–60 cm) at 400 m away from the highway. Based on Hakanson (1980), the C_f was used to classify four levels of pollution: $C_f < 1$ represents no

or minimal pollution, $1 \leq C_f < 3$ indicates moderate pollution; $3 \leq C_f \leq 6$ indicates considerable pollution, and $C_f > 6$ indicates very high pollution.

The PN was calculated using the following formula:

$$PN = \sqrt{\frac{(\max C_f)^2 + (\text{ave} C_f)^2}{2}},$$

where $\max C_f$ is the maximum C_f among the four measured metals (Cu, Zn, Pb, or Cd) in a soil sample taken at 5, 10, 20, or 50 m away from highway each site, and $\text{ave} C_f$ is the average C_f of the other three metals. Based on the Chinese soil environmental quality assessment standard for green-food production areas (State Development Center for Green-food of China 2000), the PN value was graded into five categories: $PN \leq 0.7$, safety; $0.7 < PN \leq 1.0$, guard; $1.0 < PN \leq 2.0$, low pollution; $2.0 < PN \leq 3.0$, moderate pollution; and $3.0 < PN$, severe pollution.

Results

Soil particle-size composition, pH, and soil organic carbon concentration

In the top 0–20-cm layer, soils along G212 had less sand but more silt and clay than soils along G213 (Table 1). Soil pH was similar in areas between two highways (Table 1). Soil organic carbon concentration varied among different sampling transects, but independently to altitude on each highway (Table 1).

Across sampling transects and distances away from the highway, soil particle-size composition did not change with soil depth along either G212 or G213 (data not shown). Soil pH was slightly lower in the 0–20 cm (7.9) than in the 20–40 (8.2) or 40–60 cm (8.3) in G212 but was similar between soil

Table 1 Altitude, soil particle-size composition, pH, and organic carbon (SOC) concentrations at 0–20 cm at different sampling transects (data are values averaged over 10 positions along an 800-m sampling transect perpendicular to the G212 and G213 highways; soils were sampled on each side at 5, 10, 20, 50, and 400 m from the curb)

Highway	Transect	Altitude (m)	Particle size fraction (%)			pH	SOC (g kg ⁻¹)
			Sand (2–0.05 mm)	Silt (0.05–0.002 mm)	Clay (<0.002 mm)		
G212	1	2643	27.5 ± 1.5	52.7 ± 2.2	19.8 ± 1.5	8.0 ± 0.1	35.9 ± 2.5
	2	2749	28.2 ± 1.7	51.2 ± 1.5	20.5 ± 1.7	8.1 ± 0.1	33.3 ± 3.3
	3	2845	28.4 ± 2.1	53.1 ± 2.7	18.5 ± 1.5	8.1 ± 0.1	31.6 ± 2.3
	4	2911	27.8 ± 1.2	50.9 ± 3.0	21.4 ± 1.8	8.0 ± 0.0	33.2 ± 1.9
G213	5	3163	51.8 ± 1.4	34.1 ± 2.6	14.1 ± 1.1	8.1 ± 0.1	31.2 ± 1.1
	6	3292	52.2 ± 1.9	35.5 ± 1.8	12.4 ± 0.6	8.3 ± 0.1	22.7 ± 1.8
	7	3364	49.3 ± 1.7	36.8 ± 2.6	13.9 ± 1.0	8.1 ± 0.1	40.4 ± 3.2
	8	3463	52.9 ± 3.2	33.9 ± 1.9	13.3 ± 0.7	7.9 ± 0.0	34.9 ± 2.0
	9	3563	51.8 ± 2.5	33.5 ± 1.8	14.7 ± 0.9	8.0 ± 0.1	41.5 ± 2.5

Values after means are one standard errors ($n = 10$)

depths (8.0–8.1) in G213. Soil organic carbon concentration prominently decreased with soil depth (data not shown).

Background heavy metal contents in soil

We used the soil heavy metal contents at positions 400 m away from the curb of a highway as respective background values of heavy metal contents in soil at each transect. Background concentrations of Cu, Zn, Pb, and Cd in the 0–60-cm soil depth all varied considerably among transects on each side of G212 or G213 and showed no clear dependency on the altitude for all metals (Table 2). Along G212 or G213, background concentrations of each Cu, Zn, Pb, and Cd were comparable for most transects between left and right sides (Table 2). In addition, by averaging transects on both the left and right sides, the concentrations of Cu and Cd were smaller along G213 than along G212, whereas those of Zn and Pb were greater (Table 2). These results indicate a large spatial variation in background concentrations of Cu, Zn, Pb, and Cd in soil between the two highways. There were prominent differences in the background concentrations of four heavy metals between the values measured in this study and those issued by the Chinese government (Table 2).

Effects of traffic on metal contents in soil

Block effects were generally significant on concentrations of all heavy metals on both sides of G212 or G213 (Table 3).

Averaging three soil depths of 0–20, 20–40, and 40–60 cm, the Cu concentration increased from 400- to 5-m distance from the curb on both the left and right sides of each highway

(Fig. 2a, b; Table 3). This indicates that the effect of traffic activities on soil Cu content was found beyond 50 m away from highways. Averaging all sampling distances from the curb, the soil Cu concentration increased from the lower to upper depths in the profile on both sides of each highway (Fig. 2a, b; Table 3).

