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Commentary

Curbing dioxin emissions from municipal solid waste incineration in China: Re-thinking about management policies and practices

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The management policies and practices need to be improved to curb the increasing dioxin releases from municipal solid waste incineration in China.

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ABSTRACT

As one of the countries with large amounts of dioxin releases, the control of dioxins is a major challenge for China. Municipal solid waste (MSW) incineration should be considered a high priority source of dioxin emissions because it is playing an increasingly more important role in waste management. MSW incineration in China has much higher emission rates of dioxins than in the developed countries, partially resulting from the gaps in the technologies of incineration and flue gas cleaning. Moreover, the current management policies and practices also contribute significantly to the problem. We recommend lowering dioxin emission standard, strengthening fly ash management, and improving regulation enforcement to reduce dioxin releases into the environment from MSW incineration. We also propose that alternative strategies should be considered on dioxin control and call for an expansion of economic instruments in waste management to reduce waste generation and thus the need for incineration.

1. Dioxin contamination in China

"Dioxins" refer to a family of related chlorinated organic compounds, polychlorinated dibenzo-dioxins (PCDDs) and polychlorinated dibenzo-furans (PCDFs), which differ in the number and position of chlorine atoms on the basic underlying chemical structure. They are formed unintentionally and released as byproducts of human activities such as fuel combustion, waste incineration, chlorine bleaching of pulp and paper, pesticide manufacturing, as well as by natural processes such as forest fires and volcanoes (U.S. Environmental Protection Agency, 2000). Dioxins are widely distributed in the environment at low concentrations, and combustion processes are believed to be the major cause of this (Czuczwa and Hites, 1984). Their persistence in the environment and highly lipophilic property render dioxins bioaccumulating and biomagnifying through food webs into different trophic levels of organisms, including humans. The toxicity of each member of the dioxin family varies considerably and is usually expressed by a toxic equivalency factor (TEF) relative to the most toxic of the congeners, 2,3,7,8-tetrachlorodibenzo-p-dioxin (2,3,7,8-TCDD). The U.S. Environmental Protection Agency (2000) has characterized 2,3,7,8-TCDD as a "human carcinogen" and the mixture of dioxins to which people are usually exposed as "likely human carcinogens".

It is difficult to estimate the extent of dioxin pollution across China because they are unintentionally produced in many industrial and combustion-related processes. Regional monitoring data indicate the widespread occurrence of dioxins is already a serious environment issue. For instances, sediments from Ya-er Lake in Hubei Province, which received wastewater discharged from a factory manufacturing chlorinated organic chemicals, contained 0.16–797 ng I-TEQ/g (dry wt.) of PCDD/Fs (Wu et al., 1997). Agricultural soils in the vicinity of a municipal solid waste (MSW) incinerator in Hangzhou, Zhejiang province contained 0.60–6.38 ng I-TEQ/kg of PCDD/Fs, which resulted mainly from open burning of wastes, traffic and hot water boilers, but with limited contribution from the incinerator (Xu et al., 2009a). Surface soils around Beijing showed a mean background dioxin level of about 0.88 ng WHO-TEQ/kg, which is comparable to those of lightly polluted urban and industrial soils of other countries (Chen et al., 2003). The concentrations of PCDD/Fs in the sewage sludge from 6 wastewater treatment plants in Beijing ranged from 3.47–88.24 ng I-TEQ/kg (dry wt.), although their sources were unknown (Dai et al., 2007). Screening of human breast milk

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samples using the 7-ethoxyresorufin O-deethylase (EROD)-TEQ assay showed that the mean EROD-TEQ values ranged from 58.1 to 96.5 pg/g of milk fat for Hong Kong residents aged 21–36 years, while the levels of dioxin-like compounds in a comparable group from Guangzhou were much higher (98.8–202.1 pg/g of milk fat) (Lai et al., 2004). Zheng et al. (2008) presented a comprehensive review of PCDD/F pollution in China and compared the levels found in different environmental media and in food with those reported in other countries. Due to the widespread pollution and their extreme toxicity, there is an urgent need to curb the release of dioxins to protect the environment and human health in China.

