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Seasonal variation of particle-induced oxidative potential of airborne particulate matter in Beijing

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Abstract: An *in vitro* plasmid scission assay (PSA), the cell apoptosis assay, and ICP-MS, were employed to study the oxidative potentials and trace element compositions of the airborne particulate matter (PM) in Beijing during a one year-long field campaign from June 2010 to June 2011. The cell damages induced by PM reveled by the cell apoptosis assay showed a similar variation pattern to the DNA damages obtained by PSA, verifying the feasibility of the PSA in analyzing the oxidative capacity of PM samples. The PSA experiments showed that the particle-induced DNA damage was highest in summer, followed by spring, winter and autumn in descending order. The percentages of the oxidative damages to plasmid DNA induced by the water-soluble fractions of PM under the particle doses from 10 to 250 μg/ml were generally lower than 45%, with some values peaking at above 50%. The peak values were frequently present in late spring (i.e. April and May) and early summer (i.e. June) but they were scarcely observed in other seasons. These peak values were mostly associated with haze days or the days with low wind speed (less than 4 m/s), indicating that the PM samples during haze had higher oxidative potential than those during non-haze periods. The oxidative potential induced by the water-soluble fraction of the PM displayed a significant positive correlation with the concentrations of the water-soluble elements Cd, Cs, Pb, Rb, Zn, Be and Bi, demonstrating that the particle-induced oxidative potentials were mainly sourced from these elements. The exposure risk represented by the mass concentration of these elements in unit volume of atmosphere was higher in summer and winter, and lower in autumn and spring. The haze day PM samples not only had higher level of oxidative potentials but also had higher concentrations of water-soluble elements.

Keywords: particulate matter (PM), plasmid scission assay (PSA), oxidative potential, haze, water-soluble element, Beijing

1 Introduction

Beijing, a metropolitan city with a population of over 20 million individuals, has suffered serious air pollution in recent years. The daily $PM_{2.5}$ mass concentration could be as high as 993 μg/m^3 (Beijing Environmental Monitoring Station data, 2013/1/12, Xizhimen North monitoring point). Haze and fog weather enhanced the air pollution, which has caused wide public concerns. Although the air quality in Beijing during the Olympic Summer Games 2008 had been clearly improved (Okuda et al., 2011; Schleicher et al., 2012; Shang et al., 2013), the $PM_{2.5}$ mass concentration in Beijing air remained at high levels after the Games (Okuda et al., 2011; Sun et al., 2014). The compositions and types of $PM_{2.5}$ particles have become more complex and are characterized by a predominance of fine and ultrafine, secondary particles, compared to the periods before the Olympic Summer Games (Zhang et al., 2013; Huang et al., 2014; Shen et al., 2016), which may facilitate more serious health issues. Epidemiological investigations have shown the adverse health effects of airborne $PM_{2.5}$ in Beijing in recent years (Maynarda et al., 2010; Shang et al., 2013). However, toxicological investigations of the full-year airborne $PM_{2.5}$ samples in Beijing are rarely seen in the literature. Therefore, elucidating the oxidative potential and components of full-year Beijing airborne $PM_{2.5}$ is important for identifying the seasonal variation and reason of particle-induced damages to human health.

Airborne particulate matter, as an important pollutant of urban atmosphere, has been related to morbidity and mortality (Ostro et al., 2006; Xu et al., 2013). The fine particles can cause asthma, lung function decline, and respiratory inflammation, affect the cardiovascular, nervous, and immune systems, and may eventually induce cancer (Zhang et al., 2003; Lin et al., 2007; Crabbe, 2012; Hoek et al., 2013; Kheirbek et al., 2013). However, the biological mechanisms underlying the adverse health effects of airborne $PM_{2.5}$ remain unclear. A widely accepted hypothesis is that oxidative damage originates from the surface of airborne particles (Ambroża et al., 2000; Li et al., 1997; Shao et al., 2007); that is, bioavailable ionizable trace metals on airborne particles could catalyze oxidants that could damage DNA (Costa et al., 1997; Gene et al., 2012; Carville et al., 2013). A human molecular epidemiology study has also demonstrated the important role of oxidative damage at the metabolic pathway by which such damage occurs from PAHs in the coal-burning emissions (Lan et al., 2004). Currently, many methods are being employed to assess the oxidative potential of atmospheric particles, such as the Ames test (Ames et al., 1973), micronucleus experiments (Kirsch-Volders, 1997), chromosome aberration tests (Ishidate et al., 1998), and comet assay (Tice et al., 2000). However, most of these methods are only qualitative techniques. Some other semi-quantitative or quantitative methods are more popular, including DTT-driven assay (Carville et al., 2013), and ascorbic acid assay (Gene et al., 2012). In recent years, many researchers have used the plasmid scission assay (PSA), also known as the plasmid DNA assay, to study the oxidative potential of atmospheric particulates (Greenwell et al., 2003; Shi et al., 2004; Shao et al., 2007). This method has been shown to be a simple, rapid, and highly sensitive technique to detect oxidative potential, and it allows a semi-quantitative assessment of DNA damage induced by atmospheric PM (Shao et al., 2007).

In this paper, we use the PSA to assess the oxidative potential of the full-year (one per week) 24-hours samples of airborne particles collected in Beijing from June 2010 to June 2011. The cell apoptosis assay was also used to cross check a few samples to verify the feasibility of the PSA. The inductively coupled plasma mass spectrometry (ICP-MS) was used to analyze the chemical compositions of the PM samples. The oxidative potential of whole particulate matter and water-soluble fractions were analyzed to investigate the sources of the oxidative potential. The meteorological conditions were correlated with particle oxidative potential.

2 Material and methods

2.1 Sampling

The PM samples were collected on the campus of the China University of Geoscience in Beijing, which represents an urban residential location. The sampling site is located at the east entrance of the university with a distance of approximately 10 m from a major road (Xueyuan Road) (Shen et al., 2016). As the sampling site is surrounded by trees and shielded by a 2 m high wall to the road, it cannot be classified as a traffic site but represents a "blocked residential site" . The sampler inlet tubes were installed at a height of 1.5 m above ground, which is a typical height for human exposure.

Two high volume samplers (Digital DHA-80, Hegnau, Switzerland) were used to collect PM samples automatically. The samplers were operated 24 hours a day (00:00–24:00). Quartz fiber filters (Munktell T293, Falun, Sweden) with 150 mm diameters were used as the collection substrate. Blank field samples from both samplers were collected every second week. The sampling period lasted for one year, from 25th June 2010 to 17th June 2011. The meteorological parameters, including temperature, relative humidity, wind direction and speed, and visibility, were recorded during the sampling period (Shen et al. 2016).