The Zn content throughout the 60-cm soil profile was greater at sampling positions 5, 10, and 20 m from the curb than at 50 or 400 m, on both sides of G212 (Fig. 2c, d; Table 3). On G213, Zn content averaged over the 60-cm soil profile was similar among sampling positions on the left side; however, it was greater at positions 5, 10, and 20 m than at 50 or 400 m away from the curb on the right side (Fig. 2c, d; Table 3). On both sides of G212, Zn was evenly distributed in the 0–60 cm profile (Fig. 2c, d; Table 3). However, on both sides of G213, the Zn content was greater at 0–20 cm than in the lower soil layers (Fig. 2c, d; Table 3).

The Pb content throughout the 60-cm soil profile was greater at 5 and 10 m from the curb than at 400 m on both sides of G212 (Fig. 2e, f; Table 3). On G213, soil Pb content was greater at 5, 10, 20, and 50 m from the curb than at 400 m on both sides (Fig. 2e, f; Table 3). On each side of both G212 and G213, the Pb content increased from the bottom to the surface on the soil profile (Fig. 2e, f; Table 3).

On the left side of each highway, there was a significant interaction effect between sampling distance and soil depth on Cd concentration (Fig. 2g, h; Table 3). The Cd content in the 0–20-cm soil layer was greater at 5 m from the curb than at the other distant positions on G212 (Fig. 2g; Table 3). On the left side of G213, the soil Cd content in the 0–20- and 20–40-cm depths was greater at 5 and 10 m from the curb than at the

Table 2 Background concentrations of Cu, Zn, Pb, and Cd in the 0–60 cm soil profile (average values over 0–20-, 20–40-, and 40–60-cm depths at positions 400 m from the curb) on the left and right sides at different investigation transects of the G212 and G213 highways

Highway	Transect	Altitude (m)	Cu (mg kg ⁻¹)		Zn (mg kg ⁻¹)		Pb (mg kg ⁻¹)		Cd (mg kg ⁻¹)	
			Left	Right	Left	Right	Left	Right	Left	Right
G212	1	2643	16.1	25.5	30.3	30.1	22.0	22.8	0.064	0.113
	2	2749	13.0	16.1	23.7	22.4	13.7	23.4	0.092	0.113
	3	2845	18.4	20.9	30.7	28.6	23.0	22.1	0.174	0.084
	4	2911	14.1	19.2	29.6	27.4	18.9	22.6	0.159	0.190
Mean ± one standard error			15.4 ± 1.2	20.4 ± 2.0	28.6 ± 1.7	27.1 ± 1.7	19.4 ± 2.1	22.7 ± 0.3	0.122 ± 0.03	0.125 ± 0.02
G213	5	3163	12.3	11.7	82.3	72.6	39.6	41.3	0.072	0.075
	6	3292	14.8	12.6	83.7	76.6	41.7	41.8	0.092	0.091
	7	3364	13.4	13.5	86.0	84.3	41.6	42.8	0.119	0.075
	8	3463	10.3	11.7	74.4	60.8	42.1	42.7	0.063	0.158
	9	3563	12.7	13.1	83.8	66.3	50.3	43.0	0.119	0.152
Mean ± one standard error			12.7 ± 0.7	12.5 ± 0.4	82.1 ± 2.0	72.1 ± 4.1	43.1 ± 1.9	42.3 ± 0.3	0.093 ± 0.01	0.110 ± 0.02
Tibet background value ^a			21.9		74.0		29.1		0.081	
China background value ^a			22.6		74.2		26.0		0.097	

^aData are from CNEMC (1990)

Table 3 Treatment effects (*P* values) for Cu, Zn, Pb, and Cd concentrations on both sides of the G213 and G212 highways using sampling distance (Di) and soil depth (De) as the two fixed factors. Analyses of variance were all conducted according to a block-structured sampling design (each transect was taken as a block)

Highway	Source	<i>df</i>	Left				Right			
			Cu	Zn	Pb	Cd	Cu	Zn	Pb	Cd
G212	Transect	3	0.001	<0.001	0.002	0.031	0.009	<0.001	0.010	0.093
	Di	4	<0.001	<0.001	<0.001	0.014	<0.001	<0.001	<0.001	0.519
	De	2	0.001	0.611	0.049	<0.001	0.006	0.040	0.001	0.040
	Di × De	8	0.596	0.824	0.909	<0.001	0.979	0.390	0.740	0.318
G213	Transect	4	<0.001	<0.001	0.003	0.010	0.044	0.020	0.013	0.059
	Di	4	<0.001	0.397	0.004	<0.001	<0.001	0.041	<0.001	<0.001
	De	2	0.065	0.338	0.089	<0.001	0.031	0.016	<0.001	0.014
	Di × De	8	0.207	0.981	0.249	<0.001	0.923	0.248	0.676	0.807

df degree of freedom

other positions (Fig. 2g; Table 3). On the right side of each highway, the Cd content across the 60-cm soil profile increased significantly at 5 and 10 m from the curb compared to the other distant positions (Fig. 2h; Table 3). On both highways, in areas close to the curb, the soil Cd content was generally higher in the upper 20 cm of the soil compared with the lower soil depths (Fig. 2g, h; Table 3).

