Available online at www.sciencedirect.com

ScienceDirect

www.elsevier.com/locate/jes

JES JOURNAL OF ENVIRONMENTAL SCIENCES

www.jesc.ac.cn

Effects of road dust on the growth characteristics of *Sophora japonica* L. seedlings

Le Bao[1,2], *Laiye Qu*[1], *Keming Ma*[1,*], *Lin Lin*[1,2]

1. *State Key Laboratory of Urban and Regional Ecology, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, Beijing 100085, China*
2. *University of Chinese Academy of Science, Beijing 100049, China*

ARTICLE INFO

Article history:
Received 17 April 2015
Revised 10 August 2015
Accepted 27 August 2015
Available online 5 April 2016

Keywords:
Dust composition
Dust load
Dust grain size
Nitrogen
Biomass

ABSTRACT

Road dust is one of the most common pollutants and causes a series of negative effects on plant physiology. Dust's impacts on plants can be regarded as a combination of load, composition and grain size impacts on plants; however, there is a lack of integrated dust effect studies involving these three aspects. In our study, *Sophora japonica* seedlings were artificially dusted with road dust collected from the road surface of Beijing so that we could study the impacts of this dust on nitrogen/carbon allocation, biomass allocation and photosynthetic pigments from the three aspects of composition, load and grain size. The results showed that the growth characteristics of *S. japonica* seedlings were mostly influenced by dust composition and load. Leaf N, root–shoot ratio and chlorophyll a/b were significantly affected by dust composition and load; leaf C/N, shoot biomass, total chlorophyll and carotenoid were significantly affected by dust load; stem N and stem C/N were significantly affected by dust composition; while the dust grain size alone did not affect any of the growth characteristics. Road dust did influence the growth characteristics more extensively than loam. Therefore, a higher dust load could increase the differences between road dust and loam treatments. The elements in dust are well correlated to the shoot N, shoot C/N, and root–shoot ratio of *S. japonica* seedlings. This knowledge could benefit the management of urban green spaces.

Introduction

Road dust is one of the most common pollutants in cities and consists of particles from atmospheric and vehicular-related deposition, as well as materials produced by soil erosion and pavement abrasion (Tang et al., 2013). Road dust can cause a series of negative effects to plant physiology; for example, by reducing diffusive resistance (Thompson et al., 1984), blocking the stomata (Farmer, 1993), increasing the absorption of infrared radiation (Eller, 1977), lowering pigment contents (Prusty et al., 2005; Prajapati and Tripathi, 2008), and restraining photosynthesis (Chaturvedi et al., 2013). However, quantitative studies of the effects of road dust are fewer than qualitative ones on this subject.

Dust's impacts on plants can be regarded as a combination of dust load, composition, and grain size impacts on plants. Studies on the effects of dust loads outnumber those on dust composition and grain size. In previous artificial dusting studies, several dust load treatments were compared (Armbrust, 1986; Shukla et al., 1990; Charlesworth et al.,

* *Corresponding author*. E-mail: mkm@rcees.ac.cn (Keming Ma).

http://dx.doi.org/10.1016/j.jes.2015.08.031
1001-0742/

2003; Kuki et al., 2009), concerning loam, fly ash, iron dust, and cement dust. As for the dust composition's effects on plants, in the ore dust studies, ore element contents and plant characteristics were often linked (Kuki et al., 2008; Neves et al., 2009). However, comparison is lacking for the ways dusts of different compositions affect plants. Studies of grain size effects on plants are rare. The stomatal conductance of plants dusted by carbon black of different grain sizes has been studied (Hirano et al., 1995). When the dust grain size was larger than the plants' stomata openings, then the particles piled up on the pores. If the grains were even smaller, then they clogged the stomata and affected the gas exchange and the growth of the plants(Rai et al., 2010). What now is lacking are integrated studies of dust effects resulting from the dust load, composition and grain size.

In North China, *Sophora japonica* L. is a native and widely distributed tree species. It is also the dominant street tree species planted in Beijing as it accounts for 81% of the street trees in urban areas of Beijing (Zheng and Zhang, 2011). Its growth plays an important role in adjusting the air quality and keeping the urban ecosystem healthy. In our study, *S. japonica* seedlings were artificially dusted with road dust collected from the road surfaces of Beijing in order to study the impacts of the road dust on nitrogen/carbon allocation, biomass allocation and the photosynthetic pigments related to dust composition, dust load and grain size.

Road dust includes high concentrations of heavy metals, such as Cd, Cr, Cu, Pb, and Zn (Charlesworth et al., 2003; Tang et al., 2013), which are different in composition from natural dusts such as loam. To highlight the dust composition effects of road dust, we used loam from an unpolluted rural area for comparison. Loam is often used to study the physical effects of dust on plants (Armbrust, 1986; Hirano et al., 1995). Road dust and loam were the two dust composition treatments used in our study. To determine the dust loads' effects, dust loads on the street trees *S. japonica* in our previous study and an extremely high dust load situation were simulated. As for dust grain size, a dry sieving method was used to divide the dust and loam into fine and coarse grain sizes. We assumed that the effects of dust on the growth characteristics of *S. japonica* seedlings would be increased with higher dust loads as well as finer dust grain sizes. The purposes of our work were to detect (1) whether dust load, composition, and grain size all impact the trees' growth characteristics; if so, then which characteristics do they impact? (2) Are there differences between road dust and loam effects on plants' growth characteristics? Do the elements in dust relate to these growth characteristics?

