EFFICIENT MEASURES IN WASTE MANAGEMENT AS A KEY FACTOR TO REDUCE EMISSIONS OF BFRs: CASE STUDY RESULTS FOR DecaBDE IN SWITZERLAND AND GLOBAL IMPLICATIONS

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Abstract
The significant influence of regulatory and technical measures taken in waste management on the emissions of DecaBDE is illustrated based on a dynamic substance flow analysis carried out for Switzerland. It is demonstrated that emissions would be one order of magnitude higher for the present year, if no measures had been taken after 1980. The results indicate significant differences in emissions from the end-of-life phase among different countries due to the type of waste management. Incineration and recycling technology as well as sewage sludge and e-waste disposal/recycling schemes are found to be of highest relevance.

Introduction
In different national substance flow analysis (SFA) for Denmark, Switzerland, Norway[1–3] and inventory studies[4] the sources and fate of selected brominated flame retardants BFRs have been investigated. These studies are essential to gain important information for early recognition of environmental impacts and effective chemicals management. Substance flows from consumption to solid waste management (WM) processes had been demonstrated to be relevant for polybrominated diphenyl ethers (PBDEs) and tetrabromobisphenol A (TBBPA) at the end of the last century[2]. It also was concluded that waste electric and electronic equipment (WEEE) accounted for the largest flow of the investigated BFRs compared to other waste fractions, as e.g. automobile shredder residues and construction waste. According to literature data for example roughly 75% of the entire imported OctaBDE was disposed through WEEE in the late 1990s. For DecaBDE the percentage was 44%. In a representative study, the actual flows and concentrations of BFRs in WEEE were measured by applying a SFA in a modern state-of-the-art WEEE recycling plant in Switzerland[5]. The results have confirmed the importance of WEEE fractions as an important carrier of certain BFRs, such as OctaBDE, DecaBDE and TBBPA, but did also put up new questions.

In a time-dependent model the dynamic behaviour of the anthropogenic metabolism and emission trends for selected brominated flame retardants (BFRs) from technosphere to the environment have been determined for Switzerland during the period of 1980–2020[6]. This approach allowed also investigating the effect of input changes, application pattern variations and different measures (e.g. production stop, ban for different applications, emission control enhancement) on the emissions to the environment during the last decades. The results of this study point out again the high and increasing relevance of the WM and demonstrate the benefits of a modern WM strategy in order to protect human and environment. Due to the fact that (a) electric and electronic equipment (E&E) equipment has become one of the most important application for BFRs, (b) the turn-over of WEEE in WM facilities has grown rapidly and will further increase in the future and (c) there are significant differences in WM systems around the globe, the importance of the end-of-life phase as an emission source is demonstrated. Additionally, the influence of different measures in WM on the emissions is pointed out. The case study results in this paper focus on DecaBDE and the application in E&E only.

Materials and Methods
The dynamic SFA has been carried out with a model, based on a system of coupled integro-differential equations with (time-dependent) parameter functions using SIMBOX software. The spatial system boundary is the political border of Switzerland and the temporal period 1980–2020. In order to take into account their different behaviour in the anthroposphere, the use of the selected BFRs was split up in 4 application areas (E&E, transport, textile/ furniture and construction). Time series for the parameter functions (consumption, residence times, transfer coefficients, emission factors) have been estimated based on literature data, industry contacts, measurements and own calculations and assumptions. For a more detailed description of the model, see ref 6.

In order to show the impacts of measures taken in the WM in Switzerland since 1980, the flows and emissions of DecaBDE have been calculated by applying the dynamic SFA model and omitting these changes in a special scenario "old fashion WM". In that scenario the disposal routes have been assumed to remain constant. This means that the transfer coefficients (TCs) at end-of-life to landfill, incineration, recycling and export have been kept constant from the year 1980 to 2020. For the processes recycling and incineration the TCs to landfill, incineration, sewerage and export and for the final disposal of air pollution control residues, respectively, have been assumed to be invariant during the same period, too. Sewage sludge disposal routes, meaning the TCs at wastewater treatment plants (WWTP) to agriculture (i.e. soil), landfill and incineration and the TC from landfills to the sewerage system (leachate catchment factor) have also been kept constant. The same has been assumed for the atmospheric emission factors from recycling and incineration, meaning that air pollution control efficiency would have remained at the status of the year 1980. Uncertainties of the results have been investigated, but results presented in this paper concentrate on estimated mean values only. This paper focuses on the model results for electrical and electronic equipment (E&E), which has been the by far most important application area for the consumption of DecaBDE in Switzerland.

Results and Discussion

1. Waste management as the relevant emission source in the anthroposphere
Strongly rising consumption of DecaBDE containing products during the 1980s (black line in fig. 1a) has resulted in a large built-up of the stock in the use phase up to almost 2500 tons (black line in fig. 1b). A steep increase of the total flow to WM (e.g. waste products to be recycled, incinerated, dumped on landfills and wastewater) followed with a time lag due to product lifetime (orange line in fig. 1a). The accumulation of DecaBDE in landfills in Switzerland is shown with the green line in fig. 1b. The DecaBDE use in Switzerland has been levelling out between 1990 and present. An intermediate minimum was caused by a reduced consumption in construction materials. The future consumption trend is assumed to be constant until 2020 in the reference scenario. The stock in the use phase is decreasing since about 2000 due to the levelling out of consumption figures, shorter product lifetimes and a higher flow to WM. As a consequence of the Swiss Technical Ordinance on Waste and restrictions of disposal on landfills in Switzerland, the increase of the stock on landfills has almost stopped (fig. 1b).