All filters from one of the samplers were weighed before and after sampling using an analytical balance (Mettler Analysenwaage AE240, reading precision 0.1 mg) after equilibration for 48 h in a conditioned room (temperature 20±1°C and relative humidity 40±5%). Filter aliquots from the second sampler were investigated for oxidative potential. All loaded filters were stored at -20°C before analysis and during transportation.

In this paper, after considering the meteorological conditions and average mass concentrations of PM in each season in Beijing, we randomly selected 1 PM sample per week for the whole year collection (weekday, non-rainy weather, and enough sample load) from June 2010 to June 2011. Altogether, 48 samples were selected for PSA analysis. The specific sampling information is shown in Table 1.

It should be noted that in our sampling campaign, due to a re-evaluation of the measurement data, it was found that PM_4 was collected rather than $PM_{2.5.}$ During the whole campaign the actual sampling flow of ambient air was 167 instead of 500 l/min as a default setting due to an airflow shortcut from the interior of the sampler. As a consequence to the changed flow volume, the cut off of the sampler (original setting: 2.5 μm) had to be recalculated following the impactor design theory (Gussman, 1969; Marple and Liu, 1974). It was found that particles smaller than 4 μm (i.e., PM_4) were collected onto the filters. The recalculation detail can be found in Shen et al. (2016). However, a comparison of results of oxidative potentials and the trace element compositions obtained from the current study was not significantly different from those found for $PM_{2.5}$ samples during 2010-2011 (Sun et al., 2014). ICP-MS analysis on the size-segregated airborne particles collected during the 2010-2011 haze episodes has shown that the water-soluble trace elements As, Cd, Cr, Cu, Mn, Ni, Pb, Se, Tl, and Zn were mainly concentrated in the fine particle size of 0.32–1.8 μm (Figure 3 in Sun et al., 2014) which allow us to have similar mass concentrations of trace metals in both PM_4 and $PM_{2.5}$. Similar conclusion has been obtained by Duan et al. (2014) who have found that the most analyzed heavy metals such as Pb, Cd, Zn, V, Mn and Cu exist in coarse and accumulation modes, with the particle size being mostly smaller than 4 μm. Sun et al. (2014) also showed that the DNA damages of different size-segregated airborne particles smaller than 5.6 μm were not very different. All of these facts demonstrate that the trace element compositions and oxidative potentials of the PM smaller than 4 μm are not significantly different from those of the $PM_{2.5}$.

2.2 Plasmid scission assay

Plasmid scission assay (PSA) is an *in vitro* method for studying the oxidative damage that free radicals induced by the trace metals carried by particles can cause in supercoiled DNA (Greenwell et al., 2003; Shi et al., 2004; Lu et al., 2007). The initial effect of oxidative damage causes DNA to relax, and further damage causes the DNA to become linearized. The undamaged supercoiled DNA, damaged relaxed DNA, and damaged linearized DNA can be separated by electrophoresis in an agarose gel; then, sensitive densitometry can be used to quantify the proportions of these different forms of DNA. The oxidative potential is expressed by the percentage of relaxed and linearized DNA in the total DNA.

The plasmid DNA assay was conducted in accordance with the methods reported previously (Merolla et al., 2005; Chuang et al., 2011, 2013; Reche et al., 2012). A part of the sample-loaded quartz filter was cut, and assuming a uniform deposition of PM on the filters, the deposited PM mass was determined by weighing the filters gravimetrically. Then, the sample was placed in a clean centrifuge tube (Scientific Industries, Vortex-Genie 2) with HPLC-grade water to reach a whole particle concentration of 250 μg/ml. Particle suspensions were obtained by considerable shaking in a vortex mixer for 20 h to separate the particles as much as possible from the filter. An aliquot of the particle suspension was taken and saved in a refrigerator as the whole particle suspension. The remaining suspension was centrifuged with a speed of 13000 r/min for 80min, and the supernatant was saved as the water-soluble fraction. Both the prepared whole particle suspension and water-soluble fractions were incubated in chromatographically pure water at different concentrations for PSA. All samples were confected into a final volume of 43 μl, with each containing 2 μl φX174 RF DNA (Promega, London, UK). Each resulting suspension was gently shaken in a vortex mixer (to ensure maximum mixing of the sample and to avoid sedimentation) for 6 h at room temperature. Before loading onto the electrophoresis tank, 7 μl bromophenol blue dye (Promega, London, UK) was added to each sample. Gels, comprised of 0.6% agarose and 0.25% ethidium bromide, were run in 1% TBE buffer at an electrophoretic voltage of 30V for 16h at room temperature. The finished gels were photographed, and densitometric analysis was performed using the GeneTools program (Syngene Systems, UK). A semi-quantitative protocol was established to measure the relative proportion of the damaged DNA (relaxed and linearized) in each lane of the gel (in terms of a percentage of the total DNA in each lane). The DNA damage percentage induced by airborne particles was calculated by subtracting the damage caused by the negative control (chromatographically pure water). In our experiment, five dosage levels were used by dilution, including 50 μg/ml, 100 μg/ml, 150 μg/ml, 200 μg/ml, and 250 μg/ml, a total 240 (48 samples times 5 dosages is 240; 4 for each dosage) analysis were performed. The damage percentages of different particles under these dosages were compared, and higher damage percentage represents higher oxidative potential. To guarantee the accuracy of the experiment result, we did the PSA experiment using a blank quartz fiber filter, the oxidative potential was below 10% (9.4%), so we consider the quartz filter doesn't influence the experimental results of the oxidative potentials. To test the reliability of the experiment, we selected three samples and did PSA twice in five dosages; the result showed that it is below 20% (Table S1).

2.3 Cell apoptosis

To verify the variation of results of PSA, we selected five samples (sampling date: 2010.6.28, 2010.7.12, 2010.7.26, 2011.4.15, 2011.5.20) for cell apoptosis assay. Because the sample quantities are limited, we diluted the samples to lower dosages (6.25 μg/mL, 12.5 μg/mL, 25 μg/mL and 50 μg/mL) to see the variation regularity.

Phosphatidylserine (PS) is on the internal surface of living cell membrane, PS turns from inside to outside of the membrane when apoptosis occurs. Annexin V, whose molecular weight is around 35-36 kD, combines with PS after high affinity on it. So to test apoptosis, we use Annexin

V to distinguish apoptotic cells and viable cells. Then fluorescence microscope or flow cytometry is used to observe it. But it is impossible for Annexin V to distinguish the non-viable cells overturned by PS. Propidium Iodide (PI) is a kind of nucleic acid dye which is unable to pass through the membrane of viable and apoptosis cells, but it can pass through the membrane of non-viable cells and combine with DNA, PI can be excited by certain wavelength and emits red fluorescence. So Annexin V and PI are used together to distinguish viable, apoptosis and nonviable cells.

