Guidance Document:
Potential for Exposure to Polychlorinated Dibenzo-*p*-dioxins and Dibenzofurans when Recycling Sewage Biosolids on Agricultural Land

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This study contributes to the Georgia Basin Ecosystem Initiative, a partnership that provides tools, support and a framework for action towards sustainability in the Georgia Basin.

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Executive summary

The purpose of this review was to develop a set of recommendations to assist British Columbia Medical Health Officers in assessing whether the application of biosolids to various types of agricultural lands would result in increased exposure to polychlorinated dibenzo-*p*-dioxins and dibenzofurans (dioxins and furans; PCDDs and PCDFs).

The literature review was conducted in three stages. The BC Ministry of Water, Land, and Air Protection provided a set of 50 papers and 44 references, which were assessed for relevance. These were supplemented by a search of the peer-reviewed literature using major medical, toxicological, agricultural, and environmental science databases. Finally, additional papers were collected from a review of the references provided in the articles already collected. Papers were sorted using titles and abstracts; those articles reporting empirical data relating to dioxins and furans in biosolids or soil or to the uptake and transfer of dioxins and furans from soil or feed to crops or animals were collected and reviewed in detail. In total, 56 papers were identified as relevant sources of data relating to dioxins and furans in biosolids, soil, or food products. The results of these empirical studies were used to estimate the potential effect of land application of biosolids on plant or animal tissue concentrations. Because of the many assumptions required, pathway modeling was not conducted as part of this review. However, the results of our review of the empirical studies were compared to those of studies which conducted deterministic modeling.

Studies of dioxin and furan contamination of sludge and soil indicated the following:

- Dioxin and furan levels in municipal sewage sludge ranged from 0.0005 to 8300 pg TEQ/g, with a mean of 81.4 pg TEQ/g. The concentrations of dioxins and furans in sewage sludge illustrated a declining trend over time.
- Background dioxin and furan levels in soil in rural and urban areas ranged from 0.003 to 186 pg TEQ/g, with a mean of 3.7 pg TEQ/g.
- In sludge-amended soil samples, dioxin and furan levels ranged from 1.4 to 15 pg TEQ/g, with a mean of 5.8 pg TEQ/g. Studies that examined levels in treated soil before and after sludge treatment found 1.4 to 17-fold increases in the levels of dioxins and furans after biosolids application.

The data that examined the relationship between dioxin and furan levels in soil and plant foods were limited. Most studies used highly contaminated soils with much higher levels of dioxins and furans than would be found in agricultural land treated with biosolids. The evidence showed:

- Weak positive relationships between soil and plant contamination levels in unpeeled root crops, leafy vegetables, tree fruits, and hay, and little or no associations for peeled root crops, peas and beans, grass, or herbs. Stronger relationships were observed for plants of the cucumber family. In all cases, very large increases in soil PCDD/F concentration (due to experimental contamination) were required to achieve a measurable increase in plant contamination. At soil PCDD/F concentrations associated with biosolids application, the expected increase in plant concentration would be minimal.

There was very little data available to assess the effect of dioxins and furans in land-applied biosolids on the contamination levels in animal tissues and cow's milk. The body burden in animal tissues and excretion of dioxins and furans in milk is highly dependent on the duration of exposure through the diet; the feeding studies were not of sufficient duration for animal tissue concentrations to reach steady state. The evidence to date showed:

- a positive relationship between dioxins and furans in feed and the concentrations found in the fat of cattle tissues, a much stronger effect than seen in crops, consistent with the expected bioaccumulation in animal tissues; and
- no association between feed contamination and dioxins and furans in milk; however, these compounds are known to be excreted in milk.

The above-described conclusions, based on empirical data, are consistent with the results of published pathway modeling studies for both plants crops and animal tissues.

Based on these limited data, application of biosolids to agricultural land used for certain crops (leafy vegetables, tree fruits, peas and beans, harvested forage crops) could be permitted. To ensure that the data derived from studies of highly contaminated soils can be reasonably extrapolated to soils with low contamination levels, a monitoring program is recommended to determine whether dioxin and furan contamination of these foods increases in biosolids-treated land under actual growing conditions.

It is recommended at this time that biosolids application not be permitted on land used to grow plants of the cucumber family or on grazing lands.

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1. Objectives

In populations that are not industrially exposed, diet is known to be responsible for virtually all (about 98%) of human exposure to dioxins and furans (Travis & Hattemer-Frey, 1987; Pohl et al., 1995). Dioxins and furans are common contaminants in municipal biosolids or sewage sludge; thus, it is important to consider the risk of increased exposure to these contaminants if biosolids are to be applied to agricultural lands. In British Columbia, there is currently much interest in agricultural uses of biosolids to reap their benefits as a fertilizer and to provide an alternative to incineration or landfills for disposal.

In preparation for policy decision-making about this issue, a literature review was conducted to examine the potential impact of the use of biosolids in agriculture on human dietary ingestion of dioxins and furans. The purpose of this project was twofold:

1) to review the literature regarding polychlorinated dibenzo-*p*-dioxins and dibenzofurans (dioxins and furans, or PCDD/F) in land-applied biosolids (sewage sludge) and its potential for transfer to food, and
2) to use this literature to prepare a guidance document for British Columbia Medical Health Officers to use in decisions about whether to prohibit, require conditions, or allow the application of biosolids on agricultural land to proceed without imposing any conditions in addition to those presented by the Organic Matter Recycling Regulation. Accordingly the guidance document will identify categories of land application
    a) that do not appear to present an increased risk of exposure to dioxins and furans;
    b) that do present an increased risk of exposure to dioxins and furans; or
    c) where additional research may be required to enable satisfactory evaluation of exposure potential.

To organize the literature review process, a model of the pathways by which dioxins and furans might be transferred from sewage products to humans via the food supply was developed (Figure 1). Contaminants may adhere directly to plant surfaces or they may move from the sludge into the soil. From the soil, they may be transferred to crops, which are then consumed by humans or animals. These animals may in turn be consumed by humans. Many animals also consume soil while grazing, which potentially increases their contaminant load. Small children may also be exposed to soil contaminants by inadvertent soil consumption, but this is not considered relevant for this document, as it does not relate to the food supply and is not considered a major source of exposure in humans.

2. Methods

This review was based entirely on a literature review of the empirical evidence of the impact of contaminated soil on the concentrations of PCDD/F in plant and animal tissue. Some authors who have examined this issue have done deterministic modeling, using a number of assumptions including biosolids application rates, exposure duration, PCDD/F concentrations in biosolids, application methods, timing of application with respect to harvesting or sampling, and impact of atmospheric deposition. Those interested in such reports are referred to Wild & Jones (1992), Jackson and Eduljee (1994), Wild and colleagues (1994), Duarte-Davidson and Jones (1996), Jones and Sewart (1997), and Rappe and colleagues (1999).

The literature review began with 50 papers provided by the Ministry of Water, Land and Air Protection. An additional 44 papers were identified from a reference list provided by the Ministry.

2.1 Literature search

The literature identified by the Ministry was supplemented by an extensive search of the published literature, which was conducted using the following databases:

- Medline, which indexes over 3600 international medical and health care journals, searched from 1966 to July 2001 (search date 08/01/01),
- Toxline, which indexes toxicology journals, searched from 1980 to July 2001 (search date 07/30/01),
- Current Contents, a database of science, medical, and technological literature, searched 1996 to July 2001 (search date 07/26/01),
- Agricola, an index compiled by the US Department of Agriculture's National Agricultural Library that covers all major agricultural subject, searched 1984 to March 2001 (search date 07/23/01),
- NTIS (National Technical Information Service), the US government database of scientific, technical, engineering, and related business information, (search date 07/30/01),
- EMBASE, which indexes biomedical, pharmaceutical, and life sciences journals, searched 1988 to July 2001 (search date 07/25/01),
- CAB International Abstracts, which abstracts agriculture and forestry papers and includes the TREECD database of Forestry Abstracts, Forest Products Abstracts, and Agroforestry Abstracts, searched 1973 to July 2001 (search date 07/30/01),
- Environmental Sciences & Pollution Management, a group of 12 databases including Agricultural & Environmental Biotechnology Abstracts (1993-current), ASFA 3: Aquatic Pollution & Environmental Quality (1990 - current), Ecology Abstracts (1982 - current), EIS: Digests of Environmental Impact Statements (1985 - current), Environmental Engineering Abstracts (1990 - current), Health & Safety Sciences Abstracts (1981 - current), Industrial & Applied Microbiology Abstracts (Microbiology A) (1982 - current), Bacteriology Abstracts (Microbiology B) (1982 - current), Pollution Abstracts (1981 - current), Risk Abstracts (1990 - current), Toxicology Abstracts (1981 - current), and Water Resources Abstracts (1967 - current) (search date 07/30/01),
- Food Science & Technology Abstracts, searched 1990 to July 2001 (search date 07/30/01),

- Web of Science, which includes the Science Citation Index, the Arts and Humanities Citation Index, and the Social Sciences Citation Index, searched 1989 to July 2001 (search date 07/30/01),
- Compendex, an engineering index, searched from 1987 to 2001 (search date 11/04/01),
- Dissertation Abstracts, which abstracts masters theses and doctoral dissertations, searched 1996 to July 2001 (search date 11/04/01),
- PAIS (Public Affairs Information Service) International, an index of political science, economics, international relations, public administration and current events, searched 1972-2001 (search date 25/07/01), and
- CISTI, the Canada Institute for Scientific and Technical Information, which includes science, engineering, and medicine documents (search date 26/07/01).

Combinations of the following keywords were used in the searches: agricultural, agriculture, animals, application to land, application to soil, biosolids, crops, cropland, dibenzofuran, dioxin(s), fluid waste disposal, food contamination, forage, furan(s), land application, PCDD/F, PCDD, PCDF, plants, polychlorinated dibenzo-*p*-dioxin, polychlorinated dibenzofuran, sewage, sewage sludge, sewage as fertilizer, soil, soil ingestion, and soil pollutant.

Reference lists of all relevant papers including review papers were included as a source of additional citations.

Specifically, literature was sought in relation to the following issues:

a) whether there are dioxins and furans in municipal sewage sludge,

b) the background levels of dioxins and furans in soil,

c) the levels of dioxins and furans in soil following application of sewage sludge,

d) whether dioxins and furans are transferred from soil to plant tissue,

e) whether dioxins and furans are transferred from soil or feed to the tissue of grazing animals, and

f) whether the use of biosolids on various types of agricultural land—land with edible root crops; land with edible non-root crops (edible parts grown above ground); land with livestock grazing; and land used for forage crops—will have an impact on the dioxin and furan concentrations in food.

2.2 Inclusion and exclusion criteria

All papers identified by the search were reviewed for relevance using the title and/or abstract. Those passing this initial review were collected from the UBC life sciences, forestry and agriculture, and science libraries and through their inter-library loan process. The full texts of the papers were then further reviewed for relevance. Papers were considered relevant if they reported PCDD/F concentrations in the following sample types:

- sludge (biosolids) from sewage or wastewater treatment plants handling municipal wastes,
- agricultural soil with historical or experimental treatment with biosolids,
- agricultural soil with no previous application of biosolids or experimental contamination with PCDD/Fs,
- food or forage plants grown in sludge-amended soil or soil treated experimentally with dioxins and furans,
- tissue or milk of animals fed food grown in sludge-amended soil or food otherwise contaminated with PCDD/F,
- tissue of animals grazing on sludge-amended soil, or
- plant food, forage crops, animal tissue, or milk not believed to be contaminated from a specific PCDD/F source, i.e., background concentrations in these types of food.

Papers dealing with levels of PCDD/F in soil or sludge were excluded from further review if they met any of the following criteria:

- publications that were not peer-reviewed,
- sites of industrial accidents causing major contamination (e.g., Seveso, Italy),
- non-municipal sources of sludge (e.g., industrial waste, pulp mill sludge),
- plants grown on highly contaminated sites such as Seveso,
- plants grown by soil-free methods, such as hydroponics,
- studies conducted at a time (prior to 1980) when the limits of the methodology were insufficient to detect small concentrations of PCDD/F, or
- studies which used non-standard analytical methods (e.g., the use of a bioassay to determine *dioxin-like activity* rather than directly measuring dioxin concentrations).

Of the 94 papers cited or provided by the Ministry, 35 met the above criteria. An additional 64 papers were identified, 30 of which met the criteria.

3. Results of literature search

3.1 Data management

All values have been converted to equivalent units using the International Toxicity Equivalency (TEQ) system (US EPA, 1999). Because dioxins and furans are a complex mixture of different congeners with different toxicities, concentrations of dioxins and furans with differing congener profiles are difficult to compare. Thus, concentrations of individual compounds are multiplied by toxicity equivalency factors (TEF) (Table 1) that are based on their toxicity relative to 2,3,7,8-TCDD, the most toxic of the dioxins and furans. The resulting values are summed to get a TEQ concentration in picograms per gram (US EPA, 1999). Although the TEQ system is useful when comparing samples with differing congener profiles, it is somewhat limited in that any differences in uptake or behaviour of individual congeners is not taken into account.

Many of the papers used as primary sources in this review include a reference to "EPA Method 1613. Tetra- through octa-chlorinated dioxins and furans by isotope dilution HRGC/HRMS" or "EPA Method 8290. Polychlorinated dibenzodioxins (PCDDs) and polychlorinated dibenzofurans (PCDFs) by high-resolution gas chromatography/high-resolution mass spectrometry (HRGC/HRMS)," as the analytical method (both methods are very similar). These papers either specifically noted the use of one of these methods, or described a very similar analytical method. Both methods (US EPA, 1994a; US EPA, 1994b) allow for congener-specific determination of the 2,3,7,8-substituted congeners of PCDD/Fs with four to eight chlorine atoms. They use isotope dilution, high-resolution gas chromatography (HRGC) and high-resolution mass spectrometry (HRMS). Because some of the older papers did not use high-resolution methods, all references to the analytical method include clarification of the chromatography/spectrometry method as either HRGC/HRMS or simply GCMS.

3.2 PCDD/F contamination in biosolids

In municipal sewage sludge, dioxin and furan levels ranged from 0.0005 to 8300 pg TEQ/g (Table 2). Most (85%) mean values were less than 100 pg/g, and 24% of mean values were less than 27 pg/g. One value was noticeably higher than the others (Eljarrat et al., 1999); this was the mean of a series of 24 Spanish sludge samples from urban industrial areas archived from 1979 to 1987. Although the samples tended to be highly contaminated (58% exceeded 100 pg TEQ/g), there was one extreme value of 8300 pg/g, suggesting that the median of these samples (110 pg TEQ/g), provides a more reasonable estimate of the degree of PCDD/F contamination in Spanish sewage sludges of this time.

The predominant congeners present in the sludge samples were the higher (hepta- and octa-) chlorinated dioxins. The concentrations in Table 2 are plotted in Figure 2, and suggest a declining trend over time.

3.3 PCDD/F contamination in soil

Background levels of dioxins and furans in untreated soils ranged from 0.003 to 186 pg TEQ/g (Table 3), with 87% of mean values less than 27 pg/g. Most values were quite low except those from one Swedish study, which measured concentrations of 17 and 29 pg TEQ/g on agricultural land far from and near major roads, respectively (Broman et al., 1990), and a study from the United Kingdom that found an average concentration of 23 pg TEQ/g from samples taken at intersection points of a 50-km grid across the country (Creaser et al., 1989).

In studies of soil after sludge application, concentrations of dioxins and furans ranged from 1.4 to 15 pg TEQ/g (Table 4). Although this range is very similar to the range of background values in untreated soils, all studies that measured soil PCDD/F concentrations before and after sludge application found increased contamination after sludge amendment (Figure 3). Dioxin and furan concentrations increased by factors of

1.4- to 17.0-fold (average 7.1-fold) after sludge application, indicating that application of sewage sludge increases PCDD/F contamination in soil.

3.4 PCDD/F contamination in root crops

Table 5 lists the levels of dioxins and furans in root crops, including carrots, potatoes, and beets, grown in uncontaminated soil or soil with low levels of PCDD/Fs. Mean levels ranged from undetectable (< 0.01) to 0.6 pg TEQ/g dry weight.

Root vegetables grown either in naturally contaminated soil or soil to which PCDD/F had been added for experimental purposes had concentrations ranging from undetectable (detection limit not stated (Prinz et al., 1991)) to 6488 pg TEQ/g dry weight (Table 6). All of the experimental studies that examined root uptake of dioxins and furans used soils that were much more highly contaminated than sludge-amended agricultural land. PCDD/F concentrations in experimentally contaminated soil ranged from 56 to 112,800 pg TEQ/g of soil, while the highest level found in any agricultural soil was 49 pg TEQ/g of soil.

Figure 4 presents the data in Tables 5 and 6 graphically to examine the relationship between soil levels and root crop levels of dioxins and furans. All values from these tables were included in the graph, with the exception of three measurements in which the soil PCDD/F concentration was much higher (8-fold and 20-fold) (Hulster & Marschner, 1993) than in the other samples and not relevant to the soil concentrations likely to result from biosolids application. The contaminant levels in whole carrot and potato roots showed weak positive relationships with the contaminant level in the soil (coefficients: 0.0027 and 0.0004 pg TEQ/g root dry weight per pg/g soil, both significant at $p < 0.05$). The concentration in peeled potatoes, however, did not change over a wide range of soil concentrations. This suggests that most of the PCDD/F contamination in potatoes accumulates in the peel.

3.5 PCDD/F contamination in crops with edible portions grown above ground

Table 7 indicates the levels of PCDD/Fs in crops with edible parts grown above the ground, including lettuce, silver beet, peas, zucchini, carrot tops, and tree fruits. The concentration of dioxins and furans in the aboveground parts of crops grown in soil with low levels of PCDD/F contamination ranged from less than 0.01 to 10.2 pg TEQ/g dry weight (Table 7).