1. Materials and methods

1.1. Plant experimental materials

Seed germination was performed under greenhouse conditions at the Beijing Forestry University Forest Science Co., Ltd., in April 2012. *S. japonica* seedlings were obtained from the germination of seeds provided by a nursery in Qingyuan County in Hebei Province. The seeds were soaked in 85–90°C water for 24 hr and then germinated in nursery trays after the seeds swelled. If the seeds did not swell properly, we repeated the soaking once or twice. Then, 20 days after emergence, the seedlings were transferred to plastic pots containing cultivation soil (sand + peat + vermiculite in a proportion of 2:2:1). Each pot contained one plant. In August 2012, seedling heights were 30–50 cm, and the crown widths were about 30 cm.

1.2. Collection of the road dust

The road dust used in the experiment was collected from the surfaces of some busy streets between the 2nd Ring Road and 3rd Ring Road in Beijing. The loam used in this experiment was collected from a mountainous area far from traffic in Miyun County of Beijing. The road dust and loam were sieved by using a fine nylon screen to separate coarse particle diameter in the range of 53–106 μm and fine particles diameter < 53 μm). To test the metal and phosphorus contents, road dust and loam samples were digested using HNO_3 and HF in a microwave digestion system according to USEPA method 3052 (USEPA, 1996). Concentrations of Cu, Zn, Cr, Pb, Ni, P and K elements were then determined using inductively coupled plasma mass spectrometry (ICP-MS). Nitrogen and carbon contents were tested by an Elementar Vario EL III elemental analyzer using the dry combustion method. The pH values were tested using a PHS-3c acidometer. The elemental contents and pH of coarse loam, fine loam, coarse road dust, and fine road dust are shown in Table 1.

1.3. Maximum dust load experiment and treatments

The seedlings were irrigated and then their leaves were washed 3 days before the artificial dusting. We placed plastic wrap on the soil surface to avoid any dust retention. Road dust was then applied by using a dust sprayer until the leaf surfaces could not accommodate any more dust. The maximum applied dust (A_{max}) was then recorded. Ten replicate leaves were collected to measure the maximum dust load (D_{max}). Whole leaves from each seedling were washed in distilled water and ultrasonically oscillated for 3 min. Then the wash water was vacuum filtered through a pre-weighed filter membrane ($\Phi = 0.45$ μm) (FreerSmith et al., 1997). The dry mass increments of filter membranes were divided by the leaf areas to obtain the maximum dust load (D_{max}).The results of the maximum dust load experiment are shown in Table 2, and the average of the maximum dust load D_{max} was 16.97 g/m^2, which corresponds to maximum applied dust of 73.08 g/pot.

In October 2012, a dusting experiment was conducted that included nine treatments, and each treatment had nine replicate seedlings. In our previous study, the dust load of *S. japonica* in streets was significantly higher than that of *S. japonica* in parks, and the dust load of *S. japonica* street trees had a maximum value of 2.812 g/m^2 and an average value of 0.683 g/m^2 (Dai et al., 2012). Therefore, we regarded 2.812 g/m^2 as the low dust load treatment. We defined the maximum dust load of 16.97 g/m^2 as the high dust load treatment. We took the A_0 treatment with no dust as control. Immediately after the dusting, three seedlings per treatment were cut to test their actual dust load. The dust load amounts of treatments are shown in Table 3.

Table 1 – Element contents and pH of coarse loam, fine loam, coarse road dust, fine road dust.

	Cu (mg/kg)	Zn (mg/kg)	Cr (mg/kg)	Pb (mg/kg)	Ni (mg/kg)	P (g/kg)	K (g/kg)	N (g/kg)	C (g/kg)	pH
Coarse loam	23.43	33.24	64.81	3.22	17.57	0.48	13.82	0.25	10.24	7.61
Fine loam	34.64	49.25	101.19	1.76	19.37	0.65	15.40	0.35	18.47	7.76
Coarse road dust	87.04	289.76	144.79	40.04	23.85	0.82	14.07	1.40	40.24	9.35
Fine road dust	178.79	404.08	171.92	55.13	35.93	1.08	12.42	1.83	54.71	9.46

The seedlings were irrigated and the leaves were washed 3 days before dusting and then treated with the amounts of dust shown in Table 3. The seedlings were kept stable for 21 days and irrigation water was applied directly to the soil surface using a tubule.

1.4. *Biomass, nitrogen, and pigment measurements*

Three seedlings from each treatment were excavated and washed in water. The roots, stems, and leaves were separated and oven-dried at 80°C for at least 24 hr to obtain the dry weight biomass. Then dried roots, stems, and leaves were powdered using a ball mill. Nitrogen and carbon contents were tested by a Elementar Vario EL III elemental analyzer using the dry combustion method. The second, third, and fourth leaves from the top of each sprig were collected and put into liquid nitrogen, using three seedlings for each treatment. Fresh leaves were extracted with 95% ethanol and the absorbance of the leaf pigment extract was measured separately at 470, 649, and 665 nm. Chlorophyll and carotenoid were calculated according to the specific absorption coefficients of Lichtenthaler (Lichtenthaler, 1987).

1.5. *Statistical analyses*

Comparisons of three treatments were done using the LSD test of one-way analysis of variance (ANOVA). Comparisons between two treatments were done using the independent T test. Univariate GLM was used to analysis the effects of three dust treatments and their interactions. All of the above tests were done using SPSS 15.0.

