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ABSTRACT

The food chain is the primary pathway of human exposure for a large class of lipophilic compounds, such as dioxins, DDT, and other pesticides. Since municipal waste combustors release both metals and organics into the environment, the food chain pathway must be considered as a potential source of human exposure. This paper presents estimates of human exposure through the food chain for a typical municipal waste combustor. A Monte Carlo uncertainty analysis is performed to characterize variability in exposure estimates.

INTRODUCTION

Ninety-nine municipal waste combustors (MWCs) are currently operating in the United States, having the incineration capability of more than 47,000 tons of waste. By the year 2000, that capacity is estimated to reach 250,000 tons (1). As the use of municipal waste incineration as a waste management alternative has increased, public concern over possible environmental and human health effects has also increased. Of particular concern are potential exposures through the food chain.

The food chain is the primary pathway of human exposure for a large class of organics, such as dioxin, PCBs, PCPs, DDT, and other pesticides (2-4). Because many pollutants emitted by MWCs are lipophilic, extremely persistent compounds, they tend to sorb strongly to air particles, soil, and sediment and to bioaccumulate in living organisms. As a result, the food chain can be a major pathway of exposure to pollutants emitted by MWCs (5). It is the purpose of this paper to assess the magnitude of human exposure through the food chain for two pollutants released by MWCs: cadmium and 2,3,7,8-tetrachlorodibenzo-p-dioxin (TCDD, commonly referred to as dioxin). These pollutants were chosen as representatives of two chemical classes: metals and organics. Cadmium is a metal which presumably will enter the food chain primarily through vegetative root uptake, while dioxin is an extremely lipophilic compound which will bioconcentrate in beef and milk (2).

When models are used as the basis for making estimates of exposure in risk assessment, the question arises as to the sensitivity of model predictions to uncertainties in model input parameters (6). A first step in the direction of answering this question is the identification of model parameters which make the greatest contribution to overall model error. These represent the parameters which must be determined most accurately in experiments. The second step is to determine probability distributions for the most sensitive parameters and propagate these distributions through the model to obtain a characterization of uncertainty in model output. Both of these steps will be attempted for cadmium and dioxin.

THE TERRESTRIAL FOOD CHAIN MODEL

The Terrestrial Food Chain (TFC) Model, a multimedia transport model developed at the Oak Ridge National Laboratory, was used to study the accumulation of cadmium and dioxin in the food chain. The TFC Model uses atmospheric deposition rates to calculate the human daily pollutant intake through the food chain. Deposition rates and atmospheric concentration values for this study were taken from estimated values for a proposed mass burn incinerator in Tampa, Florida, and are listed in Table 1.

Table 1. Deposition Rates and Concentration Values for Tampa

	Deposition ($g/m^2/yr$)	Concentration (ug/m^3)
Cadmium	5.298E-3	1.944E-3
Dioxin	2.350E-7	1.156E-7

The methodology used to estimate the uptake of chemicals by vegetation and forage crops is given by the following general equation:

$$C_p = Dy * (A_d + U_s + T_a) \quad (1),$$

where C_p = concentration in plants (ug/kg);
Dy = annual deposition rate ($g/m^2/yr$);
A_d = atmospheric deposition component (ug/g DW);

U_s = uptake from soil component (ug/g DW);
T_a = air-to-plant transfer component (ug/g DW).

This equation simply states that the concentration of a pollutant in vegetation results from one of or all of the following three methods (7): (1) an atmospheric deposition component in which the contaminant is deposited directly onto the plant; (2) a soil uptake component in which the pollutant is first deposited on the soil and then taken up by the roots of the plant and translocated to the edible portion of the vegetation; (3) an air-to-plant transfer component in which the pollutant is absorbed by the plant from the surrounding contaminated air.

The atmospheric deposition component is calculated by:

$$A_d = \frac{K2 * D_y * R_p * [1.0 - \exp(-K_p * T_p)]}{Y_p * K_p} \quad (2),$$

where K2 = units conversion factor of 1000;
D_y = annual deposition rate of pollutant (g/m^2/year);
R_p = interception fraction of the edible portion of the plant (unitless);
K_p = plant surface loss coefficient (1/years);
T_p = time period of exposure to deposition per harvest of the edible portion of the plant (years);
Y_p = yield or standing crop biomass of the edible portion of the plant (kg DW/m^2).