When grown in more highly contaminated soil, aboveground plants, including lettuce, silver beet, peas, zucchini, pumpkin, kale, chives, endive, leeks, beans, kohlrabi, savoy, plums, strawberries, apples, and pears, were found to have PCDD/F concentrations ranging from 0.04 to 55.2 pg TEQ/g dry weight (Table 8).

Figures 5 and 6 present the data in Tables 7 and 8 graphically to examine the relationship between PCDD/F levels in these crops and soil. Most values from these tables were included in the graphs, with the exception of the following: one measurement (Hulster & Marschner, 1993) in which the soil PCDD/F concentration was much higher (20-fold) than in the other samples; the results of a study that did not use natural growing conditions (plants growing in pots of uncontaminated soil placed in or on top of contaminated soil (Hulster et al., 1994)); data relating to inedible portions of plants (carrot leaves) (Schroll & Scheunert, 1993); and the results of a study that examined root exudates rather than plants (Hulster & Marschner, 1994). A positive relationship was found between some members of the cucumber (*Cucurbitaceae*) family (namely zucchini, pumpkin, and cucumber) and soil contamination levels (coefficient: 0.0192 pg TEQ/g plant dry weight per pg TEQ/g soil, significant, $p < 0.05$) (Figure 5). Concentration of PCDD/F in green leafy vegetables also showed a positive (though weaker) relationship with soil concentration (coefficient: 0.00422 pg TEQ/g plant dry weight per pg TEQ/g soil, not significant, $p = 0.43$) (Figure 5). Among above-ground crops, the weakest positive relationship was present between soil PCDD/F concentrations and contamination of tree fruits such as apples and pears (coefficient: 0.00159 pg TEQ/g fruit fresh weight per pg TEQ/g soil, not significant, $p = 0.42$) (Figure 6). There was insufficient data to determine any relationship between soil and plant concentrations of PCDD/Fs in peas and beans.

3.6 PCDD/F contamination of forage crops

Measured concentrations of grasses and hay grown in soil with low levels of dioxin and furan contamination were all at or below 1 pg TEQ/g (Table 9).

The contamination levels found in grass and hay grown in contaminated soil were generally higher (0.1–39 pg TEQ/g) (Table 10). Of the two studies that examined PCDD/F contamination of forage grown in contaminated soil, one did not state whether the plants were washed prior to analysis (Prinz et al., 1991) and the other used sand or clay pebbles on the soil surface to prevent soil–leaf contact (Hulster & Marschner, 1993).

Figure 7 presents the data in Tables 9 and 10 graphically to examine the relationship between PCDD/F levels in forage crops and soil. All data from the tables are included in the figure, with the exception of one value (Hulster & Marschner, 1993) in which the PCDD/F contamination level of the soil was much higher (20-fold) than the other samples. Weak positive relationships were observed between soil and plant concentrations of hay and herbs (coefficients: 0.00079 and 0.00011 pg TEQ/g root dry weight per pg TEQ/g soil, not significant, $p > 0.16$). No positive relationship was observed between concentrations of dioxins and furans in soil and grass.

3.7 PCDD/F contamination of animal foods

Background contamination of beef ranged from less than the detection limit to 30.8 pg TEQ/g fat (Table 11); all mean values were less than 5 pg/g. Dairy products were contaminated in the range of 0.3 to 1.4 pg TEQ/g fat (Table 11). Unfortunately, the contamination level of the feed eaten by the animals tested in these studies is not known.

Table 12 summarizes the limited data relating to PCDD/F contamination of meat and other tissue from cattle consuming feed contaminated with dioxins and furans. Tissue concentrations ranged from 0.6 to 130 pg TEQ/g, in such tissues as fat, liver, kidney, muscle, and plasma. Cattle were fed food with an extremely wide range of PCDD/F concentrations, ranging from those typically expected from forage crops (e.g., 2–3 pg/g) to extremely high levels (equivalent to thousands of pg/g), higher than the levels observed in sludge. For example, Jones and colleagues (1989) fed cattle 0.05 µg 2,3,7,8-TCDD/kg body weight which corresponds to a dose of 24.4×10^6 to 32.5×10^6 pg. Based on an estimated daily dry feed intake of 8 kg for beef cattle (Jones & Sewart, 1997), this dose represents a feed contamination level of approximately 3050 to 4063 (mean 3557) pg TEQ/g dry weight. In those studies that used feed grown on sludge-amended land (McLachlan et al., 1990; Jilg et al., 1992; McLachlan et al., 1994; McLachlan & Richter, 1998; Richter & McLachlan, 2001), it was not stated whether the plants were washed or otherwise treated to remove soil or sludge particles before analysis and feeding. In practice, it is highly unlikely that grass, hay or other forage would be washed before feeding to animals.

One of the great difficulties facing those studying animal uptake and contamination is the long duration required for animals to reach steady state body burdens. The elimination half-life of PCDD in lactating cows is estimated to be in the range of 50 to 76 days (Firestone et al., 1979; Tuinstra et al., 1992), though one study based on a large single dose of 2,3,7,8-TCDD found that most was excreted in the milk within 14 days (Jones et al., 1989). The biological half-life of PCDD/Fs in cattle has been estimated to be somewhat larger, in the order of 93 to 148 days (Jensen et al., 1981; Thorpe et al., 2001), based on two experiments in which the animals were fed for 28 days and 18 weeks. The exposure time in most of the feeding studies found in the literature search ranged from a single dose to 19 weeks. Given that it takes about five biological half-lives to reach steady state, the minimum time estimate to reach steady state would be 250 days in lactating animals, and 465 days for animals that are not lactating. None of the feeding studies were of sufficient duration.

Figure 8 presents the beef data from Tables 11 and 12 graphically to examine the relationship between PCDD/F levels in forage crops and soil. All data from the tables are included in the figure, with the exception of the two studies that used extremely high experimental doses (Jones et al., 1989; Thorpe et al., 2001). Because all results were reported per gram of lipid and there was no consistent pattern by tissue type, i.e. muscle, fat, plasma, kidney, and liver, all values were included in a single regression curve. The contaminant levels in beef tissue showed a strong positive relationship with the contaminant level in the feed (coefficient: 1.458 pg TEQ/g root dry weight per pg/g soil, significant, $p < 0.05$).

Table 13 summarizes the available data relating to PCDD/F contamination of milk from cows consuming dioxin/furan-contaminated feed. Milk concentrations ranged from 0.031 to 3.0 pg TEQ/g. Cows were fed food with PCDD/F concentrations typically expected from forage crops (e.g., 0.3–3 pg/g). As in the animal tissue studies, none of the studies was of sufficient duration for the body burden to reach steady state, though because of the shorter PCDD/F half-life in lactating animals and a minimum feeding duration of 17 days, the milk studies were on the whole more realistic. It should be noted that in most of these studies, milk was sampled while contaminated feed was still being consumed (McLachlan et al., 1990; Jilg et al., 1992; McLachlan et al., 1994; Fries et al., 1999) or within a week after the contaminated feeding ceased (Jilg et al., 1992; McLachlan & Richter, 1998).

Among those who studied PCDD/F levels in milk with differing levels of soil or feed contamination, two reported little or no effect (Furst et al., 1993; McLachlan & Richter, 1998), though the latter study did observe a slight increase in whole milk PCDD/F concentrations from 0.015 pg TEQ/g before the intervention to 0.049 pg/g after 23 days of consuming feed contaminated with 3.2 pg TEQ/g. Fries et al. (1999) found a 17-fold increase in dioxin and furan contamination of milk fat after pentachlorophenol-treated wood (contaminated with dioxins and furans) was added to the cow's diet for 58 days. McLachlan et al. (1994) found that the application of biosolids as fertilizer for harvested feed can increase the PCDD/F concentration in milk under certain circumstances, i.e. cows with a low level of milk production or cows lactating after their first calve. Data from five studies examining the relationships between contamination of feed or grazing land and milk contamination from cows (McLachlan et al., 1990; Jilg et al., 1992; McLachlan et al., 1994; McLachlan & Richter, 1998; Fries et al., 1999) are plotted in Figure 9. No clear pattern is observed ($p = 0.81$).

4. Discussion

4.1 Biosolids and soil

A partial list of current Canadian, US, and European guidelines for land applied biosolids and soil are outlined in Table 14. The US Environmental Protection Agency (EPA) is proposing a maximum of 300 pg TEQ/g soil for biosolids applied to agricultural lands (US EPA, 1999). Current Canadian guidelines from the Bureau de normalisation du Québec suggest a maximum of 27 pg TEQ/g soil for unrestricted use and 100 pg TEQ/g soil for restricted use of biosolids on agricultural lands (CH2M Hill, 2001). Figure 2 shows that all North American sludge samples were well below the Canadian restricted use guideline. One of the Canadian samples and almost all of the American samples were above the Canadian unrestricted used guideline. The three Canadian samples appear to have a slightly increasing trend over time.

Soils treated with biosolids had relatively low levels of contamination. All but one study found concentrations less than the Canadian interim soil remediation criteria of 10 pg TEQ/g soil (CCME, 1991) (Figure 3). It is important to note, however, that in every case, the concentration of dioxins and furans in the soil increased measurably after sludge application (McLachlan & Reissinger, 1990; McLachlan, Sewart et al., 1996; Wilson et al., 1997; Eljarrat et al., 1997; Molina et al., 2000). The elevated concentration of PCDD/F in sludge-amended soil was also shown to persist over time. Most of the studies (Wilson et al., 1997; Eljarrat et al., 1997; Molina et al., 2000) measured PCDD/F concentrations up to a year after application of biosolids. One study that measured contamination on reclaimed quarry soil found elevated dioxin and furan concentrations 4 years after a single treatment with biosolids (Molina et al., 2000), and another using archived soil samples from land that received a single sludge application in 1968 found that 59% of the PCDD/F contamination detected in 1972 was still present 18 years later (McLachlan, Sewart et al., 1996). McLachland and Reissinger (1990) compared fields with 10 to 30 years of regular sludge treatments (application rate not known) with an untreated field on the same farm and found higher PCDD/F concentrations in the treated fields. Only one other study examined the effect of multiple biosolids treatments (Eljarrat et al., 1997); after four annual treatments, the authors reported soil contamination levels no higher than those found in other studies of single biosolids treatments. In another study that compared the effects of plowing biosolids into the soil with surface application of biosolids on meadow land did not find a difference in soil PCDD/F concentration after 260 days (Wilson et al., 1997). The half-life of PCDD/F in soil is estimated to be at least 10 years (Jackson & Eduljee, 1994; Rappe et al., 1999).

4.2 Plant foods

Studies that have examined the uptake of dioxins and furans by plants growing in contaminated soils have used either field soils that were highly contaminated due to proximity to heavy industry, or experimentally contaminated soils with extremely high levels of PCDD/Fs. The dioxin/furan concentrations in the soils used as controls in these studies are closer to, if slightly lower than, the concentrations found in sludge-amended agricultural soils. In our estimates of the relationships between soil and plant concentrations, the slopes of the regression lines were very shallow, suggesting that large increases in soil contamination would be required for small increases in plant contamination (Figures 4–6). Tables 15 through 17 use our regression coefficients and standard errors to estimate PCDD/F contamination levels (mean and upper 95% confidence limit) in root and non-root crops and tree fruits, respectively, grown in soil with contamination levels in the range found for sludge-amended soils. These estimates indicate that there is very little change in plant contamination expected over the probable soil contamination range of 1 to 30 pg TEQ/g soil. Even at an extremely high estimate for soil concentration, one which assumes a concentration equivalent to that of the highest sludge concentration reported, the predicted increases in plant concentrations were only moderately elevated. It is important to note, however, that the predicted plant values at the lower soil contamination levels have been back-extrapolated, as there is no empirical data available at these lower soil concentrations.

All studies that examined the uptake of dioxins and furans from soil by carrots and by certain members of the cucumber family found that these plants take up more PCDD/Fs from the soil than do other plants. In a study comparing different members of the family *Cucurbitaceae* (Hulster et al., 1994) grown in contaminated soil (148 pg TEQ/g soil), zucchini fruits and the outer layer of pumpkin (genus *Cucurbita*) had much higher levels of PCDD/F contamination (20.0 and 11.8 pg TEQ/g dry weight, respectively) than did cucumber (genus *Cucumis*) (2.35 pg TEQ/g dry weight). In a study that compared the ability of root exudates to absorb PCDD/F from soil (Hulster & Marschner, 1994), zucchini root exudates absorbed four times more PCDD/F than tomato root exudates.

In a study that measured PCDD/F uptake by carrots grown in contaminated soil (Muller et al., 1994), more than 75% of the contamination was concentrated in the peel (mean concentration: 3 pg TEQ/g dry weight). The inner parts of the carrot had PCDD/F concentrations more comparable to other plants (mean cortex concentration: 0.29 pg TEQ/g dry weight; mean stele concentration: 0.40 pg TEQ/g dry weight). When the congener profiles were compared, it was observed that although the control (uncontaminated) soil had primarily OCDD and the contaminated soil had mostly higher chlorinated furans, the carrots from either soil contained mostly lower chlorinated furans.

Because they have a lower octanol–water partition coefficient (log K_{ow}) (Muller et al., 1993), the lower chlorinated PCDD/F congeners tend to be more bioavailable in lipid environments. The lipid content of carrots declines from the outer to inner parts of the root.

One of the primary limitations of this review is the small number of studies relevant to the subject at hand. All the data related to plant foods has been taken from only six papers, and most of the results have not been confirmed by repeated studies. The variety of plant species represented (four root; seven leafy greens; three tree fruits; six other) is also quite small relative to the number of plant foods grown in British Columbia.

4.3 Forage crops

Studies that have examined the uptake of PCDD/Fs by forage crops grown on contaminated soil, like the studies on other plant foods, used soils with extremely high levels of dioxins and furans. Within this wide range of soil contamination levels, weak positive relationships were seen between soil and hay or herb concentrations of PCDD/Fs, but not between soil and grass concentrations (Figure 7). Potential contamination levels of hay and herbs grown on sludge-amended land were estimated using the regression equations for the data (Table 18). Over the soil contamination range of 1 to 1250 pg TEQ/g soil, there is virtually no change in predicted crop contamination levels.

Only two papers were identified that met the inclusion criteria of this literature review.

Although the evidence for forage crops appears consistent with that of other plants with edible parts grown above ground, there is an outstanding issue relating to adherence of soil particles to the plants. In one study that measured the soil content of freshly cut vegetation from a pasture, the soil content ranged from approximately 1% to 46% of the dry weight of the plant, depending on the time of year. In winter, the soil content was consistently greater than 23% of plant dry weight (Beresford & Howard, 1991). Two other studies that measured the soil content of harvested cattle feed found that soil contributed less than 1% of the dry weight of the feed (Fries et al., 1981; Zach & Mayoh, 1984). It is reasonable to assume that forage is not washed prior to feeding animals under normal conditions. However, many of the plant crop studies and one of the two studies of forage crops used experimental methods which either protected the leaves from contact with soil or washed it away after harvesting. Thus, the contribution of contaminated soil to harvested forage crop PCDD/F contamination may not have been adequately assessed by the studies to date. More evidence is needed to evaluate this potentially important factor.

4.4 Animal foods

There is some evidence to suggest that consumption of contaminated feed or grazing of cattle on treated land may increase the PCDD/F levels in meat products. Unlike the plant studies, most of the studies examining the impact of PCDD/F contamination on animal tissue used feed that was contaminated at levels low enough that they might be encountered in practice. Although not obvious from a visual examination of the regression curves because of large differences in scale, the change in beef tissue contamination per unit soil contamination is much greater than for plant tissue. The coefficient is two to three orders of magnitude higher for beef than for most plants, and one order higher than for the family *Cucurbitaceae*. As a result, the predicted concentrations in Table 19 show a marked increase even over a relatively small range of feed PCDD/F concentrations. This suggests that the use of dioxin/furan-contaminated biosolids on grazing land or on land used to grow cattle feed may result in increased human exposure to dioxins and furans through the diet, especially if the biosolids are highly contaminated. Although five papers examined the effect on meat or milk when animals consumed harvested feed grown on sludge-amended land, it could not be determined whether the feed crops were washed after harvesting or grown under unusual conditions to prevent adherence of soil particles.

No studies were identified that measured dioxins and furans in pork or poultry products from animals fed from sludge-amended land; thus, these results can only be applied to beef products. None examined the effect of grazing on sludge-amended land. Although there were eight papers reporting background concentrations of PCDD/Fs in animal tissue, it is not known whether the animals in the studies grazed or consumed food grown on sludge-amended land. These data are therefore not comparable to the experimental data.

There was insufficient data to conclude whether consumption of feed grown on land treated with biosolids or grazing of animals on sludge-amended land is likely to increase the PCDD/F levels in milk products. Few studies examined the relationships between contamination of feed or grazing land and milk contamination from cows (McLachlan et al., 1990; Jilg et al., 1992; McLachlan et al., 1994; McLachlan & Richter, 1998; Fries et al., 1999) and no clear relationship could be seen in the plotted data (Figure 9). Overall, the papers that examined the relationship between feed or soil PCDD/F concentration and milk concentration show that dioxins and furans are excreted in milk. The amount excreted appears to be dependent on the timing of PCDD/F contamination in the diet (Jilg et al., 1992; Jones et al., 1989). There may be only a minimal impact of biosolids use on milk, especially if a sufficient time lag is provided between biosolids application and milking for human consumption; however, the data are still very limited.

4.5 Key data gaps

Although there is some empirical evidence to suggest that there is an impact of biosolids application on the PCDD/F uptake by grazing animals, but minimal uptake from biosolids to plants, there are a number of significant gaps in the data.