As one of the countries with large amounts of dioxin releases (approximately 10 kg I-TEQ/year), the control of dioxins is the biggest challenge for China to reduce pollution from persistent organic pollutants (POPs) (People's Republic of China, 2007). A preliminary inventory reveals that ferrous and non-ferrous metal production (45.6%), heat and power generation (18.5%), medical waste incineration (11.5%) and uncontrolled combustion processes (9.9%) contribute to the vast majority of dioxins released in China (Table S1, Supplementary Material). As part of the national implementation plan for the Stockholm Convention, which calls for global elimination or restriction of the production and use of POPs, China aims to adopt the best available techniques and best environment practices (BAT/BEP) to control the increasing trend of dioxin releases by 2015 (People's Republic of China, 2007).

Unlike most of the industrialized countries where MSW incineration is the major source of dioxins (U.S. Environmental Protection Agency, 2000), the contribution from waste incineration (338 g I-TEQ/year) to the total amount of dioxins released is relatively small (3.3%) (People's Republic of China, 2007). Nonetheless, MSW, hazardous and medical waste incineration should be considered high priority sources in dioxin control owing to the rapidly increasing reliance on incineration as an important way to dispose waste in the near future (Zhu et al., 2008). In the present work, we limit our scope to dioxin emissions from MSW incineration, although some of the discussions are also applicable to the incineration of hazardous and medical wastes.

2. Development of MSW incineration in China

With China's rapid economic development, the country is undergoing unprecedented urbanization, and disposal of the increasing volume of MSW generated presents a major challenge for the municipalities (Cheng and Hu, 2010a,b, 2009; Cheng et al., 2007). More than 150 million tonnes of MSW is produced each year, and MSW generation is increasing at an annual rate of 8–10% (Tables S2–S3, Supplementary Material). Incineration transforms heterogeneous wastes into more homogeneous residues (flue gas, fly ash and bottom ash) with the primary benefit of substantial reduction of the waste's weight and volume (up to 75% and 90%, respectively). Energy from the discarded MSW can be recovered during incineration through steam generation, which is subsequently used for power generation and/or heating (waste-to-energy, WTE). Besides reducing the need for landfill space and generating energy, incineration also reduces the transport of MSW to distant landfills and the associated fuel consumption and greenhouse gas emissions (Kaplan et al., 2009; Weitz et al., 2002).

A growing number of cities, particularly those in the economically more developed coastal region, are switching to incineration as the preferred option in MSW management. The percentage of MSW treated by incineration increased from 2.9% to 12.9% from 2001 to 2005 (Nie, 2008). With the exception of few small-scale (100–200 t/d) incinerators, all MSW incineration facilities are operated as WTE plants in China. A total of 63 MSW incineration facilities with a combined capacity of 800 MW were in operation in 2006, treating approximately 40,000 tonnes of MSW (Table S4, Supplementary Material). During the 11th five-year plan period (2006–2010), another 82 facilities are being built and planed, adding a total incineration capacity of 66,600 tonnes/day (Table S5, Supplementary Material). It is expected that incineration will play an increasingly important role in MSW management in China in the coming decade (Cheng and Hu, 2009, 2010b).

3. Formation and destruction of dioxins in MSW incineration

The dioxins emitted from MSW incinerators result from a balance of destruction and formation processes. Fig. 1 shows the major pathways for PCDD/F formation in the flue gas and fly ash. Overall, formation of PCDD/Fs depends on the evolution of precursors within combustion gases, the interactions with reactive fly ashes, and the presence of oxygen, transition metal catalysts, and gaseous chlorine (Fiedler, 1998; Weber, 2007; Altarawneh et al., 2009). Temperature of the combustion gases is the single most important factor in dioxin formation, with maximum formation occurring at around 350 °C and minimum formation outside the range of 200–450 °C. Dioxins can be totally destructed in the combustion environment when the following criteria are met: (i) homogenous high temperature of >850 °C; (ii) excess of oxygen (>6%), and (iii) sufficient residence time (>2 s). Their formation in thermal processes can also be inhibited by various chemicals, such as CaO, sulfur and nitrogen compounds (Altarawneh et al., 2009).