Vegetative uptake from soil is given by:

$$U_s = \frac{B_s * \{K1 * D_y * [1.0 - \exp(-K_s * T_c)]\}}{Z * Bd * K_s} \quad (3),$$

where B_s = soil-plant bioconcentration factor (ug/g DW)/(ug/g soil);
K1 = units conversion factor of 100;
K_s = soil loss constant (1/years);
T_p = period of long-term buildup in soil (years);
Z = soil depth (cm);
Bd = Soil bulk density (g/cm^3).

The soil loss constant is the sum of all soil losses due to leaching, (K_1), or degradation and volatilization, (K_{dv}), and therefore:

$$K_s = K_1 + K_{dv} \quad (4).$$

The air-to-plant transfer component is given by:

$$T_a = \frac{B_v * (C_v + C_y)}{Da} \quad (5),$$

where B_v = air-to-vegetation bioconcentration factor (ug/g DW)/(ug/g air);
C_v = concentration of pollutant in air due to volatilization from soil (ug/m^3 air);
C_y = average atmospheric concentration of pollutant due to direct emission from a municipal waste incinerator (ug/m^3 air);
Da = density of air (1190 g/m^3 at 25° C).

The estimation of the concentration of the pollutants in food and forage crops is just the initial phase in calculating total exposure from the food chain. The concentrations in animal tissues and milk that result from animals ingesting contaminated forage and grains must also be determined. Pollutant concentration for each animal tissue group is modeled via:

$$A_i = (Qf_i * C_f + Qg_i * C_g + Qs_i * Sc) * B_a \quad (6),$$

where A_i = concentration of pollutant in the animal tissue (ug/g DW);
Qf_i = quantity of forage eaten by the animal each day (kg DW/day);
Qg_i = quantity of locally grown grain eaten by the animal each day (kg DW/day);
Qs_i = quantity of soil eaten by the animal each day (kg soil/day);
C_f = concentration of pollutant in animal forage (ug/g DW);
C_g = concentration of pollutant in animal grain feed (ug/g DW);
Sc = soil concentration of pollutant after the total time period of deposition (ug/g soil);
B_a = biotransfer factor for the animal tissue group (ug day/kg DW).

The total exposure to a pollutant is computed by summing the pollutant intakes from each type of vegetation and from each animal tissue group.

UNCERTAINTY ANALYSIS

The first step in the uncertainty analysis of the TFC Model was to determine those model parameters which make the greatest contribution to overall model output variability. Therefore, a sensitivity analysis was performed using a Monte Carlo sensitivity and uncertainty analysis code called PRISM (8), which employs a Latin Hypercube sampling method. For the sensitivity analysis, each parameter is assumed to have a normal distribution with the standard deviation set at 1% of the mean (8). Monte Carlo sampling is then performed to determine the parameters having the greatest impact on model output variability. Since all parameters are assumed to have the same probability distribution in a sensitivity analysis, those contributing most to model output variability are the most sensitive parameters.

Parameters that contribute more than 2% to total model output variability are listed in Table 2 for cadmium and Table 3 for dioxin. Thirteen variables passed this criteria for cadmium, and they account for almost 60% of the variation in total daily intake of cadmium. Eight parameters passed this criteria for dioxin and contribute over 60% of the variation in the total daily intake of dioxin. The individual contributions of each parameter to this variation are summarized below:

Table 4. % of Parameter Influence on Total Daily Intake

Cadmium		Dioxin	
Precip	17.11%	Ba.dairy	22.06%
Evap	6.64	Ca.dairy	9.88
Irigat	4.41	Ba.beef	8.66
Cp.gfr	4.13	Qs.beef	6.49
Kd	3.70	Bd	5.33
Tc	3.67	Qs.dairy	5.00
Theta	3.23	Fa.dairy	3.33
Rp.legd	2.90	Bg	2.39
Qf.dairy	2.60		
Fa.pork	2.33	Total	63.14%
Ca.pork	2.33		
Br.pot	2.20		
Ba.pltry	2.12		
Total	57.37%		

The major contributors to the variance of cadmium intake levels are precipitation, evapotranspiration, and irrigation. These parameters are important in determining equilibrium soil concentrations of cadmium. Since ingestion of contaminated vegetation is the main route of exposure to cadmium and root uptake is responsible for almost 82% of the exposure of this pathway (see RESULTS), these variables are the prime contributors to variation in cadmium intake.