- TEQ data do not account for congener-specific differences.
- Field practices such as biosolids application rate, application method, PCDD/F concentration, and fertilization/harvesting time could not be considered in this review because such information was not usually reported in the published studies.
- The number of studies is limited, and most results have not been confirmed by repeat studies.

- Many studies did not describe the details of the analytical methods used (including limits of detection).
- There is no data on many species of plants and animals that may be grown in BC.
- There are no plant studies and few animal uptake studies that examined the effects of real biosolids application practices.
- Many studies did not state whether samples were washed prior to analysis. When special washing techniques were used, they were poorly described. This is especially important with respect to harvested forage crops, for which the contribution of soil adherence is not known.

5. Conclusions for British Columbia Medical Health Officers

5.1 Plant crops

Although the published empirical data for any one type of crop are very limited, the collective body of work indicates that

- high levels of dioxins and furans in soil are associated with increased contamination of plant crops; however,
- at the soil contamination levels expected from treatment with biosolids, it appears that there would be minimal or no increase in the dioxin and furan content of most food crops.

The data suggest that different plants have differing potentials for uptake of dioxins and furans, based on the different coefficients for the relationships between soil contamination levels and plant concentrations (listed below in order of increasing association).

Herbs	0.0001 pg TEQ/g (dry weight) in plant/ pg TEQ/g in soil
Potatoes	0.0004* pg TEQ/g (dry weight) in plant/ pg TEQ/g in soil
Hay	0.0008 pg TEQ/g (dry weight) in plant/ pg TEQ/g in soil
Peas and beans	0.0008 pg TEQ/g (dry weight) in plant/ pg TEQ/g in soil
Tree fruits	0.0016 pg TEQ/g (fresh weight) in plant/ pg TEQ/g in soil
Carrots	0.0027* pg TEQ/g (dry weight) in plant/ pg TEQ/g in soil
Leafy vegetables	0.0042 pg TEQ/g (dry weight) in plant/ pg TEQ/g in soil
Cucurbitaceae family	0.019* pg TEQ/g (dry weight) in plant/ pg TEQ/g in soil

** = statistically significant regression coefficient, $p < 0.05$*

The interpretation of the above coefficients should be limited, since they are based on relatively few data points, from only one or a few studies. Taken together, they suggest that, for most plants, large increases in soil contamination (200 to 10,000 pg TEQ/g, i.e., much higher than the increases expected from biosolids treatment) are required to produce small increases (1 pg TEQ/g) in plant contamination. They also suggest that plants in the family *Cucurbitaceae* (pumpkin, zucchini, cucumber) show a sufficiently strong association between soil PCDD/F levels and plant contamination that application of biosolids may increase the contamination levels of the plants.

Unfortunately, there is no evidence related to the potential for increased dioxin/furan contamination of other root vegetables (e.g., beets, parsnips, turnips, sweet potatoes, ginger, garlic, onions) or aboveground plant foods (e.g., cruciferous vegetables, berries, tomatoes, corn, peppers, grains).

At this time, it appears that biosolids application to agricultural land *may* have a small impact on the levels of PCDD/Fs found in root vegetables, above ground plant foods, and forage crops. Further research is needed if a more definite conclusion is to be made. Studies on a wider variety of plants and studies using real biosolids treatment rather than experimental treatment with unrealistically high levels of PCDD/F in the soil are essential to gain further insight. Of utmost importance is the issue of soil contamination of forage crops. Evidence is needed to determine whether soil particles adhering to forage have a significant impact on the PCDD/F levels found in the consuming animals. The current data are also insufficient to distinguish any potential differences associated with biosolids application method, timing, or rate.

Based on these limited data, application of biosolids to agricultural land used for certain crops (*harvested* forage crops, potatoes, peas and beans, tree fruits, carrots, leafy vegetables) could be permitted. If biosolids are to be applied to land used to grow harvested forage, concurrent monitoring is *essential* to evaluate the risks associated with adherence of soil particles.

If biosolids application to land used for growing these crops were to be approved in British Columbia, it is recommended that a study be conducted to compare the levels of dioxins and furans in crops grown in treated and untreated soils. Using a power of 0.8 and an alpha of 0.05, and assuming a geometric standard deviation of 3, the following sample sizes would be needed in both the crops grown in soil treated with biosolids and crops grown in untreated soil:

- n = 15 to detect a 3-fold increase in geometric mean concentration;
- n = 30 to detect a 2-fold increase in geometric mean; and
- n = 90 to detect a 1.5-fold increase in geometric mean.

Sampling data should be kept in a database along with dates of sludge application, planting, and sampling, as well as planting times, crops grown, amount and frequency of sludge applied, and the application method used.

It is recommended that biosolids not be applied to land used for growing crops of the family *Cucurbitaceae* (cucumber, zucchini, and pumpkin).

5.2 Animal foods

There is a need for further study on the relationships between biosolids application to grazing land or land used for feed and the PCDD/F levels found in cattle and milk. There is also a need for some information on the effects on animals other than cows, e.g., swine and poultry.

The data available at this time indicates a relationship between feed contamination levels and concentrations in the fatty tissue of cattle that is considerably stronger than that for plant tissues, with a coefficient of 1.46 pg TEQ/g per pg TEQ/g in feed (significant,

$p < 0.05$), suggesting bioaccumulation. As an example, the PCDD/F concentration in beef tissue may increase by up to 10 pg TEQ/g fat at the relatively low contamination level of 5 pg TEQ/g in feed (Table 19). There is very little information relating to the effect of biosolids application to grazing or cropland on the dioxin/furan concentration of milk products.

The application of biosolids to *grazing or forage land* presents additional exposure risk to animals beyond that resulting from direct uptake of dioxins and furans by the crops. Animals consume soil along with fodder, either by eating the soil directly while grazing or by consuming plants (e.g. grass, hay or beetroot) to which soil has adhered (Zach & Mayoh, 1984; McLachlan, Horstmann et al., 1996). As a result, they may directly ingest biosolids that have been applied to pastureland. Although estimates vary, cattle, sheep, and swine may consume an average of 6–7% (up to 18% during seasons of sparse forage) of their ingested dry matter as soil (Pohl et al., 1995; Fries, 1996). Studies from the Netherlands and the United States, where grazing is seasonal and cattle are given plenty of supplemental feed, suggest that cows may ingest an average of 150–300 g of soil per day (1–2% of their dry matter intake) (McLachlan, Horstmann et al., 1996). At a worst-case estimate of 30 pg TEQ/g soil, this would correspond to an additional intake of up to 9 ng PCDD/F per cow per day. Based on an analysis of studies from New Zealand, the United Kingdom, and the United States, Fries (1996) estimated that a 500 kg dairy cow would ingest 900 g of soil per day. With a PCDD/F concentration of 30 pg TEQ/g soil, this would contribute 27 ng PCDD/F per cow per day.

Given the potential for a large increase in meat contamination with consumption of contaminated feed, and the potential for cattle to consume not only the plants grown in treated soil but also the soil itself, it is recommended that biosolids not be applied to grazing land.

5.3 Concluding remarks

This review was based entirely on published empirical data regarding the impact of PCDD/F contamination (experimental or from biosolids application) of soil or feed on plant and animal tissue. The results reported here were compared with the results of studies that used pathway modeling to predict the effect of land application of biosolids on PCDD/F contamination in food and found to be similar. An extensive review conducted for the United States Conference of Mayors Urban Water Council (Rappe et al., 1999), which cited many of the same empirical studies used in this review, concluded that human exposure is not likely to increase due to biosolids application to crop land, but that the spraying of biosolids onto grazing land could lead to increased exposures (less so if biosolids are tilled into the soil). Similarly, other models predicted that biosolids application may lead to slight increases in PCDD/F concentration in the peel of root crops (Wild et al., 1992; Jackson & Eduljee, 1994; Duarte-Davidson & Jones, 1996) or members of the *Cucurbitaceae* family (Jones & Sewart, 1997), but would have a negligible impact on other above-ground plants (Wild et al., 1992; Duarte-Davidson & Jones, 1996; Jones & Sewart, 1997). Many modeling papers likewise concluded that biosolids application, particularly on grazing land, could significantly increase human dietary exposure to PCDD/F (Wild et al., 1992;Jackson & Eduljee, 1994; Wild et al., 1994; Duarte-Davidson & Jones, 1996; Jones & Sewart, 1997). A review by McLachlan, Horstmann and colleagues (1996) concluded that one means of reducing the risks associated with PCDD/F exposure of animal foods might be to ban application of biosolids on pasture or fodder land or to encourage harvesting techniques that minimize soil contamination of animal feed.

In conclusion, it is important to note that there is a great need for further data on the relationship between biosolids application to agricultural land and the PCDD/F concentration of crops and animal food. If human exposure to dioxins and furans is to be minimized, however, it is also essential that the levels of these contaminants in biosolids be reduced. Even if the impact of land-applied biosolids on exposure through food is small, minimizing the PCDD/F content of biosolids will further reduce human exposure and minimize bioaccumulation of these persistent compounds in the environment.

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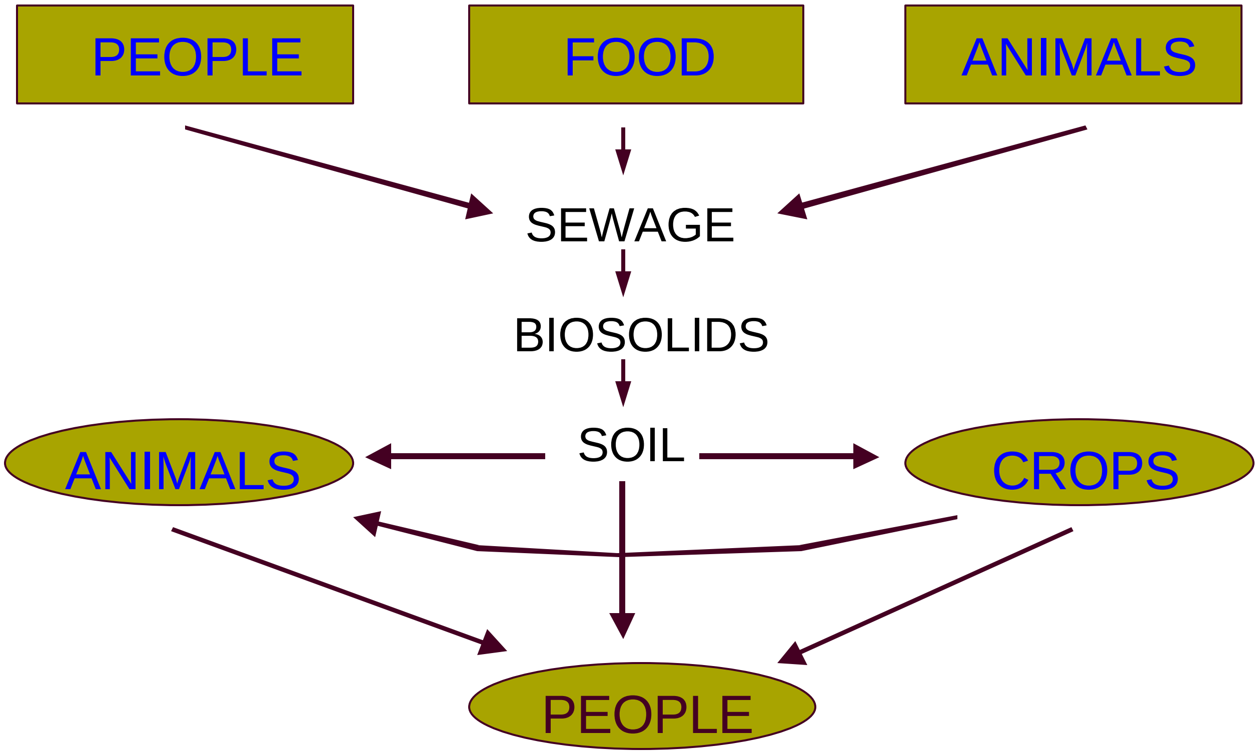

Figure 1. **Potential transfer pathways for PCDD/Fs to humans.**
Adapted from Jones, KC & Sewart, AP. (1997). Dioxins and furans in sewage sludges: a review of their occurrence and sources in sludge and of their environmental fate, behavior, and significance in sludge-amended agricultural systems. *Critical Reviews in Environmental Science and Technology* 27, 1-85.

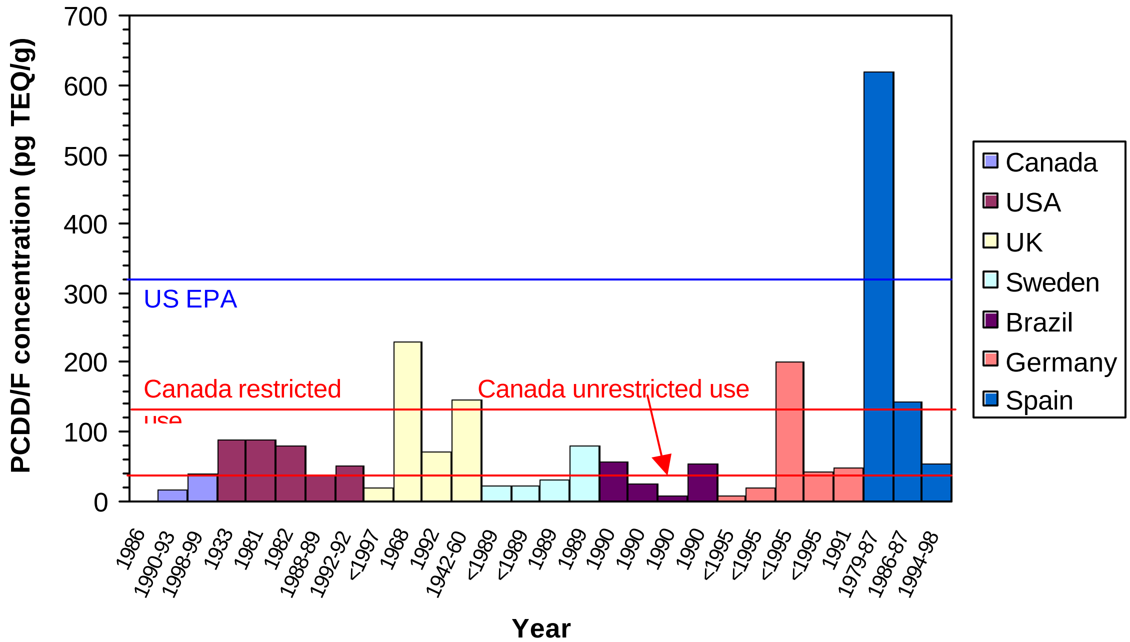

Figure 2. PCDD/F concentrations in sewage sludge.

The red lines indicate the current Canadian guidelines for PCDD/F in agricultural soil, which suggest a maximum of 27 pg TEQ/g soil for unrestricted use and 100 pg TEQ/g soil for restricted use of biosolids on agricultural lands (CH2M Hill, 2001).

The blue line indicates the US Environmental Protection Agency (EPA) proposed limit of 300 pg TEQ/g soil for biosolids applied to agricultural lands (US EPA, 1999).

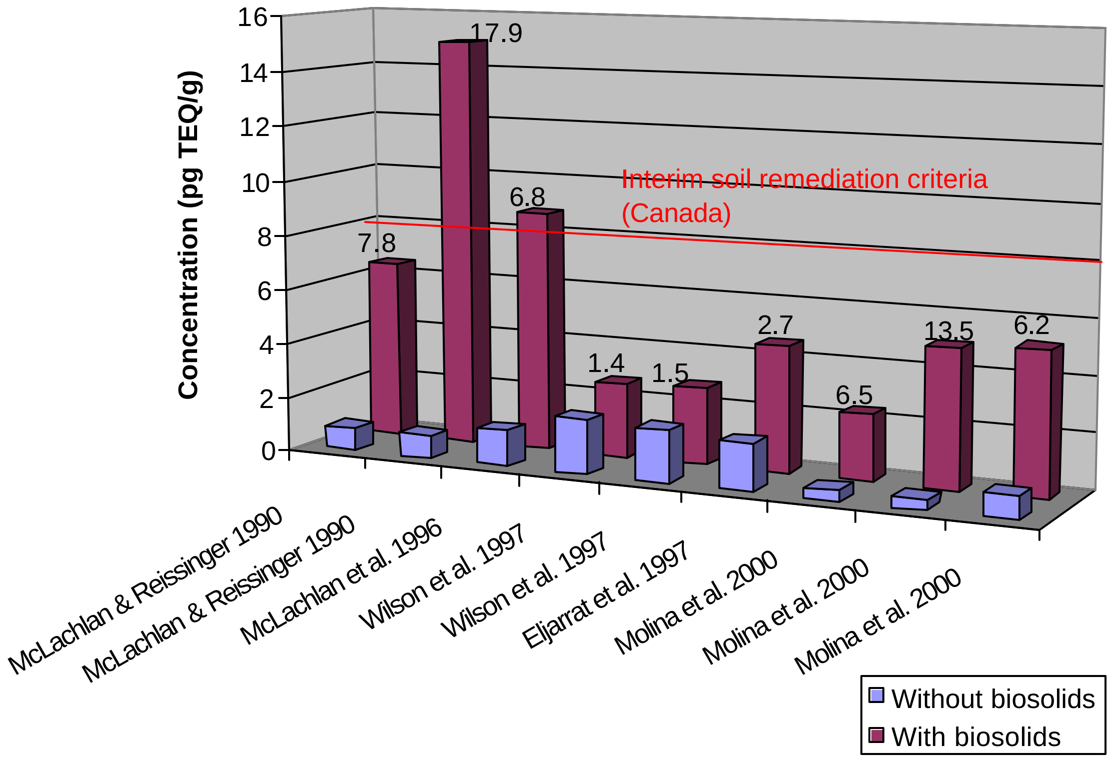

Figure 3. Change in soil PCDD/F concentration following sludge application.
The red line indicates the Canadian interim soil remediation criteria for contaminated sites (10 pg TEQ/g) (CCME, 1991).
The numbers above the bars indicate the factor by which the soil PCDD/F concentration increased following application of biosolids.

