INVENTORY OF U.S, SOURCES OF DIOXINS TO ATMOSPHERE

Henri Dwyer
Advisor: Professor Nickolas J. Themelis

Submitted in partial fulfillment of the requirements for the degree of
Master of Science in Earth Resources Engineering

Department of Earth and Environmental Engineering
The Fu Foundation School of Engineering and Applied Science
Columbia University

December 2015

Research co-sponsored by:

COLUMBIA UNIVERSITY
EARTH ENGINEERING CENTER

Table of Contents

EXECUTIVE SUMMARY

Dioxins are a group of related chemical compounds. They are persistent environmental pollutants of major concern due to their high toxicity. Dioxins are created by a wide range of processes, including industrial processes and natural processes, and are found throughout the world.

Part I of this report gives an overview of the main dioxin sources in the United States. By following the methodology used by the Environmental Protection Agency to establish previous dioxin inventories in 1987, 1995 and 2000, the 2012 air emissions were calculated, and the 2000 values were updated. The findings suggest an important change in the main emitting sectors from previous years: uncontrolled combustion processes now represent the largest emissions, while other sectors including waste incineration and metal smelting have greatly reduced their emissions.

Part II of this report examines the human health effects of dioxin exposure, by analyzing long-term epidemiological studies. Results suggest that current background exposure to dioxins due to air emissions is not quantifiably dangerous, and the human carcinogen classification may need to be reexamined.

Note by Prof. N.J. Themelis: The thesis of Henri Dwyer was the basis of a technical paper published in the peer-reviewed journal of Waste Management.

Waste Manag. 2015 Aug 18. pii: S0956-053X(15)30077-5. doi: 10.1016/j.wasman.2015.08.009. [Epub ahead of print]

Paper can be downloaded at
http://www.seas.columbia.edu/earth/wtert/sofos/WM_Dioxins_Inventory_Columbia.pdf

Acknowledgements

First, I would like to thank my advisor, Professor Themelis, for his support throughout the research and writing of my Master’s thesis. His patience, experience and knowledge were critical to the successful completion of this work.

In addition, I would like to thank the for their support during my degree.

This thesis would not have been possible without the support from the Sustainable Engineering GradUatE (SEGUE) Scholars Program, and particularly Professor Culligan and Scott Kelly, and the support from the Materials and Energy Recovery Division of the American Society of Mechanical Engineers

I thank my fellow SEGUE scholars and research group members.

Finally, I would like to thank my family for supporting me throughout.

Part I. U.S. Dioxin Emissions Inventory

I.1. Introduction

Part I of this thesis examines the major U.S. dioxin emission sources, and how emissions changed over time. Dioxins are persistent organic pollutants, released into the environment through several processes including combustion, metal smelting and refining, and chemical manufacturing. Since they do not readily degrade, they build up in the food chain. Humans' primary exposure is through ingestion of contaminated foods. Dioxins generally refer to structurally related halogenated dicyclic aromatic hydrocarbons: polychlorinated dibenzo-dioxins, polychlorinated dibenzofurans, and polychlorinated biphenyls. The health effects due to exposer to dioxins, a particularly one of the most toxic compounds - 2,3,7,8-Tetrachlorodibenzo-p-dioxin (TCDD) - have been extensively studied.

A common scale, the dioxin toxicity equivalence (TEQ), is used to assess the toxicities of different compounds in relation to TCDD. To calculate the toxicity equivalence of certain emissions, each compound is assigned a certain weight, its toxicity equivalency factor (TEF), and then a weighted sum is calculated. Unless specified, the weights used were the ones established by the World Health Organization (WHO) in 1998: the WHO_{98} TEQ. The following table shows the TEF for certain chlorinated dibenzo-p-dioxins.

Table 1 – WHO 1998 TEF (Van den Berg et al. 2006)

Compound	WHO 1998 TEF
2,3,7,8-TCDD	1
1,2,3,7,8-PeCDD	1
1,2,3,4,7,8-HxCDD	0.1
1,2,3,6,7,8-HxCDD	0.1
1,2,3,7,8,9-HxCDD	0.1
1,2,3,4,6,7,8-HpCDD	0.01

The other TEF used in this article is the International Toxic Equivalent (I-TEQ) scheme by the North Atlantic Treaty Organisation (NATO). For air emissions, using the I-TEQ values results in on average 10% higher values than the WHO 1998 standard (P.H. Dyke, 2002), so the results were assumed to be comparable.

I.2. Methodology

The United States Environmental Protection Agency (U.S. EPA) published in 2006 an inventory of dioxin emissions in the U.S. for the years 1987, 1995 and 2000 (US EPA 2006). In 2013, U.S. EPA released a draft of an update to the previous report. Generally, the revised values are used here.

Most emissions were calculated with the protocol used by the U.S. EPA and the WHO when evaluating environmental release of pollutants. The approach is based on calculating an emissions factor, which links the "*mass of [P]CDDs/[P]CDFs released into the environment with some measure of activity (e.g., kilograms of material processed per year, vehicle miles traveled per year, liters of wastewater discharged per year). It is developed by averaging the emission factors for the tested facilities or activities within the particular classification of sources*"[5]. Emissions figures are calculated by multiplying this average emissions factor by the activity level for that source.

Unless specified, the emissions factors are the ones published in (US EPA 2006), and the dioxin quantities are expressed in grams WHO$_{98}$ TEQ. The emissions are grouped into two categories based on the accuracy of the emissions values: controlled sources, for which precise emissions tests and activity levels were available, and open burning sources, for which best emissions tests and estimates were used, though these sources are by nature less accurate.

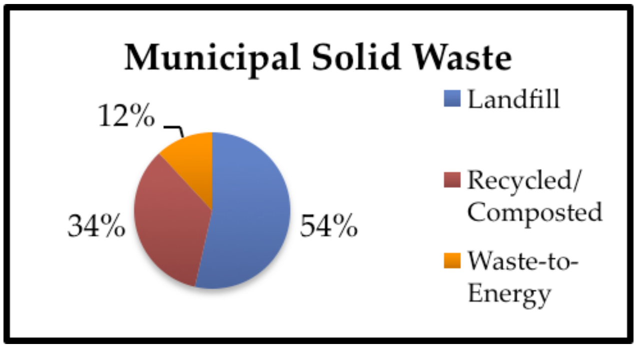
The sources of dioxins are grouped into five categories following the EPA's:

- **Waste incineration and Waste to Energy**
- **Electricity and heat generation**: fuel combustion for electricity generation, heating, and vehicles.
- **Metallurgical processes**: metal smelting, refining, and processing
- **Cement and asphalt production**
- **Open burning processes:** refer to minimally or uncontrolled combustion including, backyard barrel burning, agricultural burning, construction debris, yard waste and fires (forest, vehicle, landfill, building).

Values for 1987, 1995 and 2000 were generally taken from (US EPA 2006), except when noted as corrected, in which cases new data was used to update the values. The 2012 values were added. Sources with emissions of less than 2g for 1995 and 2000 were neglected. Dioxin quantities were rounded to the nearest gram TEQ, unless they were less than 1 g in which case they were rounded to the nearest tenth.

I.3. Waste Incineration and Waste to Energy

I.1.1. Combustion of MSW with energy recovery (waste-to-energy)



In 2012, Americans generated 251 million tons of trash. 135 million tons, or 54%, are discarded in a landfill. 87 million tons, or 35%, is recycled or composted. 30 million tons, or 12%, is combusted with energy recovery (Shin and Themelis 2014).

The first American waste incinerator was built in 1885 in New York, with hundreds built by the mid 20th century. Today's municipal solid waste thermal treatment plants are generally referred to as Waste-to-Energy (WTE) plants. Unlike historical incinerators, in addition to combusting waste they also generate energy. The current WTE infrastructure dates from before 1996: 65% of the capacity was built in the 1980s, and last 35% between 1990 and 1996. Though some plants have shut down, some have increased their capacity by adding boilers. As a result, since 1990, the amount of waste treated at WTE facilities has remained around 29 million tons. As of 2012, there are 80 waste-to-energy facilities operating in 23 states. Together, they have the capacity to treat 96,000 tons of MSW per day (Michaels 2014).

Dioxin emissions from WTE plants were calculated using 2012 stack tests provided by all facilities operated by Covanta and Wheelabrator (Michael Van Brunt, Director of Sustainability, Covanta Energy 2014) (Timothy Porter, Director, Air Quality Management, Wheelabrator Technologies Inc. 2014), which combined represent 85.8% of the WTE capacity in the USA. The other plants were assumed to have the same average emissions. The dioxin quantities are expressed using the international TEF scale.

I.3.1.1. MSW TEQ Ratio

Table 2 – WTE Plant Emissions Data

Facility ID	Avg. Dioxin Concentration (ng/dscm)	Avg. Dioxin iTEQ (ng / dscm)	Dioxin Emissions (g iTEQ)	Actual Total/TEQ RATIO	Weighted Avg. Calc. iTEQ (ng-ton/dscm)
1	1.7	0.0153	0.0474	111.1	11626.0
2	1.1	0.0197	0.0635	56.8	15587.7
3	4.0	0.0322	0.0221	124.2	5424.5
4	0.9	0.0114	0.0280	75.5	6877.0
5	10.9	0.1133	0.0640	96.2	15704.7
6	2.7	0.0311	0.1288	88.0	31609.5
7	0.6	0.0077	0.0099	79.3	2433.9
8	6.3	0.0503	0.1175	125.6	28841.2
9	5.1	0.0396	0.0226	128.0	5541.6
10	2.7	0.0321	0.1573	83.4	38594.5
11	2.8	0.0480	0.0315	57.5	7719.9
12	1.2	0.0166	0.0732	72.8	17972.2
13	0.9	0.0126	0.0282	67.4	6920.4
14	7.7	0.0385	0.0289	200.8	7086.9
15	2.4	0.0214	0.0279	114.2	6835.5
16	2.5	0.0262	0.0182	94.8	4469.0
17	1.6	0.0178	0.0320	91.4	7855.6
18	0.7	0.0107	0.0147	69.8	3611.7
19	1.8	0.0195	0.0159	92.3	3911.2
20	0.4	0.0064	0.0066	60.3	1614.8
21	1.8	0.0092	0.0178	199.0	4357.4
22	8.2	0.0939	0.1552	87.7	38095.9
23	0.8	0.0135	0.0299	60.5	7349.5
24	2.3	0.0284	0.0969	82.1	23784.3
25	1.3	0.0214	0.0152	60.7	3719.6
26	0.9	0.0134	0.0130	64.4	3186.1
27	0.9	0.0122	0.0159	74.3	3902.7
28	2.4	0.0481	0.1933	49.7	47431.2
29	0.7	0.0130	0.0179	55.7	4389.3
30	10.0	0.0986	0.1722	101.1	42269.3
31	11.6	0.2204	0.0793	52.6	19453.0

32	1.3	0.0212	0.0224	60.6	5495.3
33	0.7	0.0164	0.0126	42.9	3080.9
34	0.6	0.0091	0.0069	68.8	1697.1
35	0.7	0.0077	0.0079	90.9	1947.1
36	0.0	0.0005	0.0007	43.5	160.1
37	1.5	0.0126	0.0200	117.9	4904.4
38	2.0	0.0169	0.0246	119.1	6034.6
39	1.4	0.0159	0.0586	84.7	14385.8
40	2.3	0.0323	0.0752	70.2	18452.3
41	1.6	0.021	0.0617	76.6	15152.1
42	1.2	0.011	0.0316	114.3	7760.8
43	1.3	0.017	0.0044	80.3	1084.1
44	0.4	0.003	0.0020	116.7	492.8
45	1.0	0.017	0.0336	61.2	8253.6
46	1.8	0.016	0.0123	112.5	3022.2
47	6.0	0.045	0.0284	132.3	6977.3
48	0.3	0.002	0.0013	125.0	328.5
49	3.1	0.022	0.0291	143.2	7153.2
50	0.2	0.001	0.0021	143.5	514.9
51	1.4	0.014	0.0288	95.3	7062.8
52	3.1	0.025	0.0743	126.1	18236.5
53	12.0	0.115	0.3091	103.9	75850.7
54	2.5	0.028	0.0557	90.1	13673.8
55	8.8	0.062	0.1857	143.0	45567.1
56	0.5	0.007	0.0075	71.4	1839.6
57	0.8	0.007	0.0196	115.4	4804.3
TOTAL	**155.25**	**1.69**	**2.86**	**5,326.73**	**702,107.48**
AVERAGE	**3.88**	**0.029**	**0.049**	**91.840**	**0.028**

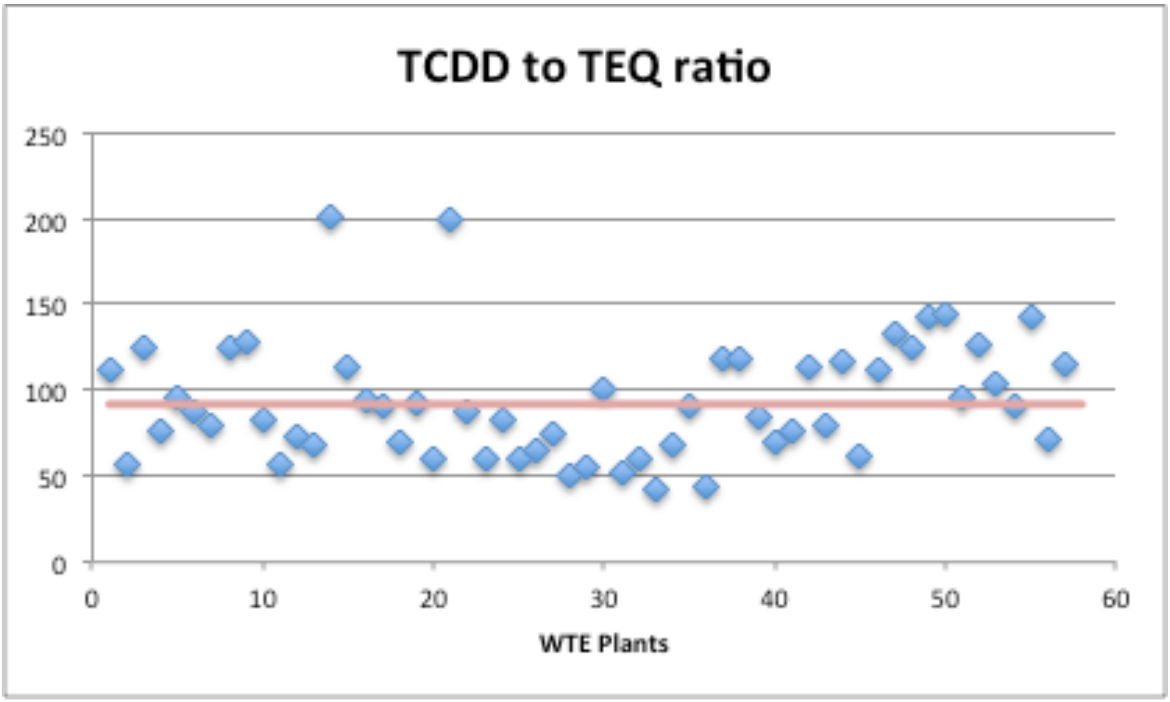
The measured stack exhaust dioxin concentrations are converted to annual mass emissions based on an EPA volume of combustion components per unit of heat content factor (F-Factor) of 9,570 dscf @ 0% O_2 / MMBtu [Ref to 40 CFR 60 Appendix A, Method 19, Table 19-2] together with an average MSW heat content of 5,000 Btu / lb using the following equation:

$$M_{DTEQ} = C_{DTEQ} \times F_d \times \frac{20.9}{20.9 - 7} \times HHV_{MSW} \times \frac{1}{35.3} \times W$$

Where:

M_{iTEQ} = Mass dioxin equivalent (iTEQ) emissions per year
C_{iTEQ} = Stack concentration of dioxin equivalent
F_d = Volume of combustion components per unit of heat content factor (9,570 scf @ 7%O_2 / MMBtu)
HHV_{MSW} = Higher heating value of MSW (10 MMBtu / short ton)
35.3 = dscf per dscm
W = Mass of waste combusted at facility per year

The data shows that in total 2.86 grams TEQ were emitted by 57 WTE plants, combusted 25.3 million short tons of MSW in 2012. To estimate the emissions of all U.S. WTE plants, this number was scaled up to the total of 30.2 million short tons combusted in U.S. WTE plants (Shin and Themelis 2014), i.e. $2.86\frac{30.2}{25.3} = 3.4\ grams\ TEQ$.



The average TCDD to TEQ ratio is 92, the median is 88 and the standard deviation is 34.

Table 3 – Municipal Waste Thermal Conversion

MUNICIPAL WASTE THERMAL CONVERSION
Emissions Factor (calculated) • 1987 – 694 ng I-TEQ/kg of waste feed. • 1995 – 40.3 ng I-TEQ/kg of waste feed.

- 2000 – 2.6 ng I-TEQ/kg of waste feed.
- 2012 – 0.1 ng I-TEQ/kg of waste feed.

Activity Levels

- 1987 – 13.7 MMT
- 1995 – 29.8 MMT
- 2000 – 29.4 MMT
- 2012 – 26.5 MMT

Releases

- 1987 – 9,510 g I-TEQ.
- 1995 – 1,200 g I-TEQ.
- 2000 – 77 g I-TEQ.
- 2012 – 3 g I-TEQ.

I.3.2. Medical waste incineration

In Sept. 1997, legislation changed, forcing MWIs to comply with Clean Air Act Amendments. This forced many facilities that used on-site incinerators to use advanced treatment techniques or switch to cheaper disposal alternatives. The EPA projected (US EPA 2006) that the closing of most MWIs would lower the annual emissions to 5-7g per year:

"In September 1997, EPA promulgated final regulations under the Clean Air Act Amendments limiting CDD/CDF stack emissions from MWIs (Federal Register, 1997a). These emission limits are specific to the sum of CDD and CDF emissions (the sum of tetra- through octa-CDDs and CDFs). For either new or existing MWIs that were operational before or after June 20, 1996, EPA limits the total CDD/CDF concentration in the stack gases to 2.3ng/dscm. This would require the application of WSs, DSI of activated carbon combined with FFs and/or SDs/FFs. EPA expects that many facilities that currently operate on-site incinerators will switch to less expensive methods of treatment and disposal of medical and infectious waste when faced with the compliance costs associated with the emission standards for MWIs. EPA projects that, following full compliance with these standards, annual emissions from MWIs will be 5 to 7 g I-TEQ/yr."

This projection seems correct: today there are 57 medical waste incinerators still in operation after over 97% of them were forced to close due to implementation of MACT regulations (United States Court of Appeals 2011).

Activity levels were obtained from a 2009 report on the impact of the latest revised MACT standards for medical waste incinerators (US EPA et al.). Since the number of incinerators is still the same, we assumed the activity level has stayed constant since 2009.

The emissions factor was assumed to be the same as in 2000 for the controlled case.

Table 4 – Medical Waste Incineration

MEDICAL WASTE INCINERATION
Emissions Factor • Uncontrolled: ○ 1987 – 1900 ng TEQ/kg of waste feed. ○ 1995 – 1900 ng TEQ/kg of waste feed. ○ 2000 – 1900 ng TEQ/kg of waste feed. ○ 2012 – N/A • Controlled: ○ 1987 – N/A ○ 1995 – 51 ng TEQ/kg of waste feed. ○ 2000 – 51 ng TEQ/kg of waste feed. ○ 2012 – 51 ng TEQ/kg of waste feed.
Activity Levels • Uncontrolled: ○ 1987 – 1.43 MMT ○ 1995 – 0.254 MMT ○ 2000 – 0.198 MMT ○ 2012 – 0 MMT • Controlled: ○ 1987 – 0 MMT ○ 1995 – 0.517 MMT ○ 2000 – 0.403 MMT ○ 2012 – 0.137 MMT
Releases • 1987 – 2,700 g TEQ. • 1995 – 510 g TEQ. • 2000 – 400 g TEQ. • 2012 – 7 g TEQ.

I.3.3. Hazardous waste incineration

Activity levels were obtained from the National Biennial RCRA Hazardous Waste Report (US EPA 2011) which gives yearly hazardous waste generation statistics.

Table 5 – Hazardous Waste Incineration

HAZARDOUS WASTE INCINERATION
Emissions Factor • 1987 – 3.9 ng TEQ/kg of waste feed. • 1995 – 3.9 ng TEQ/kg of waste feed. • 2000 – 2.1 ng TEQ/kg of waste feed. • 2012 – 2.1 ng TEQ/kg of waste feed.
Activity Levels • 1987 – 1.3 MMT • 1995 – 1.5 MMT • 2000 – 1.5 MMT • 2012 – 1.0 MMT
Releases • 1987 – 5 g TEQ. • 1995 – 6 g TEQ. • 2000 – 3 g TEQ. • 2012 – 2 g TEQ.