In the 0–2 cm surface soil, the contents of Cu, Zn, Pb, and Cd all decreased from next to the curb to 400 m from the curb, on both sides of each highway ($P < 0.001$) (Fig. 3a–h). Among the four studied heavy metals, the Cd concentration showed the most sensitive response to traffic influences; its concentration was constant at 20 m from the highways but markedly increased in areas closer to the highways (Fig. 3g, h).

Concentrations of Cu, Zn, Pb, or Cd in soil were all not correlated with soil clay content in each highway (Table 4). Soil pH was negatively correlated with Cu, Zn, Pb, or Cd content in G212 and negatively correlated with Cd in G213 (Table 4). Soil organic carbon concentration was positively correlated to all the four heavy element concentrations in G212 and was positively correlated to Zn and Cd in G213 (Table 4).

Evaluation of metal pollution in soil

The C_f -calculation clearly showed that roadside soils to the 60-cm depth, within a distance of 50 m from the curbs of both G212 and G213, were all moderately contaminated with Cu, Zn, and Pb ($1 \leq C_f < 3$) (Fig. 4a–l). Cd pollution was limited with 20 m from the curbs on G212 but to 50 m distance from the curbs on G213, with a C_f range of $1 \leq C_f < 8$ (Fig. 4m–p). Relatively, Zn and Pb pollutions were more evident on G212 than on G213 (Fig. 4a–p) whereas Cd pollution was more visible in G213 than in G212.

The *PN* index showed that integrative heavy metal pollution of soil decreased with distance from the highways and

increased from the bottom to the surface layer in the soil profile (Fig. 5a–d). In addition, the extent of integrated pollution of soil was greater along G213 than G212, due to pronounced Cd associated pollution in G213 (Figs. 4m–p and 5a–d).

Discussion

The present study showed that road traffic significantly increased concentrations of Cu, Zn, Pb, and Cd in roadside soils in the eastern part (Gansu province) of the Tibetan Plateau. Cu, Zn and Pb contents to the 60-cm soil depth were all generally higher in the range from 50 m away to the highways than background values (400 m from the highways) of the respective heavy metals. Cd concentrations in soil to the 60 cm increased prominently within a distance of 20 m away from the highways, compared to background values of Cd in different depths. With shallower depths of soil sampling, Zhang et al. (2012, 2013, 2015) and Yan et al. (2013) found that rail and road traffic have significantly increased heavy metal contents in the top 5, 10, or 30 cm of soil in roadside areas in the northern parts (Qinghai province) of the Tibetan Plateau.

Significant block effects on concentrations of all heavy metals indicated that there were significant variations in the contents of four heavy metals in soil among sampling transects of each highway. On the other hand, these effects indicated that the block-designed sampling scheme was effective for precisely identifying the effects of traffic activity on heavy metal contents in soil by controlling spatial variations (Quinn and Keough 2002). It is appropriate to use soils sampled at 400 m away from highways as references to determine background concentrations of heavy metals. Along the Qinghai–Tibet highway (north region of the Tibetan Plateau), Zhang et al. (2015) found that concentrations of Cu, Zn, Pb, and Cd in the 0–10 cm soil become constant outside a distance of