Modern MSW incinerators are well equipped for dioxin control. Fig. 2 illustrates the locations for the formation, destruction, and removal of dioxins in a typical MSW incineration facility. In general, maximum destruction of dioxins during incineration can be achieved by a combination of high combustion temperature, adequate combustion time, and turbulence to distribute heat evenly throughout the combustion chamber, while dioxin formation in the post-combustion zone can be prevented by quickly cooling the flue gas exiting the combustion chamber (to temperatures below 200 °C), and minimizing the presence of the catalytic metals. In addition, PCDD/Fs can be further removed by the air pollution control devices (APCDs) installed for flue gas cleaning.

4. Status of dioxin releases from MSW incineration and recommendations for management policies and practices

Emission rates of dioxins from MSW incinerators in China are generally higher compared to those in the developed countries (<0.5 μg I-TEQ/tonne). Most of the large incinerators in China are directly imported or based on foreign technologies, while the domestically developed incinerators are limited to 100–500 t/d treatment capacities (Cheng and Hu, 2010b). The emission factors of PCDD/F compounds to the atmosphere from the domestic incinerators varied largely, and the average emission factor was approximately 1.73 μg I-TEQ/tonne (Ni et al., 2009). A study in 2001 found that atmospheric emissions of dioxins from half of the small incinerators exceeded the national standard of 1.0 ng I-TEQ/Nm^3 (Tian and Ouyang, 2003). More recent studies reported that concentrations of dioxins emitted from MSW incinerators were generally in compliance with the Chinese standard, and could even meet the European one (0.1 ng I-TEQ/Nm^3) for the large-scale ones adopting the best available air pollution control technologies (Nie, 2008; Ni et al., 2009; Xu et al., 2009b).

Development of strategies and action plans for controlling the release of dioxins from MSW incineration is an important task. Table 1 summarizes the technologies and MSW management