We use human lung cancer cell A549 (Cell Culture Center, Institute of Basic Medical Science Chinese, Academy of Medical Sciences, School of Basic Medicine, Peking Union Medical College), Apoptosis Assays Kit (Nanjing Jiancheng Bioengineering Institute), DMEM-F12 serum-free media (GIBCO, USA), FASCailbur Flow Cytometry (FCM) (BD, USA), CO_2 Incubator (Sanyo, Japan), Clean Bench (Baker, German), 5840R refrigerated centrifuge (Eppendorf, German) in cell apoptosis assay.

Firstly digest and adjust the cell density of A549 cells which are in well-grow exponential phase to 5×10^4/mL, then inoculate onto 6 wells plate (2 ml/well), cultivate in incubators with 37℃ and 5% CO_2 for 24 h. Secondly remove the cell supernatant, gently wash cells one or two times by PBS, then add in samples, the final concentration is 6.25, 12.5, 25 and 50 μg/mL respectively, go on cultivating for 24 h. Then follow the steps of Apoptosis Assays Kit, digest cells with 0.25% trypsin, and blow it into a single cell suspension after collect cells. Collect cells after centrifuge for 10 min in 1000 rpm. Add 1 ml cool PBS, gently shaking to suspend cells. Remove the supernatant after centrifuge for 10 min in 1000 rpm, 4°C. Repeat previous two steps. Then re-suspend cells in 200 μl binding buffer. Add 10 μl Annexin V-FITC, mix gently, keep out of sun and incubate for 15 min at room temperature or 30 min at 4 °C. Add 300 μl binding buffer and 5 μl PI, test for 1 h.

At last computer-based analysis was carried out using BD FASCailbur (USA).

2.4 ICP-MS analysis

This study used a high-resolution inductively coupled plasma mass spectrometry (ICP-MS, Elan DCR-e, PerkinElmer Ltd.) for the analysis of trace elements from the PM with the detection limit being 1 ppt~1 ppb (10^{-12}~10^{-9}). The procedure used was based on Shao et al. (2013). Water-soluble elements were obtained by directly analyzing the water-soluble fractions of the PM samples that were previously obtained by centrifugation in the PSA. The elements in the bulk samples were obtained by digesting and analyzing the whole particle solutions of each PM samples previously prepared during the PSA analysis. In this study, 44 trace elements were analyzed and the results were reported as μg/g, in which the water-soluble elements were reported as a concentration of the element in its water-soluble form in intact PM.

3 Results

3.1 Overall variation in the oxidative potential of the water-soluble fraction of PM

To analyze the overall variation in the oxidative potential of the water-soluble fraction of PM, all 48 samples were analyzed using the PSA, and the results are included in the Table S2. Figure 1 shows that the damage to plasmid DNA induced by the water-soluble fraction of the PM generally varied from 17% (e.g. 2010-10-11 sample at the 50 μg/ml dosage) to 97.2% (e.g. 2010-6-25 sample at the 250 μg/ml dosage). For each sample, there is also an overall positive dose-response relationship. It is interesting that the relatively small variation of the average DNA damages between 20% and 45% was accompanied by a number of peak values (higher than 50%). These peak values were frequently present in April and sometimes in May and June, but they were scarcely observed in the other months.

To analyze the seasonal variation of the water-soluble fraction of PM, we use the box-plot to show the seasonal variation of oxidative potential under the particle dose of 150 μg/ml (Figure 2). We consider March, April and May as spring, June, July and August as summer, September, October and November as autumn, and December, January and February as winter. The values in the box represent 50% of the samples falling into this value range. The black coarse lines in the box represent average values, the normal data range is between the top edge and bottom edge. It can be seen from Figure 2 that the median of oxidative potential in summer was the highest, followed by spring, winter and autumn. We arrange the interquartile range value in ascending order: winter, autumn, spring and summer. Figure 2 also showed that the data in winter were more concentrated while the data in summer were more dispersed. There is no outlier in these data.

3.2 Effects of PM on lung cell apoptosis

To verify the dose-response relationships for the oxidative potential of PM obtained by the PSA, we have selected a few samples to do the lung cell apoptosis assay. In the experiment, the model of cell apoptosis was set up by exposing the lung epithelial cells A549 to selected PM, and AnnexinV-FITC/PI and flow cytometry (FCM) were employed to observe the effect of PM on alveolar epithelial cells. A total of 5 PM samples were analyzed by the cell apoptosis assay. The results were included in Table S3.

Table S3 showed that the cell apoptosis percentages induced by soluble fraction of PM samples increases as the particle dosage increases from 6.25 μg/ml to 12.5 μg/ml, 25 μg/ml, 50 μg/ml, indicating a clear positive dose-response relationship. Figure 3 is the scatter plot showing the relationship between the cell damages at the dose of 25 μg/ml and the DNA damage at the dose of 150 μg/ml and it can be seen that two of them have a clear positive correlation. This result supports the variation in the oxidative potential of PM obtained by the PSA method.

3.3 Contents of water-soluble elements in the PM collected for the whole year

An ICP-MS was used to detect the content of water-soluble elements in the PM samples and the results were reported in μg/g by weight in the PM (Table S4). For the total water-soluble elements (TWSE), the PM in summer had the highest level (17114 μg/g), followed by those in spring (12380 μg/g), autumn (9873 μg/g), winter (9342 μg/g). The total elemental content of particle samples on July 21st 2010 (No. 4) was the highest (17296 μg/g), while that on June 1st 2011 (No. 40) was the lowest (240 μg/g).

For the individual elements, the highest content of all the samples appeared on Zn, with the range from 89.2 μg/g to 13548 μg/g, followed by Mn with the range from 62 μg/g to 1936 μg/g, and Cu, Ba, Pb and Sr in descending order (Figure 4). Therefore, Zn, Mn, Cu, Ba, Pb and Sr were the most abundant water-soluble metals in the PM samples.