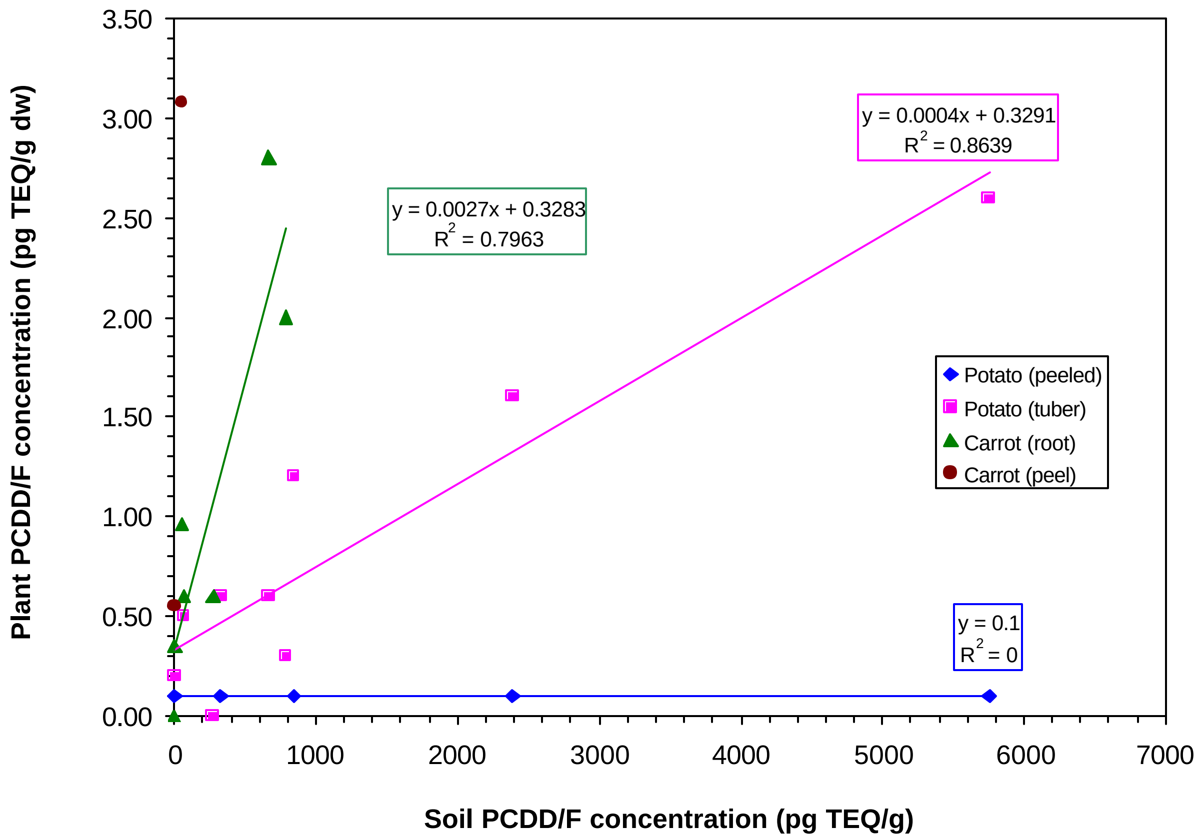

Figure 4. Relationship between PCDD/F concentrations in root crops and soil contamination levels. This figure includes all values from Tables 5 and 6, with the exception of three measurements in which the soil PCDD/F concentration was much higher (8-fold and 20-fold) (Hulster & Marschner, 1993) than in the other samples and not remotely relevant to the soil concentrations likely to results from biosolids application Data were taken from the following sources: potato (peeled): Hulster & Marschner, 1993; potato tuber: Prinz et al., 1991; Hulster & Marschner, 1993; carrot root: Prinz et al., 1991; Schroll & Scheunert, 1993; carrot peel: Muller et al., 1994.

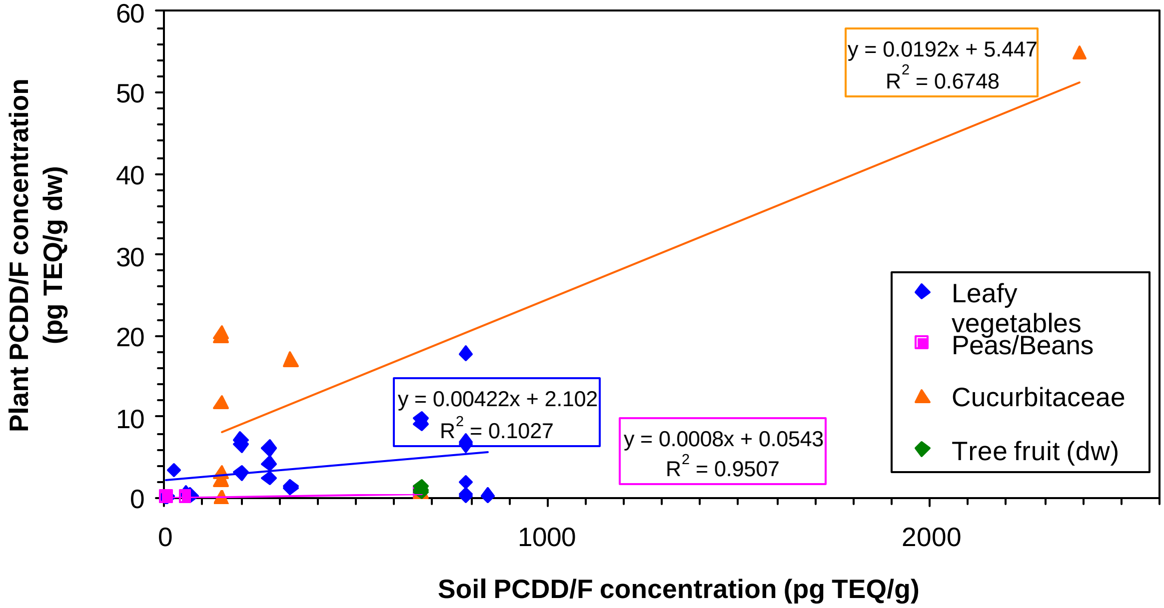

Figure 5. Relationship between PCDD/F concentrations in crops with edible portion grown above ground and soil contamination levels. This figure contains all values from Tables 7 and 8, with the exception of one measurement (Hulster & Marschner, 1993) in which the soil PCDD/F concentration was much higher (20-fold) than in the other samples; the results of a study that did not use natural growing conditions (plants growing in pots of uncontaminated soil placed in or on top of contaminated soil (Hulster et al., 1994); data relating to inedible portions of plants (carrot leaves (Schroll & Scheunert, 1993)); the results of a study that examined root exudates rather than plants (Hulster & Marschner ,1994); and data presented as fresh weight rather than dry weight, which is presented in Figure 6 (Muller et al., 1993). Data were taken from the following sources: leafy vegetables: Prinz et al., 1991; Hulster & Marschner, 1993; Muller et al., 1994; peas and beans: Prinz et al., 1991; Muller et al., 1994; *Cucurbitaceae*: Hulster et al., 1994; tree fruit: Prinz et al., 1991.

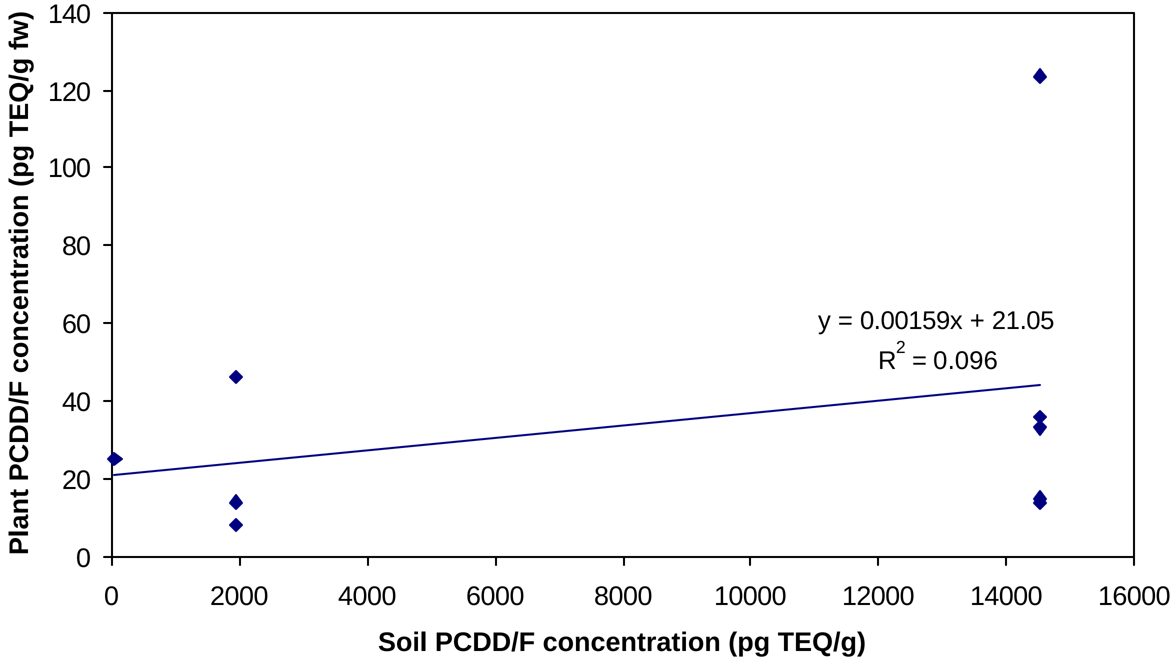

Figure 6. PCDD/F concentrations in tree fruits grown in contaminated soil. This figure contains all fresh weight values relating to tree fruits from Table 8. Data were taken from Muller et al. (1993).

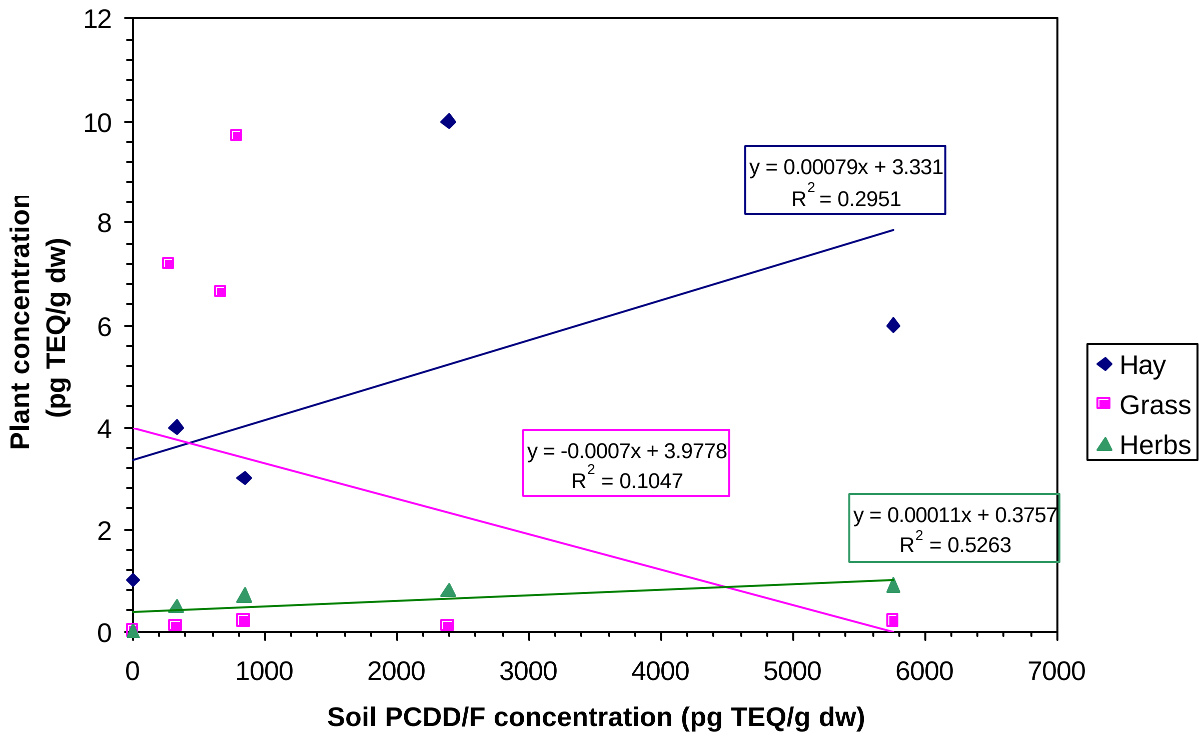

Figure 7. PCDD/F concentrations in forage crops grown in contaminated soil. This figure contains all the values form Tables 9 and 10, with the exception of one value (Hulster & Marschner, 1993) in which the PCDD/F contamination level of the soil was much higher (20-fold) than the other samples. Data were taken from the following sources: hay: Hulster & Marschner, 1993; grass: Prinz et al., 1991; Hulster & Marschner, 1993; herbs: Hulster & Marschner, 1993.

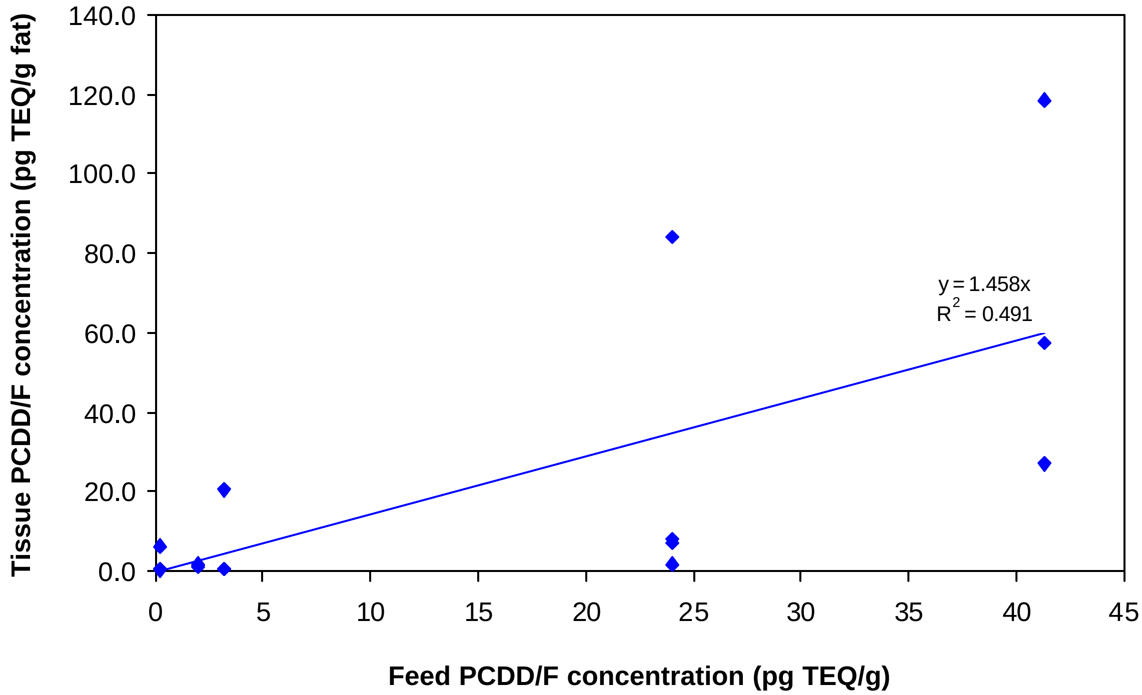

Figure 8. PCDD/F concentrations in animal tissue when consuming contaminated feed. This figure includes all values from Table 11 relating to PCDD/F concentration in tissue (not milk), with the exception of studies that did not provide the feed PCDD/F level (Schecter et al., 1994; Winters et al., 1996; Fiedler et al., 1997; Feil & Ellis, 1998; Thorpe et al., 2001), and all values from Table 12, with the exception of one study that used an experimental dose 87 times× higher than in the other studies (Jones et al., 1989; Thorpe et al., 2001). Data were taken from Jensen et al. (1981); Jilg et al. (1992); Richter & McLachlan (2001).

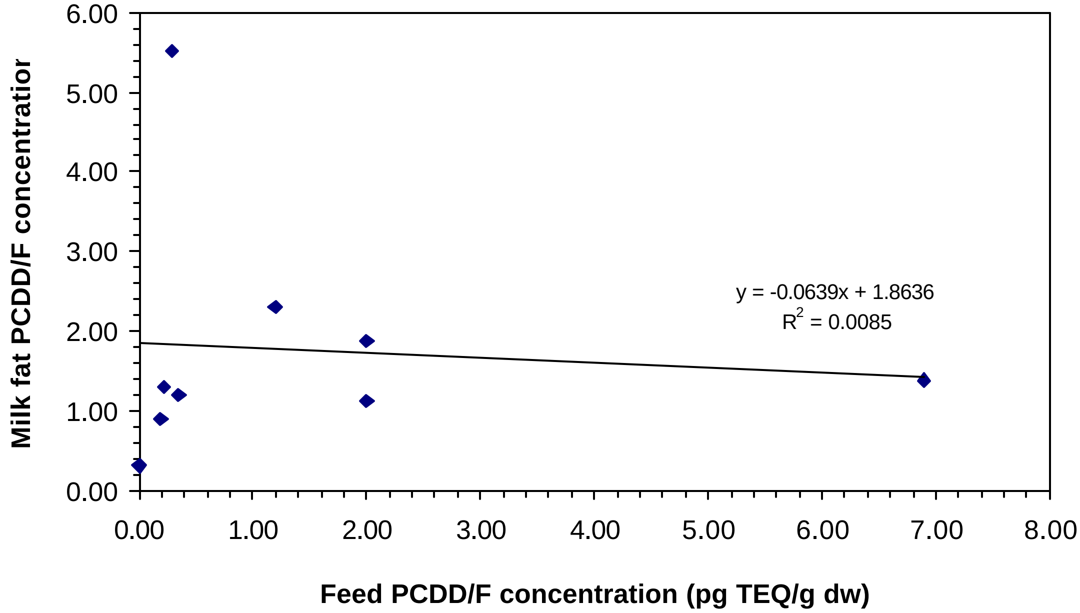

Figure 9. PCDD/F concentrations in milk fat of cows consuming contaminated feed. This figure contains all data from Table 11, relating to PCDD/F concentration in milk (not tissue), with the exception of one study that did not provide the feed PCDD/F level (Fries et al., 1999), and all values from Table 13, with the exception of the results of one study that presented the data as concentrations in whole milk rather than milk fat (McLachlan & Richter, 1998). Data were taken from McLachlan et al. (1990); Jilg et al. (1992); Fries et al. (1999).