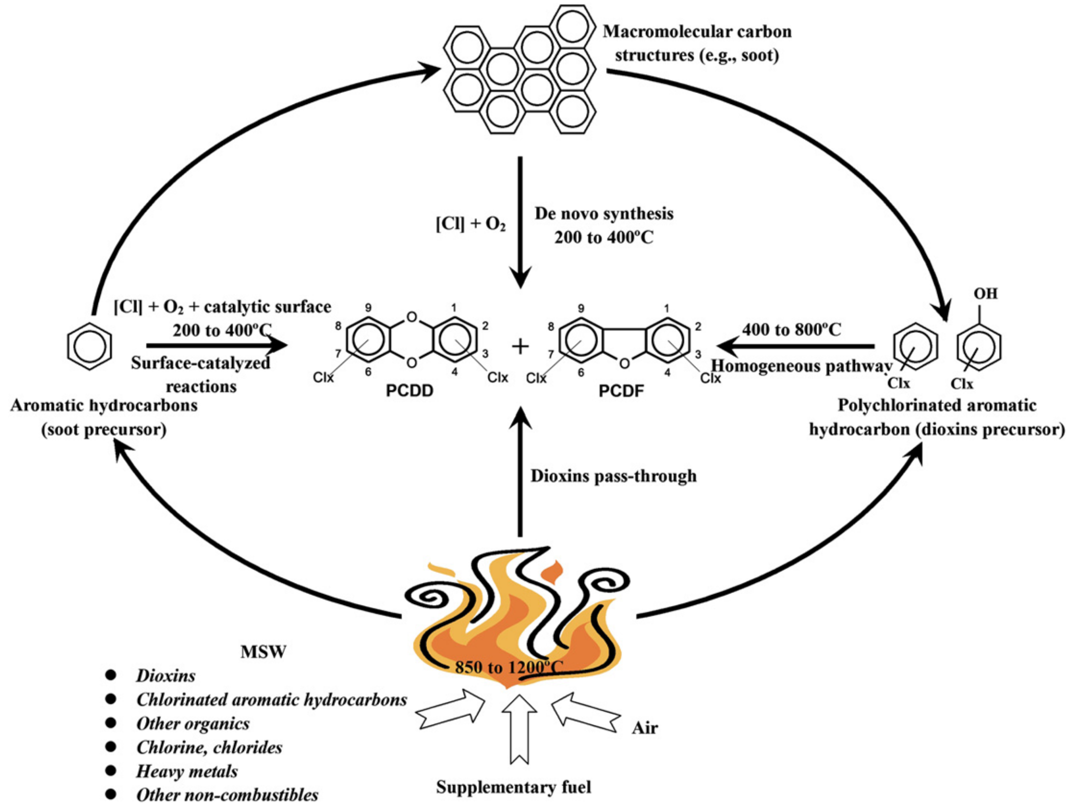

Fig. 1. Simplified pathways of PCDD/F formation in MSW incineration. Although the chemistry of PCDD/F formation in the flue gas and fly ash involves a wide variety of formation pathways, three principle mechanisms are commonly accepted (Fiedler, 1998; Weber, 2007; Altarawneh et al., 2009): (i) pass-through of PCDD/Fs contained in the incoming waste - the dioxin content in Chinese MSW is approximately 10 ng I-TEQ/kg (Yan et al., 2005), although incinerators with good combustion controls should destroy most PCDD/Fs in the feed; (ii) PCDD/Fs produced via the homogeneous pathway, which involves reaction of structurally related precursors in the gas phase at temperatures between 400 and 800 °C; and (iii) PCDD/Fs formed via heterogeneous pathways in the temperature window of 200–400 °C through the de novo synthesis, which proceeds through burn-off of a carbonaceous matrix with simultaneous oxidation and chlorination in the presence of oxygen, and the catalytic-assisted coupling of precursors assisted with transition-metal species, particularly copper compounds. It should be noted that there is no clear distinction between the precursor and de novo synthesis mechanisms.

practices for dioxin control, destruction, removal, and prevention in MSW incineration in China. The technologies used for dioxin control in developed countries, such as incineration and cooling conditions control, inhibition chemicals, flue gas scrubbing, and catalytic destruction, are also available in China. Source-classified collection, which significantly reduces the contents of Cl-containing plastics and metals in the waste stream and allows more precise control of the combustion conditions, is being gradually introduced

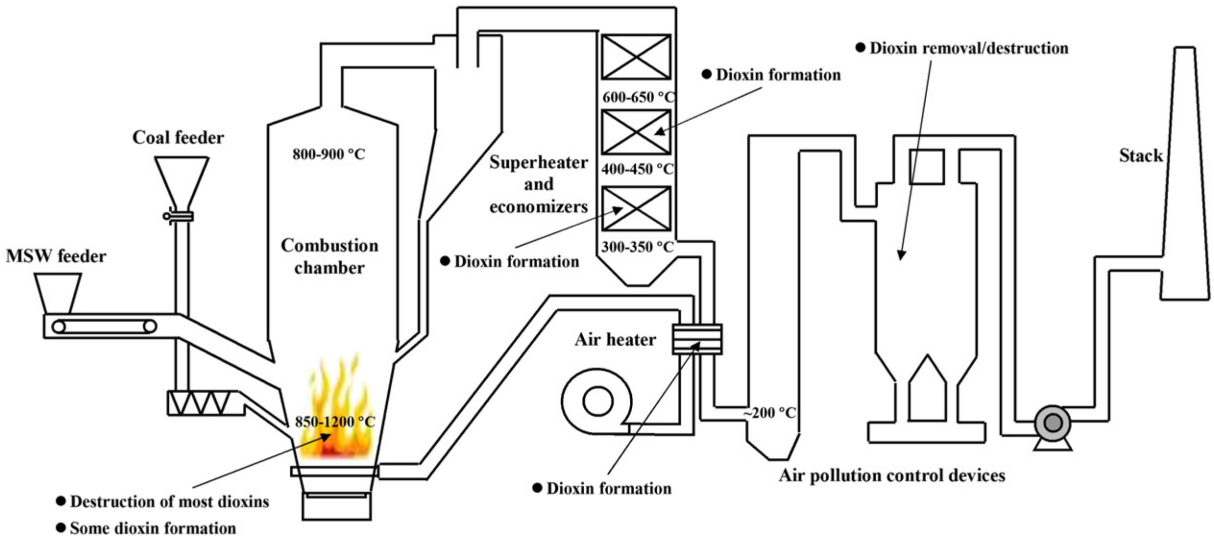

Fig. 2. Schematic illustration of the formation, destruction, and removal of dioxins at different points in typical incineration and flue gas treatment processes. Dioxins from the waste stream are readily oxidized in the combustion chamber at temperatures well above 600 °C, while some dioxins can also form. Most of the chlorinated precursor compounds volatilize and move with the gas stream through the combustion process until they reach the temperature range favorable for formation of PCDD/Fs (200–450 °C), mainly in boilers where the economizers and heat exchange equipment are located. In flue gas cleaning, dioxins can be removed by adsorption onto powdered active carbon and/or destroyed by oxidizing catalyst.