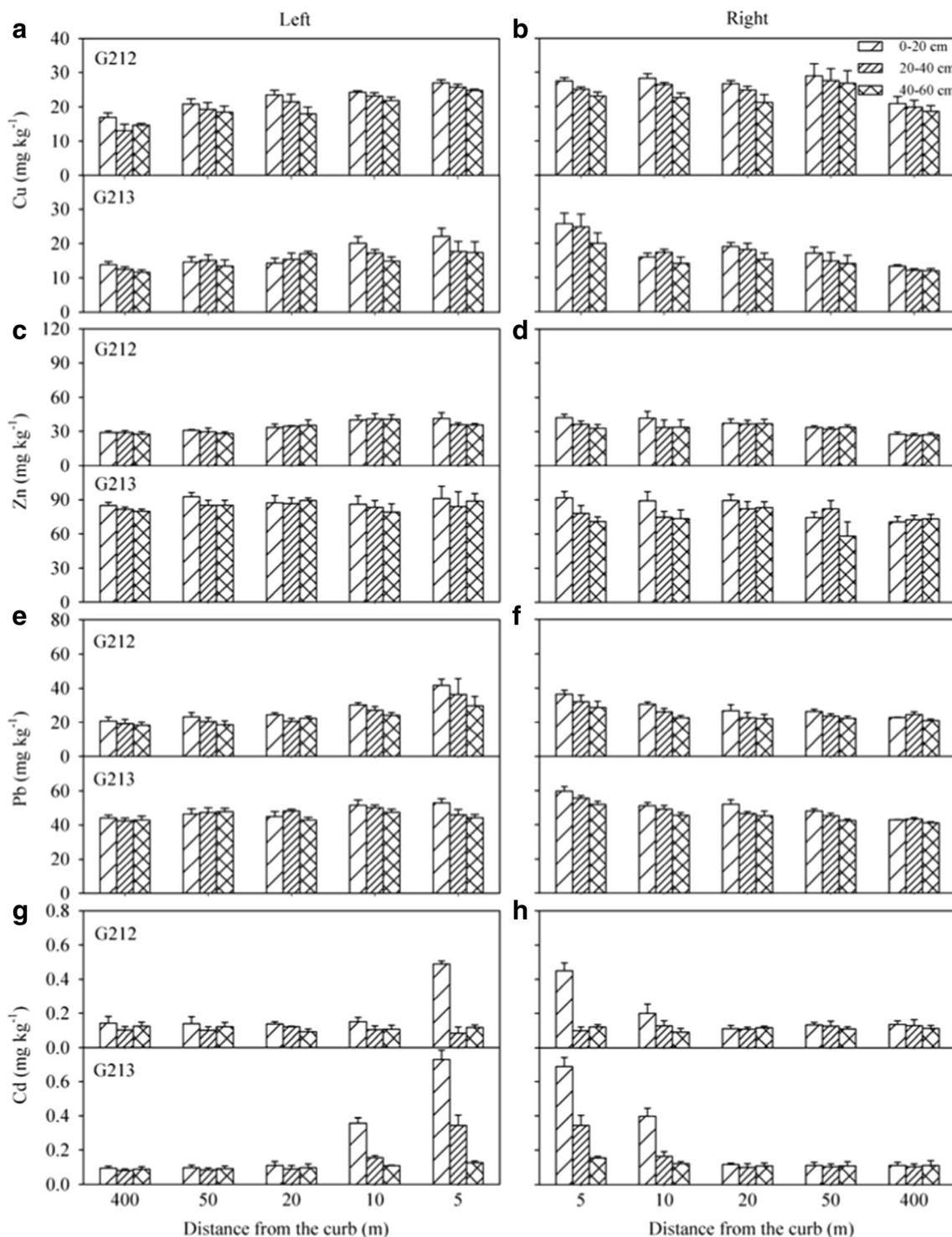


Fig. 2 Concentrations of Cu (a, b), Zn (c, d), Pb (e, f), and Cd (g, h) in the 0–20-, 20–40-, and 40–60-cm soil depths at 5, 10, 20, 50, and 400 m from the curb on the left and right sides of the G212 and G213 highways. Data shown are means + one standard errors ($n = 4$ in G212; $n = 5$ in G213)

250 m from the highway, and background concentrations of those heavy metals have been identified. In the present study, the background value of Zn at G212 was prominently lower than that found by Zhang et al. (2015); however, that of Pb at G213 was considerably higher. The background value of Zn at

G212 or Pb at G213, or Cd at both G212 and G213, was also prominently different from that of respective elements reported by Zhang et al. (2002) in the west regions (Tibet Autonomous Region) of the Tibetan Plateau. The variations in the soil heavy metal concentrations can be induced by