4. Discussion

4.1 Comparison between the oxidative potential of the intact whole particles and their water-soluble fractions

To study the sources of oxidative potential of Beijing airborne particles, the oxidative potential of the 12 whole particle suspensions of the PM samples were compared with the results from the corresponding water-soluble fractions (Table S2). It can be observed that, for most samples, the DNA damage values induced by the water-soluble fraction of PM occupied 60% to 100% of the DNA damages induced by their corresponding intact whole particles. These results indicated that the oxidative capacity of airborne particles collected in Beijing was mainly derived from their water-soluble fractions. Previous studies have revealed that the oxidative potential of atmospheric particles mainly came from the water-soluble fraction (Donaldson et al., 1997; Li et al., 1997; Adamson et al., 2000; Ambroża et al., 2000; Valavanidis et al., 2000;

Reche et al., 2012; Wang et al., 2013), although Ghio et al. (1999), Imrich et al. (2000), Soukup and Becker (2001) showed that the insoluble fraction of atmospheric particles causes the biological responses of alveolar macrophages. In the investigations of oxidative potential of the PM_{10} samples of Beijing, Macao and Lanzhou indicated that the water-soluble fraction induced oxidative damages similar to the intact whole particle sample (Zhong et al., 2010; Shao et al., 2007, 2013; Xiao et al., 2013). Similar conclusions were obtained for UK particulate matter (Merolla and Richard, 2005; Moreno et al., 2004; Koshy et al., 2008; Reche et al., 2012), which also argued that the oxidative potential of inhalable particles was mainly sourced from their water-soluble fractions.

4.2 Correlation between particle-induced DNA damages and contents of water-soluble trace elements

To examine the most probable source of the particle-induced oxidative capacities of the PM samples, the DNA damage percentages from particle doses of 250 μg/ml were correlated with corresponding contents of the water-soluble elements in the PM. The Pearson correlation coefficients are provided in Table 2. The sample number n=43 (five samples of the whole 48 samples were consumed by the PSA experiment and 43 were left for the ICP-MS analysis), a threshold correlation coefficient is 0.30 at the 95% confidence level.

According to the correlation coefficients shown in Table 2, the particle-induced oxidative potential displayed a significant positive correlation with the total water-soluble metal contents with a Pearson correlation coefficient of 0.33, implying that the oxidative capacity of the PM was derived mainly from its water-soluble trace elements, although the DNA damage may be induced by the water-soluble organic compounds as reported by Wei et al. (2009) and Liu et al. (2014). This finding is in accordance with other reports for PM_{10} and $PM_{2.5}$ from Beijing

(Shao et al., 2007, Sun et al., 2014) and studies of particulate matter in the UK (Moreno et al., 2004; Merolla and Richards, 2005; Reche et al., 2012).

The individual water-soluble trace metals Cd, Cs, Pb, Rb, Zn, Be and Bi exhibited significant positive correlations with the oxidative capacity, indicating that these elements in their water-soluble state were the components that were most likely associated with the DNA damages. Co, Ga and Hr exhibited significant negative correlations with the oxidative capacity.

Many studies have shown that soluble trace metal components produce reactive oxygen species (ROS), which can induce oxidative stress and inflammation in the lungs and respiratory tract (See et al., 2007; Distefano et al., 2009; Vidrio et al., 2009; Zhong et al., 2010). The U.S. Environmental Protection Agency (EPA) defines Zn and Pb as toxic elements (EPA/635/R-05/002. 2005). Zn is regarded as a bioreactive element (Adamson et al., 2000). Other studies have also indicated that Zn is likely to be a major element associated with the particle-induced plasmid DNA damage (Greenwell et al., 2003; Lu et al., 2006; Shao et al., 2007; Nagy et al., 2012); this finding is consistent with the results presented in our study.

Some previous studies have shown that trace metal pollutants, such as Cr, Zn, Pb, and Mn, can be produced from industrial sources (Querol et al., 2006; Liu et al., 2010). Tang and Huang (2004) found that high levels of As, Cu, Sb, Se, Zn and Pb might be sourced from the combustion of different types of coal. Most recent investigation by Shao et al. (2016) demonstrated that the water-soluble As, Cd, Ge, Mn, Ni, Pb, Sb, Se, Tl, and Zn in their water-soluble states were present in the coal burning-derived PM_{10}. Duan et al. (2014) found that Pb, Cd, and Zn show mostly in accumulation mode, V, Mn and Cu exist mostly in both coarse and accumulation modes, and Ni and Cr exist in all of the three modes in haze episode in Beijing.

4.3 Oxidative potential of the PM samples of haze days

The five haze episodes (Sample 2010.7.26, 2010.10.11, 2011.2.20, 2011.4.15, 2011.4. 29) were characterized by low wind speeds (generally less than 4 m/s) and reduced visibility (less than 10 km). Their particle-induced DNA damages were all above 60% at the 150 μg/ml dosage level. Table S4 also showed that the PM collected on these haze days were also associated with high level of water-soluble elements contents. This result indicated that the haze weather could facilitate the accumulation of toxic components in airborne particles and could induce a higher oxidative potential. Similar results have been obtained in the research conducted by Sun et al. (2014), who also concluded that the oxidative capacities were markedly elevated during the haze days.

The results in Figure 1 also suggest a gradual increasing trend in the oxidative potential of the water-soluble fraction of PM during a haze episode. To further illustrate this phenomenon, we selected five continuous days from a haze episode for PSA analysis. The five samples in Figure 5 represent a continuous period of haze days from 2010-9-12 to 2010-9-16, characterized by decreasing visibility from 23.5, 19.6, and 7.3 km to 3.8 and 4.6 km. As the visibility decreases, the particle-induced DNA damages increased until attaining the highest value. During these days, the wind speed remained low, ranging from 2 to 4 m/s, and the relative humidity remained high, with levels of 56%, 60%, 62%, 70%, and 79% in ascending order for these sequential days. This observation means that conditions with low wind speed and high relative humidity favor the formation of haze and also the accumulation of toxic components, thus promoting more particle-induced DNA damages. These results are consistent with studies previously conducted in Lanzhou and Beijing (Shao et al., 2007; Xiao et al., 2013).

4.4 Relationship between the meteorological conditions and the particle-induced plasmid damage

Correlations between meteorological conditions, such as temperature, relative humidity, wind speed, and atmospheric pressure, and the particle-induced plasmid damages were analyzed in this study. The particle-induced plasmid damages were positively correlated to average temperature with a correlation coefficient r = 0.35, which is higher than the threshold coefficient r_a (n = 48, when a is 0.05, r_a = 0.28). The particle-induced plasmid damages were negatively correlated with atmospheric pressure, with a correlation coefficient of r = -0.3. It is also interesting to note that the contents of the total water-soluble Ni, Cu, Cd in the PM also had a positive correlation with the average air temperature, with a correlation coefficient higher than 0.30 (n = 43, when a is 0.05, r_a = 0.30). These facts are in consistency with the high oxidative potential of the PM samples in summer and late spring. During haze episodes, as discussed previously, conditions with low wind speed and high relative humidity could favor the formation of haze and accumulation of toxic trace elements, and thus the higher oxidative potential of particles.