I.3.4. Sewage Sludge

According to the 2011, (Eastern Research Group, Inc. 2011), report commissioned by the U.S. UPA on sewage sludge incinerators, the 2011 dioxin emissions were 0.44g. Activity levels were calculated with the data provided in the supplemental information to the earlier report (Eastern Research Group, Inc. 2010), available online (US EPA 2015). The federate and operational hours are given for each sewage sludge incinerator. Multiplied, they allow for the calculation of total dry tons of sewage sludge incinerated. The emissions factor was calculated using the activity level and the releases reported.

The 2011 values were used as a proxy for the 2012 values.

The large decrease is due to the US EPA enacting MACT.

Table 6 – Sewage Sludge Incineration

SEWAGE SLUDGE INCINERATION
Emissions Factor • 1987 – 6.7 ng TEQ/kg. • 1995 – 6.7 ng TEQ/kg. • 2000 – 6.7 ng TEQ/kg. • 2012 – 0.5 ng TEQ/kg (calculated).

Activity Levels

- 1987 – 0.865 MMT of dry sewage sludge
- 1995 – 2.11 MMT of dry sewage sludge
- 2000 – 1.42 MMT of dry sewage sludge
- 2012 – 2.23 MMT of dry sewage sludge

Releases

- 1987 – 6 g TEQ.
- 1995 – 14 g TEQ.
- 2000 – 10 g TEQ.
- 2012 – 0.4 g TEQ.

I.3.5. Motor Vehicle Fuel

I.3.5.1. Leaded gasoline

Leaded gasoline is no longer sold.

I.3.5.2. Unleaded gasoline

Activity levels were calculated the U.S. Energy Information Administration's U.S. product supplied of finished motor gasoline in 2012: 8682 thousand barrels/day, or 5,04E+11 L/year (U.S. EIA 2014a). It was estimated in (US EPA 2006) that 95% is used on-road.

I.3.5.3. Diesel

The EIA reported (U.S. EIA 2014b) U.S. product supplied of distillate fuel in 2012 was 2.18e11 L. Similarly to the U.S. EPA in (US EPA 2006), the ratio of on-road use to off-road use was calculated using the ratio of retail deliveries to on-highway costumers to retail deliveries (63.7% in 2012, 55% in 2000) (U.S. EIA 2014b). This gives 1,39e11L used on-road, and 7,9e10L used off-road. Values for unleaded gasoline off-road and diesel on-road were updated for all years.

Table 7 – Motor Vehicle Fuel

MOTOR VEHICLE FUEL

Emissions Factor

- *Leaded Gasoline*
    - 1987 – 530 pg TEQ/L (Preliminary off-road).
- *Unleaded Gasoline*
    - 1987 – 16 pg TEQ/L (Preliminary off-road).
    - 1995 – 16 pg TEQ/L (Preliminary off-road).
    - 2000 – 16 pg TEQ/L (Preliminary off-road).
    - 2012 – 16 pg TEQ/L (Preliminary off-road).
- *Diesel*
    - 1987 – 540 pg TEQ/L (Preliminary off-road).
    - 1995 – 540 pg TEQ/L (Preliminary off-road).
    - 2000 – 540 pg TEQ/L (Preliminary off-road).
    - 2012 – 540 pg TEQ/L (Preliminary off-road).

Activity Levels

- *Leaded Gasoline, On-road*
    - 1987 – 9.5e10 L.
- *Leaded Gasoline, Off-road*
    - 1987 – 0.5e10 L.
- *Unleaded Gasoline, On-road*
    - 1987 – 3.03e11 L.
    - 1995 – 3.80e11 L.
    - 2000 – 4.68e11 L.
    - 2012 – 4.79e11 L.
- *Unleaded Gasoline, Off-road*
    - 1987 – 0.15e11 L.
    - 1995 – 0.20e11 L.
    - 2000 – 0.25e11 L.
    - 2012 – 0.25e11 L.
- *Diesel, On-road*
    - 1987 – 9.48e10 L.
    - 1995 – 1.02e11 L.
    - 2000 – 1.19e11 L.
    - 2012 – 1.39e11 L.
- *Diesel, Off-road*
    - 1987 – 3.45e10 L.

    - 1995 – 3.71e10 L.
    - 2000 – 4.32e10 L.
    - 2012 – 7.90e10 L.

Releases

- ***Leaded Gasoline, On-road***
    - 1987 – 50 g TEQ.
- ***Leaded Gasoline, Off-road***
    - 1987 – 3 g TEQ.
- ***Unleaded Gasoline, On-road***
    - 1987 – 5 g TEQ.
    - 1995 – 6 g TEQ.
    - 2000 – 7 g TEQ.
    - 2012 – 8 g TEQ.
- ***Unleaded Gasoline, Off-road***
    - 1987 – 0.2 g TEQ.
    - 1995 – 0.3 g TEQ.
    - 2000 – 0.4 g TEQ.
    - 2012 – 0.4 g TEQ.
- ***Diesel, On-road***
    - 1987 – 51 g TEQ.
    - 1995 – 55 g TEQ.
    - 2000 – 64 g TEQ.
    - 2012 – 75 g TEQ.
- ***Diesel, Off-road***
    - 1987 – 19 g TEQ.
    - 1995 – 20 g TEQ.
    - 2000 – 23 g TEQ.
    - 2012 – 43 g TEQ.

I.3.6. Wood

In the EIA's annual energy review (U.S. EIA 2014c), residential energy (U.S. EIA 2014b) records the yearly biomass energy used: 420 trillion BTU. The figure was converted using the EPA ratio in (US EPA 2006) of 14080 BTU/kg. Thus the 2012 activity level was 30Mt, which is the same as in 2000. This seems to suggest wood use is substantially the same as in 2000. No recent data could be found for outdoor wood-fired boilers, so the same activity level as in 2000 was used.

Table 8 – Residential Wood Combustion

Residential wood Combustion

Emissions Factor

- *Indoor residential Wood Burners*
  - 1987 – 0.5 ng TEQ/kg of wood.
  - 1995 – 0.5 ng TEQ/kg of wood.
  - 2000 – 0.5 ng TEQ/kg of wood.
  - 2012 – 0.5 ng TEQ/kg of wood.
- *Outdoor Wood-Fired Boilers*
  - 1987 – 20 ng TEQ/kg of wood.
  - 1995 – 20 ng TEQ/kg of wood.
  - 2000 – 20 ng TEQ/kg of wood.
  - 2012 – 20 ng TEQ/kg of wood.

Activity Levels

- *Indoor Residential Wood Burners*
  - 1987 – 71 MMT.
  - 1995 – 37 MMT.
  - 2000 – 30 MMT.
  - 2012 – 30 MMT.
- *Outdoor Wood-Fired Boilers*
  - 1987 – Not Available.
  - 1995 – Not Available.
  - 2000 – 0.448 MMT.
  - 2012 – 0.448 MMT.

Releases

- *Indoor Residential Wood Burners*
  - 1987 – 36 g TEQ.
  - 1995 – 19 g TEQ.
  - 2000 – 15 g TEQ.
  - 2012 – 15 g TEQ.
- *Outdoor Wood-Fired Boilers*
  - 1987 – Not Available.
  - 1995 – Not Available.
  - 2000 – 9 g TEQ (Preliminary).
  - 2012 – 9 g TEQ (Preliminary).

Activity levels were obtained from EIA industrial energy consumption data (U.S. EIA 2014d): 1,339 trillion BTU of wood and wood-derived products in 2012 (1,636 trillion BTU in 2000). This factor was used to convert the activity levels. No data on salt-laden wood was found, so the same ratio was used.

Table 9 – Industrial Wood Combustion

INDUSTRIAL WOOD COMBUSTION

Emissions Factor

- ***Nonsalt-Laden Wood***
    - 1987 – 0.6 ng TEQ/kg of wood.
    - 1995 – 0.6 ng TEQ/kg of wood.
    - 2000 – 0.6 ng TEQ/kg of wood.
    - 2012 – 0.6 ng TEQ/kg of wood.
- ***Salt-Laden Wood***
    - 1987 – 15 ng TEQ/kg of wood.
    - 1995 – 15 ng TEQ/kg of wood.
    - 2000 – 15 ng TEQ/kg of wood.
    - 2012 – 15 ng TEQ/kg of wood.

Activity Levels

- ***Nonsalt-Laden Wood***
    - 1987 – 116 MMT.
    - 1995 – 117 MMT.
    - 2000 – 116 MMT.
    - 2012 – 94MMT.
- ***Salt-Laden Wood***
    - 1987 – 0.5 MMT.
    - 1995 – 0.5 MMT.
    - 2000 – 0.8 MMT.
    - 2012 – 0.6 MMT.

Releases

- ***Nonsalt-Laden Wood***
    - 1987 – 70 g TEQ.
    - 1995 – 70 g TEQ.
    - 2000 – 70 g TEQ.
    - 2012 – 56.4 g TEQ.
- ***Salt-Laden Wood***
    - 1987 – 8 g TEQ.
    - 1995 – 8 g TEQ.
    - 2000 – 12 g TEQ.

- 2012 – 9.6 g TEQ.

- *Total Industrial Releases*
  - 1987 – 78 g TEQ.
  - 1995 – 78 g TEQ.
  - 2000 – 82 g TEQ.
  - 2012 – 68 g TEQ.

I.3.7. Oil

Activity levels were obtained from the EIA's U.S. Total Adjusted Sales of Distillate Fuel Oil by End Use (U.S. EIA 2014e), where the values for the residential and commercial sectors were added.

Table 10 - Commercial and Residential Oil Combustion

COMMERCIAL AND RESIDENTIAL OIL COMBUSTION

Emissions Factor

- 1987 – 190 pg TEQ/L of oil combusted.
- 1995 – 190 pg TEQ/L of oil combusted.
- 2000 – 190 pg TEQ/L of oil combusted.
- 2012 – 190 pg TEQ/L of oil combusted.

Activity Levels

- *Residential*
  - 2000 – 23.2e9 L.
  - 2012 – 12.3e9 L.
- *Commercial*
  - 2000 – 12.6e9 L.
  - 2012 – 9.6e9 L.
- *Total*
  - 1987 – 29.4e9 L.
  - 1995 – 31.7e9 L.
  - 2000 – 35.7e9 L (CORRECTED from 36.9e9 L).
  - 2012 – 21.9e9 L.

Releases

- 1987 – 6 g TEQ
- 1995 – 6 g TEQ
- 2000 – 7 g TEQ
- 2012 – 4 g TEQ

Utility sector and industrial oil combustion activity levels were obtained from the EIA's Total Adjusted Sales of Distillate Fuel Oil by End Use (U.S. EIA 2014e). The activity level for residual fuel oil was obtained from the EIA's total US. Adjusted sales of residual fuel (U.S. EIA 2014f).

Table 11 - Utility Sector and Industrial Oil Combustion

UTILITY SECTOR AND INDUSTRIAL OIL COMBUSTION

Emissions Factor

- 1987 – 230 pg TEQ/L of oil combusted.
- 1995 – 230 pg TEQ/L of oil combusted.
- 2000 – 230 pg TEQ/L of oil combusted.
- 2012 – 230 pg TEQ/L of oil combusted.

Activity Levels

- ***Electric Power***
  - 2000 – 4.3e9 L.
  - 2012 – 1.3e9 L.
- ***Industrial***
  - 2000 – 8.0e9 L.
  - 2012 – 9.1e9 L.
- ***Residual***
  - 2000 – 52.9e9 L.
  - 2012 – 21.5e9 L.
- ***Total***
  - 1987 – 83.8e9 L.
  - 1995 – 60.7e9 L.
  - 2000 – 65.2e9 L (CORRECTED from 66.0e9 L).
  - 2012 – 31.9e9 L.

Releases

- 1987 – 19 g TEQ.
- 1995 – 14 g TEQ.
- 2000 – 15 g TEQ.
- 2012 – 7.3 g TEQ.

I.3.8. Coal combustion

Activity levels were obtained from the EIA's Coal Consumption by Sector (U.S. EIA 2014g), which mainly includes consumption for electric power production, but also combined heat and power plants. Activity levels for both the electric power sector and the industrial sector (excluding coke plants) were used.

Residential coal consumption dropped to very low levels from 2000 to 2007, and the EIA no longer collects data. The activity level was thus assumed to be 0.
For residential coal, the emissions factor is the average of the anthracite emissions factor (2.1 ng TEQ/kg) and the bituminous emissions factor (7.5 ng TEQ/kg), assuming 72.5% percent of the coal burned is bituminous and 27.5% is anthracite, as in (US EPA 2006)

Table 12 – Coal Combustion

Coal Combustion

Emissions Factor

- ***Coal-Fired Utilities***
    - 1987 – 0.078 pg TEQ/kg.
    - 1995 – 0.078 pg TEQ/kg.
    - 2000 – 0.078 pg TEQ/kg.
    - 2012 – 0.078 pg TEQ/kg.
- ***Industrial Coal-Fired Boilers***
    - 1987 – 0.7 ng TEQ/kg.
    - 1995 – 0.7 ng TEQ/kg.
    - 2000 – 0.7 ng TEQ/kg.
    - 2012 – 0.7 ng TEQ/kg.
- ***Residential***
    - 1987 – 6.0 ng TEQ/kg.
    - 1995 – 6.0 ng TEQ/kg.
    - 2000 – 6.0 ng TEQ/kg.
    - 2012 – 6.0 ng TEQ/kg.

Activity Levels

- ***Coal-Fired Utilities***
    - 1987 – 651 MMT.
    - 1995 – 771 MMT.
    - 2000 – 894 MMT.
    - 2012 – 747 MMT.
- ***Industrial Coal-Fired Boilers***
    - 1987 – 68.2 MMT.
    - 1995 – 66.3 MMT.
    - 2000 – 59.2 MMT.
    - 2012 – 38.8 MMT.
- ***Residential***
    - 1987 – 1.6 MMT.
    - 1995 – 0.8 MMT.

    - 2000 – 0.5 MMT.
    - 2012 – 0 MMT.

Releases

- *Coal-Fired Utilities*
    - 1987 – 51 g TEQ.
    - 1995 – 60 g TEQ.
    - 2000 – 70 g TEQ.
    - 2012 – 58 g TEQ.
- *Industrial Coal-Fired Boilers*
    - 1987 – 48 g TEQ.
    - 1995 – 46 g TEQ.
    - 2000 – 41 g TEQ.
    - 2012 – 27 g TEQ.
- *Residential*
    - 1987 – 10 g TEQ.
    - 1995 – 5 g TEQ.
    - 2000 – 3 g TEQ.
    - 2012 – 0 g TEQ.

I.4. Other High-Temperature Sources

I.4.1. Cement kilns burning non-hazardous waste

Activity levels were obtained from the annual report U.S. Geological Survey (USGS), Mineral Commodity Summaries on Cement (U.S. Department of the Interior and U.S. Geological Survey 2014). The values for 2000 were update from (US EPA 2006) to 78.1 MMT from 63.7 MMT.

Table 13 - Cement kilns not burning hazardous waste

CEMENT KILNS NOT BURNING HAZARDOUS WASTE

Emissions Factor

- 1987 – 0.27 ng TEQ/kg of clinker produced.
- 1995 – 0.27 ng TEQ/kg of clinker produced.
- 2000 – 0.27 ng TEQ/kg of clinker produced.
- 2012 – 0.27 ng TEQ/kg of clinker produced.

Activity Levels

- 1987 – 47.2 MMT of clinker.
- 1995 – 61.3 MMT of clinker.
- 2000 – 78.1 MMT of clinker (CORRECTED from 63.7 MMT)

- 2012 – 67.1 MMT of clinker.

Releases

- 1987 – 13 g TEQ.
- 1995 – 17 g TEQ.
- 2000 – 21 g TEQ.
- 2012 – 18 g TEQ.

I.4.2. Cement kilns burning hazardous waste

Emissions were calculated by multiplying the dioxins released in 2000 with the ratio of hazardous waste used for fuel blending between 2000 (923,332 tons) and (651,974 tons). Data was obtained from the EPA report on RCRA hazardous generation (US EPA 2011).

Table 14 - Cement kilns burning hazardous waste

CEMENT KILNS BURNING HAZARDOUS WASTE

Emissions Factor

- 1987 – 31 ng TEQ/kg of clinker produced.
- 1995 – 31 ng TEQ/kg of clinker produced.
- 2000 – Not needed because all facilities were tested.
- 2012 – Not used.

Activity Levels

- 1987 – 3.8 MMT of clinker.
- 1995 – 5.04 MMT of clinker.
- 2000 – Not needed because all facilities were tested.
- 2012 – Not used.

Releases

- 1987 – 120g TEQ.
- 1995 – 160g TEQ.
- 2000 – 19g TEQ.
- 2012 – 13.4g TEQ.

I.4.3. Asphalt mixing plants

Activity levels were obtained from a report on world asphalt production (European Asphalt Pavement Association 2014).

Table 15 - Asphalt mixing plants

ASPHALT MIXING PLANTS
Emissions Factor • 1987 – 0.009 ng TEQ/kg of asphalt produced. • 1995 – 0.009 ng TEQ/kg of asphalt produced. • 2000 – 0.009 ng TEQ/kg of asphalt produced. • 2012 – 0.009 ng TEQ/kg of asphalt produced.
Activity Levels • 1987 – 500 MMT. • 1995 – 500 MMT. • 2000 – 500 MMT. • 2012 – 323.5 MMT.
Releases • 1987 – 5 g TEQ. • 1995 – 5 g TEQ. • 2000 – 5 g TEQ. • 2012 – 2,9 g TEQ.

I.5. Minimally Controlled and Uncontrolled Combustion Sources

I.5.1. Landfill gas combustion

Landfill methane emissions and flaring is detailed in the EPA report: Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 – 2012 (US EPA 2014b). In 2012, 13,331 Gg of methane were emitted in 2012, 4,040 Gg of which were flared. This value was then converted to volume of landfill gas, which is the unit the activity level was previously reported in. The molar mass of methane is 16, thus the volume of methane flared, at standard temperature and pressure, is:

$$4040\ Gg + 22.414\,\frac{L}{mol} \times \frac{1}{16\,\frac{g}{mol}} = 5.7\ billion\ m^3$$

Landfill gas consists of about 50% methane and 50% CO2, according to U.S. Environmental Protection Agency Landfill Methane Outreach Program. Thus, the total landfill gas volume flared in 2012 is $11.4\ billion\ m^3$. Using the EPA emissions factor of 1.4ng TEQ/m3 (Table 16 - Landfill Gas Combustion), the total emissions from landfill gas flaring in the U.S. are estimated at 16 g TEQ.

Table 16 - Landfill Gas Combustion

LANDFILL GAS COMBUSTION

Emissions Factor

- 1987 – 1.4 ng TEQ/m^3.
- 1995 – 1.4 ng TEQ/m^3.
- 2000 – 1.4 ng TEQ/m^3.
- 2012 – 1.4 ng TEQ/m^3.

Activity Levels

- 1987 – 1.35e9 m^3.
- 1995 – 4.7e9 m^3.
- 2000 – 16e9 m^3.
- 2012 – 11.4e9 m^3.

Releases

- 1987 – 2 g TEQ.
- 1995 – 7 g TEQ.
- 2000 – 22 g TEQ.
- 2012 – 16 g TEQ.

I.5.2. Structural fires

Number of fires were obtained from the National Fire Protection Association, Fire Analysis and Research division report on 2012 fires (Karter, Jr. 2013). All the values here were updated to reflect the latest report: 758,000 structural fires in 1987 (updated from 746,000), 573,500 fires in 1995 (updated from 574,000), 505,500 fires in 2000 (updated from 512,000), and 480,500 fires in 2012.

Table 17 – Structural Fires

STRUCTURAL FIRES

Emissions Factor

- 1987 – 32 μg TEQ/fire.
- 1995 – 32 μg TEQ/fire.
- 2000 – 32 μg TEQ/fire.
- 2012 – 32 μg TEQ/fire.

Activity Levels

- 1987 – 758,000 fires.
- 1995 – 5735000 fires.
- 2000 – 505,500 fires.
- 2012 – 480,500 fires.

Releases

- 1987 – 24 g TEQ.
- 1995 – 18 g TEQ.

- 2000 – 16 g TEQ.
- 2012 – 15 g TEQ.

I.5.3. Vehicle fires

Number of fires in 2012 were obtained from the National Fire Protection Association, Fire Analysis and Research division report on 2012 fires (Karter, Jr. 2013) in the category Highway Vehicle Fires as well as the report on U.S. vehicle fires trends and patterns (Ahrens 2008). All the values here were updated to reflect the latest report: 451,000 highway vehicle fires and 20,000 other vehicle fires in 1987 (updated from 556,000 highway vehicle fires and 5,600 other vehicle fires), 386,000 highway vehicle fires and 21,000 other vehicle fires in 1995 (updated from 402,000 highway vehicle fires and 4,060 other vehicle fires), 325,000 highway vehicle fires and 24,500 other vehicle fires in 2000 (updated from 338,000 highway vehicle fires and 3,400 other vehicle fires), and 172,500 highway vehicle fires and 30,000 other vehicle fires in 2012.