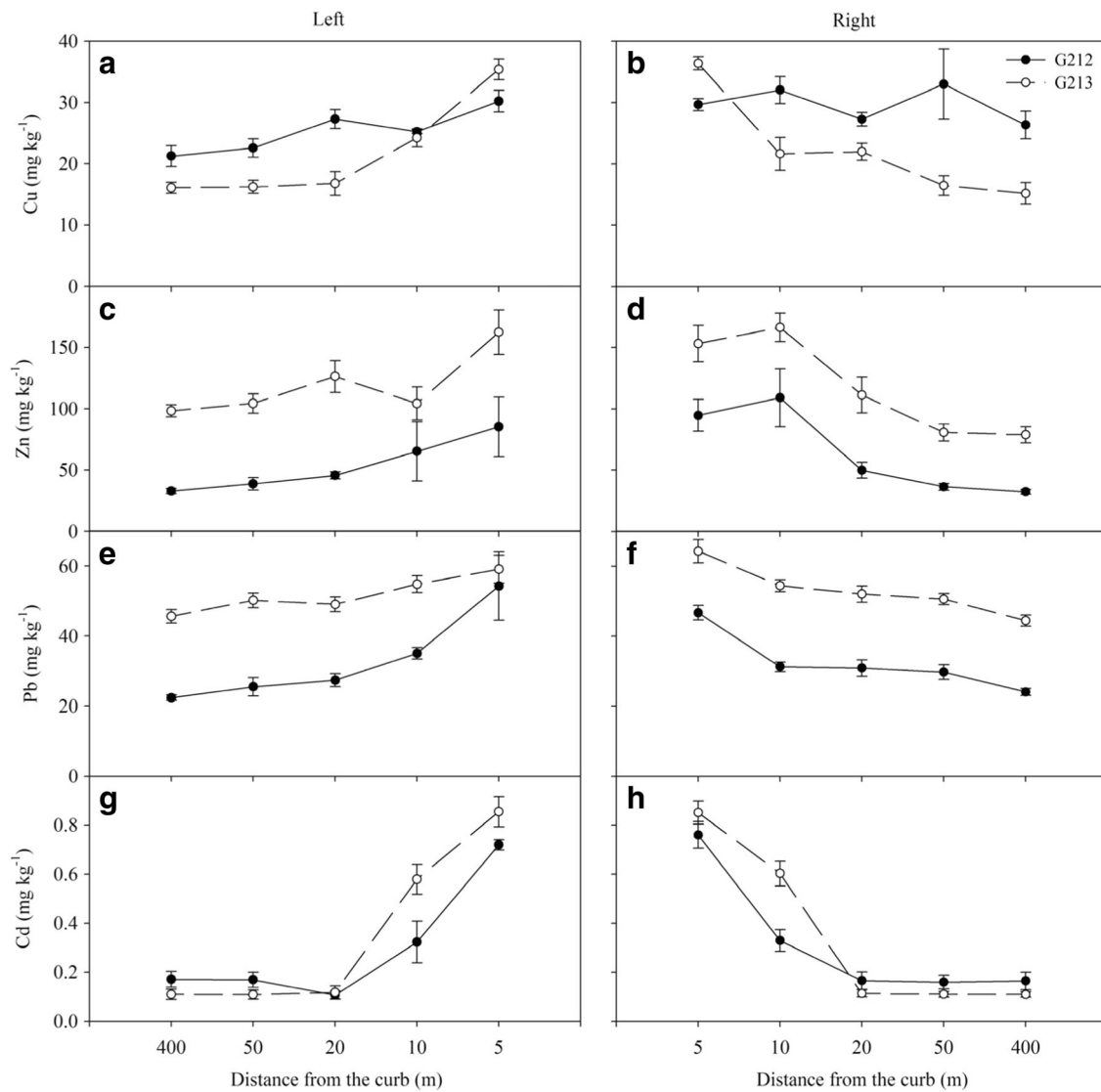


Fig. 3 Concentrations of Cu (a, b), Zn (c, d), Pb (e, f), and Cd (g, h) in the 0–2 cm soil profiles at 5, 10, 20, 50, and 400 m away from the curb on the left and right sides of the G212 and G213 highways. Data shown are means \pm one standard errors ($n = 4$ in G212; $n = 5$ in G213)

terrain, parent materials, climate, and vegetation (Pagotto et al. 2001; Zhang et al. 2002, 2012). The undulating terrain influences the accumulation and erosion of sediments that are likely to have naturally varying abundances of heavy metals (Zhang et al. 2002). In the present study, there was

considerable undulation of the terrain within sampling sections of both G212 and G213. This may have induced the considerable variation in background concentrations of heavy metals on a scale of less than 2 km² (0.8 km \times 1.5 or 2 km) at G212 or G213. The obvious differences in the background

Table 4 Pearson correlation coefficients (two-tailed) of Cu, Zn, Pb, and Cd contents with soil clay, pH, and organic carbon concentration across soil depths (0–2, 2–20, 20–40, and 40–60 cm), sampling distances (5, 10, 20, and 50 m) away from the curb and transects in G212 and G213

Metal	Clay		pH		Soil organic carbon concentration	
	G212	G213	G212	G213	G212	G213
Cu	0.024	−0.058	−0.435**	−0.003	0.364**	0.136
Zn	−0.021	−0.147	−0.334**	−0.073	0.283**	0.269**
Pb	0.039	0.020	−0.367**	−0.134	0.302**	0.076
Cd	−0.019	0.048	−0.363**	−0.259**	0.349**	0.245**