The total emissions of DecaBDE in Switzerland to the environment (fig. 1c) increased until the mid-1990s to a maximum of 60 kg/year. This has been followed by a decrease down to about 15 kg/year until the late 2000s. As no future restrictions on the use of DecaBDE have been assumed in this scenario, the emissions have been modelled to stay virtually constant within the next decade. The emissions from WM made up the largest part of the emissions during the last decades. Regulatory and technical measures lead to a significant reduction of these emissions starting in the late 1990s (fig. 1c). Direct emissions from production processes to environment have been negligible. Direct emissions from the use phase increased until the mid-1990s, which is in line with the stocks in the use phase. Today and in the future, their contribution to the total emissions has increased in Switzerland. Indirect emissions from production or the use phase (i.e. releases to wastewater) have accounted to the process, where they are released to the environment. These processes include leakages in the sewerage system, overflows, emissions from WWTP to surface water and the usage of sewage sludge as a fertilizer in agriculture. Figure 1d shows that emissions from WWTP, predominantly caused by the usage of sewage sludge in the agriculture, were of highest relevance. Leakages in sewerage system and overflows during heavy rain events have also contributed significantly to the emissions. Recycling processes of WEEE and disused vehicles have led to considerable atmospheric emissions, while emissions from incinerators have been of smaller importance due to improving flue gas cleaning technique. Atmospheric emissions and leaching from landfills have also been of minor relevance.

E&E has been the by far most important application area for the consumption of DecaBDE in Switzerland. Vehicles, textiles and construction materials only made up a share of about 20%. The fraction of E&E has been responsible for a somewhat smaller part of the total emissions, but still clearly the most important one. The reasons are that the fraction of the domestic production has been higher for the construction material than for

E&E, where DecaBDE is predominantly imported in finished or semi-finished products, and the relatively high emissions from car shredding.