Many previous studies have discussed the effect of the seasonal variation on particle pollution-related mortality and morbidity and suggested that higher temperature would significantly enhance the health effects of PM exposure and result in a stronger PM effect on daily mortality (Katsouyanni et al., 1993, 2001; Ren et al., 2006; Qian et al., 2008). It has been noticed in Beijing (Li et al., 2013b) and Tianjin (Li et al., 2011, 2013a) that adverse effects were strongest in summer compared to the other seasons. The positive association between the higher particle-induced oxidative potential of PM and the higher air temperature may explain why temperature would enhance the PM health effect.

4.5 Exposure risk of metals in atmosphere in Beijing

The correlation between the water-soluble elemental contents and the oxidative DNA damages of the water-soluble fraction (Table 2) revealed that the total water-soluble elements (TWSE), together with the individual elements Be, Bi, Cd, Cs, Pb, Rb, Zn, and Y, were positively associated with the oxidative potentials of PM. In consideration of this, we use the mass concentrations of the TWSE and these individual elements (we called them positively correlated water-soluble elements, simplified as PCWSE) to represent the health risk levels of PM Exposure. The mass concentrations of elements in atmosphere (ng/m^3) were obtained by multiplying the mass concentration of particles in the atmosphere (μg/m^3) with the content of water-soluble elements in particles (μg/g) (Table S5).

Both the total mass concentrations of the PCWSE and the TWSE showed the same trending during our sampling period from June 2010 to June 2011 (Figure 6). The peak mass values of the PCWSE and the TWSE were present on day 2010.10.8 (78.8405 and 97.0663 ng/m^3, respectively) in summer and day 2011.4.29 (59.4325 and 73.5536 ng/m^3, respectively) in spring. These mass values in days 2010.7.26, 2011.2.3, 2011.2.20, 2011.5.23 were also relatively high. In consideration of seasonal variations, the average mass concentrations of both the PCWSE and the TWSE were the higher in summer and winter, and lower in autumn and spring (Figure S1). In conclusion, the exposure risk was the high in summer and winter in Beijing.

5 Conclusions

1) The cell apoptosis assay showed the positive dose-response relationship similar to the PSA results. A similar pattern exists between the cell damages and the DNA damages, verifying the feasibility of the PSA in analyzing the oxidative capacity of PM samples.

2) There was a seasonal variation in oxidative potential of both the intact whole particles and their water-soluble fractions of PM. The average DNA damages induced by the water-soluble fractions of PM were highest in summer, followed by spring, autumn and winter in descending order.

3) The relatively smooth variation of the particle-induced DNA damages was accompanied by a number of peak values (higher than 50%). The peak values were frequently present in late spring and early summer and they were mostly associated with haze days and the days with low wind speed (less than 4 m/s), indicating that the PM samples during haze had higher oxidative potential than during non-haze periods.

4) The oxidative potentials displayed a significant positive correlation with the total water-soluble element concentrations, implying that the oxidative potentials were mainly sourced from the water-soluble elements, in which the water-soluble Cd, Cs, Pb, Rb, Zn, Be and Bi were most likely responsible for the DNA damage.

5) Correlations between meteorological conditions and the particle-induced DNA damages showed that the oxidative potentials were positively correlated to average relative humidity and average temperature, and was negatively correlated to daily average wind speed.

6) The exposure risk represented by the mass concentration of water-soluble elements in unit volume of atmosphere in Beijing was the higher in summer and winter, and lower in autumn and spring.

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Tables:

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Figure 1 The particle-induced DNA damages by water-soluble fractions of PM in Beijing from June 2010 to June 2011

Figure 2 The seasonal distribution of oxidative capacity under 150 μg/ml of samples. The values in the box represent 50% of the samples falling into this value range. The black coarse lines in the box represent average values, the normal data range is between the top edge and bottom edge.

Figure 3 The relationship between the cell damages at the dose of 25 μg/ml and the DNA damage at the dose of 150 μg/ml

Figure 4 Average contents of the individual water-soluble elements in PM in four seasons

Figure 5 Diagram showing correlation between visibility and particle-induced DNA damages of 5 continuous days during a haze episode

Figure 6 The overall mass concentrations of the elements with positive correlations with DNA damages (Cd, Cs, Pb, Rb, Zn, Be, Bi) and the mass concentrations of the total water-soluble elements in atmosphere from June 2010 to June 2011

Supplementary Figures:

Figure S1 The average mass concentrations of elements in atmosphere of four seasons