The primary sources of variation in dioxin intake are the biotransfer factor and the daily human consumption for dairy products. A vital characteristic of dioxin is that due to its high lipophilicity, it readily accumulates in living organisms. Travis and Hattemer-Frey have estimated that meat and dairy products account for 77% of human exposure to dioxin (2). Therefore, the biotransfer factor for dairy products and the daily human consumption of dairy products are parameters which contribute greatly to dioxin intake variability.

The second step in the uncertainty analysis of the TFC Model was to determine the actual probability distributions for the most sensitive parameters and to propagate these distributions through the model to obtain a characterization of uncertainty in model output. A literature search was therefore performed to determine the proper probability distribution for each parameter. The PRISM code allows for the input of several types of distributions. However, the code is designed to take only normal distributions as input and to convert those numbers to the type of distribution specified by the user. Parameter values obtained from the literature were plotted on probit paper to determine if the parameter adhered to a lognormal distribution. All parameters were found to be lognormally distributed, except *theta* which was assumed to be normally distributed. Table 5 summarizes the distributions that were used as input:

Table 5. Probability Distributions of Most Influential Parameters

Parameter	Arithmetic Mean	Standard Deviation	Distribution Type
For cadmium:			
Ba.pltry	0.0818	0.0784	lognormal
Br.pot	0.03	0.0003	lognormal
Ca.pork	11.13	2.98	lognormal
Cp.gfr	5.21	0.59	lognormal
Evap	64.81	17.98	lognormal
Fa.pork	0.4499	0.0414	lognormal
Irigat	32.99	27.08	lognormal
Kd	9.19	7.19	lognormal
Precip	88.18	34.74	lognormal
Qf.dairy	7.315	4.251	lognormal
Rp.legd	0.0031	0.001	lognormal
Tc	65.0	49.50	lognormal
Theta	0.22	0.07	normal
For dioxin:			
Ba.dairy	0.6051	0.8413	lognormal
Ba.beef	0.6275	0.8096	lognormal
Bd	1.40	0.11	lognormal
Bg	0.7978	1.37	lognormal
Ca.dairy	30.23	13.58	lognormal
Fa.dairy	0.3738	0.1048	lognormal
Qs.beef	0.7559	0.7674	lognormal
Qs.dairy	0.7559	0.7674	lognormal

RESULTS

Table 6 shows that cadmium intake due to emissions from MWCs is due mainly to the consumption of contaminated vegetation (51.3%). Almost 42% of total daily intake is attributed to the root uptake component, while atmospheric deposition contributes only 9.4%.

Table 6. Breakdown of Exposure Pathways for Cadmium (% contributions to average daily intake)

1. Direct ingestion of contaminated soil :	6.9%
2. Consumption of contaminated vegetation :	
Atmospheric deposition component	9.4%
Root uptake component	41.9%
Air-to-plant transfer component	0.0%
3. Consumption of contaminated meat and dairy products:	
Soil-Animal-Human Route	16.3%
Plant-Animal-Human Route	25.5%

The analysis also determined the breakdown of cadmium daily intake according to general food groups. Garden fruits and beef are the primary plant tissue group and animal tissue group, respectively, contributing to total daily intake. Since contaminated vegetation is the most prominent exposure pathway for cadmium, the divisions for vegetation are listed below with their corresponding estimates of percentage influence:

Table 7. Contribution to Daily Intake of Cadmium by Vegetation Food Groups

Source	Percentage of the Total Intake
Garden fruits	19.1%
Root vegetables	9.8%
Leafy vegetables	9.5%
Fresh legumes	8.7%
Potatoes	2.3%
Dried legumes	1.9%

The consumption of contaminated meat and milk products contributes 41.75% of total human exposure to cadmium through the food chain. This particular exposure route can be further subdivided into soil-animal-human and plant-animal-human. The latter pathway is the most prolific, contributing more than 25% of total cadmium intake.