Table 1. Toxicity Equivalency Factors (TEF) for PCDD/Fs.

Compound	TEF
2,3,7,8-tetrachlorodibenzo-*p*-dioxin	1.0
1,2,3,7,8-pentachlorodibenzo-*p*-dioxin	0.5
1,2,3,4,7,8-hexachlorodibenzo-*p*-dioxin	0.1
1,2,3,6,7,8-hexachlorodibenzo-*p*-dioxin	0.1
1,2,3,7,8,9-hexachlorodibenzo-*p*-dioxin	0.1
1,2,3,4,6,7,8-heptachlorodibenzo-*p*-dioxin	0.01
octachlorodibenzo-*p*-dioxin	0.0001
2,3,7,8-tetrachlorodibenzofuran	0.1
1,2,3,7,8-pentachlorodibenzofuran	0.05
2,3,4,7,8-pentachlorodibenzofuran	0.5
1,2,3,4,7,8-hexachlorodibenzofuran	0.1
1,2,3,6,7,8-hexachlorodibenzofuran	0.1
1,2,3,7,8,9-hexachlorodibenzofuran	0.1
2,3,4,6,7,8-hexachlorodibenzofuran	0.1
1,2,3,4,6,7,8-heptachlorodibenzofuran	0.01
1,2,3,4,7,8,9-heptachlorodibenzofuran	0.01
octachlorodibenzofuran	0.001

Adapted from Abt Associates Inc., 1999.

Table 2. Background concentrations of PCDD/F in sewage sludge (sorted by country and year).

Reference	Country/ Geographical area	Data collection year	Purpose for sampling	How measured	Sources of material	Congeners measured	Congener/ homolog profile	Number samples (n)	Mean conc. (pg TEQ/g) (SD)	Median (pg TEQ/g)	Range (pg TEQ/g)	Results/ Conclusion	Conclusions/ Comments
Ho & Clement 1990 Chemosphere 20:1549-1552	Canada (Ontario)	1986	to determine predominant toxic contaminants in Ontario wastewater discharges	Modified DOW method (GCMS)	treated sludge from 37 municipal water pollution control plants	tetra- through octa-CDD/F	primarily hepta- and octa-CDD	50			0.0005–0.0015		most samples were at or below detection limits of the time
					raw sludge from 37 municipal water pollution control plants			50			0.0026–0.0051		
van Oostdam & Ward 1995	Canada (BC)	1990–1993	Environmental monitoring to establish baseline levels for BC	Not stated	primary sludge	tetra- through octa-CDD/F		4	16.6		2.3–49.6		samples were from sources believed to be contaminated
Healey & Bright 2000	Canada (GVRD)	1998 – 1999	to determine whether following metal limits is sufficient to control for exposure to organic contaminants in sludge	EPA Method 1613 (HRGC-HRMS)	municipal wastewater treatment plants	tetra- through octa-CDD/F	OCDD predominant	26	40 (48) upper 95% CI = 120		5.6–250		samples from 5 wastewater treatment plants
Lamparski et al. 1984 Chemosphere 13:361-365	USA (Milwaukee)	1933	to compare PCDD levels over time	EPA Method 1613 (HRGC-LRMS)	treated municipal sludge	tetra- through octa-CDD/F		1	87.7				samples were sludge prepared for use as fertilizer
		1981						1	88.9				
		1982						1	80.8				
Telliard et al. 1990 Organo-halogen Compounds 2:307-310	USA	1988–1989	USEPA National Sewage Sludge Survey	EPA Method 1613 (HRGC-HRMS)	public owned sewage treatment works (random sample from US, stratified by flow volume)	tetra- through octa-CDD/F	primarily hepta- and octa-CDD/F	211	38.38 (ww)[1]	3.88 (ww)	0.039–1252.9		used wet weight not dry weight

Reference	Country/ Geographical area	Data collection year	Purpose for sampling	How measured	Sources of material	Congeners measured	Congener/ homolog profile	Number samples (n)	Mean conc. (pg TEQ/g) (SD)	Median (pg TEQ/g)	Range (pg TEQ/g)	Results/ Conclusion	Conclusions/ Comments
Malloy et al. 1993 Chemosphere 27:325-34	USA (NY, Midwest, northwest, southeast, east coast)	1990–1992	to compare levels from different types of composting facilities	EPA Method 1613 (GCMS)	municipal yard waste compost	tetra- through octa- CDD/F	increased concentration with increasing chlorination in all types of waste	11	29.6 51.2		5–91		solid waste + sludge > solid waste > compost
					municipal solid waste compost			6	46.5		19–96		
					municipal solid waste + dewatered sewage sludge compost			4	56		37–87		
Wilson et al. 1997 J Environ Qual 26:1467-77	UK (NW England)		to assess persistence in previously unamended soils	EPA Method 1613 (GCMS)	anaerobically digested sewage sludge	tetra- through octa- CDD/F	primarily hepta- and octa-CDD	1	19 (dw)[2]				
McLachlan, Sewart et al. 1996 Environ Sci Techno 30:2567-71	UK	1968	to determine persistence in soil	EPA Method 1613 (HRGC-HRMS)	rural uncontaminated sewage sludge	tetra- through octa- CDD/F	primarily hepta- and octa-CDD/F	2	230 (dw)		200–280		samples 2 had 3 separate extracts
Sewart & Harrad 1995 Chemosphere 30: 51-67	UK	1992	to assess levels in sludge likely to be land applied to compare current sludges with archived samples	EPA Method 1613 (HRGC-HRMS)	digested sludges from sewage treatment plants in NW England (urban, rural, and industrial)	2,3,7,8-PCDD/Fs non-o PCBs total tetra through hepta-CDD/Fs	OCDD predominant concentration increased with increasing chlorination	8	72 (dw)		19–206	concentration has decreased since 1950s	each sample analyzed 2× evidence of PCP contamination in some samples
		1942–1960			archived samples from 1942–1960			7	148 (dw)		18–402		

Reference	Country/ Geographical area	Data collection year	Purpose for sampling	How measured	Sources of material	Congeners measured	Congener/ homolog profile	Number samples (n)	Mean conc. (pg TEQ/g) (SD)	Median (pg TEQ/g)	Range (pg TEQ/g)	Results/ Conclusion	Conclusions/ Comments
Rappe et al. 1989 Chemosphere 19: 13-20	Sweden (Stockholm & Uppsala)		to determine PCDD/F levels in sludge	EPA Method 1613 (HRGC-HRMS)	sludge from urban Stockholm	tetra- through octa-CDD/F	primarily hepta- and octa-CDD	1	23.9			little difference between rural and urban sludges	
					sludge from rural Uppsala			1	23.1				
Naf et al. 1990 Chemosphere 20:1503-10	Sweden (Stockholm)	May–Aug 1989		EPA Method 1613 (GCMS)	anaerobically digested sludge from urban wastewater treatment plant	tetra- through octa-CDD/F	primarily hepta- and octa-CDD/F	1	31 (dw)				
Broman et al. 1990 Chemosphere 21:1213-20	Sweden (Stockholm)	May–Aug. 1989	to determine PCDD/F levels in sludges	not stated	digested and dewatered sludge	2,3,7,8-PCDD/F		4	79 (ow)		41–130		13 sub samples were taken from each sewage treatment plant TEQs are given as organic weight not dry weight
Grossi et al. 1998 Chemosphere 37:2153-60	Brazil	1990–?	to compare Brazilian levels with German levels and standards	EPA Method 1613 (GCMS)	municipal solid waste compost from: M – urban	tetra- through octa-CDD/F	mostly octa-CDD; then hepta- and hexa-CDD	11	57 (41) (dw)		11–150		10 sub samples were mixed from each plant
					S – small cities			5	27 (46) (dw)		3–163		
					I – coastal sandy			3	8 (2) (dw)		5–11		
					E – new, some industrial waste			2	54 (45) (dw)		10–99		

Reference	Country/ Geographical area	Data collection year	Purpose for sampling	How measured	Sources of material	Congeners measured	Congener/ homolog profile	Number samples (n)	Mean conc. (pg TEQ/g) (SD)	Median (pg TEQ/g)	Range (pg TEQ/g)	Results/ Conclusion	Conclusions/ Comments
Disse et al. 1995 Chemosphere 31: 3617-3625	Germany		to determine effects of anaerobic and aerobic digestion on PCDD/F concentrations	EPA Method 1613 (HRGC-HRMS)	undigested sludge from rural area with no heavy industry	tetra- through octa- CDD/F		1	9 (dw)				background data for more involved study was used
					undigested sludge from municipal area with no heavy industry			1	20 (dw)				
					undigested sludge from municipal area with metal industry			1	200 (dw)				
McLachlan & Reissinger 1990 Organo-halogen Compounds 1:577-82	West Germany (NE Bavaria)		to determine accumulation in sludge-amended soil over time	minimal detail provided – similar to EPA 1613?	local wastewater treatment plant	tetra- through octa- CDD/F	increased concentration with increasing chlorination primarily hepta-and octa-CDD/F	1	42 (dw)				
Horstmann et al. 1992 Chemosphere 25: 1463-1468	Germany (Bayreuth)	1991	to determine PCDD/F patterns in urban sewage sludge	EPA Method 1613 (GC-HRMS)	anaerobically digested sewage sludge	tetra- through octa- CDD/F		1	48 (dw)			no difference in sludge concentrations in dry or wet weather	
					primary sludge (dry conditions)		primarily hepta- and octa-CDD	9	31.4 (dw)		15–64		
					primary sludge (rainy conditions)			2	28.5 (dw)		21–36		
Eljarrat et al. 1999 Environ Sci Tech 33:2493-8	Spain (Catalonia)	1994–1998	to determine PCDD/F levels in sludge	EPA Method 1613 (HRGC-HRMS)	sludges from rural, urban, & industrial wastewater treatment plants archived samples from 1979–1987 (15 wastewater treatment plants)	tetra- through octa- CDD/F	PCDD higher than PCDF OCDD predominant concentration increased with increased chlorination	19	55 (dw)	42	7–160	decrease in concentration over time likely due to control of PCP use and disposal	
		1979–1987	to compare current levels with 1980s levels					24	620 (11.3X increase)	110 (2.6X increase)	29–8300		

Reference	Country/ Geographical area	Data collection year	Purpose for sampling	How measured	Sources of material	Congeners measured	Congener/ homolog profile	Number samples (n)	Mean conc. (pg TEQ/g) (SD)	Median (pg TEQ/g)	Range (pg TEQ/g)	Results/ Conclusion	Conclusions/ Comments
Molina et al. 2000 Chemosphere 40: 1173-1178	Spain (Girona)		to determine the evolution of PCDD/F in sludge-amended soils	EPA Method 1613 (HRGC-HRMS)	aerobic sewage treatment plant	tetra- through octa-CDD/F	primarily hepta- and octa-CDD	1	68.1 (dw)				
Eljarrat et al. 1997 Environ Sci Technol 31:2765-71	Spain	1986 1987	to assess effects of PCDD/F & PCB in sludge applied to soil	EPA Method 1613 (HRGC-HRMS)	sludge from wastewater treatment plants in urban area in NE Spain (aerobic digestion)	tetra- through octa-CDD/F	increased concentration with increasing chlorination OCDD predominant	7	144 (dw)		74–260		

[1] ww = wet weight
[2] dw = dry weight

Table 3. PCDD/F background levels in soil (not sludge-amended) (sorted to show relationship to Table 4).

Reference	Country/ Geographical area	Data collection year	Purpose for sampling	How measured	Sources of material	Congeners measured	Congener/ homolog profile	Number samples (n)	Mean conc. (pg TEQ/g) (SD)	Median (pg TEQ/g)	Range (pg TEQ/g)	Results/ Conclusion	Conclusions/Comments
Wilson et al. 1997 J Environ Qual 26:1467-77	UK		to assess persistence in previously unamended soils	EPA Method 1613 (GCMS)	plowed plot	tetra- through octa- CDD/F	OCDD predominant	4	2.0 (dw)[1]		1.8–2.2		experimental land used as control for sludge application experiments
					pasture plot			4	1.9 (dw)		1.7–2.0		
McLachlan & Reissinger 1990 Organo-halogen Compounds 1:577-82	West Germany (NE Bavaria)		to determine accumulation in sludge-amended soil over time	minimal detail provided – similar to EPA 1613?	farmland	tetra- through octa- CDD/F	increased concentration with increasing chlorination	1	0.84 (dw)				sample taken at bore depth 30 cm
Molina et al. 2000 Chemosphere 40: 1173-1178	Spain (Girona)		to determine the evolution of PCDD/F in sludge-amended soils	EPA Method 1613 (HRGC-HRMS)	alkaline soil	tetra- through octa- P-CDD/F	primarily hepta- and octa- dioxins	2	0.37 (dw)		0.34-0.39		
					quarry			2	0.84 dw)		0.76-0.92		
Eljarrat et al. 1997 Environ Sci Technol 31:2765-71	Spain	1986–1987	to assess effects of PCDD/F & PCB in sludge applied to soil	EPA Method 1613 (HRGC-HRMS)	acidic and basic agricultural soil	tetra- through octa- P-CDD/F	increased concentration with increasing chlorination OCDD predominant	2	1.7 (dw)		0.3–3.1		
McLachlan, Sewart et al. 1996 Environ Sci Techno 30:2567-71	UK	1968, 1972, 1976, 1981, 1985, 1990	to determine persistence in soil	EPA Method 1613 (HRGC-HRMS)	experimental agricultural land	2,3,7,8-PCDD/F	hepta- and octa- predominant	6	1.3 (dw)		0.88–2.0		

Reference	Country/ Geographical area	Data collection year	Purpose for sampling	How measured	Sources of material	Congeners measured	Congener/ homolog profile	Number samples (n)	Mean conc. (pg TEQ/g) (SD)	Median (pg TEQ/g)	Range (pg TEQ/g)	Results/ Conclusion	Conclusions/Comments
Kjeller et al. 1991 Environ Sci Technol 25:1619-1627	UK (Southeast England)	1846–1986	to assess temporal changes in soil concentrations due to atmospheric deposition	EPA Method 1613 (HRGC-HRMS)	semi-rural experimental plots	tetra- through octa- P-CDD/F	increased concentration with increasing chlorination	3	1.4 (dw) (1986)			concentrations increased over time	
Sund et al. 1993 Aust J Public Health 17:157-61	Australia (Melbourne)	1990	to quantify background soil levels to examine effects of effluent from agricultural chemical plant	EPA Method 8290	soil from urban and industrial areas in Melbourne	tetra- through octa- CDD/F		7	2.3		0.09–8.2		
van Oostdam & Ward 1995	Canada (BC)	1990–1993	environmental monitoring to establish baseline levels for BC		background soil	tetra- through octa- CDD/F		53	5.0		nd[2]–57		samples taken from areas NOT believed to be contaminated
Creaser et al. 1989 Chemosphere 18: 767-776	UK		to collect background data of soil levels	EPA Method 1613 (GCMS)	soil at intersection points of a 50-km grid covering UK	tetra- through octa CDD/F	primarily OCDD	77	23.4	20.5	1.2–161.9		adjusted values are presented to reduce effects of local sources (samples with >2.5× SD were rejected)
Broman et al. 1990 Chemosphere 21:1213-20	Sweden (Stockholm)	1989	to determine levels in top soil to determine effect of proximity to major roads	not stated	agricultural land near major roads	2,3,7,8-CDD/F		4	29 (ow)[3]		13–49	samples taken closer to the city of Stockholm had higher concentrations samples taken close to major roads had higher concentration than those taken further from major roads	each sample was homogenization of 10 soil samples TEQs are given as organic weight not dry weight
					agricultural land not near major roads			4	17 (ow)		9–32		

[1] dw = dry weight
[2] nd = not detected
[3] ow = organic weight

Table 4. PCDD/F levels in sludge-amended soil (sorted by increasing sludge PCDD/F concentration).