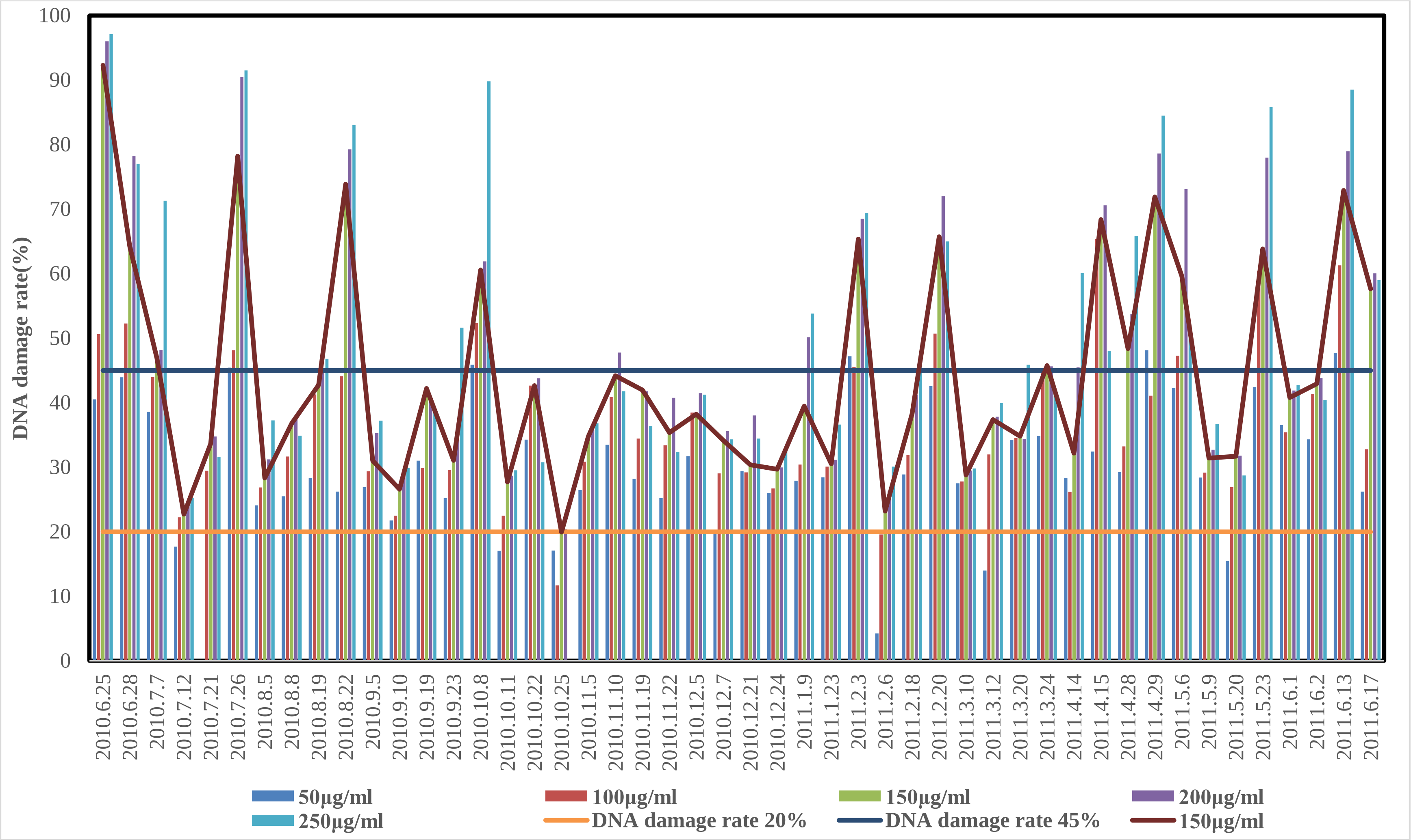
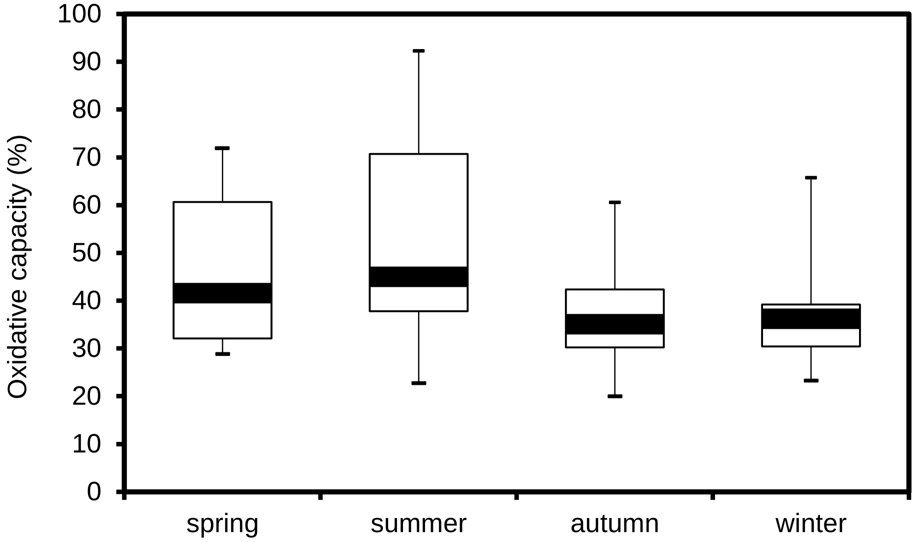


Figure 1 The particle-induced DNA damages by water-soluble fraction of PM in Beijing from June 2010 to June 2011



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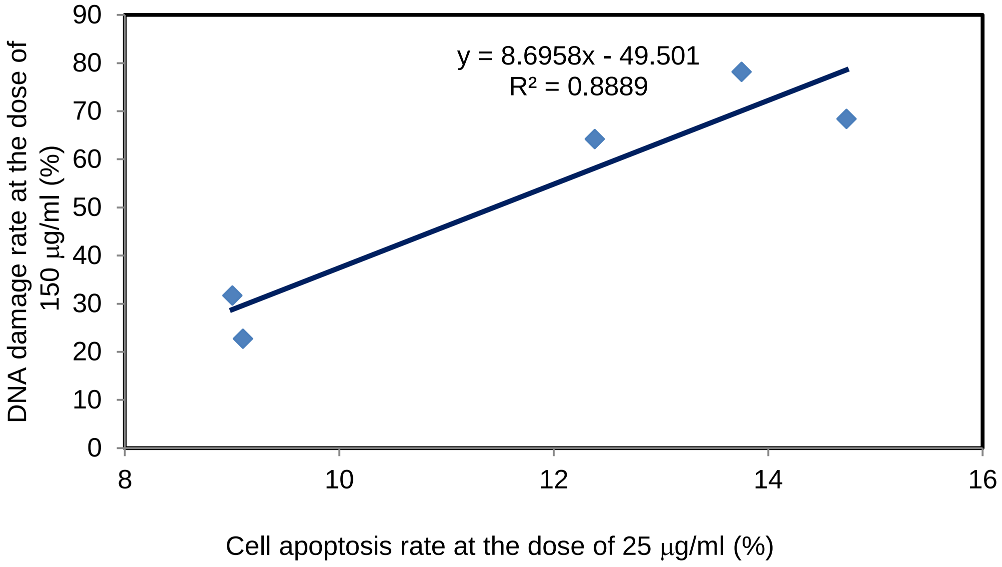