Table 1
Technologies and MSW management practices for dioxin control, destruction, removal, and prevention in MSW incineration in China.

Category	Details
1. Control technologies	
1.1 Incineration conditions control	The flue gas resulting from the combustion process is required to stay at >850 °C for at least 2 s (State Environmental Protection Administration, 2001); Homogeneous conditions for better temperature control in the combustion chamber are created through measures such as waste classification, waste de-watering, waste shredding, etc.
1.2 Inhibition chemicals	Injection of chemicals such as CaO, ammonia, urea and other amines to inhibit dioxin formation during incineration.
1.3 Cooling conditions control	Improvement of gas-cooling equipment and installation of cooling towers to prevent the new formation of dioxins in the cooling phase.
1.4 Flue gas scrubbing	Installation of bag filters and injection of activated carbon to remove dioxins from the flue gas; Technology and equipment for control of incineration fume and dioxins is one of the focus areas of the National Environmental Protection Plan in the 11th Five-Year period (2006–2010) (State Environmental Protection Administration, 2007).
1.5 Catalytic destruction	Use of selective catalytic reaction (SCR) catalysts for the combined dioxins/NO_x removal in flue gas treatment; Catalytic bag filters are also used to remove and catalytically destroy dioxins.
1.6 Phasing out small incinerators	Due to cost and management issues, small-sized incinerators tend to have higher rates of dioxin emissions. Development of large MSW incineration plants with ≥600 t/d capacities is one of the focus areas of the National Environmental Protection Plan in the 11th Five-Year period (2006–2010) (State Environmental Protection Administration, 2007).
1.7 Technological innovation	Co-firing with coal is a common practice in MSW incineration in China, with the sulfur contained in the coal (up to 4%) effectively inhibiting dioxins formation during incineration; MSW pyrolysis, and in particular gasification, which significantly reduces dioxins formation, is being developed as an alternative to incineration.
2. MSW management practices	
2.1 MSW classification and handling	Source-classified collection represents a change in MSW management in China. Removal of Cl-containing plastics and metals reduces chlorine and metal catalysts in the waste stream, and sorted trash allows more precise control of the combustion conditions, both of which significantly decrease dioxins formation in incineration.
2.2 Waste reduction, recycle, and reuse over treatment	China is making an effort to promote a recycling-based society, fully utilizing materials by reducing waste generation and increasing waste recovery (National People's Congress, 2009). Such measures reduce the total amounts of waste to be incinerated; Economic instruments for waste management, especially user charges for cost recovery in municipal waste services and for waste volume reduction, are being gradually introduced in China.

in MSW management. Although the technical requirements for dioxin control in MSW incineration in China still have a gap compared with the BAT/BEP guidelines of the Stockholm Convention (People's Republic of China, 2007), the high dioxin emission rates result equally, if not more than, from the current management policies and practices.

i) *Standard on atmospheric emission of dioxins.* MSW incinerators used to be built to wildly different standards across China and even within the same cities as the national emission standards, which are less stringent than those in Europe and U.S. (Table S6, Supplementary Material), were not established until 2001 (State Environmental Protection Administration, 2001). China should impose a tighter limit on dioxin emission from incineration to ensure cleaner air for local communities surrounding MSW incinerators and better protect human health and the environment (Supplementary Material). Meanwhile, government should provide financial support for research and development of new dioxin control technologies, which is expected to be rewarded by timely implementation of the more stringent regulation.

ii) *Fly ash management.* Compared to atmospheric emissions from MSW incineration, dioxins in the fly ash have received little attention in China. MSW incineration produces approximately 200,000 tonnes of fly ash per year (Nie, 2008), which contains PCDD/Fs at significant levels, 0.8–1.5 μg I-TEQ/kg for incinerators equipped with advanced APCDs (Bie et al., 2007). Instead of being disposed of in hazardous waste landfills, most of the MSW incineration fly ash is dumped in open pits or sold to private parties for use in construction applications without proper decontamination (Cheng and Hu, 2010b; Nie, 2008). Development of appropriate dioxin destruction technologies (e.g., vitrification, sintering, and thermocatalyic treatment) and strengthening the regulations on fly ash management and reuse, which are imperative to avoid secondary pollution, can significantly reduce the amount of dioxins released to the environment from MSW incineration.