2. Results

2.1. *Effects of dust composition, load and grain size on carbon and nitrogen allocation*

Based on the Multivariate ANOVA results (Table 4), dust composition and load significantly affected leaf N. Dust composition significantly affected stem N and stem C/N ratio. Dust load significantly affected leaf C/N ratio. The interaction of dust composition and load affected root N. The interaction of all three dust attributes affected root N and root C/N. As shown in Fig. 1, leaf N of the A8 treatment was significantly lower than A0. Stem N of A2, A4, A5, and A6 were significantly lower than A0. Root N of A7 was significantly higher than A3. Leaf C/N of the A8 treatment was significantly higher than A0, and that of A7 was significantly higher than A3. Stem C/N of A2 was significantly higher than A0 and A1, and that of A8 was significantly higher than A0. In general, leaf N and stem N decreased, while leaf C/N and stem C/N increased after dusting. Root N and root C/N had no obvious trend. Stem N for the road dust treatment (A2) was significantly lower than that of the corresponding loam treatment (A1), while stem C/N of the road dust treatment (A2) was significantly higher than that of the corresponding loam treatment (A1). High load treatment (A7) had significantly higher leaf C/N than the corresponding low-load treatment (A3).

Table 2 – Results of maximum dust load.

	Sample number	Mean	Minimum	Maximum	Std. deviation
Dust load (g/m^2)	10	16.97	13.84	20.49	0.68
Applied dust (g/pot)	10	73.08	61.27	84.85	2.43

2.2. *Effects of dust composition, load, and grain size on biomass allocation*

According to the Multivariate ANOVA results (Table 5), shoot biomass and root–shoot ratio were significantly affected by the dust load. Root–shoot ratio was also significantly affected by dust composition. As shown in Fig. 2, shoot biomass decreased, except in the A1 treatment. The shoot biomass of A5 was significantly lower than A1. Root biomass decreased in A3, A4, A5, A6, and A7. The root biomass of A5 was significantly lower than A1, and that of A8 was significantly higher than A7. Total biomass decreased, except in the A1 treatment. The total biomass of A5 was significantly lower than A1. The root–shoot ratio increased in A4, A5, A6, A7 and A8. In general, shoot biomass, root biomass and total biomass

Table 3 – Dust load, dust attribute and grain size of different treatments.

Treatment	Applied dust (g/pot)	Dust load (g/m^2)	Dust attribute	Grain size (μm)
A0	0	0	None	None
A1	12.11	3.73	Loam	53–106
A2	12.11	3.93	Road dust	53–106
A3	12.11	3.23	Loam	<53
A4	12.11	4.21	Road dust	<53
A5	73.08	15.68	Loam	53–106
A6	73.08	17.16	Road dust	53–106
A7	73.08	16.37	Loam	<53
A8	73.08	17.36	Road dust	<53

Table 4 – Effects of three dust treatments and their interactions on N and C/N of different organs.

Source	df	Leaf N (g/kg)		Stem N (g/kg)		Root N (g/kg)		Leaf C/N		Stem C/N		Root C/N	
		F	p	F	p	F	p	F	p	F	p	F	p
Dust composition	1	5.878	0.028*	8.857	0.009**	4.063	0.061	4.156	0.058	9.131	0.008**	2.185	0.159
Dust load	1	5.241	0.036*	1.627	0.220	0.221	0.645	6.276	0.023*	1.064	0.318	0.176	0.680
Grain size	1	3.253	0.090	0.896	0.358	2.947	0.105	1.544	0.232	1.281	0.274	2.342	0.145
Dust composition × load	1	0.572	0.460	0.542	0.472	4.849	0.043*	0.815	0.380	0.167	0.688	3.482	0.080
Dust composition × grain size	1	0.667	0.426	0.171	0.684	1.889	0.188	0.543	0.472	0.374	0.549	1.294	0.272
Dust load × grain size	1	0.749	0.400	0.042	0.841	0.093	0.764	0.738	0.403	0.082	0.778	0.631	0.439
Dust composition × load × grain size	1	0.005	0.945	0.317	0.581	7.213	0.016*	0.006	0.939	0.110	0.744	7.144	0.017*

F means *F*-value in analysis of variance; *p* means *p*-value in analysis of variance.
* Significant at the 0.05 level (2-tailed);
** Significant at the 0.01 level (2-tailed).

had a declining trend after dusting, while the root–shoot ratio had an increasing trend. The high load treatment (A5) had significantly lower shoot biomass, root biomass, and total biomass than the corresponding low load treatment (A1). The root biomass of the road dust treatment (A8) was significantly higher than the corresponding loam treatment (A7).

2.3. Effects of dust composition, load and grain size on photosynthetic pigments

According to the Multivariate ANOVA results (Table 6), chlorophyll a/b, total chlorophyll, and carotenoid were significantly affected by dust load. Chlorophyll a/b was significantly affected