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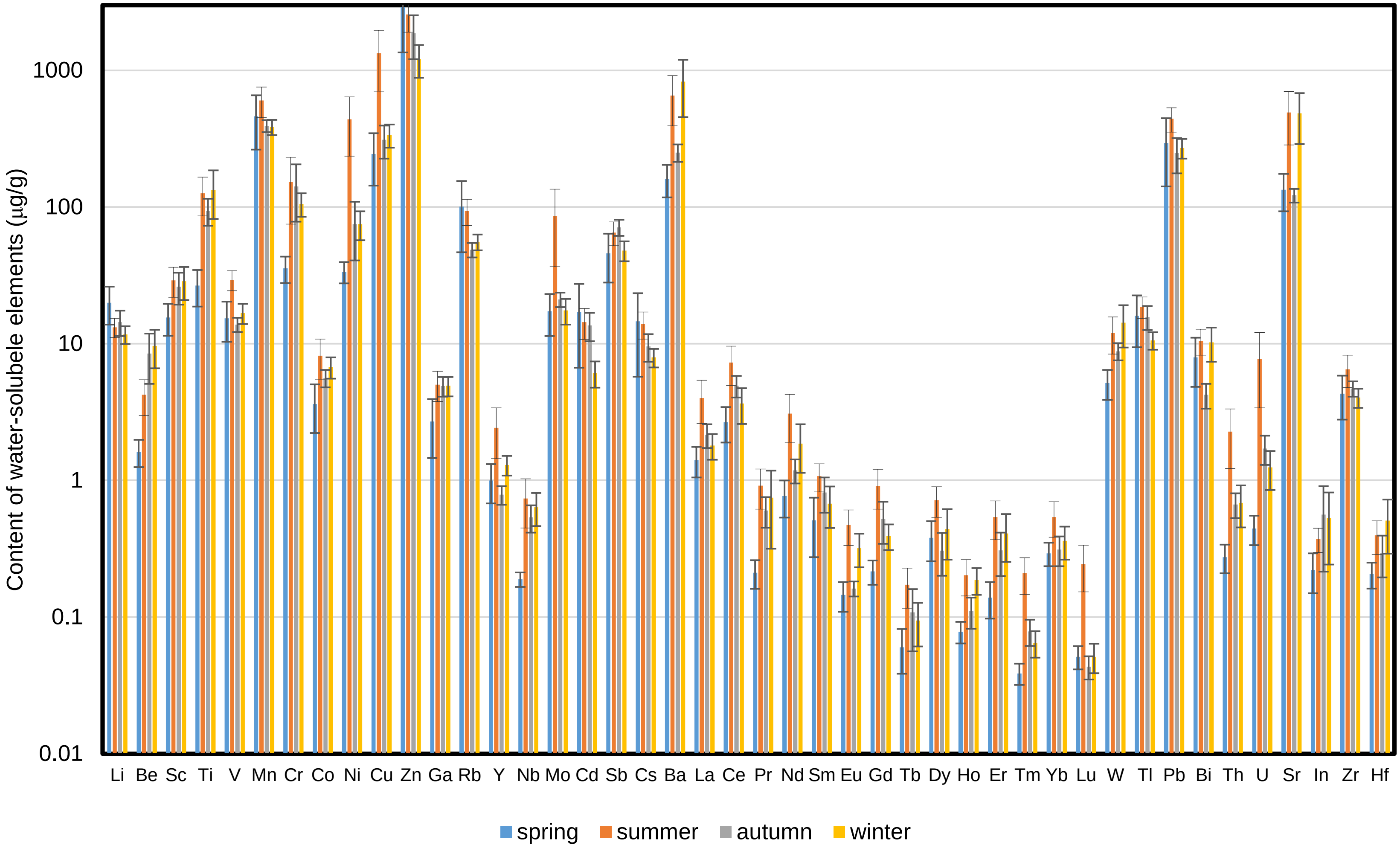
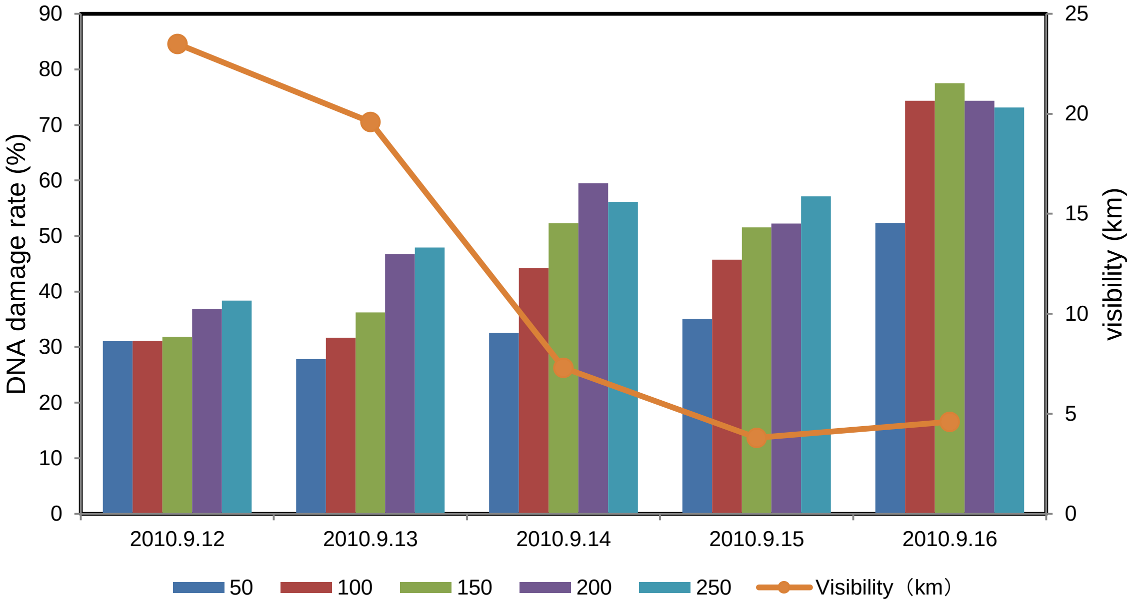


Figure 4 Average contents of the individual water-soluble elements in PM in four seasons



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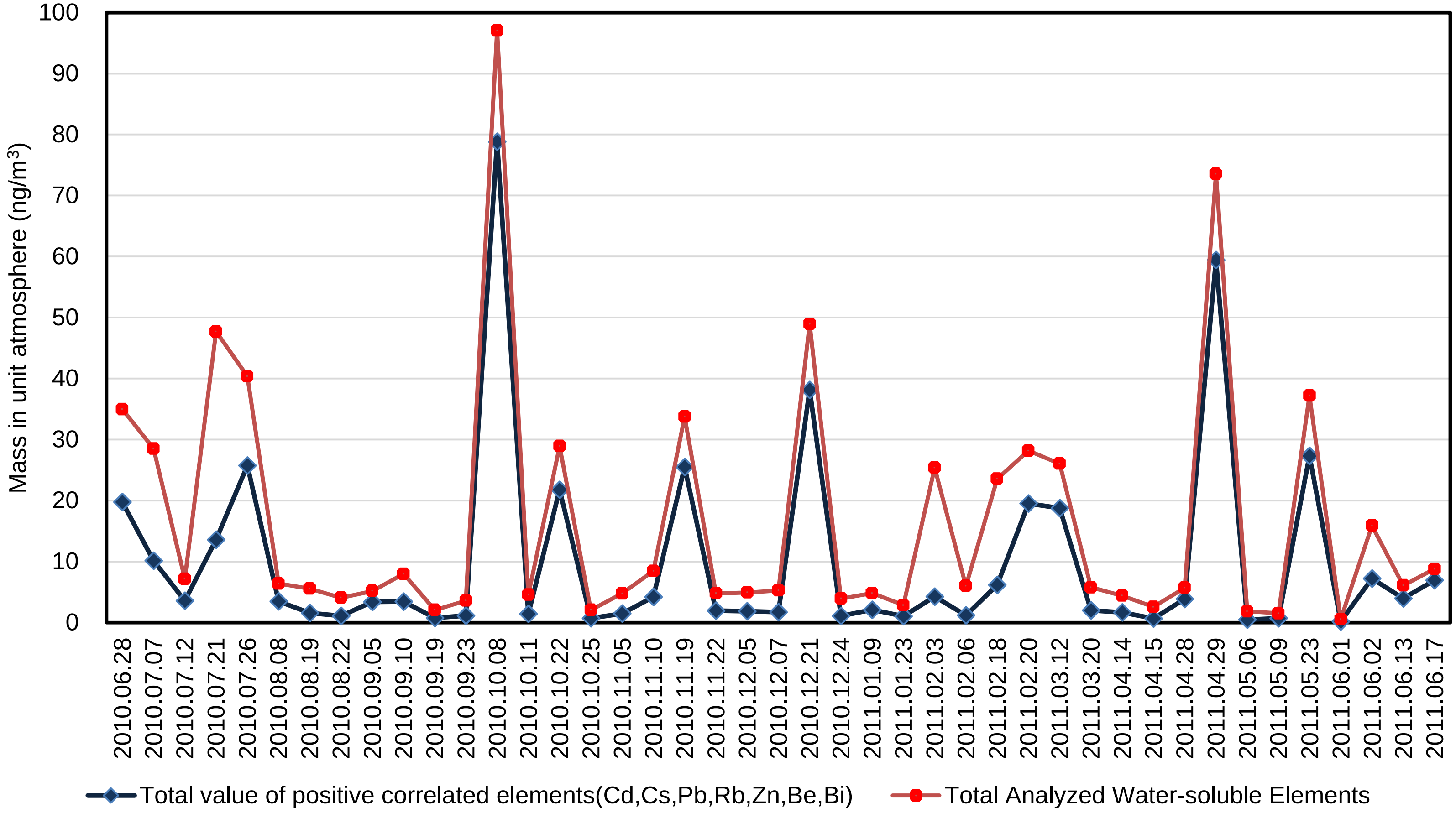

