Long-range Air Transport of Dioxin from North American Sources to Ecologically Vulnerable Receptors in Nunavut, Arctic Canada

Executive Summary

Introduction

The picture that most North Americans have of the Arctic—a pristine, snowy wilderness, sparsely peopled and unpolluted—is unfortunately not completely accurate. Although there are few pollution sources in the region itself, it is on the receiving end of emissions from sources far to the south that are transported over long distances by the prevailing air currents.

This study, commissioned by the North American Commission for Environmental Cooperation (NACEC) and conducted by the Center for the Biology of Natural Systems (CBNS), set out to model on a continental scale the rates of deposition of airborne dioxin (polychlorinated dibenzo-p-dioxins and polychlorinated dibenzofurans, PCDD/PCDF) in the new Canadian polar territory of Nunavut and to identify the major contributing North American sources.

The modeling effort detailed in this report is a response to the evidence that Nunavut is especially vulnerable to the long-range air transport of dioxin.[1] Although there are no significant sources of dioxin in Nunavut or within 500 kilometers of its boundaries, dioxin concentrations in Inuit mothers' milk are twice the levels observed in southern Quebec. This is due to the elevated dioxin content of the indigenous diet—traditional foods such as caribou, fish and marine mammals.

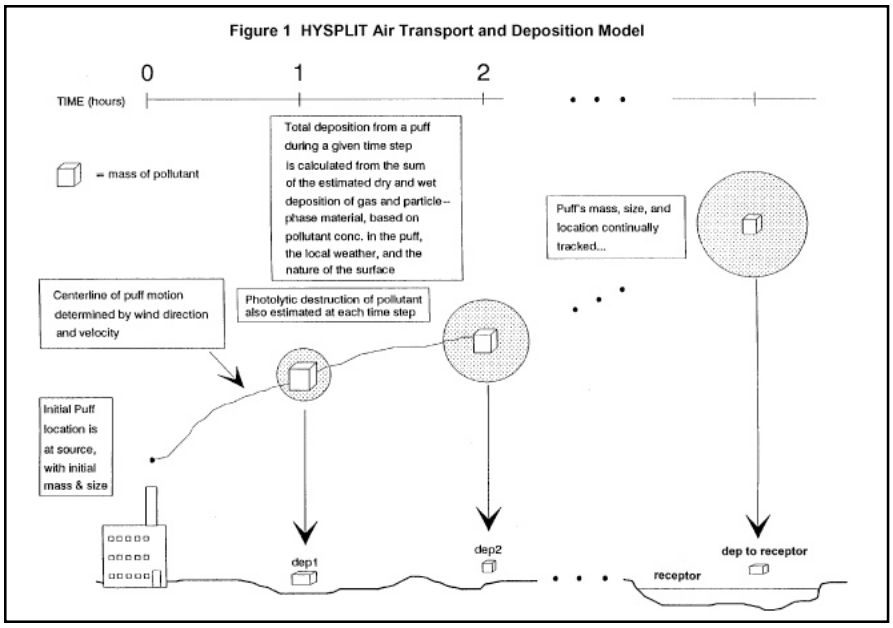
The data generated by this project directly support the conclusion that the known occurrence of dioxin in Nunavut—in the indigenous population, in the regional food chains, and in marine and terrestrial ecosystems—is due to the deposition of airborne dioxin transported from distant sources, which are chiefly in the United States, to a lesser extent in Canada, and marginally in Mexico. These results show that employing air transport modeling is an effective means of estimating the relative rates of dioxin deposition among the Nunavut receptors and of ranking the contribution of the numerous sources to that deposition.

Human exposure to dioxin is almost entirely (98 percent) through animal foods, especially those that are rich in fat. Dioxin is known to enter the food chain from the air. In temperate climates, it is taken up by animal food crops and hence appears in milk and beef, which in the United States account for about two-thirds of the diet-mediated exposure. In the Arctic, dioxin enters the major terrestrial (caribou) food chain chiefly through lichen, mosses and shrubs; dioxin enters the marine (seal, walrus) food chain chiefly through algae. Since these avenues of entry into the food chains cannot be protected from airborne pollutants, remedial measures must be directed at the sources that emit dioxin into the air. Hence, the need for relating dioxin emissions from the sources to the amounts deposited on such ecologically vulnerable receptors.

Methodology

This project was designed to assess the efficacy of the HYSPLIT (Hybrid Single-particle Lagrangian Integrated Trajectory) air transport model as a means of ranking North American sources of airborne dioxin with respect to their contribution to the amount of airborne dioxin deposited on Nunavut receptors. The model estimated the amount of the dioxin emitted by each source at its geographical location (designated by latitude and longitude) that is deposited at each of a series of receptor sites in Nunavut over a one-year period, 1 July 1996–30 June 1997, the latest year for which comparable data were available from Canada and the United States.[2] The model assumes that the dioxin is emitted as four-gram "puffs" at four-hour intervals from each source and tracks their location and dioxin content, which are recorded at one-hour intervals (using NOAA meteorological data) (see Figure 1). When the puff overlaps the receptor area, the model records the amount deposited, thus providing estimates of the amount of the dioxin emitted from each of the 44,091 North American sources that is deposited at each of

[1] This report does not seek to address the question of whether past or current dioxin exposure rates in Nunavut constitute a threat to human health or the environment. It is worth noting, however, that the body burden of dioxin in the general populations of the United States and Canada reflects an average level of exposure associated with a lifetime cancer risk several hundred times greater than the generally "acceptable" one-in-a-million level generally adopted by the US EPA.