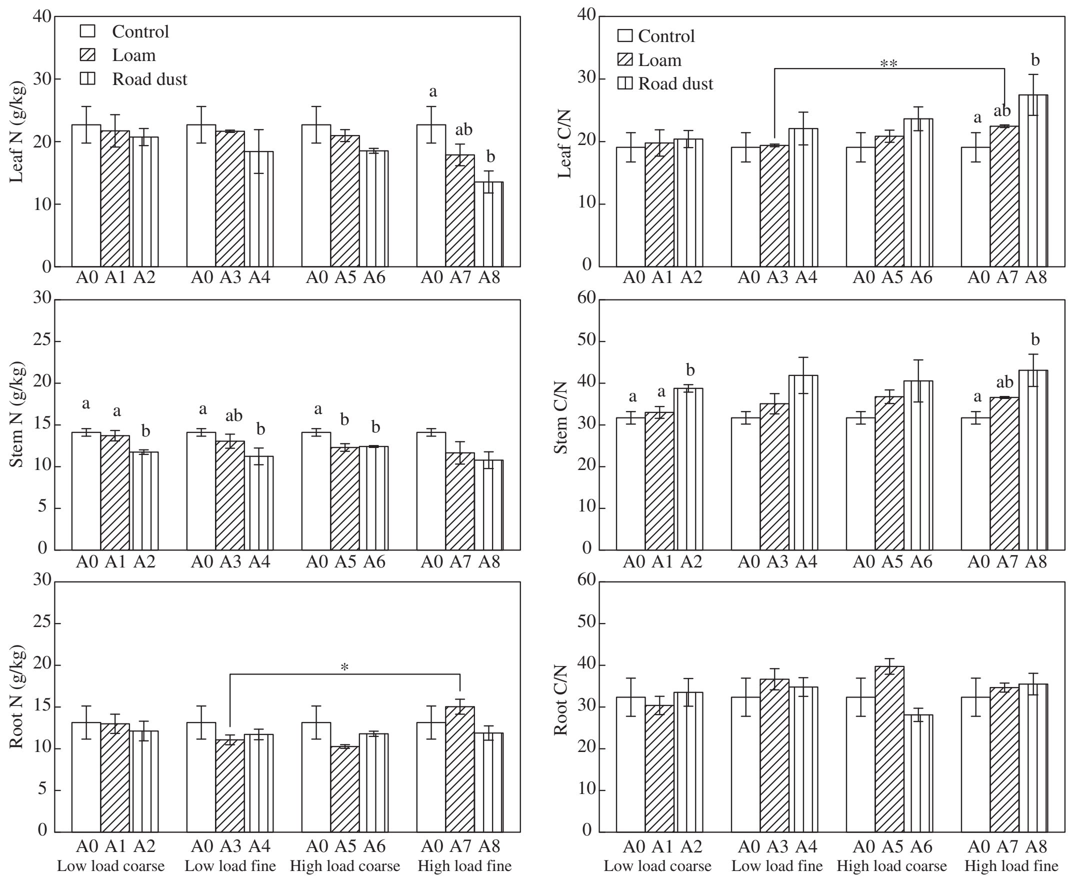

Fig. 1 – Nitrogen and C/N in leaf, stem and root of different treatments. Different letters indicate significant difference by LSD (Least Significant Difference) test ($p \le 0.05$); * indicates significant difference by *t*-test ($p \le 0.05$); * indicates significant difference by *t*-test ($p \le 0.001$). A0–A8 treatments refer to Table 3.**

Table 5 – Effects of three dust treatments and their interactions on shoot biomass, root biomass, root–shoot ratio and total biomass.

Source	df	Shoot biomass (g)		Root biomass(g)		Root–shoot ratio		Total biomass (g)	
		F	*p*	*F*	*p*	*F*	*p*	*F*	*p*
Dust composition	1	1.493	0.238	0.115	0.738	5.719	0.028*	0.220	0.644
Dust load	1	8.831	0.008**	1.171	0.293	6.612	0.019*	4.098	0.058
Grain size	1	1.188	0.290	0.189	0.669	0.739	0.401	0.103	0.752
Dust composition × load	1	2.281	0.148	1.721	0.206	0.726	0.405	1.087	0.311
Dust composition × grain size	1	0.549	0.468	1.530	0.232	2.598	0.124	0.067	0.799
Dust load × grain size	1	1.423	0.248	3.077	0.096	3.052	0.098	0.658	0.428
Dust composition × load × grain size	1	0.652	0.430	1.090	0.310	0.372	0.549	1.660	0.214

F means *F*-value in analysis of variance; *p* means *p*-value in analysis of variance.
* Significant at the 0.05 level (2-tailed);
** Significant at the 0.01 level (2-tailed).

by dust composition. Carotenoid was significantly affected by the interaction of dust load and grain size. As shown in Fig. 3, chlorophyll a/b values of the A6 and A8 treatments were significantly lower than A0. The total chlorophyll values of A7 and A8 were significantly lower than A0. The carotenoid level of A6 was significantly higher than A0. In general, dust treatments decreased chlorophyll a/b, total chlorophyll, and carotenoid. Significant differences appeared in all high load treatments.

2.4. Relationship between dust elements and growth characteristics

Metal and nutrient elements in the dust caused a dust composition difference between road dust and loam (Table 1), which correlated well with the growth characteristics (Table 7). Leaf N was negatively correlated with Cu, Zn, Cr, Ni, P, and C contents of dust. Stem N was negatively correlated with all elements, except the K contents in the dust, while