Figure 6 The overall mass concentrations of the elements with positive correlations with DNA damages (Cd, Cs, Pb, Rb, Zn, Be, Bi) and the mass concentrations of the total water-soluble elements in atmosphere

Table1 Sample information

Date	Average Temperature(℃)	RH (%)	WS (m/s)	Weather Condition	Mass concentration (μg/m^3)	Date	Average Temperature(℃)	RH (%)	WS (m/s)	Weather Condition	Mass concentration (μg/m^3)
2010.6.25	26	58	2.1	sunny	112.0	2010.12.21	7.7	23	1.3	fog	290.3
2010.6.28	28	49	2.5	haze	98.7	2010.12.24	5.8	26	2.9	sunny	43.5
2010.7.7	28.1	77	2.2	sunny	57.4	2011.1.9	6.2	27	8.0	sunny	24.7
2010.7.12	23.1	85	1.6	cloudy	56.2	2011.1.23	-4.7	24	7.2	sunny	35.0
2010.7.21	29.6	33	2.2	sunny	51.9	2011.2.3	1.9	35	2.9	sunny	85.6
2010.7.26	31.1	24	2.0	haze	121.7	2011.2.6	5.5	50	3.1	cloudy	40.1
2010.8.5	27.2	38	5.7	cloudy	39.3	2011.2.18	2.8	51	2.4	sunny	289.1
2010.8.8	25.9	43	2.2	sunny	65.9	2011.2.20	4.5	21	1.3	haze	204.7
2010.8.19	24.7	62	2.1	cloudy	68.5	2011.3.10	10	35	2.9	sunny	52.2
2010.8.22	19.9	33	3.1	sunny	59.8	2011.3.12	10.9	41	1.4	cloudy	178.1
2010.9.5	18.7	25	1.9	cloudy	93.1	2011.3.20	8.7	16	3.2	cloudy	190.1
2010.9.10	17.8	35	1.6	sunny	83.3	2011.3.24	7.4	30	7.8	sunny	29.4
2010.9.19	15.8	27	1.9	cloudy	44.1	2011.4.14	22.8	17	4.0	sunny	215.2
2010.9.23	11.9	79	2.8	sunny	43.0	2011.4.15	21.3	41	5.5	haze	182.9
2010.10.8	8.8	59	1.4	haze	259.0	2011.4.28	18.4	61	2.5	sunny	79.6
2010.10.11	12.3	85	3.8	sunny	23.4	2011.4.29	17.4	27	2.4	haze	120.2
2010.10.22	6	36	1.3	cloudy	126.2	2011.5.6	20.3	55	3.9	sunny	26.0
2010.10.25	7.7	54	7.1	sunny	25.6	2011.5.9	18.9	28	3.1	cloudy	38.2
2010.11.5	5.8	54	1.9	sunny	96.4	2011.5.20	18.3	39	4.6	cloudy	54.9
2010.11.10	6.2	63	1.5	cloudy	105.7	2011.5.23	22.5	31	3.6	sunny	88.0
2010.11.19	3.5	32	2.0	fog	248.0	2011.6.1	26.5	34	3.4	sunny	38.8
2010.11.22	3.4	34	1.6	sunny	51.5	2011.6.2	27.7	45	3.7	cloudy	85.8
2010.12.5	-6.6	27	5.6	cloudy	74.1	2011.6.13	28.2	62	2.5	sunny	69.3
2010.12.7	-5.2	48	3.1	sunny	43.7	2011.6.17	26	66	2.1	cloudy	76.0

RH: relative humidity, WS: wind speed

Table 2 Correlation between the water-soluble elemental contents and the oxidative DNA damages of the water-soluble fraction under 250 μg/ml

	Li	**Be**	Sc	Ti	V	Mn	Cr	**Co**	Ni
DNA damages	0.17	0.43	-0.13	-0.11	0.11	0.18	0.22	-0.37	0.01
	Cu	**Zn**	**Ga**	**Rb**	**Y**	Nb	Mo	**Cd**	Sb
DNA damages	0.09	0.41	-0.61	0.35	0.50	-0.27	-0.18	0.46	0.11
	Cs	Ba	La	Ce	Pr	Nd	Sm	Eu	Gd
DNA damages	0.40	0.09	0.08	0.04	-0.02	-0.05	0.21	-0.08	0.02
	Tb	Dy	Ho	Er	Tm	Yb	Lu	W	Tl
DNA damages	0.26	0.07	-0.21	-0.12	-0.02	-0.05	-0.13	-0.21	0.18
	Pb	**Bi**	Th	U	Sr	In	Zr	**Hr**	**Total**
DNA damages	0.40	0.33	-0.07	-0.11	0.07	0.25	0.07	-0.31	0.33

The elements with bold font represent that these elements are significantly correlated with the oxidative potentials of particles.

(A threshold correlation coefficient is 0.30 at the 95% confidence level)