A final goal of the uncertainty analysis was to determine a probability distribution for the daily human intake of cadmium due to emissions of the contaminant from MWCs (in this case, based on deposition rates for a proposed incinerator in Tampa). Figure 1 shows that these values fit a lognormal distribution, and their statistical summary is as follows:

Table 8. Distribution of Daily Cadmium Intake Values (ug/day)

Geometric Mean	Geo St Dev	Minimum	Maximum
0.99	0.15	0.55	2.80

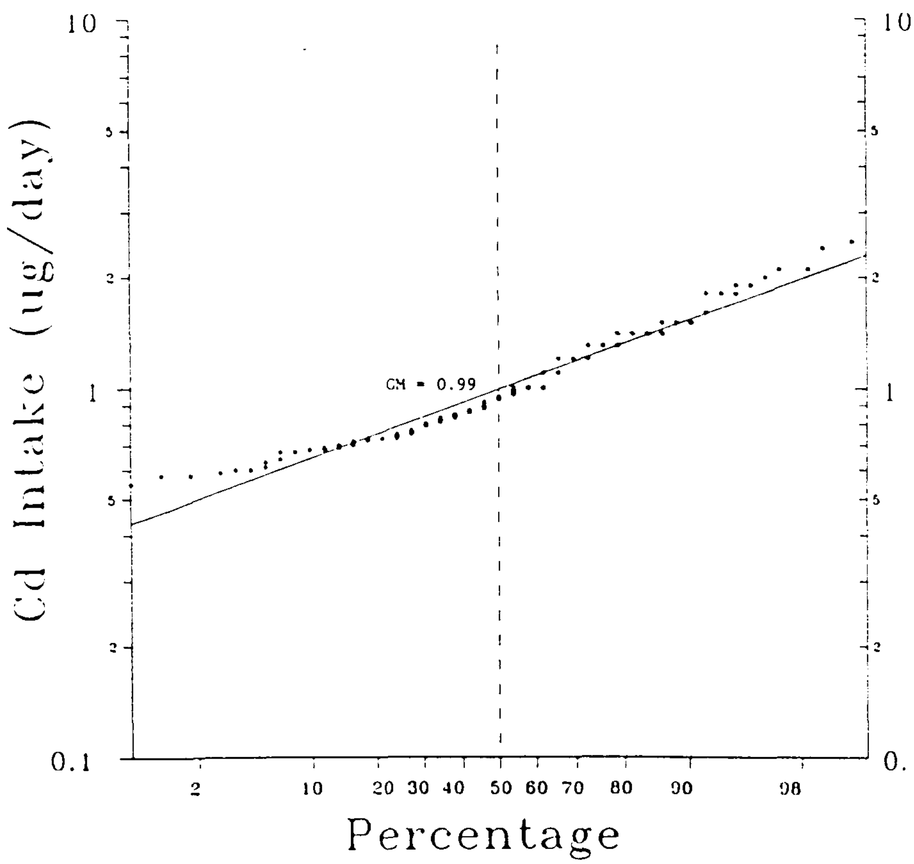

Figure 1. Cadmium Daily Intake Values

Table 9 shows that the primary route of human exposure to dioxin from the food chain is through meat and dairy products, contributing 99% of total exposure:

Table 9. Breakdown of Exposure Pathways for Dioxin (% contributions to average daily intake)

1. Direct ingestion of contaminated soil :	<.01%
2. Consumption of contaminated vegetation :	
Atmospheric deposition component	0.5%
Root uptake component	<.1%
Air-to-plant transfer component	0.3%
3. Consumption of contaminated meat and dairy products:	
Soil-Animal-Human Route	44.1%
Plant-Animal-Human Route	54.9%

The soil-animal-human route accounts for 44.1% of this exposure pathway, and the plant-animal-human mechanism composes 54.9%. Dairy products and beef dominate as the primary contributing animal tissue groups, while no plant tissue group exhibits more than 1% influence. The breakdown of contributions according to the general food groups by meat is summarized by the following Table 10:

Table 10. Contribution to Daily Intake of Dioxin by Meat Food Groups

Source	Percentage of the Total Intake
Dairy	52.8%
Beef	42.5%
Beef liver	3.6%
Lamb	0.1%
Pork	<.003%
Eggs	<.001%
Poultry	<.001%

The uncertainty analysis also determined a probability distribution for the daily human intake of dioxin due to MWC emissions. Figure 2 shows that dioxin's intake values adhere to a lognormal distribution, and their statistical description is as follows:

Table 11. Distribution of Daily Dioxin Intake Values (ug/day)