The number of car and truck fires has been decreasing but the number of other vehicle fires has been increasing. Since the emissions factor for other vehicles is much larger than for cars and trucks, this results in an overall increase in emissions.

Table 18 – Vehicle Fires

VEHICLE FIRES
Emissions Factor - *Cars and Trucks* ○ 1987 – 44 μg I-TEQ/incident. ○ 1995 – 44 μg I-TEQ/incident. ○ 2000 – 44 μg I-TEQ/incident. ○ 2012 – 44 μg I-TEQ/incident. - *Other Vehicles* ○ 1987 – 2.6 mg I-TEQ/incident. ○ 1995 – 2,6 mg I-TEQ/incident. ○ 2000 – 2.6 mg I-TEQ/incident. ○ 2012 – 2.6 mg I-TEQ/incident.
Activity Levels - *Cars and Trucks* ○ 1987 – 451,000 vehicle fires. ○ 1995 – 386,000 vehicle fires. ○ 2000 – 325,000 vehicle fires.

    - 2012 – 172,500 vehicle fires.
- *Other Vehicles*
    - 1987 – 20,000 vehicle fires.
    - 1995 – 21,000 vehicle fires.
    - 2000 – 24,500 vehicle fires
    - 2012 – 30,000 vehicle fires.

Releases

- *Cars and Trucks*
    - 1987 – 19,8 g I-TEQ.
    - 1995 – 17,0 g I-TEQ.
    - 2000 – 14,3 g I-TEQ.
    - 2012 – 7.6 g I-TEQ.
- *Other Vehicles*
    - 1987 – 52 g I-TEQ.
    - 1995 – 54,6 g I-TEQ.
    - 2000 – 63.7 g I-TEQ .
    - 2012 – 78,0 g I-TEQ.
- *Total*
    - 1987 – 72 g I-TEQ.
    - 1995 – 72 g I-TEQ.
    - 2000 – 78 g I-TEQ.
    - 2012 – 86 g I-TEQ.

I.5.4. Landfill fires

According to the report: Landfill Fires, Their Magnitude, Characteristics and Mitigation (TriData Corporation 2002), sponsored by the Federal Emergency Management Agency, United States Fire Administration, National Fire Data Center, there were 8300 landfill fires during 2000.

Many fire departments report fires using the National Fire Incident Reporting System (NFIRS). This data was made available by the Federal Emergency Management Agency under the OpenFEMA initiative. This data records a statistically representative fraction of fires all fires. In the data, during the year 2000, there were 2500 fires on dumps or sanitary landfills. According to the landfill fire report, there were 8300 fires, so this means 30% of such fires were reported using NFIRS. In 2011, there were 3324 fires on dumps or sanitary landfills reported using the NFIRS. Assuming the fraction of reported to unreported landfill fires stayed the same between 2000 and 2011, we estimate that in 2011 there were 11000 landfill fires.

According to the EPA report, (US EPA 2006), each landfill fire represented about 225,000 kg of burned material, giving us the activity level of 2011 (and by extension 2012, assuming the same values):

$$3324\ fires\ reported \ast \frac{1\ fire}{0.3\ fires\ reported} \ast 225{,}000\,\frac{kg}{fire} = 2.5\ MMT$$

Table 19 – Landfill Fires

LANDFILL FIRES
Emissions Factor • 1987 – 700 ng TEQ/kg burned. • 1995 – 700 ng TEQ/kg burned. • 2000 – 700 ng TEQ/kg burned. • 2012 – 700 ng TEQ/kg burned.
Activity Levels • 1987 – 1.9 MMT. • 1995 – 1.9 MMT. • 2000 – 1.9 MMT. • 2012 – 2.5 MMT.
Releases • 1987 – 1,300 g TEQ. • 1995 – 1,300 g TEQ. • 2000 – 1,300 g TEQ. • 2012 – 1,750 g TEQ.

I.5.5. Forest and Brush Fires

Activity levels were obtained from the National Interagency Fire Center website (National Interagency Coordination Center 2014), which publishes data by the National Interagency Coordination Center. In 2012, there were 9,326,238 acres of of wild fires and 1,971,834 acres of prescribed fires. It's important to note that the acres burned by wild fire are highly variable, and that 1987 and 1995 were well below average, while 2000 and 2012 were above average.

To estimate the amount of biomass, we assumed it was proportional to the surface burned, extrapolating from 2000 data (8,357,958 acres for wild fires and 1,261,607 acres for prescribed fires).

Table 20 – Forest and Brush Fires

FOREST AND BRUSH FIRES
Emissions Factor • 1987 – 3 ng TEQ/kg.

- 1995 – 3 ng TEQ/kg.
- 2000 – 3 ng TEQ/kg.
- 2012 – 3 ng TEQ/kg.

Activity Levels

- 1987 – 61 MMT.
- 1995 – 55 MMT.
- 2000 – 243.8 MMT.
- 2012 – 279 MMT.

Releases

- 1987 – 180 g TEQ.
- 1995 – 170 g TEQ.
- 2000 – 730 g TEQ.
- 2012 – 837 g TEQ.

I.5.6. Backyard barrel burning

Backyard barrel burning refers to people burning municipal solid waste directly in their back yard. In (US EPA 2006), they calculate that 28% of the rural population takes part in backyard barrel burning, and that they burn about 63% of their non recycled and non composted trash. Since there was no change in legislation regarding backyard barrel burning (it is banned), we assumed the same prevalence. According to the 2014 EPA report on municipal waste generation (US EPA 2014a), the per capita waste generation in 2012 was 475 kg. According to the latest US census data (US Census 2015), the rural population in 2010 was 59,492,267. Assuming the same today, we can calculate the activity level for backyard barrel burning:

$$59.5e6 \ast 28\% \ast 63\% \times 475\ kg = 5.0\ MMT$$

Table – Backyard Barrel Burning

BACKYARD BARREL BURNING

Emissions Factor

- 1987 – 77 ng TEQ/kg.
- 1995 – 77 ng TEQ/kg.
- 2000 – 77 ng TEQ/kg.
- 2012 – 77 ng TEQ/kg.

Activity Levels

- 1987 – 7.87 MMT.
- 1995 – 8.18 MMT.
- 2000 – 7.79 MMT.
- 2012 – 5.0 MMT.

Releases

• 1987 – 610 g TEQ. • 1995 – 630 g TEQ. • 2000 – 600 g TEQ. • 2012 – 385 g TEQ.

I.5.7. Residential yard waste burning

Activity levels were assumed to be proportional to the total population, as in (US EPA 2006). According to the US census data (US Census 2015), the population was 313.9 million in 2012, compared to 282,1 million in 2000. As a result, the activity level was calculated to be 567,000 MMT.

Table 21 - Residential Yard Waste Burning

RESIDENTIAL YARD WASTE BURNING
Emissions Factor • 1987 – 10 ng TEQ/kg. • 1995 – 10 ng TEQ/kg. • 2000 – 10 ng TEQ/kg. • 2012 – 10 ng TEQ/kg.
Activity Levels • 1987 – 441,000 MMT. • 1995 – 485,000 MMT. • 2000 – 510,000 MMT. • 2012 – 567,000 MMT.
Releases • 1987 – 4 g TEQ. • 1995 – 5 g TEQ. • 2000 – 5 g TEQ. • 2012 – 6 g TEQ.

I.5.8. Land clearing debris

Activity levels where estimated using area perturbed by construction.

Previously, the EPA estimated residential construction area by using US census data on new residential construction and approximating the lot size. Since 1999, the US Census reports the lot size for residential construction projects (US Census 2015). Thus, we can use the actual area perturbed, assuming the entire lot size is perturbed. In 2000, about 11% of the construction projects did not report have an associated lot size. In the calculations, those lots were assigned the average of the other lots. Similarly, in 2012, about 27% of the construction projects did report the lot size. Using this new data, we find the total area perturbed by residential construction in 2000 is 31,500 acres and in 2012 it is 18,000 acres. These values are far below the estimates obtained using the EPA's previous method, which were both above 250,000 acres. However these estimates likely largely overestimated the average area of residential construction lots.

For nonresidential construction, the area perturbed was estimated by converting the value spent on construction projects (in 2012 $573 billion according to census data (US Census 2013)) to acres. The conversion factor was estimated using the 2000 conversion factor, and adjusted for 2012 is using the Constant Quality (Laspeyres) Price Index of New Single-Family Houses Under C onstruction – assuming this index also applies to nonresidential construction. In 2012 the price index is 97.6, and in 2000 75.6. Thus, the 2000 factor of 1.6 acres per $1m[1] becomes 1.24 acres per $1m.

The area perturbed can thus be calculated:

In 2000:
$208 billion (nonresidential private construction) + $181 billion (public non residential construction) = $399 billion of construction
Area perturbed = $\$399\ billion \times 1.6 \frac{acres}{\$1\ million} + 31{,}500\ acres = 670{,}000\ acres$

In 2012: $\$573\ billion \times 1.23 \frac{acres}{\$1\ million} + 18{,}000\ acres = 722{,}000\ acres$

The area perturbed was converted to tonnes of biomass using the average loading factor of 33 tonnes per acre.

Table 22 - Land-Clearing Debris Burning

LAND-CLEARING DEBRIS BURNING
Emissions Factor • 1987 – 3 ng TEQ/kg. • 1995 – 3 ng TEQ/kg.

---

[1] The EPA report likely has an error here because they write 1.6 acres per $100,000 which is too low. Also, using this same method for 2000 gives slightly different values than found by the EPA. In particular, the non-residential spending is slightly different - 440,000 compared to 336,000 and the public works accounts for 290,000 compared to 190,000.

- 2000 – 3 ng TEQ/kg.
- 2012 – 3 ng TEQ/kg.

Activity Levels

- 1987 – 22.7 MMT.
- 1995 – 26.4 MMT.
- 2000 – 22.1 MMT.
- 2012 – 23.9 MMT.

Releases

- 1987 – 83 g TEQ.
- 1995 – 79 g TEQ.
- 2000 – 66 g TEQ.
- 2012 – 72 g TEQ.

I.5.9. Open burning of demolition/construction wood

Activity levels were estimated using a U.S. Forest Products Laboratory (USFPL) report (Falk and McKeever 2012) on wood residue there are 36.7 million tons of wood residue generated from construction and demolition debris. Of this, 19.1 million tons are either recovered, combusted, or not usable. If we assume that 10% of that is burned in the open, as in (US EPA 2006), this gives us a total of 1.9 tons burned.

Table 23 - Open burning of Demolition/Construction wood

Open burning of Demolition/Construction wood

Emissions Factor

- 1987 – 28 ng TEQ/kg.
- 1995 – 28 ng TEQ/kg.
- 2000 – 28 ng TEQ/kg.
- 2012 – 28 ng TEQ/kg.

Activity Levels

- 1987 – 0.8 MMT.
- 1995 – 0.8 MMT.
- 2000 – 0.8 MMT.
- 2012 – 1.9 MMT.

Releases

- 1987 – 22 g TEQ.
- 1995 – 22 g TEQ.
- 2000 – 22 g TEQ.
- 2012 – 53 g TEQ.

I.5.10. Agricultural burning (sugarcane)

The EPA noted that sometimes agriculture fields are burned to make space for new plantations. Sugarcane is the crop for which this practice is most common. Activity levels were obtained from the Food and Agriculture Organization of the United Nations statistics web page (UN FAO 2015), 29.2 million tonnes in 2012 and 36 million tonnes in 2000. The EPA estimates that 50% of the production mass ends up burned at 90% efficiency, giving 13.1 million tonnes burned in 2012 and 16.2 million tonnes burned in 2000. The previous report (US EPA 2006) published that only 3.5 million tonnes were burned in 2000, but did not have accurate production statistics and estimated production by looking at average cultivated area and multiplying by a yield per acre. This method seems more robust and certain as it directly uses sugarcane production values.

Table 24 – Agricultural Burning

AGRICULTURAL BURNING
Emissions Factor • 1987 – 10 ng TEQ/kg. • 1995 – 10 ng TEQ/kg. • 2000 – 10 ng TEQ/kg. • 2012 – 10 ng TEQ/kg.
Activity Levels • 1987 – 2.8 MMT. • 1995 – 3.1 MMT. • 2000 – 16.2 MMT. • 2012 – 13.1 MMT.
Releases • 1987 – 28 g TEQ. • 1995 – 31 g TEQ. • 2000 – 162 g TEQ. • 2012 – 131 g TEQ.

I.6. Metal Smelting and Refining Sources

Activity levels for the yearly production values of various metals were obtained from the U.S. Geological Survey, Mineral Commodity Summaries website (USGS 2015).

I.6.1. Magnesium smelting

There is only one plant in operation (the same plant as in 2000). Therefore we assumed the same activity levels and dioxin releases as 2000.

Table 25 - Primary Magnesium Smelting

PRIMARY MAGNESIUM SMELTING
Emissions Factor • 1987 – 94 ng TEQ/kg. • 1995 – 94 ng TEQ/kg. • 2000 – 94 ng TEQ/kg. • 2012 – 94 ng TEQ/kg.
Activity Levels • 1987 – 0.142 MMT. • 1995 – 0.142 MMT. • 2000 – 0.083 MMT. • 2012 – 0.083 MMT.
Releases • 1987 – 13g TEQ. • 1995 – 13g TEQ. • 2000 – 8 g TEQ. • 2012 – 8 g TEQ.

I.6.2. Secondary Aluminum Smelting

The activity levels in 2012 were the same as in 2000: 1.6 million tonnes.

Table 26 - Secondary Aluminum Smelting

SECONDARY ALUMINUM SMELTING
Emissions Factor • 1987 – 15 ng TEQ/kg. • 1995 – 15 ng TEQ/kg. • 2000 – 5.2 ng TEQ/kg. • 2012 – 5.2 ng TEQ/kg.
Activity Levels • 1987 – 0.7 MMT. • 1995 – 1.3 MMT. • 2000 – 1.6 MMT. • 2012 – 1.6 MMT.
Releases • 1987 – 11g TEQ. • 1995 – 20g TEQ.

- 2000 – 8 g TEQ.
- 2012 – 8 g TEQ.

I.6.3. Copper secondary smelting

The activity level for secondary copper was 230 thousand tonnes in 2012.
In the reference years, there were only 3 active facilities (US EPA 2006). The Chemetco smelter closed in 2001, so there are no secondary copper smelters left. As a result, there is no data for 2012 emissions (assumed to be 0). The value for 2000 was updated from 235,000 MMT to 209,000 MMT.

Table 27 - Secondary Copper Smelting

SECONDARY COPPER SMELTING

Emissions Factor

- ***Franklin***
  - 1987 – 17,000 ng TEQ/kg.
  - 1995 – 17,000 ng TEQ/kg.
- ***Chemetco***
  - 1987 – 3.7 ng TEQ/kg.
  - 1995 – 3.7 ng TEQ/kg.
  - 2000 – 3.7 ng TEQ/kg.
- ***Gaston***
  - 1987 – 8,900 ng TEQ/kg.

Activity Levels

- ***Franklin***
  - 1987 – 13,600 MMT.
  - 1995 – 16,000 MMT.
- ***Chemetco***
  - 1987 – 120,000 MMT.
  - 1995 – 135,000 MMT.
  - 2000 – 209,000 MMT.
- ***Gaston***
  - 1987 – 8,900 ng TEQ/kg.

Releases

- 1987 – 990 g TEQ.
- 1995 – 270 g TEQ.
- 2000 – 0.9 g TEQ.
- 2012 – 0 g TEQ.

I.6.4. Secondary Zinc Production

Table 28 - Secondary Zinc Production

SECONDARY ZINC PRODUCTION

Emissions Factor

- 1987 – 50 ng I-TEQ/kg.
- 1995 – 50 ng I-TEQ/kg.
- 2000 – 50 ng I-TEQ/kg.
- 2012 – 50 ng I-TEQ/kg.

Activity Levels

- 1987 – 82,500 MT.
- 1995 – 131,000 MT.
- 2000 – 135,000 MT.
- 2012 – 150,000 MT.

Releases

- 1987 – 4 g I-TEQ.
- 1995 – 7 g I-TEQ.
- 2000 – 7 g I-TEQ.
- 2012 – 8 g I-TEQ.

I.6.5. Sinter production

Activity levels for sinter production were extrapolated from pig iron production data, assuming the ratio of pig iron production (33 MMT in 2012, 50.6 MMT in 2000) to sinter consumption stayed the same. This gives us 6.9 million tonnes in 2012, compared to 10.6 million tonnes in 2000.

We assumed the same ratio of wet scrubbers to bag-houses (no available data, though this may have shifted towards better controls).

Table 29 – Sinter Production

SINTER PRODUCTION

Emissions Factor

- *Wet Scrubber*
    - 1987 – 0.62 ng TEQ/kg.
    - 1995 – 0.62 ng TEQ/kg.
    - 2000 – 0.62 ng TEQ/kg.
    - 2012 – 0.62 ng TEQ/kg.
- *Fabric Filter*
    - 1987 – 4.6 ng TEQ/kg.
    - 1995 – 4.6 ng TEQ/kg.
    - 2000 – 4.6 ng TEQ/kg.

    - 2012 – 4.6 ng TEQ/kg.

Activity Levels

- 1987 – 14.5 MMT.
- 1995 – 12.4 MMT.
- 2000 – 10.6 MMT.
- 2012 – 6.9 MMT.

Releases

- 1987 – 33 g TEQ.
- 1995 – 28 g TEQ.
- 2000 – 24 g TEQ.
- 2012 – 16 g TEQ.

I.6.6. Coke Consumption

Activity levels were obtained from the EIA's coal industry data (U.S. EIA 2014g). The values for 2000 are slightly different than those published by the EPA (23,2 million tonnes in 2000, 14 million tonnes in 2012, and 26,2 million tonnes reported for 2000 by the EPA).

Table 30 – Coke Production

COKE PRODUCTION

Emissions Factor

- 1987 – 0.29 ng I-TEQ/kg.
- 1995 – 0.29 ng I-TEQ/kg.
- 2000 – 0.29 ng I-TEQ/kg.
- 2012 – 0.29 ng I-TEQ/kg.

Activity Levels

- 1987 – 33.5 MMT.
- 1995 – 29.9 MMT.
- 2000 – 23.2 MMT.
- 2012 – 15.5 MMT.

Releases

- 1987 – 10 g TEQ.
- 1995 – 9 g TEQ.
- 2000 – 6 g TEQ.
- 2012 – 4 g TEQ.

I.6.7. Secondary ferrous smelting

Production values were taken from the electric arc furnace category: 49 million tonnes in 2000, and 53.7 million tonnes in 2012.

Table 31 - Secondary Ferrous Metal Smelting

SECONDARY FERROUS METAL SMELTING
Emissions Factor • 1987 – 1.2 ng TEQ/kg. • 1995 – 1.2 ng TEQ/kg. • 2000 – 1.2 ng TEQ/kg. • 2012 – 1.2 ng TEQ/kg.
Activity Levels • 1987 – 30.8 MMT. • 1995 – 38.4 MMT. • 2000 – 49 MMT. • 2012 – 53.7 MMT.
Releases • 1987 – 37 g TEQ. • 1995 – 46 g TEQ. • 2000 – 59 g TEQ. • 2012 – 64 g TEQ.

I.6.8. Ferrous foundries

Activity levels are: Steel casting production in 2000: 9,8 million tonnes. In 2012: 0,4 million tonnes. Iron casting production in 2000: 1,3 million tonnes. In 2012: 4 million tonnes.

Table 32 - Secondary Ferrous Metal Smelting

SECONDARY FERROUS METAL SMELTING
Emissions Factor • 1987 – 1.4 ng TEQ/kg. • 1995 – 1.4 ng TEQ/kg. • 2000 – 1.4 ng TEQ/kg. • 2012 – 1.4 ng TEQ/kg.
Activity Levels • 1987 – 9.19 MMT. • 1995 – 13.9 MMT. • 2000 – 11.1 MMT. • 2012 – 4.4 MMT.
Releases • 1987 – 13 g TEQ. • 1995 – 19 g TEQ. • 2000 – 16 g TEQ. • 2012 – 6 g TEQ.

I.6.9. Complex chemical plants

According to (Dyke and Amendola 2007), about a 2g I-TEQ reduction is expected for 2002 because of implementation of MACT rules. Assuming no new sources since 2007, and no evidence was found to suggest the contrary, and otherwise the same emissions as 2002, this gives us a total of 3g I-TEQ for 2012.

Table 33 - Complex Chemical Plants Producing Chlorine/Chlorinated Organics

COMPLEX CHEMICAL PLANTS PRODUCING CHLORINE/CHLORINATED ORGANICS
Releases • 1987 – Not available. • 1995 – Not available. • 2000 – 5 g TEQ. • 2012 – 3 g TEQ.