$n = 128$ and 160 for G212 and G213, respectively

*Significant at $P \leq 0.05$; **significant at $P \leq 0.01$

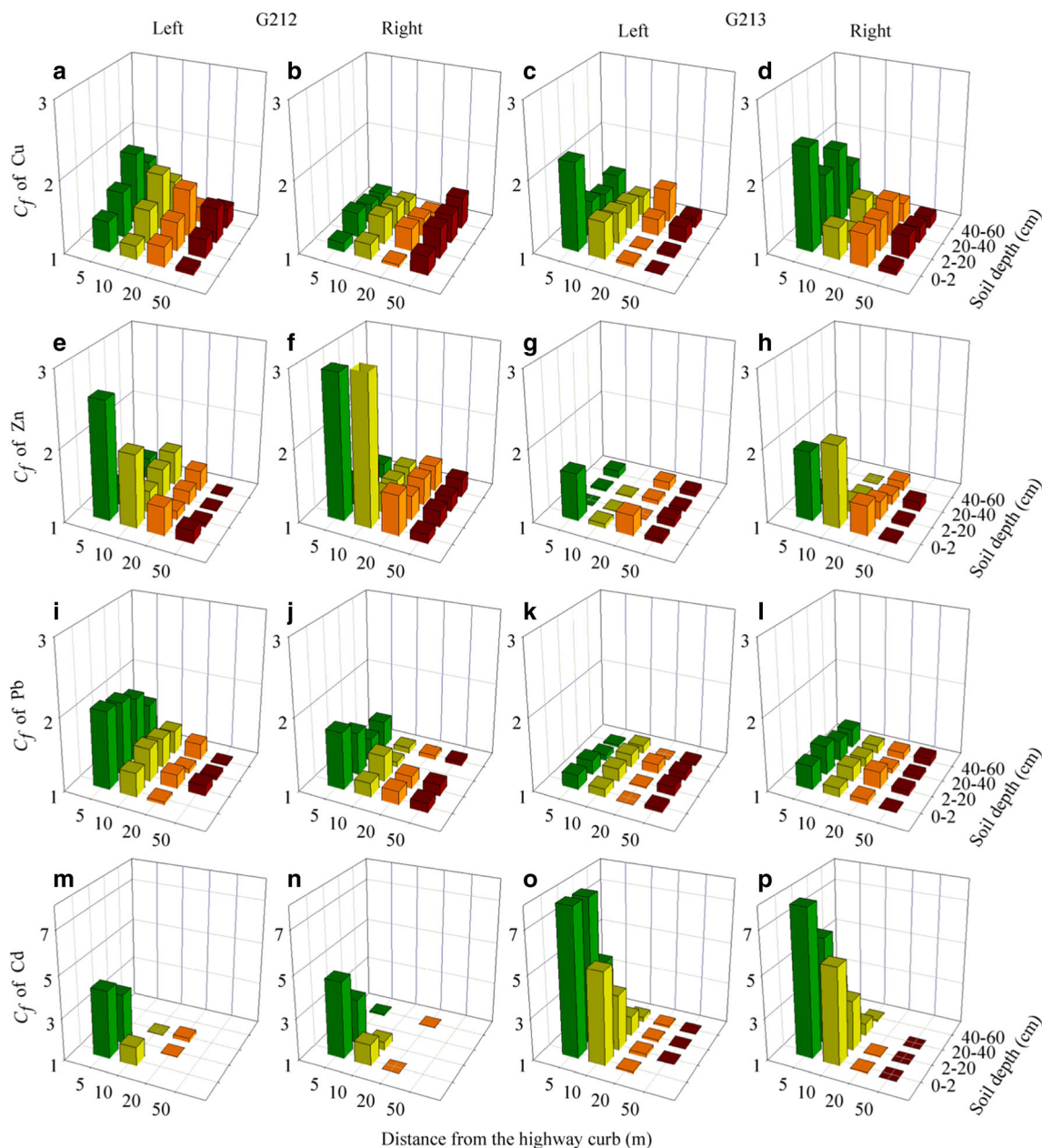


Fig. 4 Contamination factors (C_f) of the traffic-related metals on the left and right sides of the G212 and G213 highways. These factors were calculated by referring metal concentrations in the 0–2-, 2–20-, 20–40-, and 40–60-cm depths at different distances (5, 10, 20, and 50 m from the

curb) to respective metal concentrations in the same depths at 400 m away from the curb each side of highways. Data are values averaged over four and five transects for G212 and G213, respectively. **a–d** Contamination factors of Cu; **e–h** Zn; **i–l** Pb; **m–p** Cd

values of heavy metals in soils between the two highways could be associated with different soil parent materials. In the sampling section of G212, soils were developed from primary or modified loess materials, whereas in the sampling sections of G213, soils were developed from alluvial deposits. In addition, the climate and vegetation both differed between the sampling sections of G212 and G213. These differences were likely to have contributed to the observed variation in the background values of heavy metals between G212 and G213 (Pagotto et al. 2001; Zhang et al. 2002).

Heavy metals accumulate in roadside soils following their release from vehicles due to tailpipe emissions and the wearing of brakes, tires, and engine parts (Gratani et al. 1992; Zereini et al. 2012). Heavy metals in roadside soils may also come from casual scattering and rain washing of goods (e.g., metal wares, oils, coals, phosphate fertilizers, insecticides, concretes, and asphalts) carried by vehicles. The amount of heavy metal loss via uptake by plants is relatively small compared with the total quantity entering the soil (Nicholson et al. 2003). Therefore, roadside soils were major sinks of traffic-related heavy metals