Geometric Mean	Geo St Dev	Minimum	Maximum
0.0063	0.0850	0.0038	0.0091

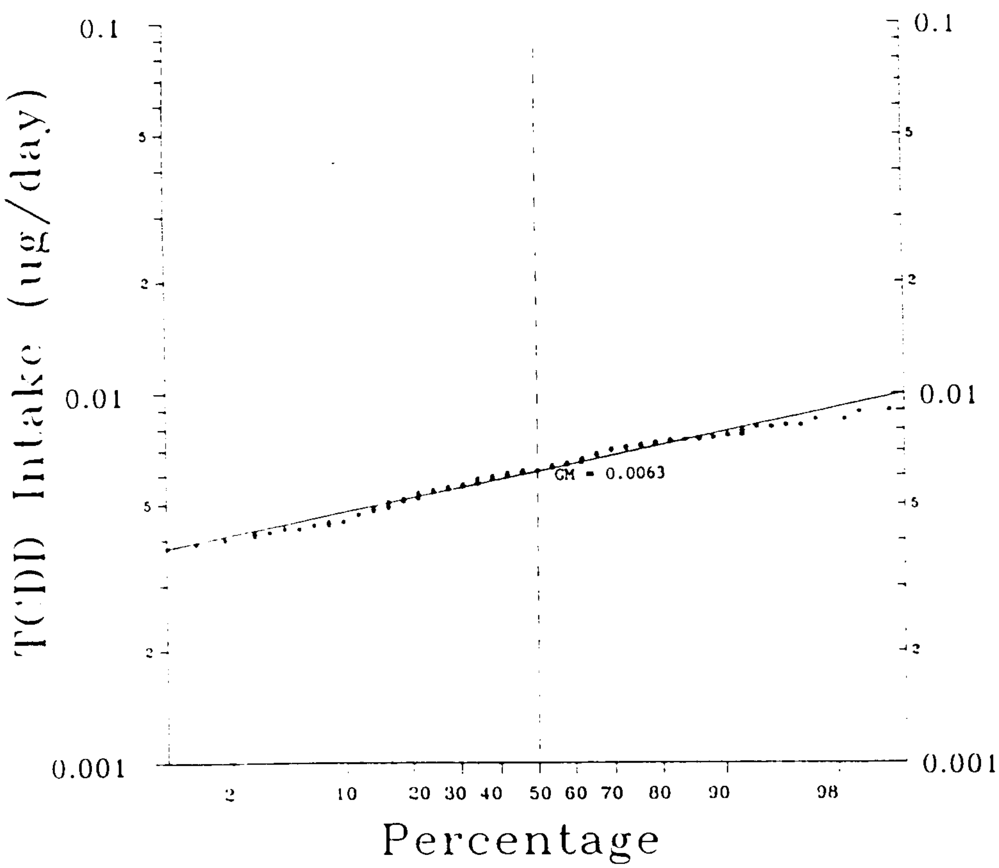

Figure 2. Dioxin Daily Intake Values

Figures 3 and 4 show the 95% confidence intervals for the daily intakes of cadmium and dioxin, respectively, from the various exposure pathways. An inhalation estimate is included to demonstrate the magnitude of the food chain's contribution to intake. Only 4.3% of the total average individual intake (inhalation plus food chain) is attributable to inhalation for cadmium, while less than 1% is due to inhalation for dioxin. Also, the 95% confidence interval for total intake is less than a factor of 1.6 times the best estimate for dioxin exposure and is less than a factor of 2.1 times the best estimate for cadmium exposure. Thus, this study confirms previous studies that have shown that the food chain can be an important contributor to human exposure of organic chemicals released from MWCs (2,5).