I.7. Summary and Table and Figure

The following graphs summarize the dioxin emissions for the reference years 1987, 1995, 2000 and 2012. They are all to scale.

Darker lines indicate subtotals.

Table 34 – Summary: dioxin emissions from all sources

Source	**1987**	**1995**	**2000**	**2012**
Waste To Energy	9500	1200	77	3
Hazardous Waste Incineration	5	6	3	2
Medical Waste Incineration	2700	510	400	7
Sewage Sludge	6	14	10	0
Waste Incineration/Waste-To-Energy	12211	1730	490	13
Gasoline	58	6	7	8
Leaded Gasoline On Road	50	0	0	0
Leaded Gasoline On Road	3	0	0	0
Unleaded Gasoline On Road	5	6	7	8
Unleaded Gasoline Off Road	0	0	0	0
Diesel	70	75	87	118
Diesel On Road	51	55	64	75
Diesel Off Roads	19	20	23	43
Wood Combustion	114	97	106	92
Indoor Residential Wood Burners	36	19	15	15
Outdoor Residential Wood Burners			9	9
Industrial Wood Combustion	78	78	82	68
Oil	25	20	22	11
Commercial And Residential	6	6	7	4
Industrial And Utility	19	14	15	7
Coal Combustion	109	112	114	85
Industrial Coal-Fired Utilities	51	61	70	58
Industrial Coal-Fired Boilers	48	46	41	27
Residential Coal Combustion	10	5	3	0
Power Generation	376	310	336	314
Combustion Of Landfill Gas	2	7	22	16
Structural Fires	24	18	16	15
Vehicle Fires - Cars And Other Vehicles	72	72	78	86
Landfill Fires	1300	1300	1300	1750
Forest And Brush Fires	180	170	730	837
Backyard Burning	610	630	600	385
Residential Yard Burning	4	5	5	6
Land Clearing Debris Burning	83	79	66	72
Open Burning Of Demolition/Construction Wood	22	22	22	53
Agricultural Burning (Sugarcane)	28	31	162	131
Open Burning Processes	2325	2334	3001	3351
Primary Magnesium Smelting And Refining	13	13	8	8
Secondary Aluminum Smetling	11	20	8	8
Secondary Zinc Production	4	7	7	8

Secondary Coper Smelting	990	270	1	0
Sinter Production	33	28	24	16
Coke Production	10	9	8	4
Secondary Ferrous Metal Smelting/Refining	37	46	59	64
Ferrous Foundries	13	19	16	6
Metallurgical Processes	1111	412	131	114
Complex Chemical Plants Producing Chlorine And A Variety Of Chlorinated Organics	0	0	5	3
Cement Kilns Burning Hazardous Waste	120	160	19	13
Cement Kilns Not Burning Hazardous Waste	13	17	21	18
Asphalt Mixing Plants	5	5	5	3
Cement And Asphalt Production	138	182	45	34
Total	**16349**	**5123**	**4174**	**3985**

Table 35 – Summary: dioxin emissions by category

Source	**1987**	**1995**	**2000**	**2012**
Waste Incineration/Waste-To-Energy	12211	1730	490	13
Power Generation	376	310	336	314
Open Burning Processes	2325	2334	3001	3351
Metallurgical Processes	1111	412	131	114
Cement And Asphalt Production	138	182	45	34
Year Total	16161	4968	4003	3826

The following figures show the relative size of each emissions source for the reference years 1987, 1995, 2000 and 2012.

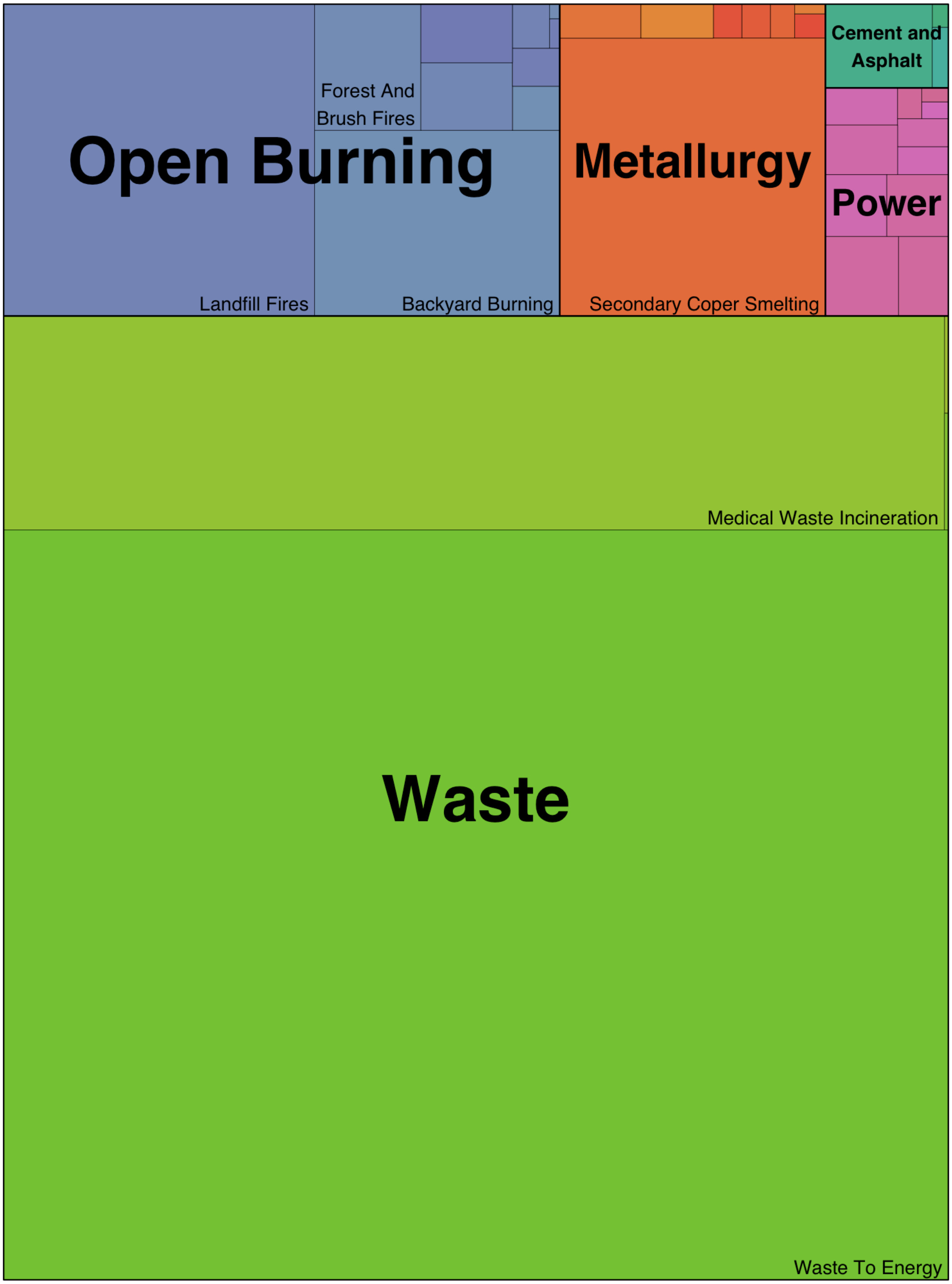


Figure 1 - 1987 Dioxin Emissions Treemap

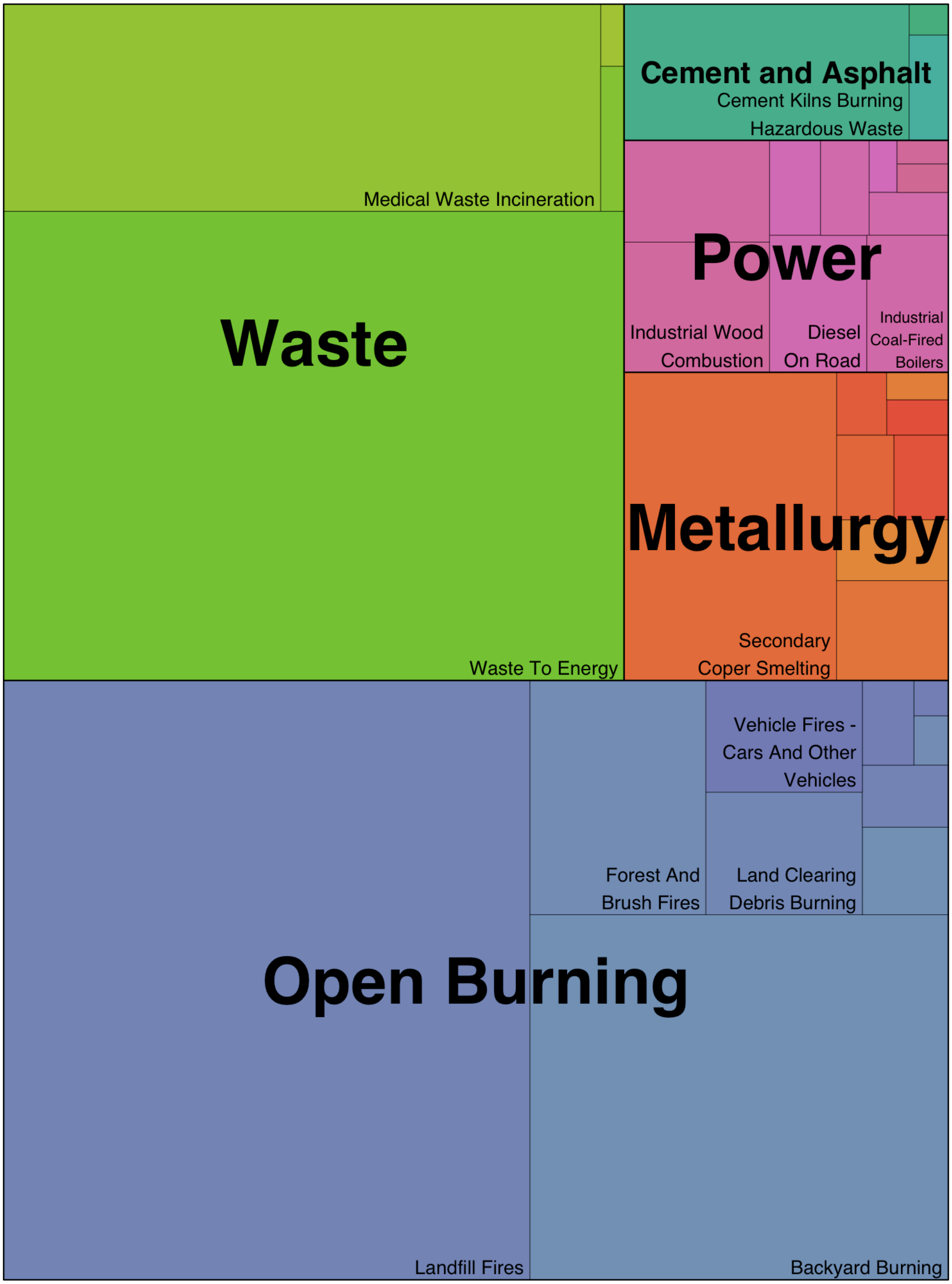


Figure 2 - 1995 Dioxin Emissions Treemap

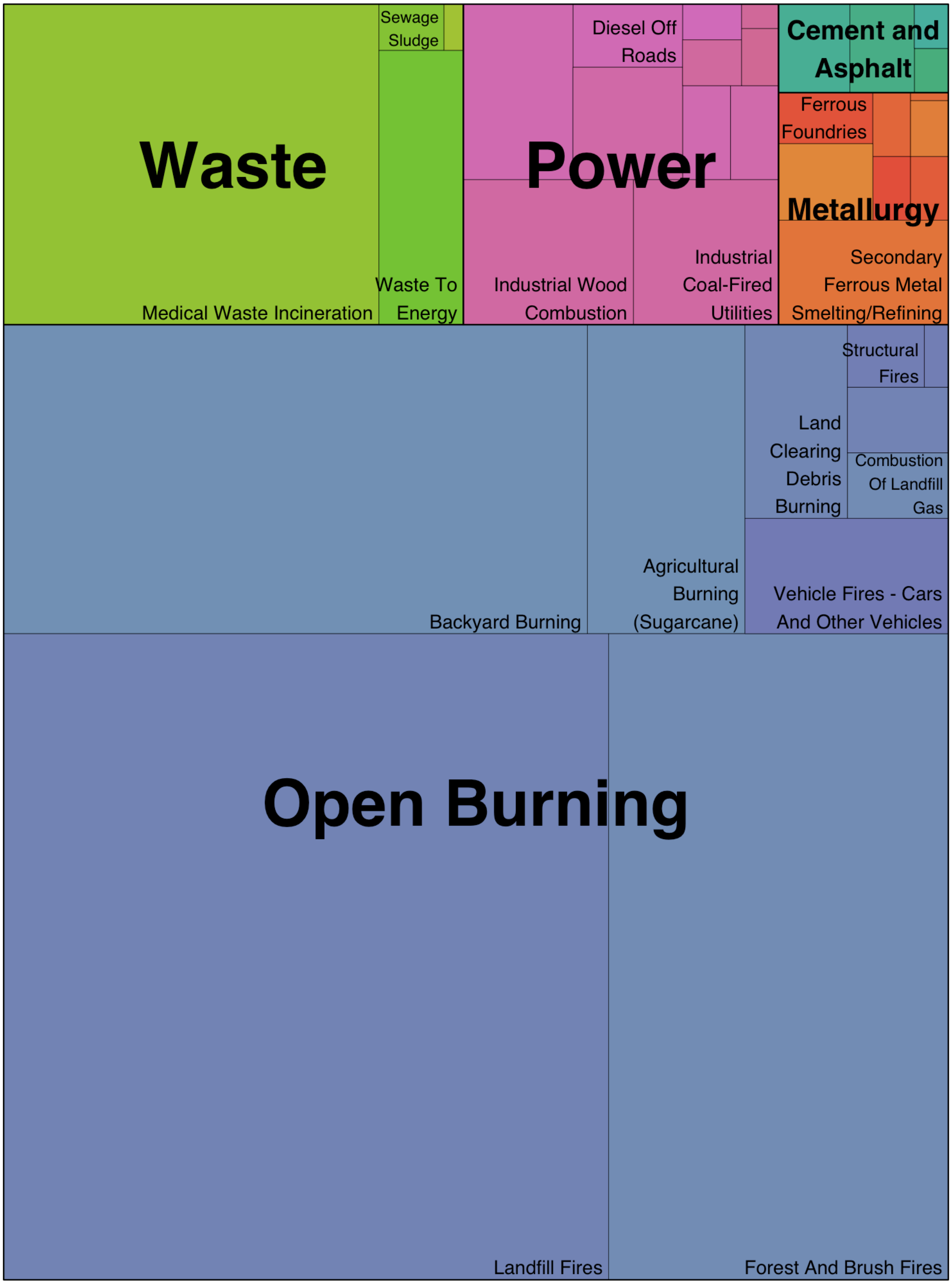


Figure 3 - 2000 Dioxin Emissions Treemap

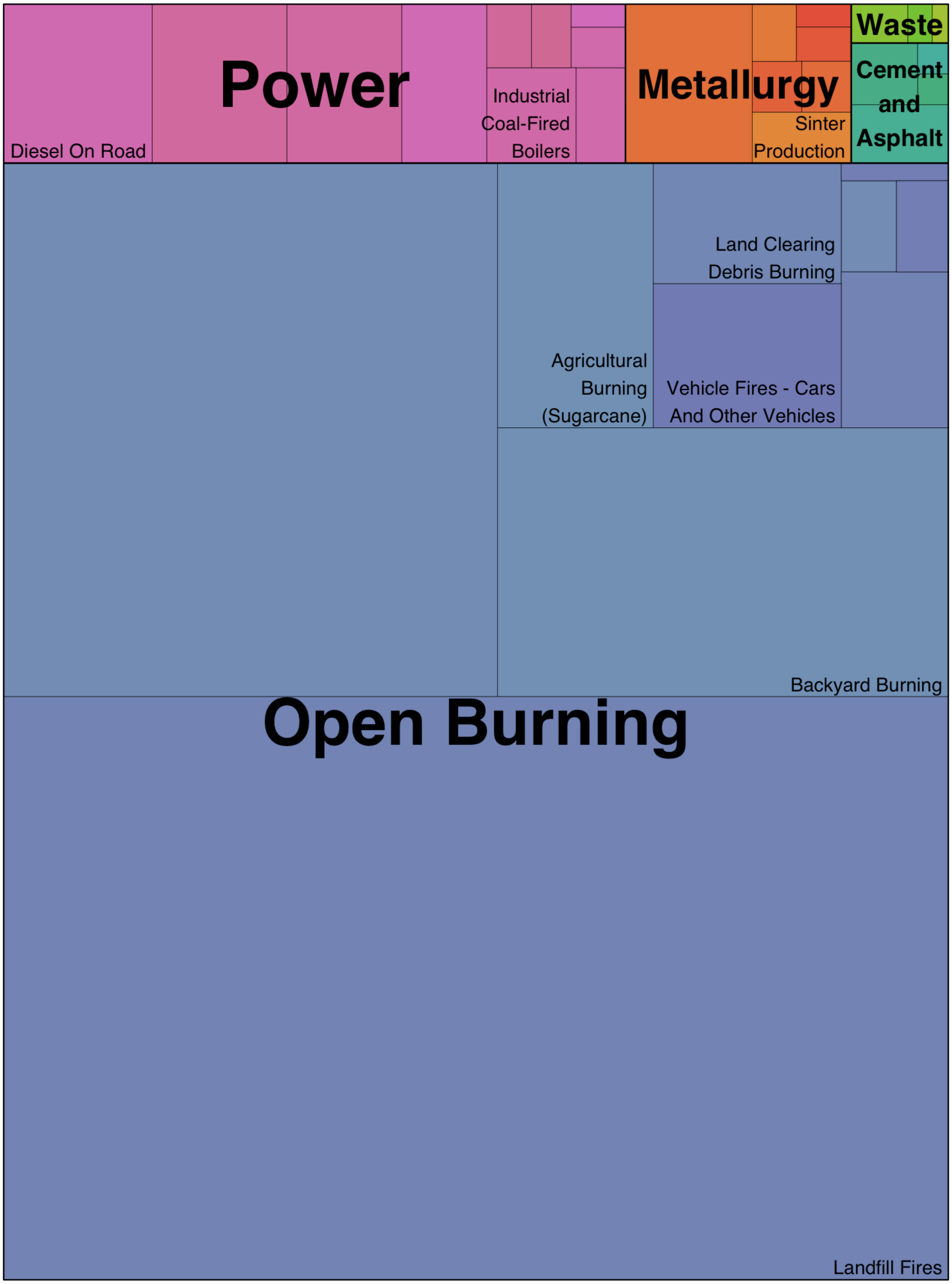


Figure 4 - 2012 Dioxin Emissions Treemap

Part II. Assessment of Health Risks (in the light of international experience)

II.1. Introduction

Dioxin is a very toxic substance to many mammals. A common measure of toxicity is the lethal dose to 50%, i.e. the amount the must be injected in a members of a species in order to kill 50% of the population. For guinea pigs, the LD50 of dioxins is 0.6 µg/kg, and for rats it is 20 µg/kg. For comparison, in rats the LD50 of ethanol is 7.06g/kg, cyanide is 6.4mg/kg and Polonium is 1 µg/kg. Though generally low, the LD50 of TCDD shows great variability between species (e.g. 33 times less toxic to rats than guinea pigs, and 500 times less toxic to rabbits than guinea pigs) (Hites 2011).

As discussed in Part I, humans are exposed to dioxins through a large variety of sources. In the USA, the average daily intake is around 2.2 pg/kg bw/day (Schecter et al. 2001).

In this part we will first analyze the possible health risks of dioxins using several long-term studies, and notably the Seveso Incident, one of the most significant dioxin exposure accidents. Second, we will model exposure from living near a dioxin source and analyze the risks due to the additional dioxin exposure. We will then calculate the risk of living near WTE plants using this model during the 4 reference years.

II.2. The Seveso Accident

On July 10th, 1976, a chemical plant producing trichlorophenol located near the town of Seveso, 25km north of Milan, accidentally released about 6 tonnes of a chemical mixture, including a substantial amount of 2,3,7,8,-TCDD (Consonni et al. 2008). During the following days, over 1000 chickens and rabbits died (Hites 2011). Within 1 year, zone A was decontaminated by removing the top 40cm of soil and by storing it in a hazardous waste facility.

The company responsible tried to reproduce the conditions of the experiment in order to estimate how much dioxin was released – they initially estimated about 240g (Hay 1979). Later soil measurements estimated the release in Zone A to be at least 2kg (Hites 2011).

The contaminated area was divided into three zones (A, B and R) based on soil TCDD concentrations, as shown in Figure 5 – Seveso Accident Map. Table 1 shows the populations in the different zones, and Table 2 shows dioxin soil concentrations and median serum concentrations in the different zones.