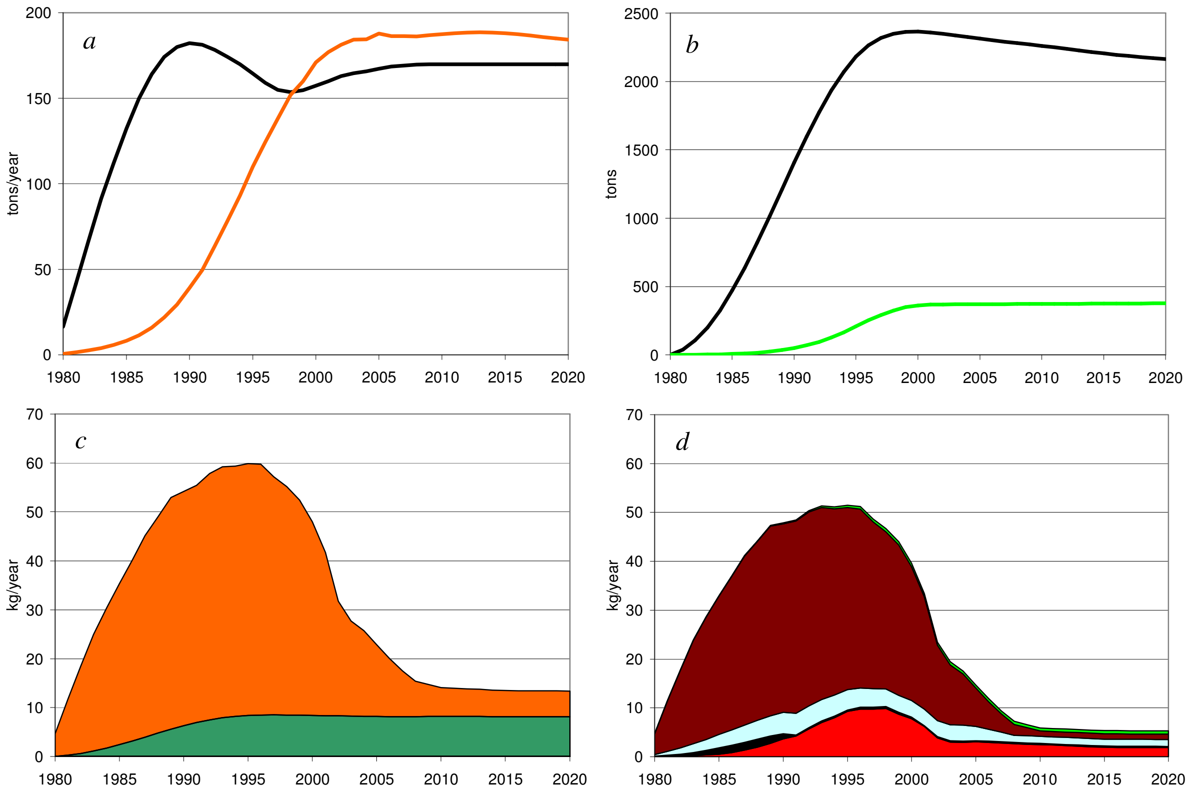

Figure 1. *a* DecaBDE consumption (black) and flow to WM (orange), *b* stock in the use phase (black) and on landfills (green), *c* emissions to environment, split up by the subsystem emitted from: production (invisible), use (green), WM (orange), *d* emissions from WM, split up by process emitted from: recycling (red), incineration (black), sewerage (light blue), WWTP (brown), landfill (green).

Table 1. Relative relevance of E&E in consumption, flow to WM and emissions of DecaBDE in Switzerland.

Year	Consumption		Flow to WM		Emissions to environment	
	Total [tons/year]	E&E [%]	Total [tons/year]	E&E [%]	Total [kg/year]	E&E [%]
1985	132	77%	8	70%	35	63%
1995	164	81%	110	78%	60	56%
2005	167	82%	188	82%	23	56%
2015	170	82%	188	80%	13	44%

2. Efficient measures in waste management as a key factor to reduce emissions to the environment

The model results of the "old fashion WM" scenario have been compared with the model results of the real situation in Switzerland (reference scenario) for the DecaBDE application in the E&E only. The results demonstrate that in the "old fashion WM" scenario (without measures taken in the WM since 1980), the total emissions to the environment for the E&E application of DecaBDE would have been more than a factor three higher compared to the maximum emissions in reference scenario. As illustrated in figure 2, the maximum emission in this case would have been at approximately 125 kg/year. The emissions in this scenario are even over one order of magnitude higher as in the realistic case for the present year and would decrease only very slightly in the near future.

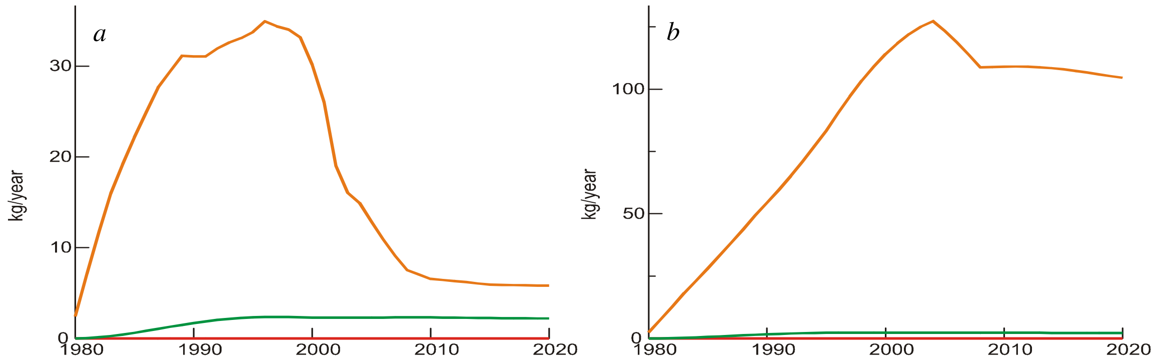

Figure 2. Emissions of DecaBDE in E&E to the environment, split up by the sources: production (red), use (green) and WM (orange); *a* reference scenario (real situation in Switzerland) with measures in the WM and *b* "old-fashion" scenario without measures taken (note the different scales).

The three main emission sources and pathways in the scenario are the atmospheric emissions from recycling and incineration and the usage of sewage sludge in the agriculture. For the present year, the emissions through these pathways would be approximately 40 kg/year (2 kg/year in the reference scenario) from recycling to the atmosphere, 20 kg/year (0.2 kg/year) from incineration to the atmosphere and 40 kg/year (3 kg/year) from sludge to soil. The emissions from sewerage, landfills and WWTP effluents would also increase, but none of them would be larger than 3 kg/year. While most of the emissions would be to soil in the beginning, the atmospheric emissions would make up 60% at present (36% to soil, 4% to hydrosphere).

The scenario results allow (i) demonstrating the effectiveness of real measures taken in the WM in Switzerland regarding the reduction of emissions to the environment and (ii) drawing conclusions regarding efficient measures for WM in other regions of the world. They indicate significant differences for BFR emissions in countries that for example do not have state of the art incineration or recycling technology and have different sewage sludge and WEEE disposal/recycling schemes. Also the size of accumulated stocks as a future potential hazard will be rather different. Illegal combustion and landfill fires[7] as well as production of dioxins and furans have not been taken into account in the model so far. Including these aspects that seem to be of high relevance especially in developing countries, the situation would be even more drastic as demonstrated for example in refs 8 and 9. The dynamic SFA model for the DecaBDE in E&E applications is suitable to apply for other applications, other BFRs or substances like POPs, too.

Acknowledgements
The project was funded by the Swiss National Science Foundation (Project FABRO, 4050-111389, National Research Programme 50).

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