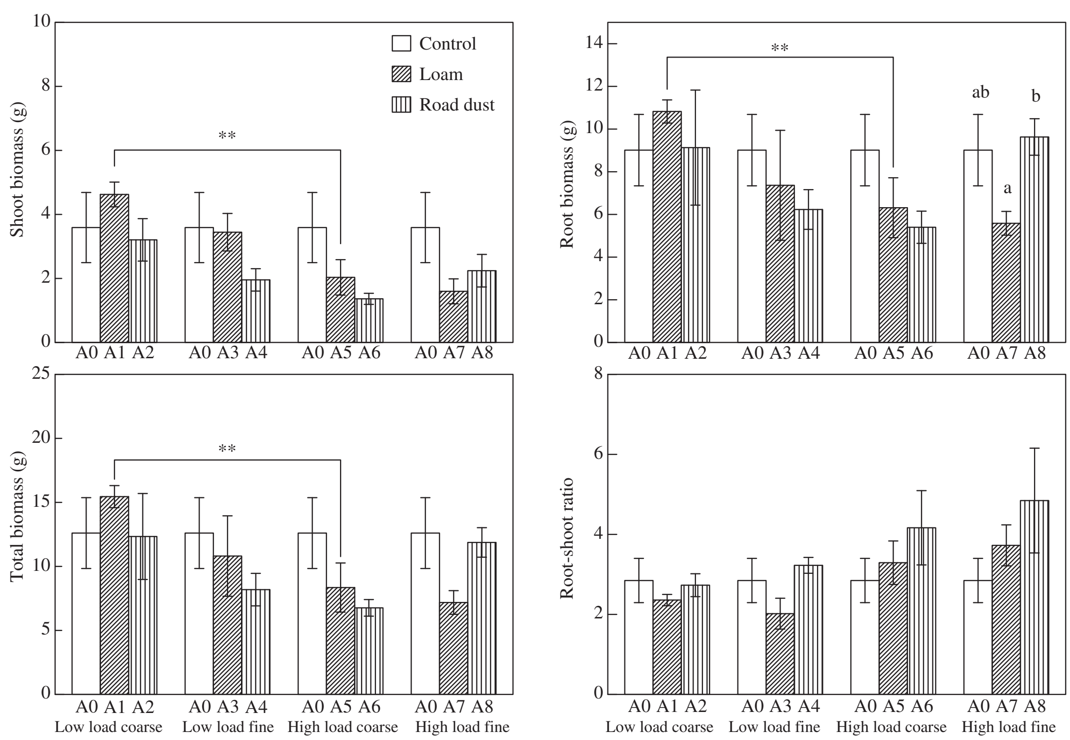

Fig. 2 – Shoot biomass, root biomass, total biomass and root–shoot ratio of different treatments. Different letters indicate significant difference by LSD test ($p \le 0.05$), * indicates significant difference by *t*-test ($p \le 0.05$). A0–A8 treatments refer to Table 3.

Table 6 – Effects of three dust treatments and their interactions on chlorophyll a/b, total chlorophyll and carotenoid.

Source	df	Chlorophyll a/b		Total chlorophyll (mg/g)		Carotenoid (mg/g)	
		F	*p*	*F*	*p*	*F*	*p*
Dust composition	1	5.464	0.028 *	3.587	0.070	3.935	0.059
Dust load	1	5.089	0.033 *	5.173	0.032 *	5.665	0.026 *
Grain size	1	1.151	0.294	0.696	0.412	2.040	0.166
Dust composition × load	1	3.561	0.071	0.156	0.696	1.549	0.225
Dust composition × grain size	1	0.005	0.944	0.677	0.419	0.095	0.760
Dust load × grain size	1	1.627	0.214	2.499	0.127	4.367	0.047 *
Dust composition × load × grain size	1	0.007	0.933	0.977	0.333	1.703	0.204

F means *F*-value in analysis of variance; *p* means *p*-value in analysis of variance.
* Significant at the 0.05 level (2-tailed).

stem C/N ratio was positively correlated with all elements, except K contents. Leaf C/N ratio was positively correlated with Cr, Ni, P, and C contents of the dust. Root–shoot ratio was positively correlated with Cu, Cr, Ni, P, and C contents of the dust. Pigments were not correlated with dust elements. To sum up, metals, P, N, and C contents in the dust had negative effects on shoot N, but had positive effects on shoot C/N ratio and the root–shoot ratio. Higher N contents in road dust did not make the shoot or root N of the road dust treatments higher.

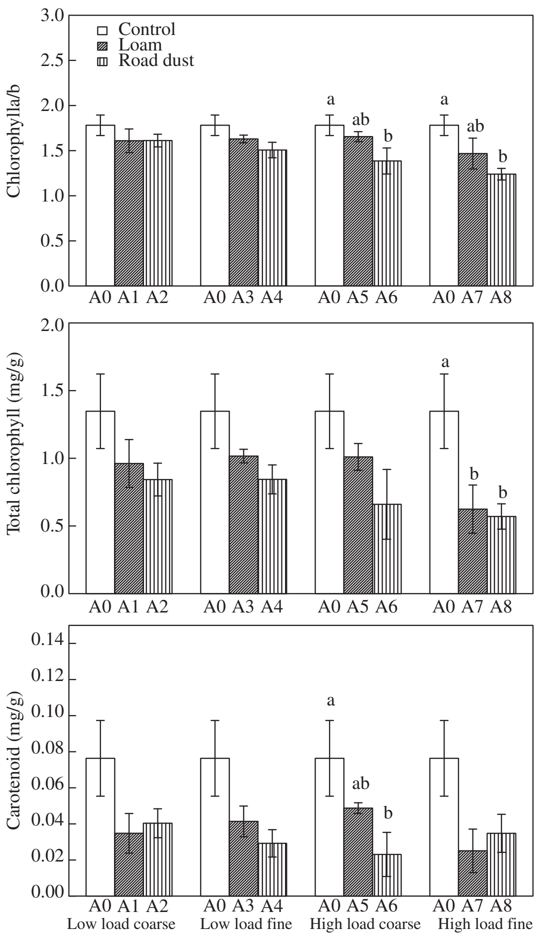

Fig. 3 – Chlorophyll a/b, total chlorophyll and carotenoid of different treatments. Different letters indicate significant difference by LSD test ($p \leq 0.05$). A0–A8 treatments refer to Table 3.

As shown in Table 8, leaf N positively correlated with chlorophyll a/b and total chlorophyll, but negatively correlated with leaf C/N, stem C/N, and root–shoot ratio. Stem N positively correlated with chlorophyll a/b, but negatively correlated with leaf C/N, stem C/N, and root–shoot ratio. Root N negatively correlated with root C/N. Higher root–shoot ratio and lower pigments in road dust treatments corresponded to lower shoot N and higher shoot C/N.

3. Discussion

3.1. Growth characteristics were affected by dust

In our study, most growth characteristics were influenced by the dust. Shoot biomass, root biomass, total biomass, leaf N, stem N, chlorophyll a/b, total chlorophyll, and carotenoid of *S. japonica* seedlings had a declining trend after dusting, while root–shoot ratio, leaf C/N, and stem C/N had an increasing trend. A higher root–shoot ratio and lower pigments in road dust treatments corresponded to lower shoot N and higher shoot C/N. Plants allocate relatively less biomass to leaves and more to their roots when nitrogen is in short supply (Lambers et al., 1998). N plays a crucial role in photosynthetic production, and total leaf N had a linear correlation with chlorophyll content (Evans, 1989; Watari et al., 2012). Our results were consistent with these studies.