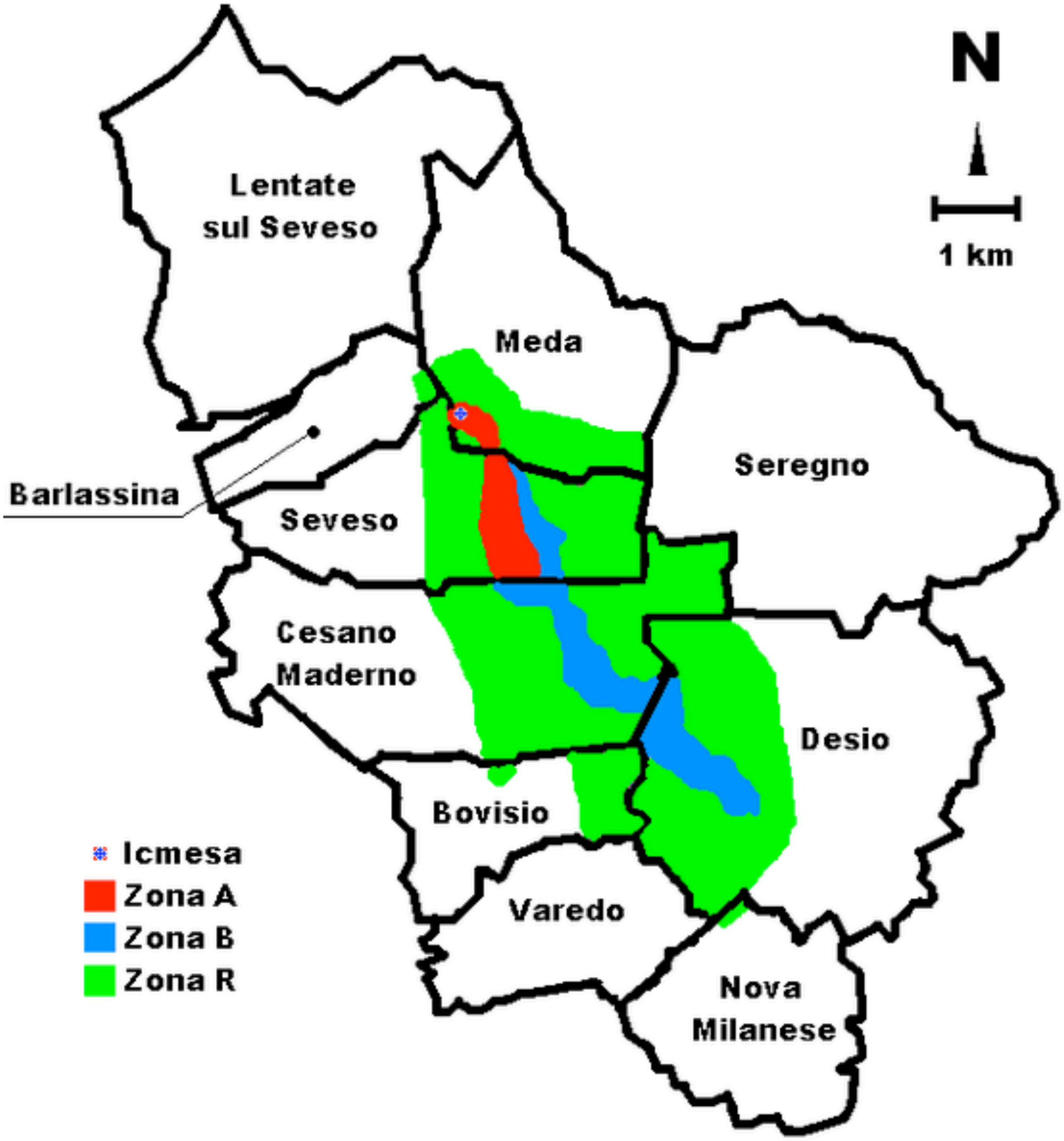


Figure 5 – Seveso Accident Map

Table 36: Number of subjects in the Seveso, Italy, cohort, at the time of the accident by zone of residence

Zone	Resident on July 10, 1976		
	Males	Females	Total

A	371	352	723
B	2,350	2,471	4,821
R	15,928	15,715	31,643
Reference	93,224	88,350	181,574
Total	111,873	106,888	218,761

Table 37: TCDD soil levels and serum concentrations by contamination area.

Zone	Mean soil level (μg/m^2)	Median lipid adjusted serum level concentrations (pg/g)	
	Minimum - Maximum	1976-1977 samples (nb)	1992-1996 samples (nb)
A	15.5-580.4	447 (296)	73.3 (7)
B	1.7-4.3	94.0 (80)	12.4 (51)
R	0.9-1.4	48.0 (48)	NA
Reference	NA	NA	5.5 (52)

Zone A covered about 87 hectare, had 723 inhabitants at the time of the incident. The soil TCDD concentrations were between 15.5 μg/m2 and 580.4 μg/m2, and the inhabitants' median serum lipid adjusted concentration level was 447.0 pg/g.
Zone B covered about 270hectares, and had a population of 4821 at the time of the incident. The soil TCDD concentrations were between 1.7 μg/m2 and 4.3 μg/m2, and the inhabitants' median serum lipid adjusted concentration level was 94.0 pg/g.
Zone R covered about 1430 hectares, and had a population of 31643 at the time of the incident. The soil TCDD concentrations were between 0.9 μg/m2 and 1.4 μg/m2, the inhabitants' median serum lipid adjusted concentration median level was 48.0 pg/g (Consonni, 2008).

For reference, average US population levels for TEQ and TCDD are 16.8 and 1.9 ppt lipid-adjusted, respectively(Patterson Jr et al. 2004), or at 30.4g TEQ (Ferriby et al. 2006).

II.2.1. Acute Health Effects

II.2.1.1. Chloracne

A large increase in the number of chloracne cases was observed following the incident, particularly in children. Table 3 shows the 164 children (<=14 years old) cases up to April 1977 by zone. There were 23 adult cases during that time, and 6 additional cases by mid 1978.

Table 38: Children chloracne cases diagnosed by April 1977, by contamination area.

Zone	Subjects	Chloracne	Percent
A	214	42	19.6
B	1,468	8	0.5
R	8,680	63	0.7
Reference	48,263	51	0.1

The data shows 185 times more chloracne cases for children in zone R than for children in the reference zone. The difference between adults and children could possible be due to the fact that children spent more time outdoors, giving them more chances to come into contact with the contaminated cloud or soil. Other factors could include selection bias or more different reactions with age.

The population surveillance, supervised by an international committee, ended in 1984. They concluded that the only statistically significant effect that could be attributed to dioxins was chloracne. Long-term investigations continued in order to examine mortality and cancer.

II.2.2. Long Term Health Effects

II.2.2.1. Cancer

Table 4 shows the mortality relative risks from 1976-2001. Though the results suggest a slight increase in risk for all cancers, they are only statistically significant for one type of cancer.

A recent review of TCDD carcinogenicity, based on several long term studies, including the Seveso study, concluded that “the carcinogenicity of TCDD may be plausible on the basis of animal experiments conducted at high doses, but the epidemiological evidence falls far short of conclusively demonstrating a causal link” (Boffetta et al. 2011).

Table 39: Results of Poisson regression analyses of mortality in the Seveso, Italy, area, 1976–2001, for selected causes of death: number of deaths, rate ratios, and 95% confidence intervals for the polluted zones (A, B, and R) compared with the reference zone (Consonni, 2008)

Cancer Site	Zone A	Zone B	Zone R

	N	RR	95% CI	N	RR	95% CI	N	RR	95% CI
All causes	118	1.02	0.85-1.22	750	0.96	0.89-1.03	5,934	1.03	1.01-1.06
All cancers	42	1.03	0.76-1.39	244	0.92	0.81-1.05	1,848	0.97	0.92-1.02
Digestive	15	0.95	0.57-1.57	81	0.78	0.63-0.97	718	0.95	0.88-1.03
Respiratory	11	1.11	0.62-2.01	70	1.10	0.87-1.40	432	0.97	0.88-1.07
Lymphatic and hematopoietic tissue	6	2.23	1.00-4.97	28	1.59	1.09-2.33	124	0.99	0.82-1.20
All circulatory diseases	45	1.06	0.79-1.42	289	0.99	0.88-1.11	2,357	1.07	1.02-1.12
Respiratory disease	9	1.14	0.73-2.71	48	1.03	0.77-1.36	341	0.99	0.89-1.11
Digestive disease	5	0.72	0.30-1.74	45	0.99	0.74-1.33	366	1.11	1.00-1.24

II.2.2.2. *Sex ratio at birth*

Another possible effect of dioxin exposure was enlightened some time after the accident. This was the change in the male/female sex ratio at birth that was observed in the offspring of people exposed to high concentrations of TCDD. The M/F ratio at birth is fairly constant, worldwide, and corresponds to 106 males to 100 females. As shown in Table 10, in nine families with both parents with very high dioxin levels in 1976, the birth sex ratio was completely changed with 12 females vs. 0 males53). The study was later extended to the period from 1977 to 1996, and those results were confirmed. Paternal blood concentration emerged as the most important predictor of lowered sex ratio at birth (Mocarelli et al. 2000).

II.2.3. Seveso Accident Conclusions

The Seveso incident, and other studies on dioxin exposed populations have shown the toxicity of dioxins:

- Chloracne
- Lymphatic and hematopoitic cancer
- All cause cancer (still debated)
- Sex-ratio

II.3. Dioxin Contamination Model

Human exposure to dioxins is calculated considering using the S-Risk model(C. Cornelis, A. Standaert, and H. Willems 2013), an updated version of the VLIER-HUMAAN mathematical model previously used for human exposure to dioxins modeling(Nouwen et al. 2001),(Domingo et al. 2002), (Lee et al. 2007). Three pathways are considered:

- Inhalation of gas
- Dermal exposure
- Oral exposure
  - Ingestion of soil and dust
  - Intake of vegetables, meat and milk

We modeled the exposure of a 70kg adult for 1 day given constant meteorological conditions. Children have higher inhalation rates, and usually have slightly higher exposures. The goal is to calculate the worst-case exposures, so the model variable values were chosen in order to calculate a worst-case scenario, as described in (C. Cornelis, A. Standaert, and H. Willems 2013).

II.3.1. Inhalation

We assume that the concentration of dioxins is constant everywhere the individual goes during the day. Therefore, they are always exposed to and inhaling the same amount of dioxins, which can be modeled using the following equation:

$$I = C_{air} * T * Fa * IR$$

Where I is the inhalation rate in pg/day, C_{air} is the concentration in the air in $pg\ TEQ/m^3$, T is the fraction of time spent in the exposed area (here 1), F is an age-dependent inhalation-rate based factor, between 1.5 and 3.6. We use the maximum value of $Fa = 3.6$ for 8h of the day, and 1 for the other 16h, indicating a long time spent on activities requiring higher than average breathing (e.g. sports), so Fa=1.9, and IR is the bodyweight normalized inhalation rate (20m3 for a 70kg adult).

II.3.2. Dermal exposure

Dermal exposure is calculated using the following equation:

$$D = C_{soil} * AF * ABS * SA * E$$

Where D is the dermal exposure in pg/day, C_{soil} is the concentration in the soil or dust in pg TEQ/g dry soil, AF is the adherence of soil on skin (1g/m2) ABS is the dermal absorption factor (1), SA is the skin surface area covered in soil or dust per day ($0.7m^2$) and E is the number of events (1/day).

II.3.3. Oral exposure

II.3.3.1. Intake from soil and dust

Assuming a 100% bioavailability of dioxins, the following equation gives the oral exposure from ingested soil and dust:

$$O_{soil} = C_{soil} * IR_{soil} * F_{oral\_soil}$$

Where O_{soil} is oral intake in pg/day, C_{soil} is the concentration in the top of settled soil and dust in pg TEQ/g, IR_{soil} the ingestion rate of soil and dust (77 mg/d), and F_{oral_soil} the fraction of soil contributing to the intake (0.55).

II.3.3.2. Intake from vegetables, meat and milk

We model food exposure by assuming a diet of exclusively chicken eggs, chicken and tomatoes, and assuming chickens have a diet composed only locally grown vegetables. Water is not considered a significant source of exposure due to its low solubility (Nouwen et al. 2001). We assume 100% bioavailability.

For consumers of locally produced food, we assumed an average diet of 2 eggs (100g), 300g of chicken, 3 tomatoes (350g), and other dioxin-free food.

Plant concentration can be calculated using the following equation:

$$C_{plant} = C_{soil\_plant} + C_{deposition}$$

Where C_{soil_plant} is the concentration resulting from soil-plant transfer, and $C_{deposition}$ is the concentration resulting from deposition.

$$C_{deposition} = T * w$$

Where T is the transfer coefficient published in (Prinz, Krause, and Radermacher 1993) of 0.2 (pg/g dm)/pg/m2 day, and w the particle deposition rate calculated in II.3.5.

$$C_{soil\_plant} = BCF * C_{soil} * dm$$

Where BCF is the bioconcentration factor (0.0057 for stems (Nouwen et al. 2001)), C is the soil concentration (pg TEQ/g soil), dm is the dry matter content (35% for grass and 5% for tomatoes). The soil concentration used here is an annual value (the hourly value multiplied by 0.08, as mentioned in (Wark, Warner, and Davis 1997)).

The concentration in chickens is calculated using their daily intake:

$J_{food} = q_{food} * C_{plant}$

Where J_{food} is the intake from grass in pg/d, q_{food} is the daily consumption of food (0.123 kg dm/d), and C_{plant} is the concentration in plants (an average of tomatoes and grass), calculated with the above equation. In addition, chickens are exposed through inhalation (which is neglected here because of their very low inhalation rate), and soil ingestion:

$J_{soil} = q_{soil} * C_{soil}$

Where q_{soil} is the daily ingestion of soil (30 g/day), and C_{soil} the soil concentration.

The chicken and egg concentrations can then be calculated using biotransfer factors: ratios of concentration to daily intake (in pg kg^{-1} fat per pg/d). We used the BTF values for 2,3,7,8-TCDD obtained in (Fernandes et al. 2011):

$C_{egg} = BTF_{egg}(J_{soil} + J_{food})$

$C_{chicken} = BTF_{chicken}(J_{soil} + J_{food})$

Where BTF_{egg}= 66.0 and $BTF_{chicken}$= 40.7. These are modified to account for the fat fraction: 10% in eggs and 3.5% in chicken.

Finally the food intake is calculated using:

$F = 100C_{egg} + 300C_{chicken} + 350C_{tomato}$

II.3.4. Gaussian plume model

The dioxin air concentrations were modeled using the Gaussian plume model described in (Wark, Warner, and Davis 1997). Dioxins were modeled as conservative pollutants, with no reaction during dispersion, and spherical particles without reflection. The ground level concentration can be written as:

$$C(x,y) = \frac{Q_p}{2\pi u \sigma_y \sigma_z} \exp\{-\frac{1}{2}[(\frac{y}{\sigma_y})^2 + (\frac{H - \frac{V_t x}{u}}{\sigma_z})^2]\}$$

Where $C(x,y)$ is the concentration at the coordinates (x,y) in m, with the origin at the stack, Q_p is the particle emission rate, V_t is the particle terminal velocity, u the wind speed, H the stack height (100m), and σ_y and σ_z are the mass diffusion coefficients standard deviations.

We use the urban area coefficients, and assume an atmospheric stability of C to account for an average high stability during the night, and lower average stability during the day.

$\sigma_y = 0.22 * x * (1.0 + 0.0004x)^{-1/2}$
$\sigma_z = 0.20 * x$
We assume that all particles have a diameter d=2 μm and a density of ρ =1.4 g/cm^3 as in (Lorber, Eschenroeder, and Robinson 2000) and (Oh et al. 2002). Since the particle size is 1 μm < 10 μm, we use the corrected Stokes-Cunningham law (Wark, Warner, and Davis 1997):

$$V_t = K_c * V_{t,Stokes}$$

$$V_t = (1 + \frac{9.73 * 10^{-3} T^{\frac{1}{2}}}{d}) \frac{g\, d^2\, \rho}{18\, \mu_g}$$

$$V_t = 0.018\, cm/s = 1.8 * 10^{-4} m/s$$

Where T is the temperature (434K=20C), g is the local acceleration of gravity (981 cm/s^2), and μ_g air's dynamic viscosity (1.846 10^{-4} g/cm s).

The following plots show the daily air concentrations of dioxins for the reference years.