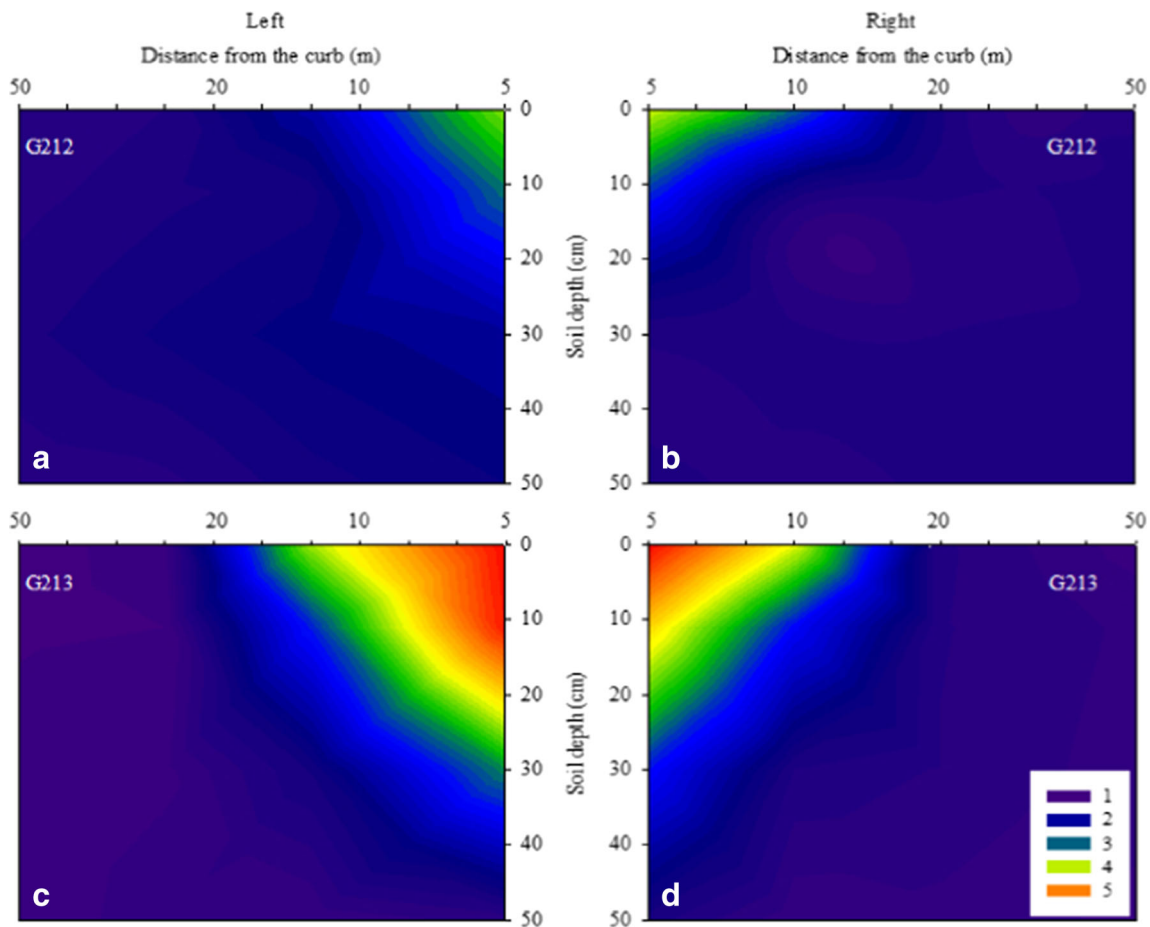


Fig. 5 Distributions of synthetic pollution index in the soil profile (across 0–2-, 2–20-, 20–40-, and 40–60-cm in depth and 5, 10, 20, and 50 m away from the curb in width, averaged over four transects in G212 and

five transects along G213 highway) on the left (**a, c**) and right (**b, d**) sides of the highways. Colors show different synthetic pollution levels (indexes)

on the Tibetan Plateau. Annual precipitations in the investigated areas are about 580 and 704 mm at G212 and G213, respectively. However, evapotranspiration is weak in the investigated areas because of the low air temperature and high altitude. Thus, the moderate amount of precipitation combined with a weak evapotranspiration potential might have led to a large infiltration flow through the profile. This would have helped convey heavy metals from the surface soil into the deeper soil layers (Calace et al. 2001; Zhao and Hazelton 2016). In G212, soil pH was lower in the top 20 cm than in the lower depth, favoring the leaching of heavy metals from the upper to the lower depths (Blake and Goulding 2002).

The generally higher heavy metal concentrations in the upper soil layers than in the lower layers could not be explained by road traffic factors alone, because this variation of heavy metals on the soil profile also applied to the reference locations (400 m away from highway) on each side of both highways. Besides the local traffic source, heavy metals in

areas may also derive from the atmospheric deposition (Rouillon et al. 2013; Bourcier et al. 1980; Chen et al. 1991; Martin and Coughtrey 1982). At reference locations, we calculated C_f of heavy metals in the 0–2-, 2–20-, and 20–40-cm depths, referring to the 40–60-cm depth (Fig. 6a–d). This result indicated that compared to the 40–60 cm, the upper depths were all generally contaminated with four measured heavy metals. At the reference locations 400 m away from highways, traffic effects would be trivial. It is very likely that pollutants transported by airstreams from regions beyond the Tibetan Plateau were also contributable to the increased heavy metal concentrations in the upper relative to the lower soil depths in areas. This conjecture, however, needs to be further clarified. Exogenous heavy metals first accumulate in the surface layer and then gradually transfer downwards. In addition, upper soil layers contain large amounts of soil organic matter that has a great affinity to heavy metals (Balabane and Oort 2002). This was true in the present study, as shown by positive correlations