Reference	Country/ Geo-graphical area	Data collec-tion year	Purpose for sampling	How measured	Sources of material	Sludge conc. (pg TEQ/g)	Congeners measured	Congener/ homolog profile	Number samples (n)	Mean conc. (pg TEQ/g) (SD)	Median (pg TEQ/g)	Range (pg TEQ/g)	Results/ Conclusion	Conclusions/Comments
Wilson et al. 1997 J Environ Qual 26:1467-77	UK		to assess persis-tence in previously un-amended soils	EPA Method 1613 (GCMS)	plowed plot (depth of 15-20 cm)	19	tetra- through octa- CDD/F	OCDD predominant	4	2.7 (dw)[1]		2.4–3.0	PCDD/F is persistent in plowed soil	single application of anaerobically digested sludge
					pasture plot (surface application to vegetation)				4	2.8 (dw)		1.6–4.3	sludge applied to pasture surface adheres to vegetation (risk to grazing animals)	2 plots each: 50 t/ha dw and 20 t/ha dw sampled regularly from time of sludge application to 260 days
McLachlan & Reissinger 1990 Organo-halogen Compounds 1:577-82	West Germany (NE Bavaria)		to determine accum-ulation in sludge-amended soil over time	minimal detail provided – similar to EPA 1613?	farmland	42 (dw)	tetra- through octa- CDD/F	increased concentration with increasing chlorination	2	6.55 (dw)		3.7-9.4	PCDD/F accumulated in soil	sludge applied regularly (frequency and amount not known) for 10 to 30 years samples taken at bore depth 20-30 cm
					meadow				1	15 (dw)				

Reference	Country/ Geo-graphical area	Data collec-tion year	Purpose for sampling	How measured	Sources of material	Sludge conc. (pg TEQ/g)	Congeners measured	Congener/ homolog profile	Number samples (n)	Mean conc. (pg TEQ/g) (SD)		Median (pg TEQ/g)	Range (pg TEQ/g)	Results/ Conclusion	Conclusions/Comments
Molina et al. 2000 Chemosphere 40: 1173-1178	Spain (Girona)		to determine the evolution of PCDD/F in sludge-amended soils	EPA Method 1613 (HRGC-HRMS)	soil with 7.5% sludge (time 0)	68.1 (dw)	tetra- through octa- CDD/F	primarily hepta- and octa- dioxins		2.43 (dw)	2.4			concentrations were higher in all amended soils no trend was seen for different application types PCDD/F are persistent in amended soils	single application of aerobically digested sludge soil samples were taken 1 year after sludge application quarry samples were taken 4 years after sludge application
					soil with 7.5% sludge (1 year)					2.37 (dw)					
					soil with 15% sludge (time 0)					5.28 (dw)	5.0				
					soil with 15% sludge (1 year)					4.61 (dw)					
					quarry with direct application of 7.5% sludge (time 0)					1.4 (dw)	5.3				
					quarry with direct application of 7.5% sludge (4 years)					12.1 (dw)					
					quarry with soil-sludge mixture 7.5% (time 0)					3.14 (dw)					
					quarry with soil-sludge mixture 7.5% (4 years)					4.24 (dw)					
					quarry with direct application of 15% sludge (time 0)					5.26 (dw)	5.1				
					quarry with direct application of 15% sludge (4 years)					8.50 (dw)					
					quarry with soil-sludge mixture 15% (time 0)					2.56 (dw)					
					quarry with soil-sludge mixture 15% (4 years)					4.24 (dw)					

Reference	Country/ Geo-graphical area	Data collec-tion year	Purpose for sampling	How measured	Sources of material	Sludge conc. (pg TEQ/g)	Congeners measured	Congener/ homolog profile	Number samples (n)	Mean conc. (pg TEQ/g) (SD)	Median (pg TEQ/g)	Range (pg TEQ/g)	Results/ Conclusion	Conclusions/Comments
Eljarrat et al. 1997 Environ Sci Technol 31:2765-71	Spain	1986–1987	to assess effects of PCDD/F & PCB in sludge applied to soil	EPA Method 1613 (HRGC-HRMS)	sludge from watewater treatment plants in urban area in NE Spain (aerobic digestion)	144 (dw)	tetra- through octa- CDD/F	increased concentration with increasing chlorination OCDD predominant	4	4.6 (dw)		2.4–8.6	sludge treated soils had levels 1.2–2.8X (basic soil) and 7.4–11.6X (acid soil) higher than non-sludge soils	2 doses (low: 22–37 pg TEQ/g and high: 43–75 pg TEQ/g) of sludge applied yearly to 2 different soils for 4 consecutive years between 1982-1986 planted with raygrass final samples taken 1 year after last sludge application
McLachlan, Sewart et al. 1996 Environ Sci Techno 30:2567-71	UK	1972, 1976, 1981, 1985, 1990	to determine persis-tence in soil	EPA Method 1613 (HRGC-HRMS)	sludge applied experimentally in 1968	230 (dw)	2,3,7,8-PCDD/F	primarily hepta and octa	5	8.8 (dw)		6.5–13	evidence of long term persistence of PCDD/F in soil (50% of contamination present in 1972 still there in 1990) no difference in persistence between congeners estimated half-life ~20 years	samples were dried and stored until 1993 single application of sludge applied to depth of 15 cm at 125 t dw/ha (with 230 pg/g TEQ)

[1] dw = dry weight

Table 5. PCDD/F levels in root vegetables grown in uncontaminated soil (sorted to show relationship to Table 6).

Reference	Purpose of study	Growing environment	How measured	Congeners measured	Soil conc. (pg TEQ/g)	Soil congener profile	Plant type (part)	N (plant samples)	Mean plant conc. (pg TEQ/g)	Range of plant conc. (pg TEQ/g)	Plant congener profile	Conclusions/ Comments
Muller et al. 1994 Chemosphere 29: 2175-2181	to examine contamination pathways for plants grown in contaminated agricultural soil	field conditions, near former electric wire scrap incinerator	not stated – sent to lab	all	5 (dw)[1]	similar proportion of all congeners	carrots (peel)	1	0.55 (dw)		mostly lower chlorinated furans	all plants washed after harvest
							carrots (cortex)	1	0.27 (dw)			
							carrots (stele)	1	0.32 (dw)			
							carrots (whole)	1	0.35 (dw)			
Prinz et al. 1991 Chemosphere 23: 1743-1761	to develop criteria for dioxins in plants and soils	field conditions (Fredebaum, Germany)	not stated – sent to lab	all	68 (dw)		potato (tuber)		~0.5 (dw)			not known whether plants were washed
							carrot (root)		~0.6 (dw)			
Hulster & Marschner 1993 Chemosphere 27: 439-446	to determine PCDD/F transfer from soils with differing levels of contamination to potato, lettuce, and hay	field conditions, near former electric wire scrap incinerator	not stated – sent to lab	all	4.8	primarily furans mostly higher chlorinated	potato (unpeeled tuber)		~0.2 (dw)		decrease in higher chlorinated congeners	polypropylene fleece used to prevent soil-leaf contact
					4.8		potato (peeled tuber)		~0.1 (dw)		OCDD highest	
Schroll & Scheunert 1993 Chemosphere 26: 1631-1640	to examine uptake pathways by carrots from soil	closed system growing chamber uncontam-inated air	recovery of labeled C14 (mass balance)	OCDD	0	n/a	carrots (roots)	2	<LOD[2]			plants cleaned with water after harvest

[1] dw = dry weight
[2] LOD = limit of detection

Table 6. PCDD/F levels in root vegetables grown in contaminated soil (sorted by increasing soil PCDD/F concentration).

Reference	Purpose of study	Growing environment	How measured	Congeners measured	Source of PCDD/F	Soil conc. (pg TEQ/g)	Soil congener profile	Plant type (part)	N (plant) samples)	Mean plant conc. (pg TEQ/g)	Range of plant conc. (pg TEQ/g)	Plant congener profile	Conclusions/ Comments
Muller et al. 1994 Chemosphere 29: 2175-2181	to examine contamination pathways for plants grown in contaminated agricultural soil	field conditions	not stated – sent to lab	all	contamin-ated soil near former electric wire scrap incinerator	56 (dw)[1]	primarily furans mostly higher chlorinated	carrots (peel)	2	3.08 (dw)	2.86-3.3	mostly lower chlorinated furans	all plants washed after harvest lower chlorinated congeners are more bioavailable >75% is in peel
								carrots (Cortex)	2	0.29 (dw)	0.28-0.3		
								carrots (Stele)	2	0.395 (dw)	0.29-0.5		
								carrots (whole)	2	0.96 (dw)	0.87-1.05		
Prinz et al. 1991 Chemosphere 23: 1743-1761	to develop criteria for dioxins in plants and soils	field conditions (Hafenwiese, Germany)	not stated – sent to lab	all	contamin-ated soil near cable waste incincerator	274 (dw)		potato (tuber)		<LOD[2]			not knownwhether plants were washed soil–plant transfer factor is likely ≤0.1
								carrot (root)		~0.6 (dw)			
		-Field conditions (Westerholz, Germany)				670 (dw)		potato (tuber)		~0.6 (dw)			
								carrot (root)		~2.8 (dw)			
								celery		~0.4 (dw)			
		-Field conditions (Hobertsburg, Germany)				788 (dw)		potato (tuber)		~0.3 (dw)			
								carrot (root)		~2.0 (dw)			
								red beet (tuber)		~0.4 (dw)			

Reference	Purpose of study	Growing environment	How measured	Congeners measured	Source of PCDD/F	Soil conc. (pg TEQ/g)	Soil congener profile	Plant type (part)	N (plant) samples)	Mean plant conc. (pg TEQ/g)	Range of plant conc. (pg TEQ/g)	Plant congener profile	Conclusions/ Comments
Hulster & Marschner 1993 Chemosphere 27: 439-446	to determine PCDD/F transfer from soils with differing levels of contamination to potato, lettuce, and hay to determine effect of post-harvest processing to examine ways to decrease soil-plant transfer	field conditions – polypropylene fleece used to prevent soil-leaf contact	not stated – sent to lab	all	contaminated soil near former electric wire scrap incinerator	112,800 5752 2390 845 **328**	predominantly furans mostly higher chlorinated	potato (unpeeled tuber)		~6.1 (dw) ~2.6 ~1.6 ~1.2 **~0.6**	0.6–6.1	decrease in higher chlorinated congeners	not known whether plants were washed decrease in high chlorinated congeners suggests soil-plant transfer because bioavailability decreases with increasing chlorination
						112,800 5752 2390 845 **328**		(peeled tuber)		~0.1 (dw) ~0.1 ~0.1 ~0.1 **~0.1**	0.1–0.1	OCDD highest	little correlation between soil and plant concentrations
Schroll & Scheunert 1993 Chemosphere 26: 1631-1640	to examine uptake pathways by carrots from soil	closed system growing chamber uncontaminated air	recovery of labeled C14 (mass balance)	OCDD	soil treated experimentally with OCDD	6400 (dw)	OCDD	carrots (roots)	2	4811.1 (dw) 397.8 (fw)[3]	3134.3–6488.5 (dw) 259.1–536.4 (fw)	OCDD	plants cleaned with water after harvest OCDD is taken up by roots of carrots bioconcentration factors of 0.742 (dw) and 0.0615 (fw)

[1] dw = dry weight
[2] LOD = limit of detection
[3] fw = fresh weight

Table 7. PCDD/F levels in plants with edible parts grown above ground grown in uncontaminated soil (sorted to show relationship to Table 8).

Reference	Purpose of study	Growing environment	How measured	Congeners measured	Soil conc. (pg/TEQ/g)	Soil congener profile	Plant type (part)	N (plant samples)	Mean plant conc. (pg TEQ/g)	Range of plant conc. (pg TEQ/g)	Plant congener profile	Conclusions/ Comments
Prinz et al. 1991 Chemosphere 23: 1743-1761	to develop criteria for dioxins in plants and soils	field conditions (Fredebaum, Germany)	not stated – sent to lab	all	68 (dw)[1]		salad		~0.4 (dw)			not known whether plants were washed
							silver beet		~0.3 (dw)			
Muller et al. 1994 Chemosphere 29: 2175-2181	to examine contamination pathways for plants grown in contaminated agricultural soil	field conditions, near former electric wire scrap incinerator	not stated – sent to lab	all	5	similar proportion of all congeners	peas (pods)	1	0.13 (dw)		primarily OCDD & TCDF	all plants washed after harvest
							peas (seeds)	1	<0.01(dw)			
							peas (whole)	1	0.08 (dw)			
Muller et al. 1994 Chemosphere 29: 2175-2181	to examine contamination pathways for plants grown in contaminated agricultural soil	field conditions, near former electric wire scrap incinerator	not stated – sent to lab	all	5	similar proportion of all congeners	lettuce (outer leaves)	1	0.13 (dw)		primarily OCDD & TCDF	all plants washed after harvest
Hulster et al. 1994 Environ. Sci. Technol. 28: 1110-1115	to determine soil-plant uptake of PCDD/F in cucumber family	field conditions	EPA method 1613	all	0.4	primarily OCDD	zucchini (fruits) (pots in contaminated soil)	2	1.0 (dw)	0.9–1.1	primarily lower chlorinated furans and OCDD	plants were not washed
							zucchini (leaves) (pots in contaminated soil)	2	7.3 (dw)	4.4–10.2		
							zucchini (fruits) (pots 1.5 m above contaminated soil)	2	0.6 (dw)	0.5–0.7		

Reference	Purpose of study	Growing environment	How measured	Congeners measured	Soil conc. (pg/TEQ/g)	Soil congener profile	Plant type (part)	N (plant samples)	Mean plant conc. (pg TEQ/g)	Range of plant conc. (pg TEQ/g)	Plant congener profile	Conclusions/ Comments
Hulster & Marschner 1993 Chemosphere 27: 439-446	to determine PCDD/F transfer from soils with differing levels of contamination to potato, lettuce, and hay to determine effect of post-harvest processing	field conditions, near former electric wire scrap incinerator	not stated – sent to lab	all	4.8	primarily furans mostly higher chlorinated	lettuce		~0.2 (dw)		primarily OCDD and TCDFs	polypropylene fleece used to prevent soil-leaf contact
Hulster & Marschner 1993 Chemosphere 27: 439-446	to examine ways to decrease soil-plant transfer to verify role of surface contamination in lettuce to re-examine contamination of hay	field conditions near former incinerator	not stated – sent to lab	all	4.8	primarily furans mostly higher chlorinated	lettuce (whole)		~0.2 (dw)		primarily OCDD and TCDFs	plants grown without polypropylene fleece to prevent soil-leaf contact

[1] dw = dry weight

Table 8. PCDD/F levels in plants with edible parts grown above ground grown in contaminated soil (sorted in order of increasing soil PCDD/F concentration).

Reference	Purpose of study	Growing environment	How measured	Congeners measured	Source of PCDD/F	Mean soil conc. (pg TEQ/g)	Soil congener profile	Plant type (part)	N (plant samples)	Mean plant conc. (pg TEQ/g)	Range of plant conc. (pg TEQ/g)	Plant congener profile	Conclusions/Comments
Prinz et al. 1991 Chemosphere 23: 1743-1761	to develop criteria for dioxins in plants and soils	field conditions (Fredebaum, Germany)	not stated – sent to lab	all	contaminated soil 1.5 km from cable waste incincerator	25 (dw)[1]		silver beet		~3.5 (dw)			not known whether plants were washed leaf vegetable have higher concentrations than root vegetables leafy vegetables take up dioxins from the air with a transfer factor of ≤0.5
Muller et al. 1994 Chemosphere 29: 2175-2181	to examine contamination pathways for plants grown in contaminated agricultural soil	field conditions, near former electric wire scrap incinerator	not stated – sent to lab	all	contaminated soil	56 (dw)	primarily furans mostly higher chlorinated	peas (pods)	1	0.12 (dw)		primarily OCDD	all plants washed after harvest no root uptake or translocation PCDD/F in peas is from atmospheric origin
								peas (seeds)	1	0.04 (dw)			
								peas (whole)	1	0.09 (dw)			
Muller et al. 1994 Chemosphere 29: 2175-2181	to examine contamination pathways for plants grown in contaminated agricultural soil	field conditions, near former electric wire scrap incinerator	not stated – sent to lab	all	contaminated soil	56 (dw)	primarily furans mostly higher chlorinated	lettuce (outer leaves)	2	0.19 (dw)	0.17–0.21	primarily higher chlorinated dioxins	all plants washed after harvest no difference between inner and outer leaves no root uptake or translocation PCDD/F in lettuce is from atmospheric origin
								lettuce (inner leaves)	2	0.25 (dw)	0.2–0.3		
								lettuce (whole)	2	0.21 (dw)	0.21–0.21		
Hulster et al. 1994 Environ. Sci. Technol. 28: 1110-1115	to determine soil-plant uptake of PCDD/F in cucumber family	field conditions	EPA method 1613	all	contaminated soil	148 (dw)	primarily OCDD	pumpkin (outer fruit)	2	11.8 (dw)	11.6–12.0	primarily furans decreasing from tetra- to hexa-	plants were not washed pumpkin mainly contaminated by root uptake and translocation to shoots
								pumpkin (inner fruit)	2	3.25 (dw)	3.1–3.4		
								pumpkin (leaves)	2	3.0 (dw)	2.4–3.6		