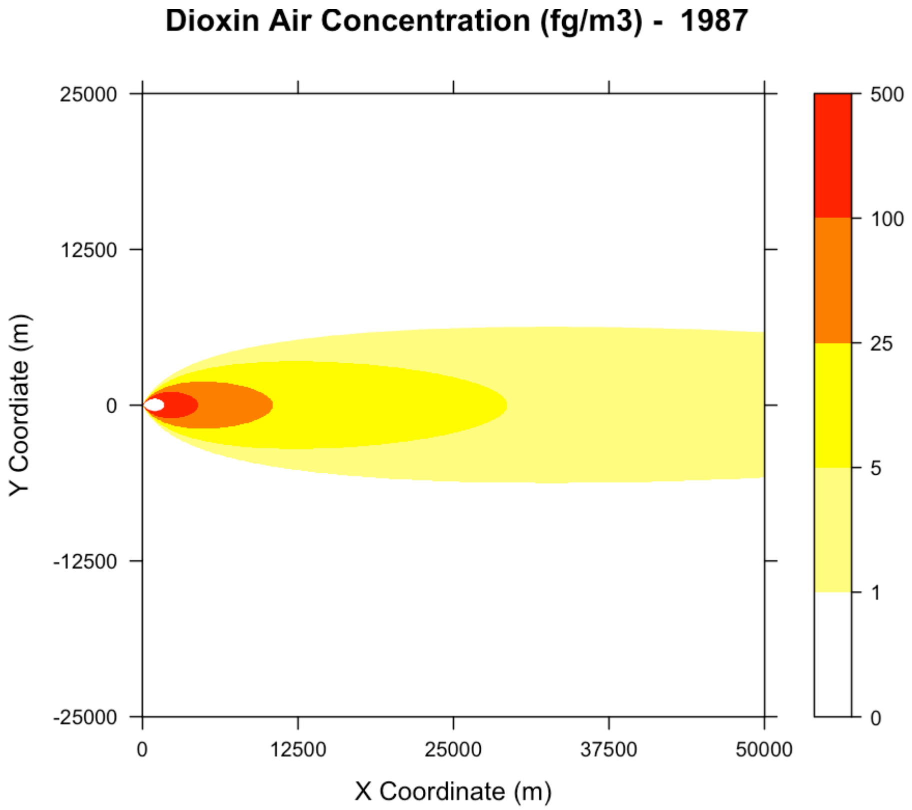


Figure 6 – 1987 dioxin air concentration

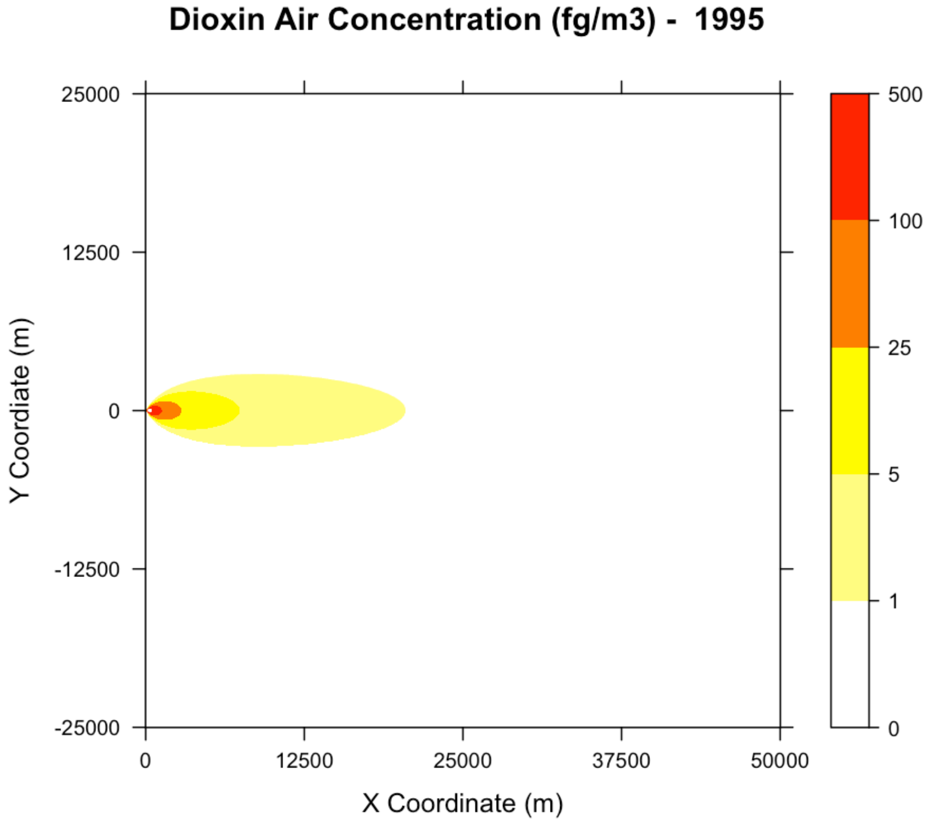


Figure 7 - 1995 dioxin air concentration

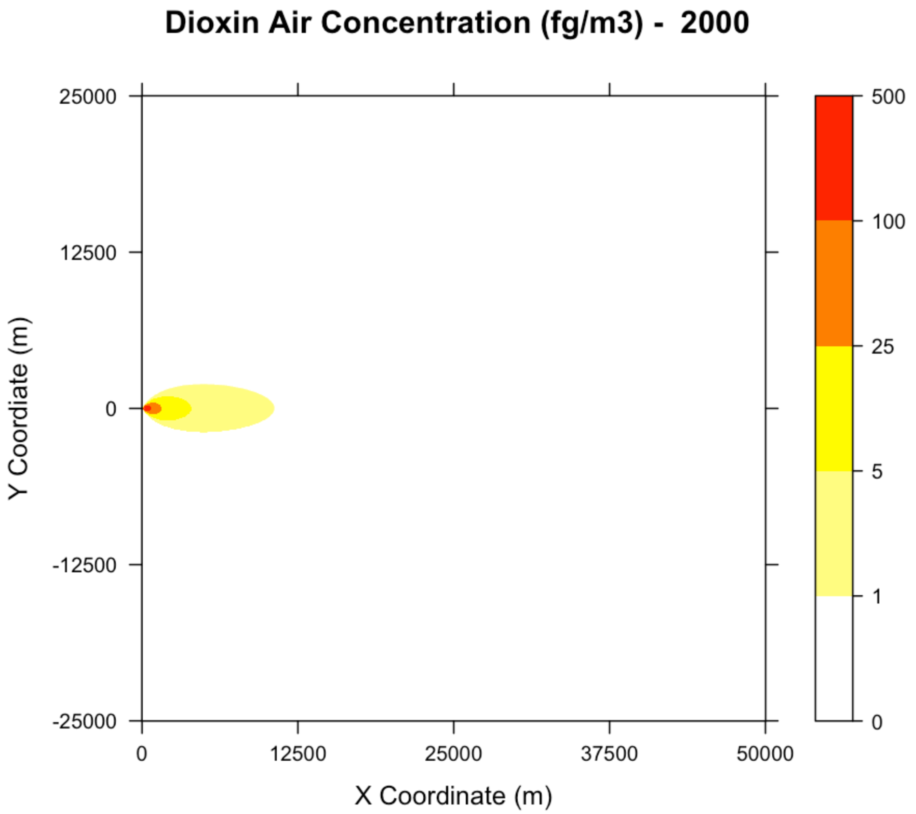


Figure 8 - 2000 dioxin air concentration

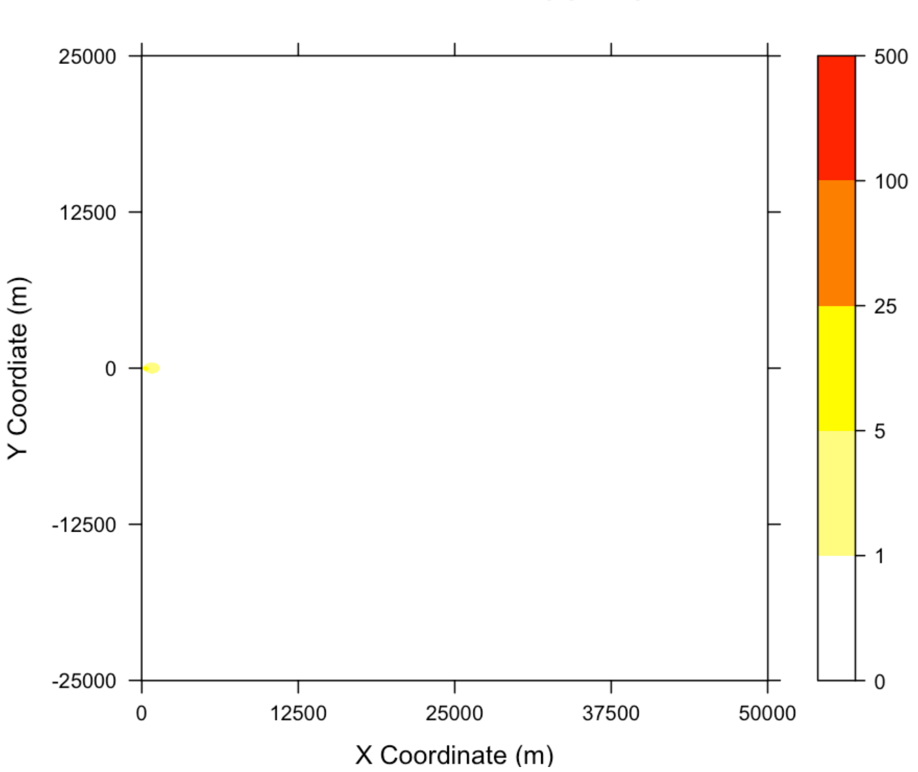


Figure 9 - 2012 dioxin air concentration

Table 40 – WTE plant average daily emissions during reference years 1987, 1995, 2000 and 2012

Year	1987	1995	2000	2012
Number of facilities	105	130	104	84
Yearly emissions (g)	12211	1730	490	13
Q_p (g/day)	0,318617091	0,036459431	0,012908325	0,000424005
Q_p (g/s)	3,6877E-06	4,21984E-07	1,49402E-07	4,90747E-09

Wind speed in terms of altitude is estimated using the wind power law: $\frac{u}{u_1} = \left(\frac{z}{z_1}\right)^p$, where p is 0.20 for urban environments in C stability class, as given in (Wark, Warner, and Davis 1997). A constant wind speed of 3 m/s is used for ground level (z=10m).

II.3.5. Soil concentration model

We will assume the dioxins only come from the air, and that we know the air concentration. The following equation gives us the soil concentration in terms of the deposition rate:

$$C_{soil} = \frac{w(1 - e^{-kt})}{kM}$$

Where C_{soil} is the soil concentration in pg TEQ/g, w is the deposition rate in $pg\ TEQ/m^2 year$, k is the first order annual soil dissipation rate in $year^{-1}$ (here 0.0138, or a half-life of 50 years), t is the operation time of the source (here 30 years), and M is the soil mixing mass in g/m^2 (here 15,000, which assumes a soil density of 1.5g/cm^3, and a soil depth of 1 cm.

For modeling the deposition rate, we use the models described in (Wark, Warner, and Davis 1997):

$$w = V_t C_{air} = \frac{Q_p V_t}{2\pi u \sigma_y \sigma_z} \exp\{-\frac{1}{2}[(\frac{y}{\sigma_y})^2 + \frac{(H - \frac{V_t x}{u})^2}{\sigma_z}]\}$$

Where w is the deposition rate of a particle, Q_p is the particle emission rate, V_t is the particle terminal velocity, u the wind speed, H the stack height, and σ_y and σ_z are the mass diffusion coefficients standard deviations.

II.3.6. Daily values

The model described above concerns short-term exposition. For longer times – daily for air concentration and yearly for soil concentration - (Wark, Warner, and Davis 1997) notes that the dispersion coefficients probably underestimate the variability, thus it is suggested to increase the dispersion coefficients by a correction factor $K = \left(\frac{t_1}{t_2}\right)^{0.2}$, where t_1 is the required sampling time and t_2 is 1h the sampling time used to calculate the dispersion coefficients. This leads to K=1.92 for daily values and 6.1 for yearly values.

II.3.7. Model Accuracy

Results for the dioxin concentrations from the model were compared to measured data described in (Lorber, Eschenroeder, and Robinson 2000). The maximum values obtained for air and soil concentration are 1 order of magnitude larger, most likely due to the assumptions that favored worst-case scenarios and that the Gaussian model has high peaks. The risk assessments therefore most likely overestimate the actual risks.

II.3.8. Results

We modeled two different scenarios: one where the persons do not consume any locally produced food, and one where the persons consume nearly half of the diet from locally produced food.

The world health organization established a tolerable daily intake (TDI) of 1-4 pg per kg bodyweight per day (van Leeuwen et al. 2000). We chose the lower value of that range, and will use the ratio of actual intake to the tolerable daily intake due to the dioxin source as a measure of the risk:

$$Risk = \frac{Intake}{TDI}$$

Using this, we can plot the risk areas using the results from the model for the two scenarios.

II.3.8.1. Scenario without locally produced food consumption

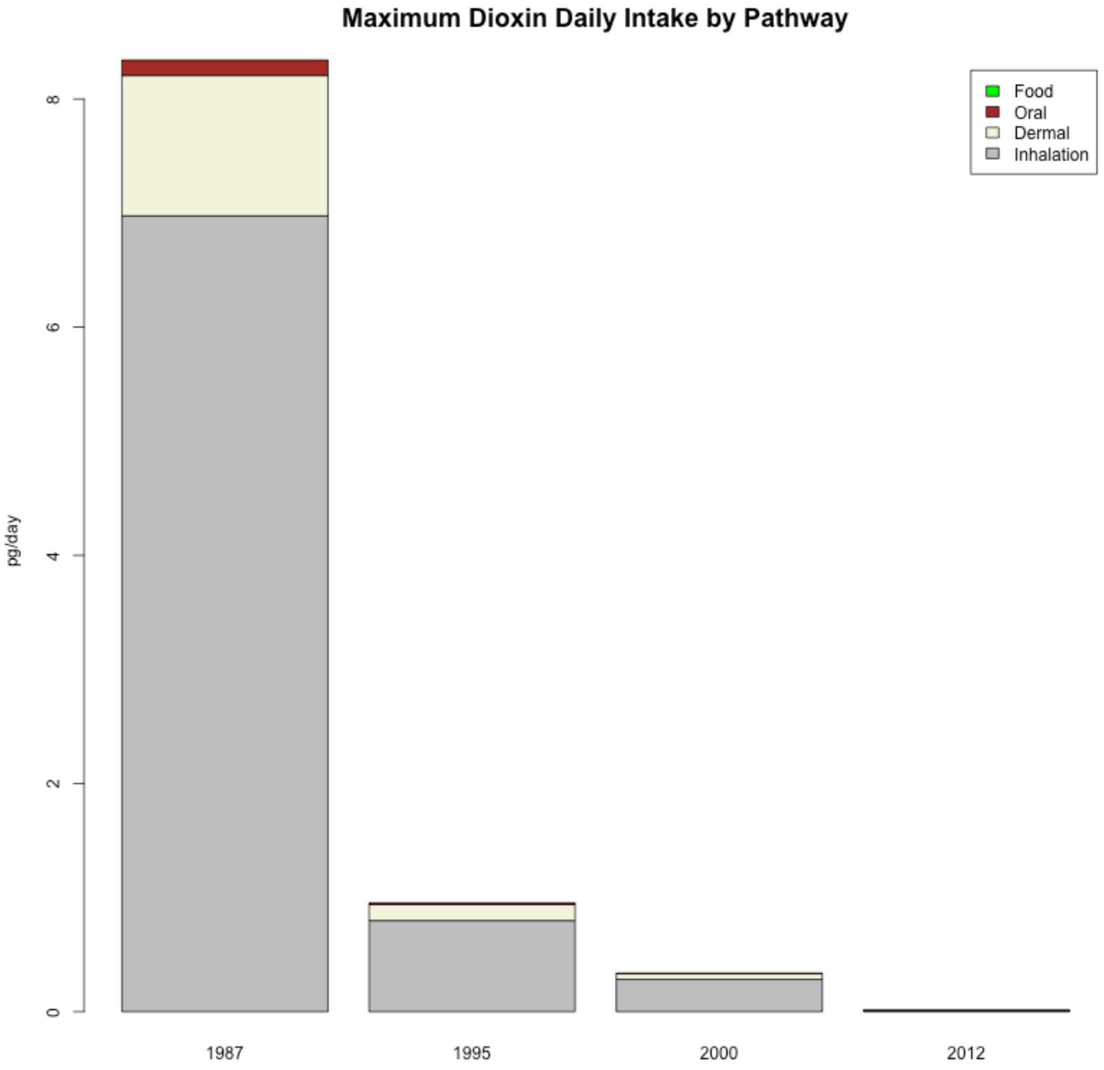


Figure 10 - Maximum daily intake in pg/day.

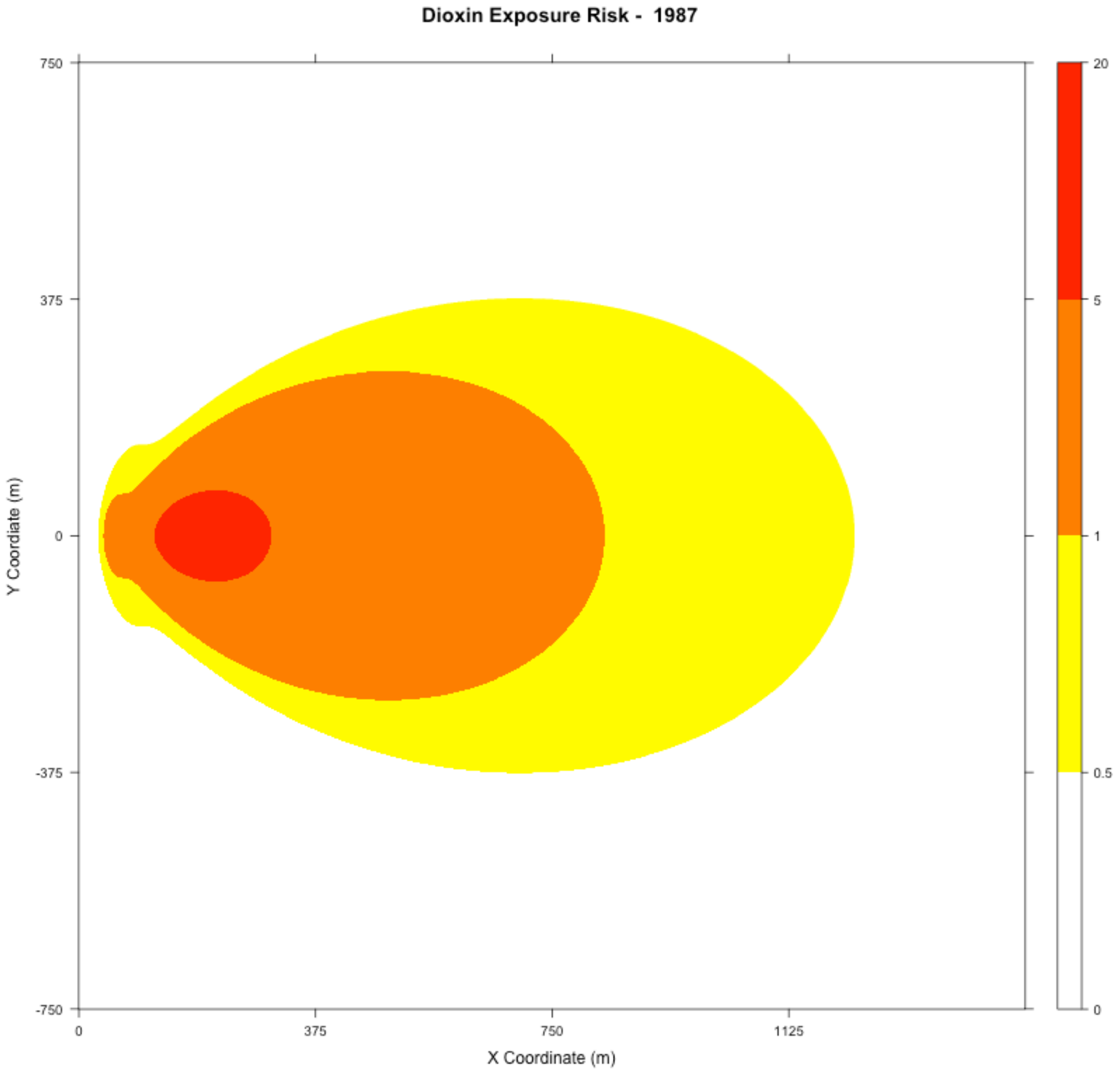


Figure 11 - 1987 dioxin exposure risk

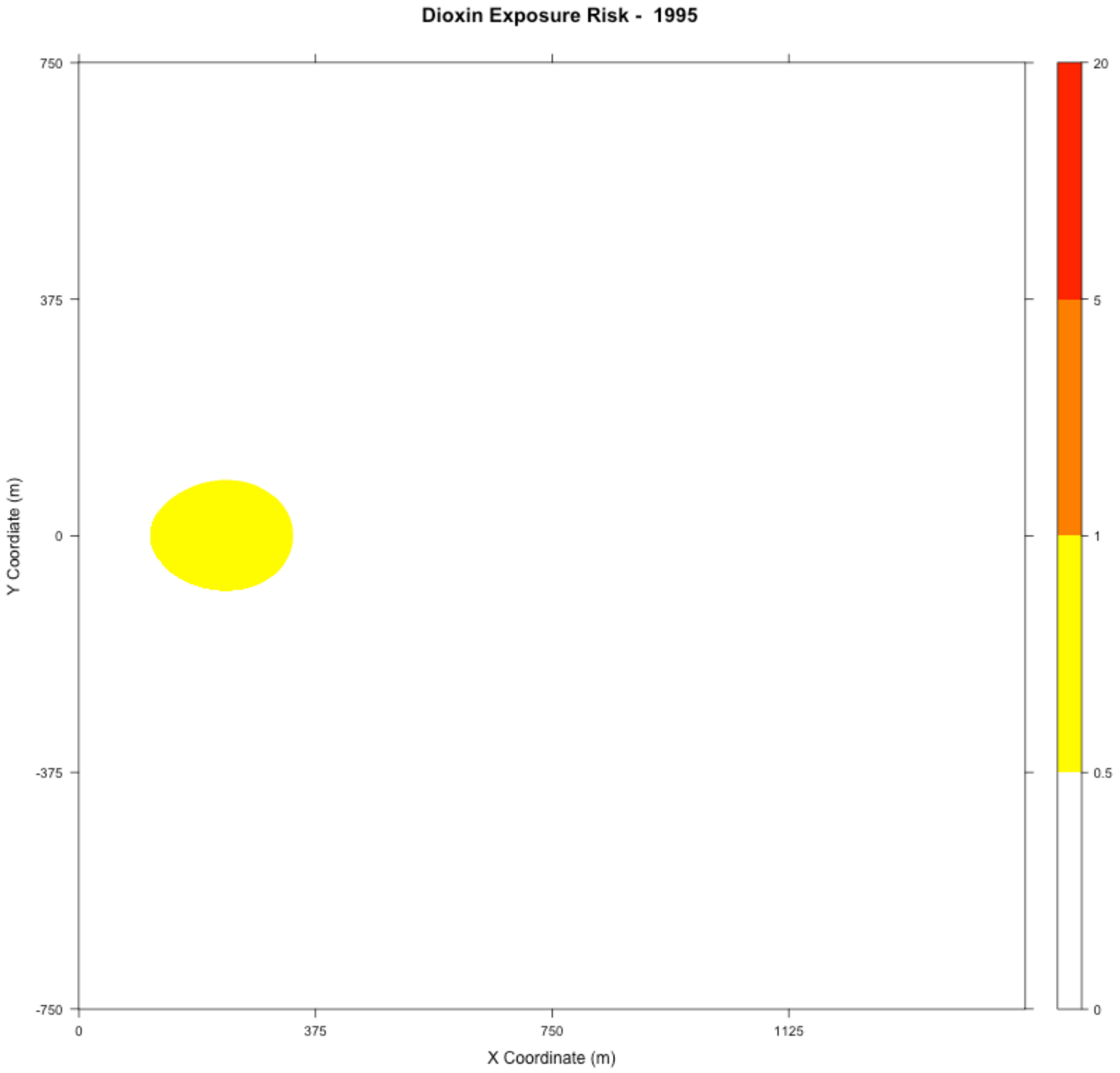


Figure 12 - 1995 dioxin exposure risk

For the 2000 and 2012 models, the exposure risk was below 0.5 everywhere.