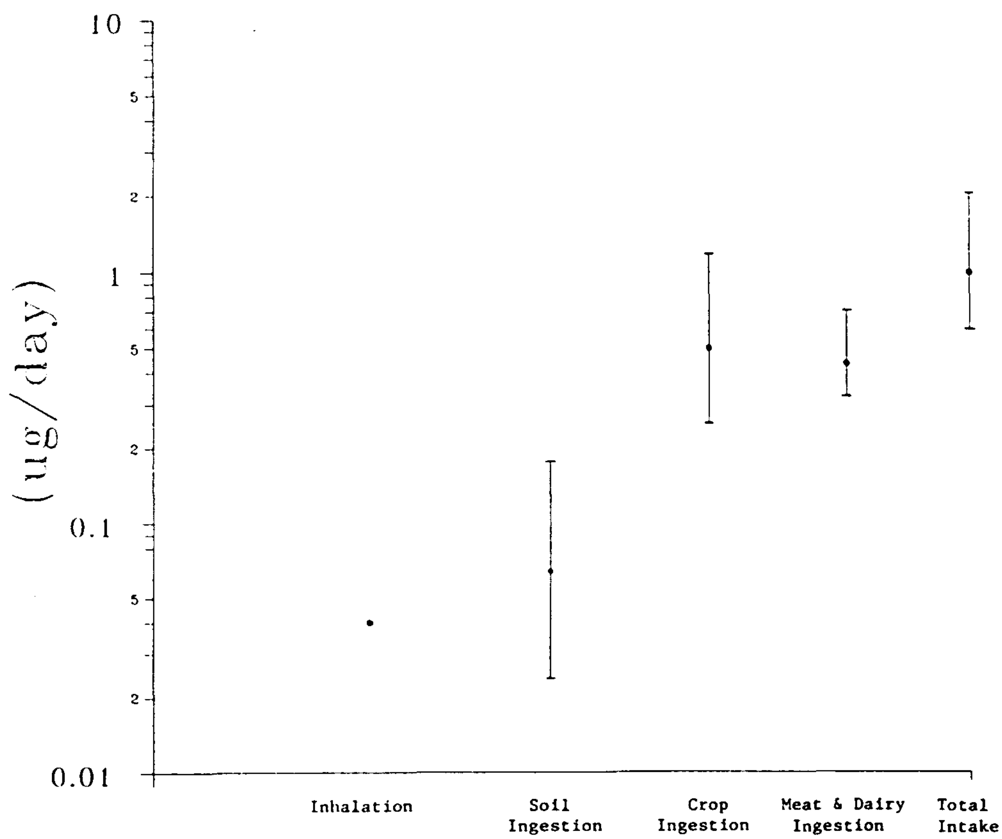

Figure 3. Daily Intake of Cadmium from Various Exposure Pathways. Error Bars Represent 95% Confidence Intervals.