Reference	Purpose of study	Growing environment	How measured	Congeners measured	Source of PCDD/F	Mean soil conc. (pg TEQ/g)	Soil congener profile	Plant type (part)	N (plant samples)	Mean plant conc. (pg TEQ/g)	Range of plant conc. (pg TEQ/g)	Plant congener profile	Conclusions/Comments
Hulster et al. 1994 Environ. Sci. Technol. 28: 1110-1115	to determine soil-plant uptake of PCDD/F in cucumber family	field conditions	EPA method 1613	all	contaminated soil	148 (dw)	primarily OCDD	cucumber (outer fruit)	2	2.35 (dw)	2.3–2.4	primarily lower chlorinated furans and OCDD	plants were not washed atmospheric deposition likely means of contamination
								cucumber (inner fruit)	2	0.2 (dw)	0.2–0.2		
								cucumber (leaves)	2	2.7 (dw)	2.0–3.4		
Hulster et al. 1994 Environ. Sci. Technol. 28: 1110-1115	to determine soil-plant uptake of PCDD/F in cucumber family	field conditions	EPA method 1613	all	contaminated soil	148 (dw)	primarily OCDD	zucchini (fruits)	2	20.0 (dw)	19.1–21.0	primarily furans decreasing from tetra to hexa	zucchini mainly contaminated by root uptake and translocation to shoots
								zucchini (no soil-fruit contact)	2	20.5 (dw)	19.4–21.6		
								zucchini (leaves)	2	22.0 (dw)	21.4–22.6		
Prinz et al. 1991 Chemosphere 23: 1743-1761	to develop criteria for dioxins in plants and soils	field conditions (Hansa, Germany)	not stated – sent to lab	all	contaminated soil 1.5 km from former electric wire scrap incinerator	199 (dw)		kale		~7.3 (dw)			not known whether plants were washed leaf vegetable have higher concentrations than root vegetables leafy vegetables take up dioxins from the air with a transfer factor of ≤0.5
		field conditions (Nord, Germany)				200 (dw)		salad		~3.2 (dw)			
								kale		~6.6 (dw)			
		field conditions (Hafenwiese, Germany)				274 (dw)		salad		~4.3 (dw)			
								chive		~6.1 (dw)			
								endive		~2.5 (dw)			
								kale		~6.3 (dw)			
Hulster et al. 1994 Environ. Sci. Technol. 28: 1110-1115	to determine soil-plant uptake of PCDD/F in cucumber family	field conditions	EPA method 1613	all	contaminated soil	328 (dw)	primarily OCDD	zucchini (fruit)	2	17.2 (dw)	17.0–17.4	primarily lower chlorinated furans	plants were not washed zucchini mainly contaminated by root uptake and translocation to shoots
								zucchini (leaves)	2	28.0 (dw)	26.7–29.2		

Reference	Purpose of study	Growing environment	How measured	Congeners measured	Source of PCDD/F	Mean soil conc. (pg TEQ/g)	Soil congener profile	Plant type (part)	N (plant samples)	Mean plant conc. (pg TEQ/g)	Range of plant conc. (pg TEQ/g)	Plant congener profile	Conclusions/Comments
Prinz et al. 1991 Chemosphere 23: 1743-1761	to develop criteria for dioxins in plants and soils	field conditions (Westerholz, Germany)	not stated – sent to lab	all	contamin-ated soil near cable waste incinerator	670 (dw)		salad		~9.2 (dw)			not known whether plants were washed leaf vegetable have higher concentrations than root vegetables leafy vegetables take up dioxins from the air with a transfer factor of ≤0.5
								silver beet		~9.8 (dw)			
								leek		~1.6 (dw)			
								cucumber		~0.8 (dw)			
								bean		~0.6 (dw)			
								plum		~1.1 (dw)			
								strawberry		~0.8 (dw)			
								apple		~1.4 (dw)			
		field conditions (Hobertsburg, Germany)				788 (dw)		salad		~6.6 (dw)			
								silver beet		~7.0 (dw)			
								kohlrabi		~0.3 (dw)			
								savoy		~0.5 (dw)			
								endive		~17.8 (dw)			
								kale		~2.0 (dw)			
Hulster et al. 1994 Environ. Sci. Technol. 28: 1110-1115	to determine soil-plant uptake of PCDD/F in cucumber family	field conditions	EPA method 1613	all	contamin-ated soil	2390 (dw)	primarily hexa- through octa-CDD	zucchini (fruits)	2	54.9 (dw)	54.6–55.2	primarily lower chlorinated furans	plants were not washed zucchini mainly contaminated by root uptake and translocation to shoots
Hulster & Marschner 1993 Chemosphere 27: 439-446	to determine PCDD/F transfer from soils with differing levels of contamination to potato, lettuce, and hay to determine effect of post-harvest processing	field conditions, near former electric wire scrap incinerator	not stated – sent to lab	all	contamin-ated soil	112,800	predominantly furans mostly higher chlorinated	lettuce		~4.2 (dw)		primarily OCDD and TCDFs	polypropylene fleece used to prevent soil-leaf contact
						5752				~1.0			
						2390				~0.7			
						845				~0.3			
						328				~1.3			

Reference	Purpose of study	Growing environment	How measured	Congeners measured	Source of PCDD/F	Mean soil conc. (pg TEQ/g)	Soil congener profile	Plant type (part)	N (plant samples)	Mean plant conc. (pg TEQ/g)	Range of plant conc. (pg TEQ/g)	Plant congener profile	Conclusions/Comments
Hulster & Marschner 1993 Chemosphere 27: 439-446	to examine ways to decrease soil-plant transfer to verify role of surface contamination in lettuce to re-examine contamination of hay	field conditions near former incinerator	not stated – sent to lab	all	contamin-ated soil	5752	predominantly furans mostly higher chlorinated	lettuce (whole)		~1.0 (dw)		primarily OCDD and TCDFs	plants grown without polypropylene fleece to prevent soil-leaf contact contamination of lettuce leaves with soil particles is not major pathway
						2390				~0.7			
						845				~0.4			
						328				~1.4			
Muller et al. 1993 Chemosphere 27: 195-201	to determine transfer from soil to tree fruits	field conditions	not stated – sent to lab	all	contamin-ated soil	448 (topsoil) **48** (subsoil)	primarily OCDD and HxCDF	pear 2 (washed, whole)	1	25 (fw)[2]		primarily higher dioxins and lower furans (peel)	no correlation between soil and plant concentrations peak levels of OCDD major pathway is air-plant
Muller et al. 1993 Chemosphere 27: 195-201	to determine transfer from soil to tree fruits	field conditions	not stated – sent to lab	all	contamin-ated soil	2970 (topsoil) **14530** (subsoil)	primarily lower chlorinated furans	pear 1 (unprocessed, whole)	2	33 (fw)	20–46		no correlation between soil and plant concentrations peak levels of OCDD major pathway is air-plant
								pear 1 (washed, peel)	2	123.5 (fw)	105–142	primarily higher dioxins and lower furans	
								pear 1 (washed, pulp)	2	15 (fw)	8–22		
								pear 1 (washed, whole)	2	36 (fw)	27–45		
								pear 1 (wrapped, whole)	2	14 (fw)	11–17		

Reference	Purpose of study	Growing environment	How measured	Congeners measured	Source of PCDD/F	Mean soil conc. (pg TEQ/g)	Soil congener profile	Plant type (part)	N (plant samples)	Mean plant conc. (pg TEQ/g)	Range of plant conc. (pg TEQ/g)	Plant congener profile	Conclusions/Comments
Schroll & Scheunert 1993 Chemosphere 26: 1631-1640	to examine uptake pathways by carrots from soil	closed system growing chamber uncontaminated air	recovery of labeled C14 (mass balance)	OCDD	treated soil	6400 (dw)	OCDD	carrots (leaves)	2	549.2 (dw) 54.1 (fw)	498.6–599.7 (dw) 49.1–59.1 (fw)	OCDD	plants cleaned with water after harvest volatilization from soil can contaminate leaves bioconcentration factors of 0.085 (dw) and 0.0085 (fw)
								carrots (stem)		2306.2 (dw) 227.6 (fw)	2029.4–2582.9 (dw) 201.0-254.2 (fw)		-OCDD not translocated from roots to shoots -Bioconcentration factors of 0.357 (dw) and 0.0355 (fw)
Muller et al. 1993 Chemosphere 27: 195-201	to determine transfer from soil to tree fruits	field conditions	not stated – sent to lab	all	contaminated soil	7480 (topsoil) 1950 (subsoil)	primarily furans (mostly hexa-)	apple (washed, pulp)	1	8 (fw)		primarily higher dioxins and lower furans (peel)	no correlation between soil and plant concentrations peak levels of OCDD major pathway is air-plant
								apple (washed, peel)	1	46 (fw)			
								apple (washed, whole)	1	14 (fw)			
Hulster & Marschner 1994 Organo-halogen Compounds 20: 31-34	to verify whether zucchini roots release PCDD/F mobilizing substances to the rhizosphere	concentrated root exudates in soil suspensions	not stated – sent to lab	all	experimental contamination	14,530 (dw)	primarily lower chlorinated furans	zucchini root exudates		~0.82 ng TEQ/l solution	primarily lower chlorinated furans		zucchini releases root exudates that can extract PCDD/F congeners from soil, possibly by forming hydrophilic complexes
								tomato root exudates		~0.21 ng TEQ/l solution			
								blank (water)		~0.9 ng TEQ/l solution			

[1] dw = dry weight
[2] fw = fresh weight

Table 9. PCDD/F levels in forage crops grown in uncontaminated soil (sorted to show relationship to Table 10).

Reference	Purpose of study	Growing environment	How measured	Congeners measured	Soil conc. (pg/TEQ/g)	Soil congener profile	Plant type (part)	N (plant samples)	Mean plant conc. (pg TEQ/g)	Range of plant conc. (pg TEQ/g)	Plant congener profile	Conclusions/ Comments
Hulster & Marschner 1993 Chemosphere 27: 439-446	to determine PCDD/F transfer from soils with differing levels of contamination to potato, lettuce, and hay to determine effect of post-harvest processing	field conditions, near former electric wire scrap incinerator	not stated – sent to lab	all	4.8	primarily furans mostly higher chlorinated	hay		~1 (dw)[1]		similar to soil	sand used to prevent soil-leaf contact
Hulster & Marschner 1993 Chemosphere 27: 439-446	to examine ways to decrease soil-plant transfer to verify role of surface contamination in lettuce to re-examine contamination of hay	field conditions	not stated – sent to lab	all	4.8	primarily furans mostly higher chlorinated	herbs (hay)		<LOD[2]		primarily OCDD	clay pebbles used to prevent soil-leaf contact
					4.8		grass (hay)		<LOD			

[1] dw = dry weight
[2] LOD = limit of detection

Table 10. PCDD/F levels in forage crops grown in contaminated soil (sorted in order of increasing soil PCDD/F concentration).

Reference	Purpose of study	Growing environment	How measured	Congeners measured	Source of PCDD/F	Mean soil conc. (pg TEQ/g)	Soil congener profile	Plant type (part)	N (plant samples)	Mean plant conc. (pg TEQ/g)	Range of plant conc. (pg TEQ/g)	Plant congener profile	Conclusions/Comments
Prinz et al. 1991 Chemosphere 23: 1743-1761	to develop criteria for dioxins in plants and soils	field conditions (Hafenwiese, Germany)	not stated – sent to lab	all	contamin-ated soil 1.5 km from former electric wire scrap incinerator	274 (dw)[1]		grass		7.2 (dw)			not known whether plants were washed leaf vegetable have higher concentrations than root vegetables leafy vegetables take up dioxins from the air with a transfer factor of ≤0.5
Prinz et al. 1991 Chemosphere 23: 1743-1761	to develop criteria for dioxins in plants and soils	field conditions (Westerholz, Germany)	not stated – sent to lab	all	contamin-ated soil near cable waste incincerator	670 (dw)		grass	2	6.65 (dw)	5.8–7.5		not known whether plants were washed leaf vegetable have higher concentrations than root vegetables leafy vegetables take up dioxins from the air with a transfer factor of ≤0.5
Prinz et al. 1991 Chemosphere 23: 1743-1761	to develop criteria for dioxins in plants and soils	field conditions (Hobertsburg, Germany)	not stated – sent to lab	all	contamin-ated soil near cable waste incincerator	788 (dw)		grass		9.7 (dw)			not known whether plants were washed leaf vegetable have higher concentrations than root vegetables leafy vegetables take up dioxins from the air with a transfer factor of ≤0.5

Reference	Purpose of study	Growing environment	How measured	Congeners measured	Source of PCDD/F	Mean soil conc. (pg TEQ/g)	Soil congener profile	Plant type (part)	N (plant samples)	Mean plant conc. (pg TEQ/g)	Range of plant conc. (pg TEQ/g)	Plant congener profile	Conclusions/Comments
Hulster & Marschner 1993 Chemosphere 27: 439-446	to determine PCDD/F transfer from soils with differing levels of contamination to potato, lettuce, and hay to determine effect of post-harvest processing	field conditions, near former electric wire scrap incinerator	not stated – sent to lab	all	contamin-ated soil	112,800 5752 2390 845 328	predominantly furans mostly higher chlorinated	hay		~39 (dw) ~6 ~10 ~3 ~4	3–39	similar to soil	contamination by soil particles was primary pathway of transfer sand used to prevent soil-leaf contact
Hulster & Marschner 1993 Chemosphere 27: 439-446	to examine ways to decrease soil-plant transfer to verify role of surface contamination in lettuce to re-examine contamination of hay	field conditions	not stated – sent to lab	all	contamin-ated soil	5752 2390 845 328	predominantly furans mostly higher chlorinated	herbs (hay)		~0.9 (dw) ~0.8 ~0.7 ~0.5	0.5–0.9	primarily OCDD	soil-plant transfer is unlikely because OCDD is least bioavailable congener air-plant transfer exceeds soil-plant transfer clay pebbles used to prevent soil-leaf contact
						5752 2390 845 328		grass (hay)		~0.2 (dw) ~0.1 ~0.2 ~0.1	0.1–0.2		

[1] dw = dry weight

Table 11. Background levels of PCDD/F in food from animal sources (sorted to show relationship to Tables 12 and 13).

Reference	Sample collection year	Purpose of study	How measured	Congeners measured	Food source of PCDD/F	Feeding (exposure) time	Mean food conc. (pg TEQ/g)	Food congener profile	Animal/ Food product	N (tissue) samples)	Mean tissue conc. (pg TEQ/g fat)	Range of tissue conc. (pg TEQ/g)	Animal congener profile	Conclusions/ Comments
Richter & McLachlan 2001 J. Agric. Food Chem. 49: 5857-5865	1994	to gather data on the uptake and transfer of PCDD/Fs by cattle from naturally contaminated feed	mass balance and EPA Method 1613 (HRGC-HRMS)	all	Grass silage from meadow without sewage sludge application ("low levels of PCDD/F")	10 weeks	0.2 (dw)[1]	primarily higher chlorinated PCDDs and Hp- and O-CDF	muscle	2 cows	0.41	0.30–0.51		
									fat		0.47	0.34–0.61	primarily higher chlorinated dioxins	
									liver		6.5	5.1–7.9	primarily higher chlorinated dioxins and OCDF	
									kidney		0.50	0.41–0.58		
Thorpe et al. 2001 Chemosphere 43: 869-879		to determine fate of dosed PCDD/F in non-lactating cattle	GCMS	2378-TCDD, 12378-PeCDD, 123678-HxCDD, 23478-PeCDF, 123478-HxCDF	undosed (control) animals in study using experimen-tally prepared pellets	28 days (testing at 31 weeks)		2378-TCDD, 12378-PeCDD, 123678-HxCDD, 23478-PeCDF, 123478-HxCDF	liver	4 cows	3.9			
									muscle		5.9			
									fat		3.7			
Schecter et al. 1994 Chemosphere 29: 2261-2265		to survey PCDD/F levels in animal foods in New York	GCMS	total PCDD/F					chicken	1	0.03 (ww)[2]	0.03 (ww)		
									beef	4	0.578 (ww)	0.04–1.5 (ww)		
									pork	2	0.165 (ww)	0.03–0.3 (ww)		
									lamb	1	0.4 (ww)	0.4 (ww)		
									dairy	5	0.348 (ww)	0.04–0.7 (ww)		
Fiedler et al. 1997 Chemosphere 34: 1411-1419	1994	to survey PCDD/F levels in animal foods in southern Mississippi, USA	EPA Method 1613	2378-PCDD/F					chicken fat	6	0.7±0.06	0.610–1.31	lower chlorinated	
									beef fat	3	0.67±0.17	0.528–1.1		
									pork/ sausage fat	3	0.74±0.12	0.564–0.866		
									dairy fat	9	0.77±0.10	0.416–0.970	lower chlorinated, dioxins>furans	
									egg fat	3	0.23±0.06	0.176–0.326		

Reference	Sample collection year	Purpose of study	How measured	Congeners measured	Food source of PCDD/F	Feeding (exposure) time	Mean food conc. (pg TEQ/g)	Food congener profile	Animal/ Food product	N (tissue) samples)	Mean tissue conc. (pg TEQ/g fat)	Range of tissue conc. (pg TEQ/g)	Animal congener profile	Conclusions/ Comments
Feil & Ellis 1998 J. Anim. Sci. 76: 152-159		to survey PCDD/F levels in beef	EPA Method 8290	2378-PCDD/F					cattle (perirenal fat)	20	4.1275	0.3341–30.8373		
Winters et al. 1996 Chemosphere 32: 469-478	1993	to survey PCDD/F levels in US beef	EPA Method 1613	2378-PCDD/F					beef back fat	63	0.35 (SE 0.08)	<LOD[3]–3.8	1234678-HpCDD most common 2378-TCDD found in 16% of samples	bulls had 3-10 × higher concentrations than other types of cattle
Fries et al. 1999 Environ. Sci. Technol. 33: 1165-1170		to characterized transport of PCDD/F to milk and tissue	EPA Method 1613A	all	none (controls in experiment with PCP-treated wood)				milk	4 cows	0.315			
McLachlan & Richter 1998 J. Agric. Food Chem. 46: 1166-1172	1994	to gather data on the uptake and transfer of PCDD/Fs by cattle from naturally contaminated feed	mass balance and EPA Method 1613 (HRGC-HRMS)	All	Grass silage from meadow without sewage sludge application ("low levels of PCDD/F")	12 weeks	0.2 (dw)	primarily higher chlorinated PCDDs and Hp- and O-CDF	milk (whole)	4 cows	0.015 (whole milk)	0.010–0.02 (whole milk)		

[1] dw = dry weight
[2] ww = wet weight
[3] LOD = limit of detection

Table 12. PCDD/F levels in tissue from animals consuming contaminated feed or feed grown on sludge-amended land (sorted in order of increasing feed PCDD/F concentration).