II.3.8.2. Scenario with locally produced food consumption

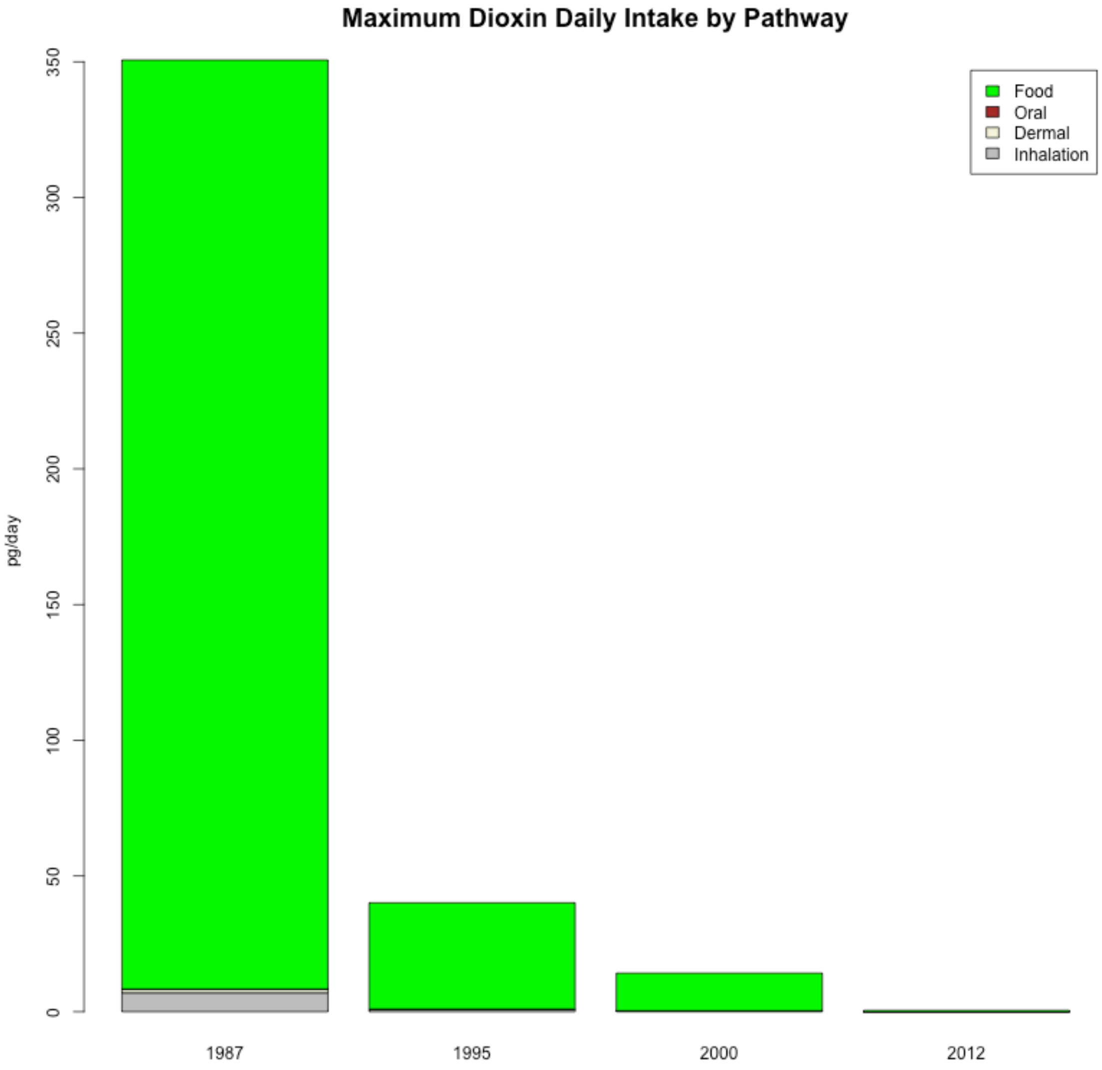


Figure 13 - Maximum intake of dioxins in pg/day, food scenario.

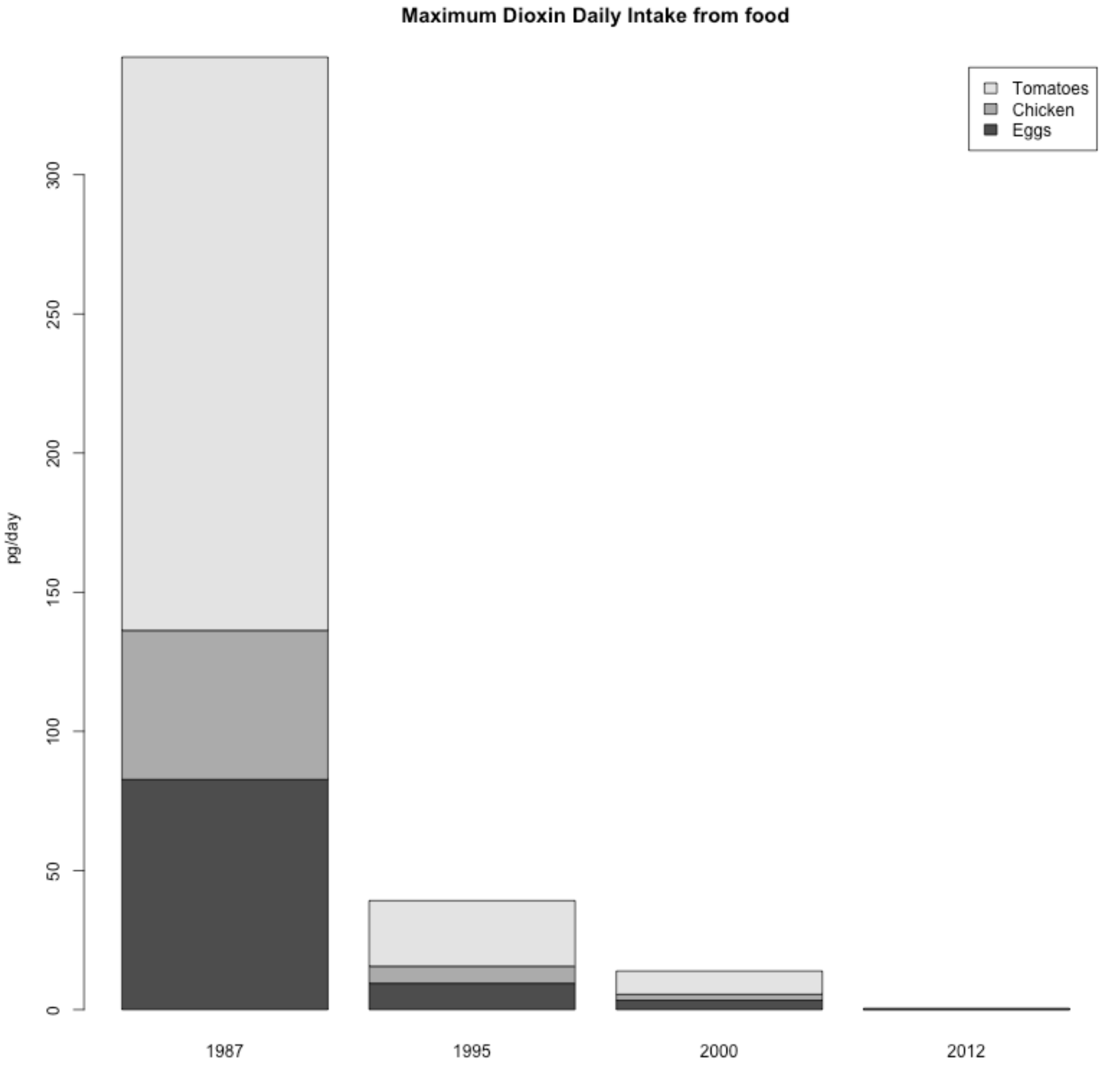


Figure 14 - Maximum daily intake from food, by source, in pg/day.

The graphs for the food scenario use a different scale than above.

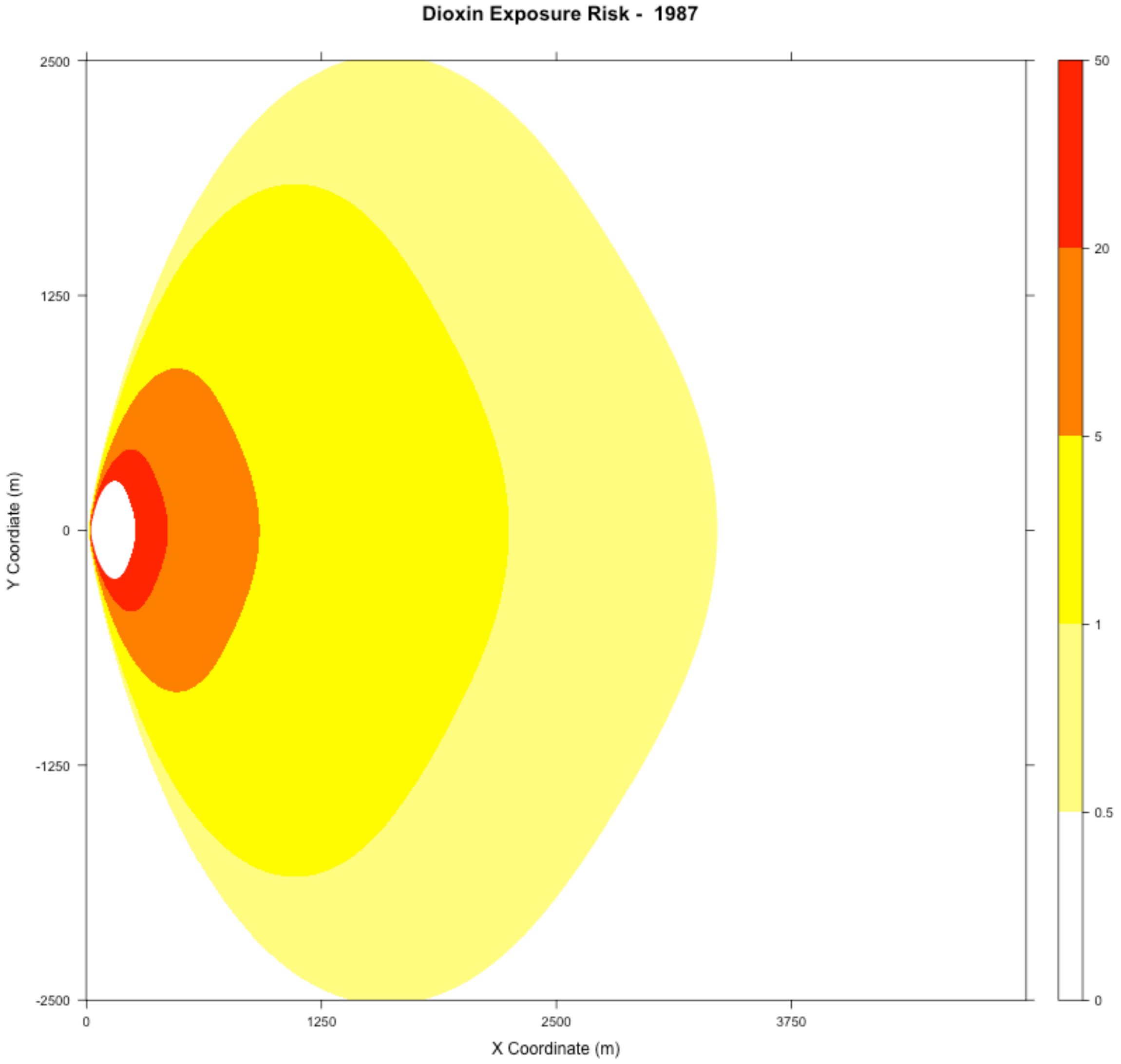


Figure 15 - 1987 dioxin exposure risk.

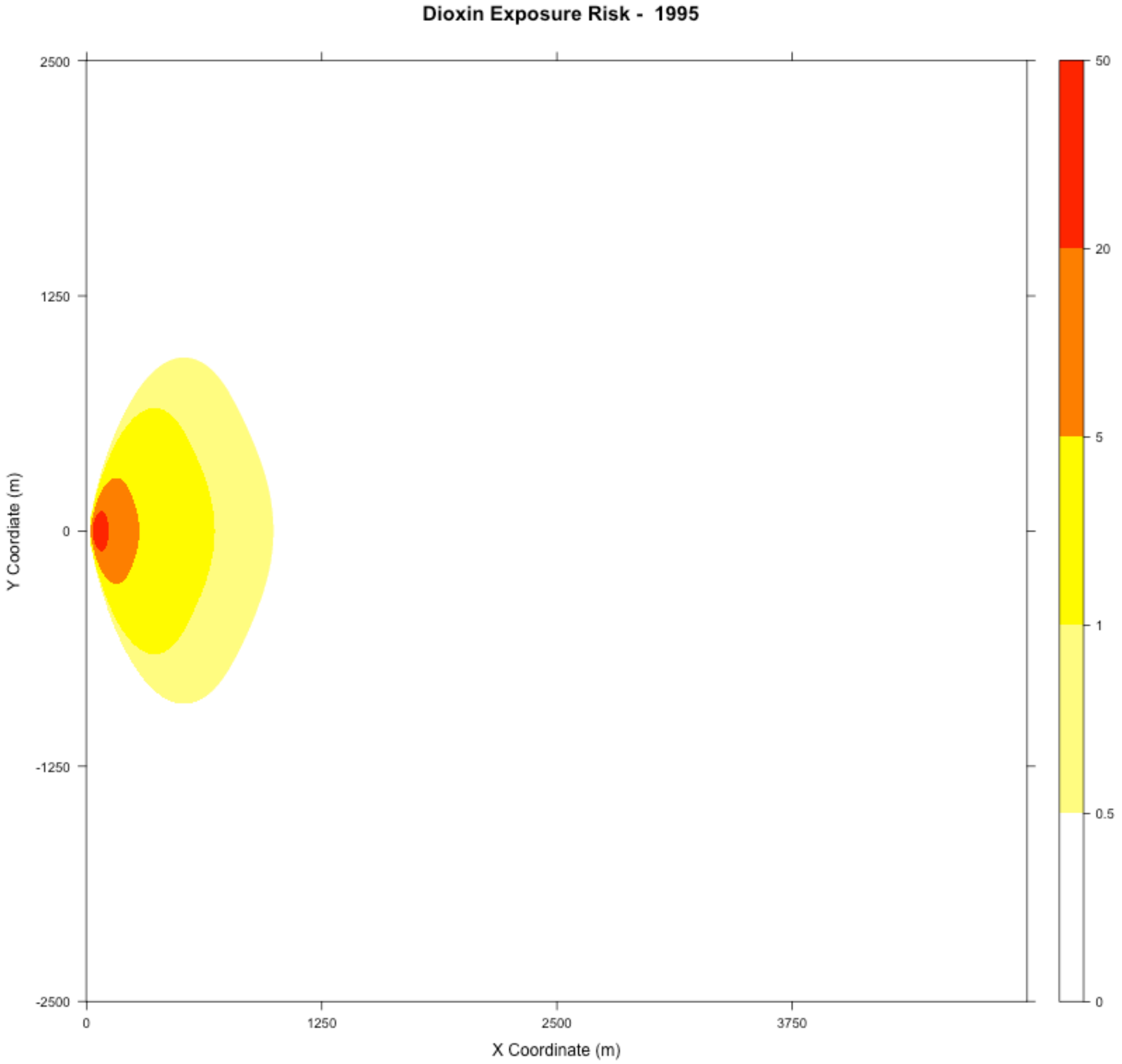


Figure 16 - 1995 dioxin exposure risk

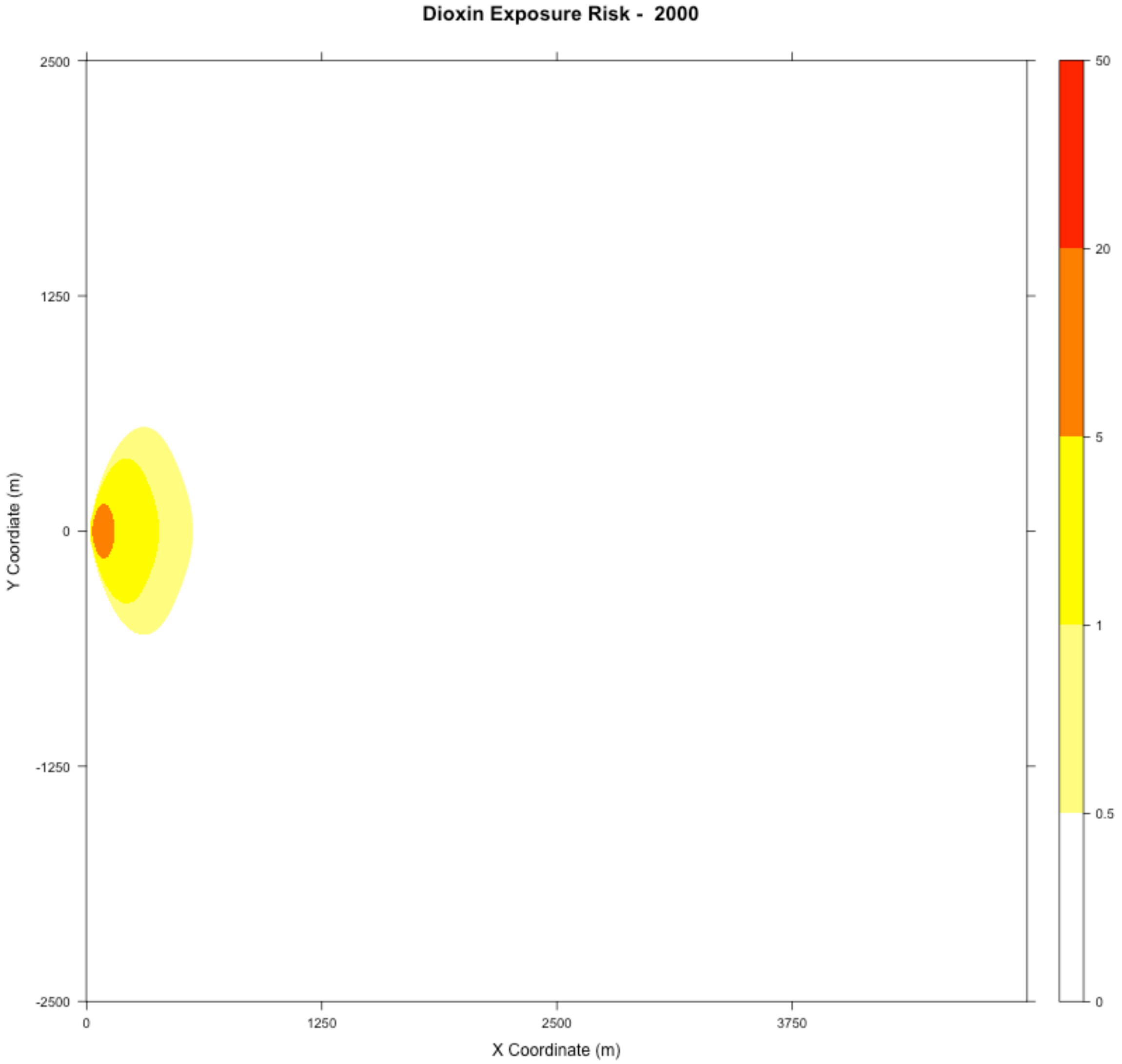


Figure 17 - 2000 dioxin exposure risk.

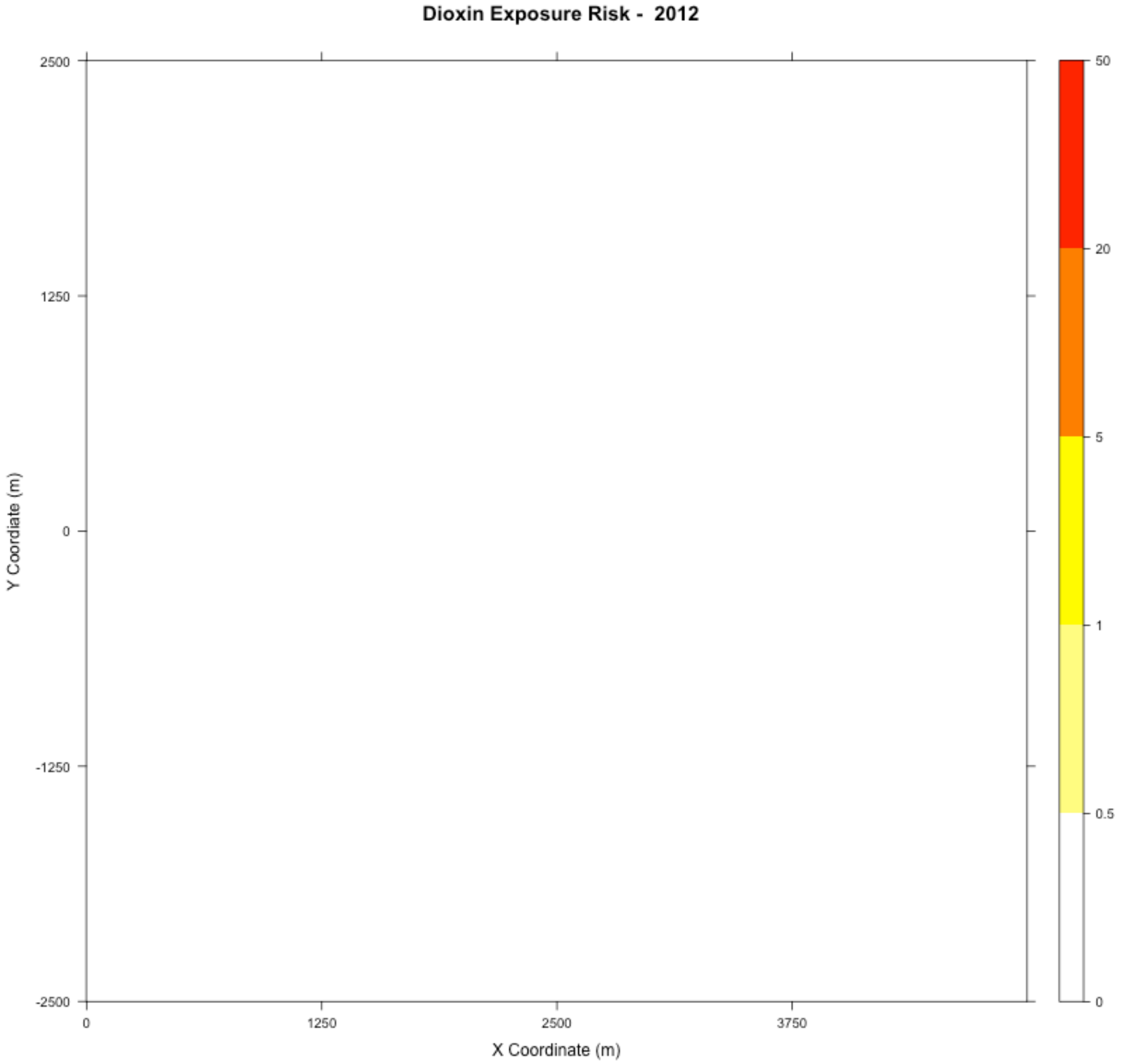


Figure 18 - 2012 dioxin exposure risk

II.3.9. Area at risk

Using the above models, we can calculate how much area is at risk near a dioxin source such as a WTE plant.