Decreases in N content, biomass, and pigments were found in previous research, while C/N, root biomass and root–shoot ratio were not reported. Leaf N of street trees was significantly lower than in trees in clean areas (Chaturvedi et al., 2013). Simulated dusting caused leaf and stem N of cotton to decrease (Li, 2005). Cement dust caused a decline in needle N content of *Pinus sylvestris* (Mandre, 2009) and N content of wheat (Pandey and Sanjeev, 1996).Cement dust also decreased the dry mass of *Picea abies* (Ots et al., 2011) and the biomass of tomato and radish (Magray et al., 2013). Dust on street trees decreased the amounts of photosynthetic pigments (Prusty et al., 2005; Prajapati and Tripathi, 2008).

Table 7 – Pearson correlation coefficients of dust elements and growth characteristics.

	Cu	Zn	Cr	Pb	Ni	P	K	N	C
Leaf N	−0.806a*	−0.725*	−0.760*	−0.700	−0.819*	−0.814*	0.538	−0.699	−0.765*
Stem N	−0.797*	−0.857**	−0.928**	−0.836**	−0.773*	−0.884**	0.390	−0.847**	−0.893**
Root N	0.569	0.517	0.415	0.525	0.569	0.482	−0.648	0.514	0.487
Leaf C/N	0.819*	0.700	0.745*	0.670	0.843**	0.820*	−0.544	0.667	0.750*
Stem C/N	0.817*	0.878**	0.917**	0.864**	0.791*	0.881**	−0.473	0.872**	0.900**
Root C/N	−0.406	−0.393	−0.263	−0.412	−0.396	−0.311	0.571	−0.400	−0.342
Shoot biomass	−0.490	−0.438	−0.627	−0.389	−0.509	−0.617	−0.027	−0.403	−0.538
Root biomass	−0.037	−0.009	−0.171	0.025	−0.054	−0.147	−0.303	0.013	−0.087
Total biomass	−0.205	−0.167	−0.346	−0.126	−0.223	−0.326	−0.216	−0.139	−0.257
Root–shoot ratio	0.789*	0.667	0.778*	0.624	0.819*	0.837**	−0.385	0.627	0.747*
Chlorophyll a/b	−0.672	−0.645	−0.672	−0.627	−0.672	−0.692	0.434	−0.629	−0.671
Total chlorophyll	−0.514	−0.540	−0.612	−0.521	−0.503	−0.585	0.202	−0.530	−0.577
Carotenoid	−0.310	−0.344	−0.432	−0.325	−0.302	−0.393	0.020	−0.335	−0.384

* Correlation is significant at the 0.01 level (2-tailed);
** Correlation is significant at the 0.05 level (2-tailed).

Nitrogen is an important nutrient element that closely relates to growth development and organ formation in plants. The decrease of leaf N and stem N in our study contributed to the increase of leaf C/N and stem C/N ratios. Moreover, the seedlings were very young, so root biomass took up a large proportion of total biomass. A reduction in shoot biomass did not cause a very significant decrease in total biomass, but contributed to an increase in the root–shoot ratio. Increasing the root–shoot ratio means *S. japonica* seedlings allocate more biomass to roots than to crowns when stressed by dust.

3.2. Dust load impacts leaf N, leaf C/N, shoot biomass, root–shoot ratio, chlorophyll a/b, total chlorophyll, and carotenoid

In our study, the dust load significantly affected leaf N, leaf C/N, shoot biomass, root–shoot ratio, chlorophyll a/b, total chlorophyll, and carotenoid. High load treatments tended to have lower leaf N, shoot biomass, and pigments than those of low load treatments, as well as higher leaf C/N and root–shoot ratio.

Dust load impacts on shoot biomass and pigments were studied in previous research, but N content, C/N ratio, and root–shoot ratio were not studied. The biomass of wheat and *S. tomentosa* increased and then deceased with dust load (Singh and Siddiqui, 2003; Kuki et al., 2009). Biomass and pigments of cotton fluctuated and then decreased with a series of rising dust loads (Armbrust, 1986). Pigments of wheat increased and then deceased with increasing dust loads of fly ash (Singh and Siddiqui, 2003). In other words, shoot biomass and pigments of plants may increase or decrease at a lower dust load, but would surely decrease at very high dust load, which was consistent with our studies. High dust load represented the maximum dust load of *S. japonica* and the low dust load represented the maximum value measured for street tree *S. japonica*. Most growth characteristics differed for these two dust loads.

3.3. Dust composition impacts leaf N, stem N, stem C/N, root–shoot ratio, and chlorophyll a/b

In our study, dust composition significantly affected leaf N, stem N, stem C/N, root–shoot ratio, and chlorophyll a/b. Road dust treatments had lower leaf N, stem N, and chlorophyll a/b than those of loam treatments, as well as a higher stem C/N and a higher root–shoot ratio.

Previous studies of road dust effects concentrated on pigments, gas exchange, and chlorophyll fluorescence (Prusty et al., 2005; Prajapati and Tripathi, 2008; Chaturvedi et al., 2013). Loam effects on photosynthesis and biomass were studied (Armbrust, 1986; Hirano et al., 1995). However, the effects of road dust and loam on growth characteristics were not compared before. As two kinds of dusts that have great differences in composition, road dust contains much higher contents of Cu, Zn, Cr, Pb, Ni, P, N, and C compared to loam. In our correlation analysis, the heavy metal, P, N, and C contents in the dust had negative effects on shoot N, but had positive effects on shoot C/N and root–shoot ratio. Stress from heavy metals like Pb can reduce the N absorption of plants, because excessive heavy metals disturb plants' cellular metabolism, and thus influence the root absorption of necessary nutrient elements (Sharma and Dubey, 2005;

Table 8 – Pearson correlation coefficients among growth characteristics.