Reference	Purpose of study	How measured	Congeners measured	Food source of PCDD/F	Feeding (exposure) time	Mean food conc. (pg TEQ/g)	Food congener profile	Animal/ Food product	N (tissue) samples)	Mean tissue conc. (pg TEQ/g fat)	Range of tissue conc. (pg TEQ/g fat)	Animal congener profile	Conclusions/ Comments
Jilg et al. 1992 Agrobiological Research 45: 303-310	to determine the influence of feed on the contamination of milk	described else-where		hay grown in contamin-ated soil (mean soil conc. = 1944 pg TEQ/g dw)	19 weeks	2 (range 0.5–8.7)		plasma	4 cows	1.95	0.8–4.1		
								fat	4 cows	1.1	0.6–2.8		
								muscle	4 cows	1.75	1.3–2.8		
Richter & McLachlan 2001 J. Agric. Food Chem. 49: 5857-5865	to gather data on the uptake and transfer of PCDD/Fs by cattle from naturally contaminated feed	mass balance and EPA Method 1613 (HRGC-HRMS)	all	grass silage from meadow with repeated sewage sludge applications	17 days	3.2 (dw)	primarily higher chlorinated PCDDs and hepta- and octa-CDF	muscle	2 non-lactating cows	0.70	0.54–0.91		cows had not been dry long enough for much PCFF/F to accumulate in the tissues (feeding time in this study was short relative to kinetic behaviour of the contaminants)
								fat		0.64	0.49–0.79	primarily higher chlorinated dioxins	
								liver		20.5	17.0–24.0	primarily higher chlorinated dioxins and OCDF	
								kidney		0.74	0.61–0.86		
Jensen et al. 1981 J. Agric. Food Chem. 29: 265-268	to determine distribution of TCDD in edible tissues and to determine the rate of dissipation of TCDD from fat	EPA Method 1613 (HRGC)	TCDD	experimen-tally contamin-ated feed	28 days	24 ± 5	TCDD	cow fat	7 cattle	84	66-95	TCDD	average fat concentration 50 days after feeding ceased was 11.25 pg/g dissipation half-life estimated to be 16.5±1.4 weeks (elimination constant of 0.042±0.0003 week^{-1})
								cow liver		8.2	7-10		
								kidney		7	6-8		
								muscle		2	2		
Thorpe et al. 2001 Chemosphere 43: 869-879	to determine fate of dosed PCDD/F in non-lactating cattle	GCMS	2378-TCDD, 12378-PeCDD, 123678-HxCDD, 23478-PeCDF, 123478-HxCDF	experimen-tally prepared pellets	28 days (testing at 31 weeks)	~41.3 (330,000 pg TEQ/day (total dose 9,240,000 pg TEQ))	2378-TCDD, 12378-PeCDD, 123678-HxCDD, 23478-PeCDF, 123478-HxCDF	liver	4 cows	118.5			concentrations were higher at 5 weeks (plateau at about 18 weeks) concentration found in edible tissue may be higher than in fat deposits half-lives range from 93–148 days
								muscle		57.3			
								fat		27.2			

Reference	Purpose of study	How measured	Congeners measured	Food source of PCDD/F	Feeding (exposure) time	Mean food conc. (pg TEQ/g)	Food congener profile	Animal/ Food product	N (tissue) samples)	Mean tissue conc. (pg TEQ/g fat)	Range of tissue conc. (pg TEQ/g fat)	Animal congener profile	Conclusions/ Comments
Jones et al. 1989 Chemosphere 18: 1257-1263	to compare bioavailability of 2,3,7,8-TCDD from grain or soil	recovery of tritiated TCDD	2,3,7,8-TCDD	single oral dose in grain	1 dose	~3557 (0.05 ug TCDD/kg body weight)	2,3,78-TCDD	cow fat	2	105	80–130	2,3,7,8-TCDD	~13% of dose was secreted in milk within 2 weeks
				or soil						155	130–180		

Table 13. PCDD/F levels in milk from animals consuming contaminated feed or feed grown on sludge-amended land (sorted in order of increasing feed PCDD/F concentration).

Reference	Purpose of study	How measured	Congeners measured	Food source of PCDD/F	Feeding (exposure) time	Mean food conc. (pg TEQ/g)	Food congener profile	Animal/ Food product	N (tissue) samples)	Mean tissue conc. (pg TEQ/g fat)	Range of tissue conc. (pg TEQ/g fat)	Animal congener profile	Conclusions/ Comments
Fries et al. 1999 Environ. Sci. Technol. 33: 1165-1170	to characterize transport of PCDD/F to milk and tissue	EPA Method 1613A	all	PCP-treated wood	58 days	0.289 (dw)[1]	primarily higher chlorinated PCDD/F	milk	4 cows	5.518		lower chlorinated congeners had higher bioconcentration factors	
McLachlan et al. 1994 Environ. Pollut. 85: 337-343	to determine the influence of sewage sludge on concentrations of PCDD/Fs and PCBs in soil, feed, and milk	EPA Method 1613 (GCMS)	tetra- through hexa-CDD/F (true TEQ expected to be 25% higher for soil and feed, and 3% higher for milk fat)	regular fertilization (30 years) with digested sewage sludge (mean conc. = 34 and 38 pg TEQ/g dw (LS and HS, respectively) max 5 t dw sludge/ hectare every 3 years	6 months	0.22 dw (H0) (9.25 in soil-probably from atmospheric deposition) 0.35 dw (HS) (3.4 in soil) 0.19 dw (L0) (2.1 in soil) 1.2 dw (LS) (7.5 in soil)	high ratio of 1,2,3,6,7,8-HxCDD to 1,2,3,4,7,8-HxCDD indicates non-combustion sources (especially in LS farm)	milk	12 cows 36 samples	1.3 (H0) 1.2 (HS) 0.9 (L0) 2.3 (LS)	0.7-2.6	HS had high ratio of 1,2,3,6,7,8-HxCDD to 1,2,3,4,7,8-HxCDD	cows did not graze H=high milk production L=low milk production 0=no sludge S=sludge application higher levels found in cows on fist calving than cows with multiple calves use of sludge as fertilizer can increase PCDD/F in food under some conditions
Jilg et al. 1992 Agrobiological Research 45: 303-310	to determine the influence of feed on the contamination of milk	described else-where		hay grown in contamin-ated soil (mean soil conc. = 1944 pg TEQ/g dw)	19 weeks	2 (range 0.5–8.7)		milk (weeks 1–19)	4 cows	1.88	0.8–3.0		no significant correlations between milk fat and tissue fat no clear plateau of excretion was observed
								milk (weeks 20–28)	3 cows	1.13	0.6–2.1		

Reference	Purpose of study	How measured	Congeners measured	Food source of PCDD/F	Feeding (exposure) time	Mean food conc. (pg TEQ/g)	Food congener profile	Animal/ Food product	N (tissue) samples)	Mean tissue conc. (pg TEQ/g fat)	Range of tissue conc. (pg TEQ/g fat)	Animal congener profile	Conclusions/ Comments
McLachlan & Richter 1998 J. Agric. Food Chem. 46: 1166-1172	to gather data on the uptake and transfer of PCDD/Fs by cattle from naturally contaminated feed	mass balance and EPA Method 1613 (HRGC-HRMS)	all	grass silage from meadow with repeated sewage sludge applications	17 days	3.2 (dw)	primarily higher chlorinated PCDDs and hepta- and octa-CDF	milk (whole)	4 cows	0.049 (day 23) (whole milk)	0.031-0.069 (day 23) (whole milk)		
McLachlan et al. 1990 Chemosphere 20: 1013-1020	to determine PCDD/F fluxes in and out of a cow	MS	2378-PCDD/F isomers and 1234679-HpCDD	grain feed	n/a	6.9		milk	1 cow (6 milk samples)	1.39		decrease in transfer to milk with increasing K_{ow} (increasing chlorination)	20% of all toxic equivalents are excreted in milk (25–30% of most toxic congeners—2378-TCDD, 12378-PCDD, 23478-PCDF—are transferred to milk)

[1] dw = dry weight

Table 14. Selected regulations for PCDD/F concentrations in land-applied biosolids and agricultural soil.

Jurisdiction	Act Name	Regulation	Unit Conversion	Basis/Rationale	Reference
Canada	Interim Remediation Criteria for Soil – PCDD and PCDFs	agricultural soil: 10 pg TEQ/g	10 pg TEQ/g soil		CCME, 1991
Canada		land applied biosolids: 27 ppt unrestricted use 100 ppt restricted use	 27 pg TEQ/g biosolids 100 pg TEQ/g biosolids		CH2M Hil, 2001
Canada (British Columbia)	Waste Management Act: Contaminated Sites Regulation, BC Reg. 375/96 (Schedule 5)	matrix numerical soil standards: polychlorinated dioxins and furans (PCDDs and PCDFs) agricultural land: 0.00035 mg/g	350 pg TEQ/g soil	human health protection from inadvertent intake of contaminated soil	Government of BC, 2000
USA	Standards for the Use or Disposal of Biosolids (40 CFR Part 503)	300 pg TEQ/g in biosolids that are land applied	300 pg TEQ/g biosolids	proposed	EPA 1999
Germany		Maximum 100 ng TEQ/kg for dioxins in biosolids applied to agricultural land; maximum application rate of 5 t (dw) over 3 years	100 pg TEQ/g biosolids		McLachlan, Sewart et al., 1996

Table 15. Potential change in PCDD/F concentration in root vegetables when grown in different soil concentrations.

Soil PCDD/F concentration (pg TEQ/g)[1]	Potato tuber concentration (pg TEQ/g dw)	Upper 95% confidence limit—potato tuber (pg TEQ/g dw)	Carrot root concentration (pg TEQ/g dw)	Upper 95% confidence limit—carrot root (pg TEQ/g dw)
x	y = 0.0004x + 0.3291*	y = [0.0004 + (1.96)(0.000063)]x + [0.3291 + (1.96)(0.1331)]	y = 0.0027x + 0.3283*	y = [0.0027 + (1.96)(0.000608)]x + [0.3283 + (1.96)(0.2469)]
1	0.33	0.59	0.33	0.82
5	0.33	0.59	0.34	0.83
10	0.33	0.60	0.36	0.85
15	0.34	0.60	0.37	0.87
30	0.34	0.61	0.41	0.93
160	0.39	0.67	0.76	1.43
230	0.42	0.71	0.95	1.71
1250	0.83	1.24	3.70	5.68

[1] Soil concentration values are intended to represent the following potential scenarios:

- 1–10 pg TEQ/g is the typical range in sludge-amended agricultural soil;
- 15 pg TEQ/g represents the maximum concentration reported in sludge-amended soil (McLachlan & Reissinger 1990);
- 30 pg TEQ/g represents the maximum mean concentration reported in soil (not sludge-amended) (Broman et al. 1990);
- 160 pg TEQ/g is the maximum value reported in soil (not sludge-amended) (Creaser et al. 1989);
- 230 pg TEQ/g represents the maximum mean concentration reported in non-archived sewage sludge samples (McLachlan et al. 1996);
- 1250 pg TEQ/g is the maximum concentration reported in non-archived sludge samples (Telliard et al. 1990).

* Regression coefficient significant at $p < 0.05$.

Table 16. Potential change in PCDD/F concentration in vegetables with edible parts grown above ground, when grown in different soil concentrations.

Soil PCDD/F concentration (pg TEQ/g)[1]	*Cucurbiticeae* concentration (pg TEQ/g dw)	Upper 95% confidence limit—*Cucurbiticeae* (pg TEQ/g dw)	Leafy vegetables concentration (pg TEQ/g dw)	Upper 95% confidence limit—leafy vegetables (pg TEQ/g dw)
x	y = 0.0192x + 5.447*	y = [0.0192 + (1.96)(0.00503)]x + [5.447 + (1.96)(4.242)]	y = 0.00422x + 2.102	y = [0.00422 + (1.96)(0.00255)]x + [2.102 + (1.96)(1.292)]
1	5.47	13.79	2.11	4.64
5	5.54	13.91	2.12	4.68
10	5.64	14.05	2.14	4.73
15	5.74	14.20	2.17	4.77
30	6.02	14.63	2.23	4.91
160	8.52	18.41	2.78	6.11
230	9.86	20.44	3.07	6.75
1250	29.45	50.08	7.38	16.16

[1] Soil concentration values are intended to represent the following potential scenarios:

- 1–10 pg TEQ/g is the typical range in sludge-amended agricultural soil;
- 15 pg TEQ/g represents the maximum concentration reported in sludge-amended soil (McLachlan & Reissinger 1990);
- 30 pg TEQ/g represents the maximum mean concentration reported in soil (not sludge-amended) (Broman et al. 1990);
- 160 pg TEQ/g is the maximum value reported in soil (not sludge-amended) (Creaser et al. 1989);
- 230 pg TEQ/g represents the maximum mean concentration reported in non-archived sewage sludge samples (McLachlan et al. 1996);
- 1250 pg TEQ/g is the maximum concentration reported in non-archived sludge samples (Telliard et al. 1990).

* Regression coefficient significant at $p < 0.05$.

Table 17. Potential change in PCDD/F concentration in tree fruits when grown in different soil concentrations.

Soil PCDD/F concentration (pg TEQ/g)[1]	Tree fruits concentration (pg TEQ/g fw)	Upper 95% confidence limit—tree fruits (pg TEQ/g fw)
x	y = 0.00159x + 21.05	y = [0.00159 + (1.96)(0.00185)]x + [21.05 + (1.96)(20.10)]
1	21.05	60.45
5	21.06	60.47
10	21.07	60.50
15	21.07	60.52
30	21.10	60.60
160	21.30	61.28
230	21.42	61.65
1250	23.04	66.97

[1] Soil concentration values are intended to represent the following potential scenarios:

- 1–10 pg TEQ/g is the typical range in sludge-amended agricultural soil;
- 15 pg TEQ/g represents the maximum concentration reported in sludge-amended soil (McLachlan & Reissinger 1990);
- 30 pg TEQ/g represents the maximum mean concentration reported in soil (not sludge-amended) (Broman et al. 1990);
- 160 pg TEQ/g is the maximum value reported in soil (not sludge-amended) (Creaser et al. 1989);
- 230 pg TEQ/g represents the maximum mean concentration reported in non-archived sewage sludge samples (McLachlan et al. 1996);
- 1250 pg TEQ/g is the maximum concentration reported in non-archived sludge samples (Telliard et al. 1990).

* Regression coefficient significant at $p < 0.05$.

Table 18. Potential change in PCDD/F concentration in forage crops when grown in different soil concentrations.

Soil PCDD/F concentration (pg TEQ/g)[1]	Hay concentration (pg TEQ/g dw)	Upper 95% confidence limit—hay (pg TEQ/g dw)	Herb concentration (pg TEQ/g dw)	Upper 95% confidence limit—herbs (pg TEQ/g dw)
x	y = 0.00079x + 3.331	y = [0.00079 + (1.96)(0.000703)]x + [3.331 + (1.96)(1.979)]	y = 0.00011x + 0.3757	y = [0.00011 + (1.96)(0.00006)]x + [0.3757 + (1.96)(0.1690)]
1	3.33	7.21	0.38	0.71
5	3.33	7.22	0.38	0.71
10	3.33	7.23	0.38	0.71
15	3.33	7.24	0.38	0.71
30	3.33	7.27	0.38	0.71
160	3.33	7.56	0.38	0.74
230	3.33	7.71	0.38	0.76
1250	3.33	9.92	0.38	0.99

[1] Soil concentration values are intended to represent the following potential scenarios:

- 1–10 pg TEQ/g is the typical range in sludge-amended agricultural soil;
- 15 pg TEQ/g represents the maximum concentration reported in sludge-amended soil (McLachlan & Reissinger 1990);
- 30 pg TEQ/g represents the maximum mean concentration reported in soil (not sludge-amended) (Broman et al. 1990);
- 160 pg TEQ/g is the maximum value reported in soil (not sludge-amended) (Creaser et al. 1989);
- 230 pg TEQ/g represents the maximum mean concentration reported in non-archived sewage sludge samples (McLachlan et al. 1996);
- 1250 pg TEQ/g is the maximum concentration reported in non-archived sludge samples (Telliard et al. 1990).

* Regression coefficient significant at $p < 0.05$.

Table 19. Potential change in PCDD/F concentration in animal tissue when consuming contaminated feed.

Feed PCDD/F concentration (pg TEQ/g)[1]	Tissue concentration (pg TEQ/g dw)	Upper 95% confidence limit—animal tissue (pg TEQ/g dw)
x	y = 1.458x*	y = [1.458 + (1.96)(0.278)]x
0.1	0.1	0.2
0.2	0.3	0.4
0.3	0.4	0.6
0.4	0.6	0.8
0.5	0.7	1.0
1.0	1.5	2.0
2.0	2.9	4.0
3.0	4.4	6.0
4.0	5.8	8.0
5.0	7.3	10.0
10.0	14.6	20.0
25.0	36.5	50.1
41.0	59.8	82.1

[1] Soil concentration values are intended to represent the following potential scenarios:

- 1–10 pg TEQ/g is the typical range in sludge-amended agricultural soil;
- 15 pg TEQ/g represents the maximum concentration reported in sludge-amended soil (McLachlan & Reissinger 1990);
- 30 pg TEQ/g represents the maximum mean concentration reported in soil (not sludge-amended) (Broman et al. 1990);
- 160 pg TEQ/g is the maximum value reported in soil (not sludge-amended) (Creaser et al. 1989);
- 230 pg TEQ/g represents the maximum mean concentration reported in non-archived sewage sludge samples (McLachlan et al. 1996);
- 1250 pg TEQ/g is the maximum concentration reported in non-archived sludge samples (Telliard et al. 1990).

***** Regression coefficient significant at $p < 0.05$.s