II.3.9.1. Scenario without locally produced food consumption

Table 41 - Area at risk due to dioxin exposure from dioxin emissions from 1 WTE plant

	Area (km2)			
Risk	1987	1995	2000	2012
0.1<R<0.5	3.1	0.33	0.092	0

0.5<R<1	0.37	0.031	0	0
1<R<2	0.18	0	0	0
2<R<5	0.11	0	0	0
5<R<20	0.02	0	0	0
20<R	0	0	0	0

Table 42 – US total population at risk due to dioxin exposure from WTE plants

	Population			
Risk	1987	1995	2000	2012
0.1<R<0.5	11087	1461	326	0
0.5<R<1	1323	137	0	0
1<R<2	644	0	0	0
2<R<5	393	0	0	0
5<R<20	72	0	0	0
20<R	0	0	0	0

II.3.9.2. Scenario with locally produced food consumption

Table 43 – Area at risk due to dioxin exposure from dioxin emissions from 1 WTE plant

	Area (km2)			
Risk	1987	1995	2000	2012
0.1<R<0.5	52.4	5.5	1.9	0.055
0.5<R<1	6.2	0.66	0.23	0
1<R<2	3.0	0.33	0.11	0
2<R<5	1.8	0.19	0.067	0
5<R<20	0.87	0.095	0.027	0
20<R<50	0.17	0.014	0	0
50<R	0.09	0	0	0

Table 44 - US total population at risk due to dioxin exposure from WTE plants

	Population			
Risk	1987	1995	2000	2012
0.1<R<0.5	187398	24353	6730	157
0.5<R<1	22173	2922	815	0
1<R<2	10729	1461	390	0
2<R<5	6437	841	237	0
5<R<20	3111	421	96	0
20<R<50	608	62	0	0
50<R	322	0	0	0

II.4. Conclusions regarding health effects

Dioxins were shown to have acute health effects, and long-term health effects although the carcinogenicity is still under debate.
Exposure to dioxins is mainly from food, and this is particularly true in the exposure model where most of the dioxins came from locally produced food.
According to the model, 1987 emissions of dioxins were potentially dangerous, however in 2012, even with conservative assumptions, the calculated risk is lower than 0.1. Therefore, we conclude that if emissions are maintained at or below the national average, the increased risk due to dioxin exposure from a WTE plant is very low.

Bibliography- Part 1

Boffetta, Paolo, Kenneth A Mundt, Hans-Olov Adami, Philip Cole, and Jack S Mandel. 2011. "TCDD and Cancer: A Critical Review of Epidemiologic Studies." *Critical Reviews in Toxicology* 41 (7): 622–36. doi:10.3109/10408444.2011.560141.

C. Cornelis, A. Standaert, and H. Willems. 2013. *S-Risk - Technical Guidance Document*. Mol, Belgium. https://s-risk.be/sites/s-risk.be/files/SRisk%20model%20equations_1.pdf.

Consonni, Dario, Angela C. Pesatori, Carlo Zocchetti, Raffaella Sindaco, Luca Cavalieri D'Oro, Maurizia Rubagotti, and Pier Alberto Bertazzi. 2008. "Mortality in a Population Exposed to Dioxin after the Seveso, Italy, Accident in 1976: 25 Years of Follow-Up." *American Journal of Epidemiology* 167 (7): 847–58. doi:10.1093/aje/kwm371.

Domingo, J. L., M. C. Agramunt, M. Nadal, M. Schuhmacher, and J. Corbella. 2002. "Health Risk Assessment of PCDD/PCDF Exposure for the Population Living in the Vicinity of a Municipal Waste Incinerator." *Archives of Environmental Contamination and Toxicology* 43 (4): 0461–65. doi:10.1007/s00244-002-1280-6.

Fernandes, A. R., C. Foxall, A. Lovett, M. Rose, and A. Dowding. 2011. "The Assimilation of Dioxins and PCBs in Conventionally Reared Farm Animals: Occurrence and Biotransfer Factors." *Chemosphere* 83 (6): 815–22. doi:10.1016/j.chemosphere.2011.02.083.

Ferriby, Laura L., Jeffrey S. Knutsen, Mark Harris, Kenneth M. Unice, Paul Scott, Paul Nony, Laurie C. Haws, and Dennis Paustenbach. 2006. "Evaluation of PCDD/F and Dioxin-like PCB Serum Concentration Data from the 2001–2002 National Health and Nutrition Examination Survey of the United States Population." *Journal of Exposure Science and Environmental Epidemiology* 17 (4): 358–71. doi:10.1038/sj.jes.7500498.

Hay, Alastair. 1979. "Séveso: The Crucial Question of Reactor Safety." *Nature* 281 (5732): 521–521. doi:10.1038/281521a0.

Hites, Ronald A. 2011. "Dioxins: An Overview and History†." *Environmental Science & Technology* 45 (1): 16–20. doi:10.1021/es1013664.

Lee, Se-Jin, Sung-Deuk Choi, Guang-Zhu Jin, Jeong-Eun Oh, Yoon-Seok Chang, and Sun Kyoung Shin. 2007. "Assessment of PCDD/F Risk after Implementation of Emission Reduction at a MSWI." *Chemosphere* 68 (5): 856–63. doi:10.1016/j.chemosphere.2007.02.036.

Lorber, Matthew, Alan Eschenroeder, and Randall Robinson. 2000. "Testing the USA EPA's ISCST-Version 3 Model on Dioxins: A Comparison of Predicted and Observed Air and Soil Concentrations." *Atmospheric Environment* 34 (23): 3995–4010. doi:10.1016/S1352-2310(00)00163-1.

Mocarelli, Paolo, Pier Mario Gerthoux, Enrica Ferrari, Donald G Patterson, Stephanie M Kieszak, Paolo Brambilla, Nicoletta Vincoli, et al. 2000. "Paternal Concentrations of Dioxin and Sex Ratio of Offspring." *The Lancet* 355 (9218): 1858–63. doi:10.1016/S0140-6736(00)02290-X.

Nouwen, J, C Cornelis, R De Fré, M Wevers, P Viaene, C Mensink, J Patyn, et al. 2001. "Health Risk Assessment of Dioxin Emissions from Municipal Waste Incinerators: The Neerlandquarter (Wilrijk, Belgium)." *Chemosphere*, Dioxin '99, 43 (4–7): 909–23. doi:10.1016/S0045-6535(00)00504-X.

Oh, Jeong-Eun, Yoon-Seok Chang, Eun-Jung Kim, and Dai-Woon Lee. 2002. "Distribution of Polychlorinated Dibenzo-P-Dioxins and Dibenzofurans (PCDD/Fs) in Different Sizes of Airborne Particles." *Atmospheric Environment* 36 (32): 5109–17. doi:10.1016/S1352-2310(01)00457-5.

Patterson Jr, Donald G., Donald Patterson, Rick Canady, Lee-Yang Wong, Robin Lee, Wayman Turner, Sam Caudill, Larry Needham, and Alden Henderson. 2004. "Age Specific Dioxin TEQ Reference Range." *Organohalogen Compounds* 66: 2878–83.

Prinz, B., G. H. M. Krause, and L. Radermacher. 1993. "Standards and Guidelines for PCDD/PCDF - an Integrated Approach with Special Respect to the Control of Ambient Air Pollution." *Chemosphere*, Proceedings of the Twelfth International Symposium, 27 (1–3): 491–500. doi:10.1016/0045-6535(93)90331-X.

Schecter, Arnold, Paul Cramer, Kathy Boggess, John Stanley, Olaf Päpke, James Olson, Andrew Silver, and Michael Schmitz. 2001. "Intake Of Dioxins and Related Compounds from Food in the U.S. Population." *Journal of Toxicology and*

Environmental Health, Part A 63 (1): 1–18. doi:10.1080/152873901750128326.

Van Leeuwen, F. X. Rolaf, Mark Feeley, Dieter Schrenk, John Christian Larsen, William Farland, and Maged Younes. 2000. "Dioxins: WHO's Tolerable Daily Intake (TDI) Revisited." *Chemosphere* 40 (9–11): 1095–1101. doi:10.1016/S0045-6535(99)00358-6.

Wark, Kenneth, Cecil F. Warner, and Wayne T. Davis. 1997. *Air Pollution: Its Origin and Control*. 3 edition. Menlo Park, Calif: Prentice Hall.

Bibliography – Part 2

Ahrens, Marty. 2008. *U.S. Vehicle Fire Trends and Patterns*. Quincy, MA 02169: National Fire Protection Association. http://www.nfpa.org/~/media/Files/Research/NFPA%20reports/Vehicles/vehiclefires08.pdf.

C. Cornelis, A. Standaert, and H. Willems. 2013. *S-Risk - Technical Guidance Document*. Mol, Belgium. https://s-risk.be/sites/s-risk.be/files/SRisk%20model%20equations_1.pdf.

Domingo, J. L., M. C. Agramunt, M. Nadal, M. Schuhmacher, and J. Corbella. 2002. "Health Risk Assessment of PCDD/PCDF Exposure for the Population Living in the Vicinity of a Municipal Waste Incinerator." *Archives of Environmental Contamination and Toxicology* 43 (4): 0461–65. doi:10.1007/s00244-002-1280-6.

Dyke, Patrick H., and Gary Amendola. 2007. "Dioxin Releases from US Chemical Industry Sites Manufacturing or Using Chlorine." *Chemosphere*, Halogenated Persistent Organic Pollutants Dioxin 2004 Selected, extended and updated proceedings of the 24th International Symposium on Halogenated Environmental Organic Pollutants and POPs convened at the Technical University of Berlin, Germany, September 2004, 67 (9): S125–34. doi:10.1016/j.chemosphere.2006.05.140.

Eastern Research Group, Inc. 2010. *Estimation of Baseline Emissions from Existing Sewage Sludge Incineration Units*. http://www.epa.gov/ttn/atw/129/ssi/ssi_baseline_emissions.pdf.

———. 2011. *Revised Estimation of Baseline Emissions from Existing Sewage Sludge Incineration Units*. http://www.epa.gov/ttn/atw/129/ssi/2011/epa-hq-oar-2009-0559-0154.pdf.

European Asphalt Pavement Association. 2014. *Asphalt in Figures - 2012*. Brussels, Belgium.

http://www.eapa.org/userfiles/2/Asphalt%20in%20Figures/Asphalt%20in%20figures%2022-11-2013.pdf.

Falk, B., and D. McKeever. 2012. "Generation and Recovery of Solid Wood Waste in the U.S." *BioCycle* 53 (8): 30–32.

Fernandes, A. R., C. Foxall, A. Lovett, M. Rose, and A. Dowding. 2011. "The Assimilation of Dioxins and PCBs in Conventionally Reared Farm Animals: Occurrence and Biotransfer Factors." *Chemosphere* 83 (6): 815–22. doi:10.1016/j.chemosphere.2011.02.083.

Karter, Jr., Michael J. 2013. *Fire Loss in the United States During 2012*. Quincy, MA 02169: National Fire Protection Association. http://www.nfpa.org/~/media/Files/Research/NFPA%20reports/Overall%20Fire%20Statistics/FireLoss2013.pdf.

Lee, Se-Jin, Sung-Deuk Choi, Guang-Zhu Jin, Jeong-Eun Oh, Yoon-Seok Chang, and Sun Kyoung Shin. 2007. "Assessment of PCDD/F Risk after Implementation of Emission Reduction at a MSWI." *Chemosphere* 68 (5): 856–63. doi:10.1016/j.chemosphere.2007.02.036.

Lorber, Matthew, Alan Eschenroeder, and Randall Robinson. 2000. "Testing the USA EPA's ISCST-Version 3 Model on Dioxins: A Comparison of Predicted and Observed Air and Soil Concentrations." *Atmospheric Environment* 34 (23): 3995–4010. doi:10.1016/S1352-2310(00)00163-1.

Michaels, Ted. 2014. *The 2014 ERC Directory of Waste-To-Energy Facilities*. Energy Recovery Council. http://www.wte.org/userfiles/files/ERC_2014_Directory.pdf.

Michael Van Brunt, Director of Sustainability, Covanta Energy. 2014. "Personal Communication," February 25.

National Interagency Coordination Center. 2014. "National Interagency Fire Center." Accessed February 10. http://www.nifc.gov/fireInfo/fireInfo_stats_totalFires.html.

Nouwen, J, C Cornelis, R De Fré, M Wevers, P Viaene, C Mensink, J Patyn, et al. 2001. "Health Risk Assessment of Dioxin Emissions from Municipal Waste Incinerators: The Neerlandquarter (Wilrijk, Belgium)." *Chemosphere*, Dioxin '99, 43 (4–7): 909–23. doi:10.1016/S0045-6535(00)00504-X.

Oh, Jeong-Eun, Yoon-Seok Chang, Eun-Jung Kim, and Dai-Woon Lee. 2002. "Distribution of Polychlorinated Dibenzo-P-Dioxins and Dibenzofurans (PCDD/Fs) in Different Sizes of Airborne Particles." *Atmospheric Environment* 36 (32): 5109–17. doi:10.1016/S1352-2310(01)00457-5.

Prinz, B., G. H. M. Krause, and L. Radermacher. 1993. "Standards and Guidelines for PCDD/PCDF - an Integrated Approach with Special Respect to the Control of Ambient Air Pollution." *Chemosphere*, Proceedings of the

Twelfth International Symposium, 27 (1–3): 491–500. doi:10.1016/0045-6535(93)90331-X.

Schecter, Arnold, Paul Cramer, Kathy Boggess, John Stanley, Olaf Päpke, James Olson, Andrew Silver, and Michael Schmitz. 2001. "Intake Of Dioxins and Related Compounds from Food in the U.S. Population." *Journal of Toxicology and Environmental Health, Part A* 63 (1): 1–18. doi:10.1080/152873901750128326.

Shin, Dolly, and Nickolas Themelis. 2014. "Generation and Disposition of Municipal Solid Waste (MSW) in the United States – A National Survey." New York, NY: Columbia University. http://www.seas.columbia.edu/earth/wtert/sofos/Dolly_Shin_Thesis.pdf.

Timothy Porter, Director, Air Quality Management, Wheelabrator Technologies Inc. 2014. "Personal Communication," February 11.

TriData Corporation. 2002. *Landfill Fires - Their Magnitude, Characteristics, and Mitigation*. Federal Emergency Management Agency, United States Fire Administration, National Fire Data Center. http://www.usfa.fema.gov/downloads/pdf/publications/fa-225.pdf.

UN FAO. 2015. "Food and Agriculture Organization of the United Nations - FAOSTAT." Accessed February 1. http://faostat.fao.org/site/567/DesktopDefault.aspx.

United States Court of Appeals. 2011. "Medical Waste Institute and Energy Recovery Council V. Environmental Protection Agency."

US Census. 2013. *Construction Spending Historic Press Releases - Annual Value of Construction Put in Place in the United States*. Washington DC: U.S. Environmental Protection Agency.

———. 2015. *Characteristics of New Housing - Microdata*. US Census. http://www.census.gov/construction/chars/microdata.html.

———. 2015. "2010 Census Urban and Rural Classification and Urban Area Criteria." Accessed January 30. https://www.census.gov/geo/reference/ua/urban-rural-2010.html.

U.S. Department of the Interior, and U.S. Geological Survey. 2014. *Mineral Commodity Summaries 2014*. Reston, Virginia. http://minerals.usgs.gov/minerals/pubs/mcs/2014/mcs2014.pdf.

U.S. EIA. 2014a. "U.S. Product Supplied of Finished Motor Gasoline." December 30. http://www.eia.gov/dnav/pet/hist/LeafHandler.ashx?n=pet&s=mgfupus2&f=a.

———. 2014b. "Residential Sector Energy Consumption." December 30. http://www.eia.gov/totalenergy/data/monthly/pdf/sec2_5.pdf.

———. 2014c. “Annual Energy Review.” December 30. http://www.eia.gov/totalenergy/data/annual/.

———. 2014d. “Renewable Energy Consumption: Industrial and Transportation Sectors.” December 30. http://www.eia.gov/totalenergy/data/monthly/pdf/sec10_5.pdf.

———. 2014e. “Adjusted Sales of Distillate Fuel Oil by End Use.” December 30. http://www.eia.gov/dnav/pet/pet_cons_821dsta_dcu_nus_a.htm.

———. 2014f. “Adjusted Sales of Residual Fuel Oil by End Use.” December 30. http://www.eia.gov/dnav/pet/pet_cons_821rsda_dcu_nus_a.htm.

———. 2014g. “Coal Consumption by Sector.” December 30. http://www.eia.gov/totalenergy/data/monthly/pdf/sec6_4.pdf.

US EPA. 2006. *An Inventory of Sources and Environmental Releases of Dioxin-Like Compounds in the U.S. for the Years 1987, 1995, and 2000*. Washington DC: U.S. Environmental Protection Agency. http://cfpub.epa.gov/ncea/cfm/recordisplay.cfm?deid=159286.

———. 2011. *The National Biennial RCRA Hazardous Waste Report (Based on 2011 Data)*.

———. 2014a. *Municipal Solid Waste Generation, Recycling, and Disposal in the United States: Facts and Figures for 2012*. Washington DC: United States Environmental Protection Agency. http://www.epa.gov/osw/nonhaz/municipal/pubs/2012_msw_fs.pdf.

———. 2014b. *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 – 2012*. Washington, DC: U.S. Environmental Protection Agency. http://www.epa.gov/climatechange/Downloads/ghgemissions/US-GHG-Inventory-2014-Main-Text.pdf.

US EPA, Katherine Heller, Vesall Nourani, and Fern Braun. *Economic Impacts of Revised MACT Standards for Hospital/Medical/Infectious Waste IncineratorsKatherine Heller Vesall Nourani Fern Braun*. Research Triangle Park, NC 27709.

US EPA, OAR. 2015. “Sewage Sludge Incinerators| Technology Transfer Network Air Toxics Web Site | US EPA.” Accessed January 20. http://www.epa.gov/airtoxics/129/ssi/ssipg.html.

USGS. 2015. “U.S. Geological Survey, Mineral Commodity Summaries - Commodity Statistics and Information.” Accessed February 7. http://minerals.usgs.gov/minerals/pubs/commodity/.

Van den Berg, Martin, Linda S. Birnbaum, Michael Denison, Mike De Vito, William Farland, Mark Feeley, Heidelore Fiedler, et al. 2006. “The 2005 World Health Organization Reevaluation of Human and Mammalian Toxic Equivalency Factors for Dioxins and Dioxin-like Compounds.”

Toxicological Sciences: An Official Journal of the Society of Toxicology 93 (2): 223–41. doi:10.1093/toxsci/kfl055.

Van Leeuwen, F. X. Rolaf, Mark Feeley, Dieter Schrenk, John Christian Larsen, William Farland, and Maged Younes. 2000. "Dioxins: WHO's Tolerable Daily Intake (TDI) Revisited." *Chemosphere* 40 (9–11): 1095–1101. doi:10.1016/S0045-6535(99)00358-6.

Wark, Kenneth, Cecil F. Warner, and Wayne T. Davis. 1997. *Air Pollution: Its Origin and Control*. 3 edition. Menlo Park, Calif: Prentice Hall.