	Leaf C/N	Stem C/N	Root C/N	Shoot biomass	Root biomass	Total biomass	R/S	Chl a/b	Total chl	Carotenoid
Leaf N	−0.984*	−0.824**	0.073	0.563	0.038	0.232	−0.916*	0.950*	0.832**	0.464
Stem N	−0.751**	−0.988*	−0.075	0.674	0.220	0.396	−0.754**	0.761**	0.698	0.378
Root N	0.242	0.119	−0.966*	−0.092	−0.012	−0.042	0.277	−0.117	−0.103	−0.406

* Correlation is significant at the 0.01 level (2-tailed);
** Correlation is significant at the 0.05 level (2-tailed).

Kang, 2012).Trace elements in PM can cause an increasing concentration of trace elements in plant shoots by covering foliage (Uzu et al., 2010; Pavlik et al., 2012). Whether heavy metals absorbed by the leaf surface could disturb the cell metabolism is worth exploring in the future. Higher contents of N in road dust did not result in higher shoot or root N in road dust treatments.

Besides inorganic substances, PM also contains organic matters, such as alkanes, PAHs, fatty acids, oxalic acid and alkenols (Li et al., 2009). The harmful effects of PAHs on plants were often concentrated on the roots (*e.g.* Li et al., 2013). How the organic matters like PAHs in dust on foliage influence plant growth would be interesting to determine in the future.

3.4. Combination of dust load, composition, and grain size

In our study, leaf N, root–shoot ratio and chlorophyll a/b were significantly affected by dust composition and load; leaf C/N ratio, shoot biomass, total chlorophyll, and carotenoid were significantly affected by dust load; stem N and stem C/N ratio were significantly affected by dust composition; and dust grain size alone did not affect any growth characteristics. Combinations of dust composition and load had obvious effects. A high dust load influenced growth characteristics more seriously than low dust loads; and road dust influenced the growth characteristics more seriously than loam. Higher dust loads could increase the differences between road dust and loam treatments. The two dust grain sizes in our study may not be far enough apart to present different effects on the growth characteristics. However, for leaf N, stem N, leaf C/N, stem C/N, root–shoot ratio, chlorophyll a/b, and carotenoid, the treatment with the strongest effect was the high load fine road dust (A8), which meant the combination of high dust load, road dust, and fine grain size could affect the growth characteristics most seriously.

4. Conclusions

Most growth characteristics of *S. japonica* seedlings were influenced by dust composition and load. Leaf N, root–shoot ratio, and chlorophyll a/b were significantly affected by dust composition and load; leaf C/N, shoot biomass, total chlorophyll, and carotenoid were significantly affected by dust load; stem N and stem C/N were significantly affected by dust composition; and dust grain size alone did not affect any growth characteristics. Road dust influenced the growth characteristics more seriously than loam. Higher dust loads could increase the differences between road dust and loam treatments. The elements in dust correlated well to the shoot N, shoot C/N, and root–shoot ratio of *S. japonica* seedlings.

Acknowledgments

This research was supported by the National Natural Science Foundation of China (Project 41430638 to KMM). The authors express their appreciation to the laboratory members, especially Mr. Guorui Xu for providing assistance in cultivation and measurements of materials.

REFERENCES

Armbrust, D.V., 1986. Effect of particulates (dust) on cotton growth, photosynthesis, and respiration. Agron. J. 78 (6), 1078–1081.

Charlesworth, S., Everett, M., McCarthy, R., Ordonez, A., de Miguel, E., 2003. A comparative study of heavy metal concentration and distribution in deposited street dusts in a large and a small urban area: Birmingham and Coventry, West Midlands, UK. Environ. Int. 29 (5), 563–573.

Chaturvedi, R.K., Prasad, S., Rana, S., Obaidullah, S.M., Pandey, V., Singh, H., 2013. Effect of dust load on the leaf attributes of the tree species growing along the roadside. Environ. Monit. Assess. 185 (1), 383–391.

Dai, S.D., Ma, K.M., Bao, L., 2012. Distribution and heavy metal character of foliar dust on roadside tree *Sophora japonica* of urban area in Beijing. Acta Ecol. Sin. 32 (16), 5095–5102.

Eller, B.M., 1977. Road dust induced increase of leaf temperature. Environ. Pollut. 13 (2), 99–107.

Evans, J.R., 1989. Photosynthesis and nitrogen relationships in leaves of C-3 plants. Oecologia 78 (1), 9–19.

Farmer, A.M., 1993. The effects of dust on vegetation — a review. Environ. Pollut. 79 (1), 63–75.

FreerSmith, P.H., Holloway, S., Goodman, A., 1997. The uptake of particulates by an urban woodland: site description and particulate composition. Environ. Pollut. 95 (1), 27–35.

Hirano, T., Kiyota, M., Aiga, I., 1995. Physical effects of dust on leaf physiology of cucumber and kidney bean-plants. Environ. Pollut. 89 (3), 255–261.

Kang, L.N., 2012. Effects of Pb Stress on the Growth of Popular (*Populus deltoids* × *P. nigra*) Seedling and its Pb Accumulation (Master's thesis. Chengdu, China).