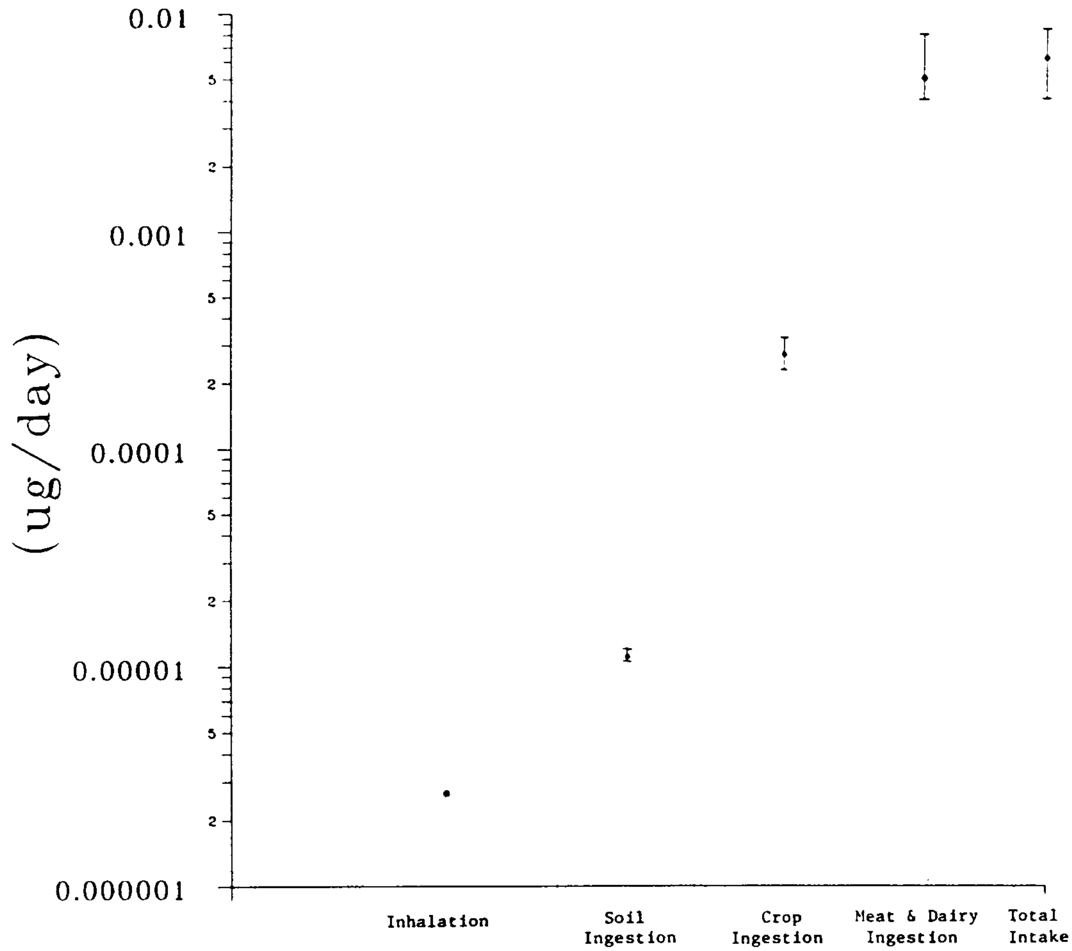

Figure 4. Daily Intake of Dioxin from Various Exposure Pathways. Error Bars Represent 95% Confidence Intervals

CONCLUSION

The food chain can be a primary pathway of human exposure to contaminants released by MWCs. An uncertainty analysis was performed on the TFC Model to determine the extent of this exposure for cadmium and dioxin. Two main pathways of exposure were analyzed: consumption of contaminated vegetation and consumption of contaminated meat and dairy products. Three routes of food and forage crop contamination were considered: (1) atmospheric deposition; (2) uptake from the soil; and (3) air-to-plant transfer. The analysis showed that cadmium intake is due mainly to the consumption of contaminated plants, especially garden fruits. The main pathway of vegetation contamination is via root uptake. Dioxin intake occurs primarily through the ingestion of contaminated meat and dairy products, especially milk and beef.

Based on deposition rates for a proposed MWC in Tampa, the distributions for cadmium and dioxin daily intake values were determined. Cadmium values ranged from 0.55 to 2.80 (ug/day), having a geometric mean of 0.99. Also, the 95% confidence interval was less than a factor of 2.1 times the best estimate for cadmium exposure. Dioxin values varied from 0.0038 to 0.0091 (ug/day) and had a geometric mean of 0.0063, with the 95% confidence interval less than a factor of 1.6 times the best estimate for dioxin total intake. Inhalation was shown to be a minor source of cadmium and dioxin intake in comparison to the contributions of the food chain pathways.

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Table 2. Cadmium Parameters Exhibiting Greatest Influence on Total Daily Intake

Ba.pltry	:	Biotransfer factor for poultry representing the relationship between equilibrium concentration of pollutant in an animal tissue and daily intake of pollutant (ug pollutant day/kg animal tissue DW).
Br.potato	:	Soil-to-plant bioconcentration factor for potatoes consumed by humans (ug pollutant/g plant tissue DW) / (ug pollutant/g soil).
Ca.pork	:	Daily human consumption of pork (g animal tissue DW/day).
Cp.gfr	:	Daily dietary consumption, by age and sex, of garden fruits (g plant tissue DW/day).
Evap	:	Average annual evapotranspiration (cm/year).
Fa.pork	:	Fraction of pork consumed by humans that is locally produced (unitless).
Irigat	:	Average annual irrigation (cm/year).
Kd	:	Soil-to-water partitioning coefficient (ml/g).
Precip	:	Average annual precipitation (cm/year).
Qf.dairy	:	Quantity of forage eaten by an animal per day (kg/day).
Rp.legdr	:	Interception fraction for the edible portion of dried legumes consumed by humans (unitless).
Tc	:	Total time period over which deposition occurs (years).
Theta	:	Soil volumetric water content (ml/cm**3).

Table 3. Dioxin Parameters Exhibiting Greatest Influence on Total Daily Intake

Ba.beef :	Biotransfer factor for beef representing the relationship between equilibrium concentration of pollutant in an animal tissue and daily intake of pollutant (ug pollutant day/kg animal tissue DW).
Ba.dairy:	Biotransfer factor for dairy representing the relationship between equilibrium concentration of pollutant in an animal tissue and daily intake of pollutant (ug pollutant day/kg animal tissue DW).
Bd :	Soil bulk density (g/cm**3).
Bg :	Soil-to-plant bioconcentration factor for animal grain feed (ug pollutant/g plant tissue DW) / (ug pollutant/g soil).
Ca.dairy:	Daily human consumption of the dairy group (g animal tissue DW/day).
Fa.dairy:	Fraction of the dairy group consumed by humans that is locally produced (unitless).
Qs.beef :	Quantity of soil eaten by an animal per day (kg/day).
Qs.dairy:	Quantity of soil eaten by an animal per day (kg/day).

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