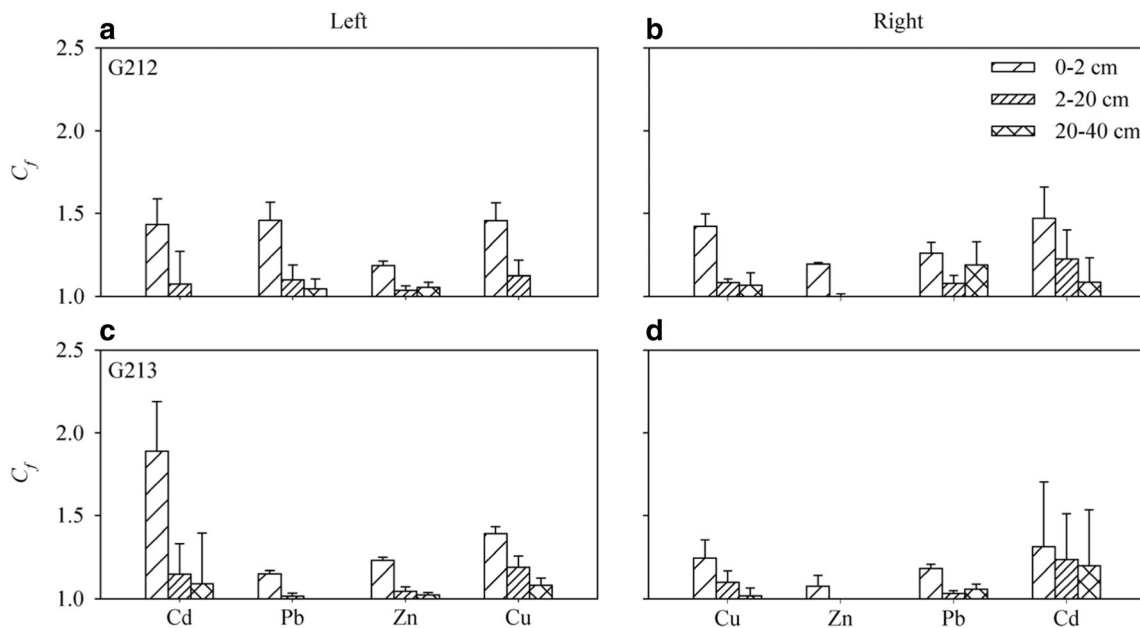


Fig. 6 Contamination factors (C_f) of the traffic-related metals in the 0–2-, 2–20-, and 20–40-cm depths in positions at 400 m away from the curb on each of the left and right sides of the G212 and G213 highways. These factors were calculated by comparing respective metal concentrations in

the 0–2-, 2–20-, and 20–40-cm depths with those in the 40–60 cm of the same position. Data are values averaged over 4 and 5 positions for G212 and G213, respectively. **a** C_f of Cu, Zn, Pb, and Cd on the left side of G212; **b** right side of G212; **c** left side of G213; **d** right side of G213

in concentrations between soil organic carbon and heavy metals except Cu and Pb in G213. Negative correlations between soil pH and four heavy metals on G212 were ascribed to contrasted change patterns between soil pH and heavy metal concentrations in the profile. Soil pH increased with depth in G212 while heavy metal concentrations were all greater in the upper than in the lower soil layers.

G212 was built earlier than G213 while the highway G213 had a larger traffic flow than the G212. Zn may come from paving materials (asphalt) (Al-Awadhi and Aldhafiri 2016). Pb is mainly contained in gasoline (Al-Awadhi and Aldhafiri 2016), which however, has been forbidden to use for about two decades in China. Thus, a shorter service term for G213 than G212 would be responsible for less evident pollutions from Zn and Pb in G213, despite a larger traffic flow on the G213 than the G212. Cd widely exists in lubricating oils, diesel oils, tires, batteries, electroplated surfaces, and many goods in circulation (Al-Awadhi and Aldhafiri 2016). Therefore, the larger traffic flow on G213 might have induced more visible contamination from Cd, compared to G212.

Among the four heavy metals studied, Cd was most sensitive to traffic activity, as also indicated in other research (Yan et al. 2013; Wang et al. 2017). The background concentration of Cd in soil was much smaller than those of Cu, Zn, and Pb. Therefore, the Cd pollution induced by traffic had a stronger contrast with the smaller

background values than was observed for Cu, Zn, or Pb. In addition, Cd can be more rapidly adsorbed on soil substrates than the other elements (Christensen 1984; Pagotto et al. 2001; Liu et al. 2009).

Conclusions and implications

Traffic effects in increasing concentrations of Cu, Zn, and Pb in roadside soils in the eastern Tibetan Plateau were found in areas within 50 m from the curb, and the effects reached as deep as 60 cm in the soil profile. Cd was the most sensitive element to the effect of traffic activities, having more prominent enrichments in the top 20-cm depth in areas within 20 m from the curb than the other three metals. Background values of heavy metals changed significantly in space in the investigated region. For assessment of heavy metal pollutions in soil of mountainous areas, it is necessary to in situ identify the background values. Clean fuel, automotive components resistant to wear and careful packing of shipped goods should be encouraged. Moreover, construction of an isolation belt is crucial to prevent animals from grazing within 50 m of highways on the Tibetan Plateau.

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