iii) Enforcement of regulations. In China, the environmental laws and regulations are enforced by local governments, which often focus more on the local economic development and frequently ignore the environmental issues, intentionally or unintentionally. More effective administrative mechanisms should be developed to ensure that regulations on dioxin emissions from MSW incineration are not only strict, but also well enforced. Regulation enforcement requires strong monitoring capacities, although monitoring data on dioxin releases are quite insufficient in China yet due to the high analysis cost (People's Republic of China, 2007). This challenge can be met by developing on-line monitoring techniques for key surrogate compounds of PCDD/Fs (Supplementary Material). Besides making institutional changes, the government should increase the financial investment to help the waste incineration industry comply with environmental regulations, while strengthen and extend the use of economic instruments (e.g., taxes and charges) to implement environmental policies in more environmentally effective and economically efficient ways.

5. Alternative dioxin control strategies

There is a need to improve considerations of mitigating measures and alternative options when developing strategies for reducing, eliminating, and preventing dioxins. Besides the emission concentrations, it is necessary to set up total daily dioxin output (to air, water and soil) for a geographic region to protect human health. Measures that can achieve realistic and meaningful level of release reduction or source elimination should be evaluated for all dioxin sources. As human dioxin exposure comes predominantly from dietary intake, efforts on dioxin control should focus on reducing the environmental levels (and thus the levels in food) of PCDD/Fs (Supplementary Material). Try to eliminate dioxin emission from waste incineration at all cost is not necessarily the best option. With the resources and investment, much greater amounts of dioxins may be eliminated from other sources. For example, uncontrolled combustions, including forest fires, open burning of agricultural residues and household waste, are well known as a large potential source of dioxins (Gullett et al., 2006; Hedman et al., 2006). The open burning of crop residues alone released 1380 to 1520 g I-TEQ of dioxins each year between 1997 and 2004, which amounts to 10–20% of China's annual emissions (Zhang et al., 2008). The contribution of open burning of wastes and accidental fires to China's dioxin emission inventory has not been quantified yet due to lack of relevant data (People's Republic of China, 2007). Nonetheless, significant amounts of dioxins are expected given the fact that approximately half of the MSW are being dumped in open space on the outskirts of towns and cities (Ministry of Construction, 2006). Therefore, improvement on MSW collection and environmentally sound disposal of all the MSW can bring greater dioxin reduction than trying to achieve zero dioxin emissions from MSW incineration. Furthermore, materials (e.g., paper, plastics and metals) can be recycled and energy can be recovered (through waste-to-energy) from the collected waste, which will bring in a range of environmental benefits.

6. Concluding remarks

As China increasingly relies on incineration for MSW disposal, it is necessary to curb the dioxin emissions from incinerators through promoting the BAT/BEP and improving MSW management system. Furthermore, reforms in the current management policies and practices, which discourage voluntary abatement and inhibit development of new technologies, must be made to effectively and efficiently reduce dioxin releases. Alternative strategies, such as establishing total daily dioxin output and increased collection and disposal of MSW, should also be considered to protect the human health and the environment on regional scale.

It should be noted development of incineration should not discourage the use of best practice techniques that focus on the highest priorities of the waste management hierarchy: waste prevention, reuse and recycle. Ultimately, China aims to establish a recycling-based society and fully utilize materials by reducing waste generation and increasing waste recovery (National People's Congress, 2009), thereby minimizing the need for incineration and the associated dioxin emissions. Appropriate expansion of economic instruments, especially user charges, in waste management is expected to accelerate this process. Finally, the increasing reliance on incineration for MSW disposal and the need to curb dioxin emissions are not unique in China; many developing countries in Asia, such as India, Thailand and Indonesia, face a similar situation (United Nations Environment Programme, 2005). It is expected that the experience from China can offer some helpful lessons to other developing counties.

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Appendix. Supplementary data

Supplementary data associated with this article can be found in the online version, at doi:10.1016/j.envpol.2010.06.014.

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