Kuki, K.N., Oliva, M.A., Pereira, E.G., Costa, A.C., Cambraia, J., 2008. Effects of simulated deposition of acid mist and iron ore particulate matter on photosynthesis and the generation of oxidative stress in *Schinus terebinthifolius* Radii and *Sophora tomentosa* L. Sci. Total Environ. 403, 207–214.

Kuki, K.N., Oliva, M.A., Costa, A.C., 2009. The simulated effects of iron dust and acidity during the early stages of establishment of two coastal plant species. Water Air Soil Pollut. 196, 287–295.

Lambers, H., Chapin, F.S., Pons, T.L., 1998. Plant Physiological Ecology. Springer-Verlag New York, Inc., USA.

Li, E., 2005. The Effects of Dust-Fall Upon the Growth–Development of Cotton (Master's thesis. Changsha, China).

Li, X.R., Guo, X.Q., Liu, X.R., Liu, C.S., Mang, S.S., Wang, Y.S., 2009. Distribution and sources of solvent extractable organic compounds in PM2.5 during 2007 Chinese Spring Festival in Beijing. J. Environ. Sci. (China) 21 (2), 142–149.

Li, Q.S., Lu, Y.L., Shi, Y.J., Wang, T.Y., Ni, K., Xu, L., et al., 2013. Combined effects of cadmium and fluoranthene on germination, growth and photosynthesis of soybean seedlings. J. Environ. Sci. 25 (9), 1936–1946.

Lichtenthaler, H.K., 1987. Chlorophylls and carotenoids — pigments of photosynthetic biomembranes. Methods Enzymol. 148, 350–382.

Magray, R.A., Khan, M.A., Lone, F.A., 2013. Environmental impact of cement dust pollution on foliar physiology, growth and yield of some commonly cultivated vegetable crops in Kashmir Himalayan Valley, India. Acta Bot. Hungar. 55 (3–4), 367–376.

Mandre, M., 2009. Vertical gradients of mineral elements in *Pinus sylvestris* crown in alkalised soil. Environ. Monit. Assess. 159, 111–124.

Neves, N.R., Oliva, M.A., Centeno, D.d.C., Costa, A.C., Ribas, R.F., Pereira, E.G., 2009. Photosynthesis and oxidative stress in the restinga plant species *Eugenia uniflora* L. exposed to simulated acid rain and iron ore dust deposition: potential use in environmental risk assessment. Sci. Total Environ. 407 (12), 3740–3745.

Ots, K., Indriksons, A., Varnagiryte-Kabasinskiene, I., Mandre, M., Kuznetsova, T., Kloseiko, J., et al., 2011. Changes in the canopies of *Pinus sylvestris* and *Picea abies* under alkaline dust impact in the industrial region of Northeast Estonia. For. Ecol. Manag. 262 (2), 82–87.

Pandey, D.D., Sanjeev, K., 1996. Impact of cement dust pollution on biomass, chlorophyll, nutrients and grain characteristics of wheat. Environ. Ecol. 14 (4), 872–875.

Pavlik, M., Pavlikova, D., Zemanova, V., Hnilicka, F., Urbanova, V., Szakova, J., 2012. Trace elements present in airborne particulate matter—stressors of plant metabolism. Ecotoxicol. Environ. Saf. 79, 101–107.

Prajapati, S.K., Tripathi, B.D., 2008. Seasonal variation of leaf dust accumulation and pigment content in plant species exposed to urban particulates pollution. J. Environ. Qual. 37, 865–870.

Prusty, B.A.K., Mishra, P.C., Azeez, P.A., 2005. Dust accumulation and leaf pigment content in vegetation near the national highway at Sambalpur, Orissa, India. Ecotoxicol. Environ. Saf. 60 (2), 228–235.

Rai, A., Kulshreshtha, K., Srivastava, P.K., Mohanty, C.S., 2010. Leaf surface structure alterations due to particulate pollution in some common plants. Environmentalist 30 (1), 18–23.

Sharma, P., Dubey, R.S., 2005. Lead toxicity in plants. Braz. J. Plant Physiol. 17 (1), 35–52.

Shukla, J., Pandey, V., Singh, S.N., Yunus, M., Singh, N., Ahmad, K.J., 1990. Effect of cement dust on the growth and yield of *Brassica campestris* L. Environ. Pollut. 66 (1), 81–88.

Singh, L.P., Siddiqui, Z.A., 2003. Effects of *Alternaria triticina* and foliar fly ash deposition on growth, yield, photosynthetic pigments, protein and lysine contents of three cultivars of wheat. Bioresour. Technol. 86 (2), 189–192.

Tang, R.L., Ma, K.M., Zhang, Y.X., Mao, Q.Z., 2013. The spatial characteristics and pollution levels of metals in urban street dust of Beijing, China. Appl. Geochem. 35, 88–98.

Thompson, J.R., Mueller, P.W., Fluckiger, W., Rutter, A.J., 1984. The effect of dust on photosynthesis and its significance for roadside plants. Environ. Pollut. A. Ecol. Biol. 34 (2), 171–190.

USEPA, 1996. Microwave Assisted Acid Digestion of Siliceous and Organically Based Matrices. SW-846 EPA Method 3052. Washington, DC.

Uzu, G., Sobanska, S., Sarret, G., Munoz, M., Dumat, C., 2010. Foliar lead uptake by lettuce exposed to atmospheric fallouts. Environ. Sci. Technol. 44 (3), 1036–1042.

Watari, R., Nagashima, H., Hirose, T., 2012. Growth and nitrogen use in *Xanthium canadense* grown in an open or in a dense stand. Physiol. Plant. 144 (4), 335–345.

Zheng, X.P., Zhang, Q.X., 2011. Status and prospects of urban landscape plants' application in Beijing. Chin. Landsc. Archit. 5, 81–85.