Nunavut receptors, it has produced significant information about critical source-receptor relationships, among them the following:

Of the total North American annual emissions of airborne dioxin (see Figure 2), 4,713 grams TEQ, Canadian sources account for 364 grams TEQ, US sources for 2,937 grams TEQ, and Mexican sources for 1,412 grams TEQ. Emissions from sources within Nunavut total 0.12 grams TEQ annually. (TEQ, or Toxicity Equivalent Quotient, is a measure of the overall toxicity of the dioxin and furan congeners, commonly grouped as "dioxin," based on their individual car-

the 16 Nunavut receptor sites. These are contiguous terrestrial and marine areas at each of eight sites.

Source emissions were derived from national Canadian and US inventories that were obtained from Environment Canada and US EPA respectively, to which were added data on backyard trash burning and several point source classes. Since the Mexican environmental agency, the *Instituto Nacional de Ecología* had not yet developed a dioxin inventory, with their cooperation a provisional inventory was assembled that accounts for most of the likely emissions.

Findings

Since the model is designed to estimate the amount of dioxin emitted from each of the numerous sources that is deposited on each of the

[2] Given that the emission data are now a few years old, it should be apparent that some of the sources may have reduced their dioxin emissions in the interim in response to new regulations in both Canada and the United States. However, this in no way alters the fundamental validity of the modeling approach used.

Figure 2: Geographic Distribution of Annual Dioxin Emission from North American Sources, 1996/97

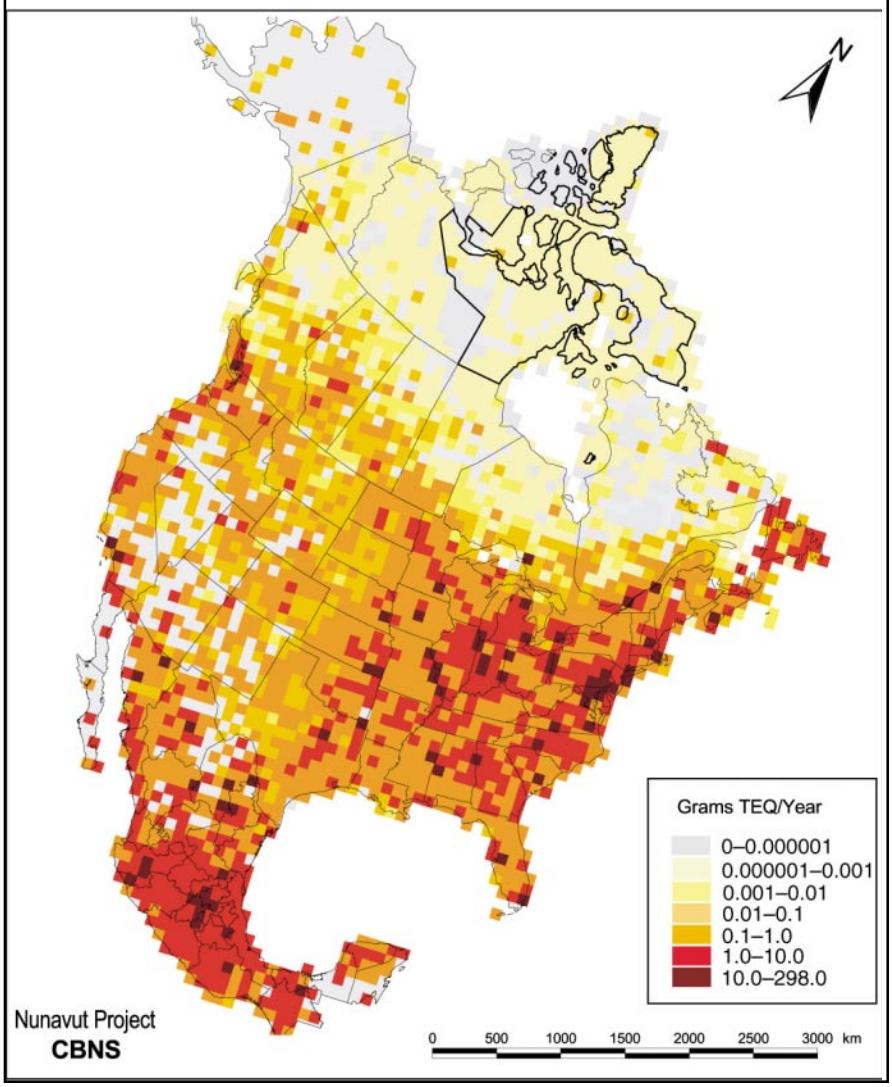


Figure 2: This map was prepared by creating a 100x100 km North American grid and summing up the annual emissions from all sources within each grid zone. Each grid zone is color-coded to indicate the total emissions.

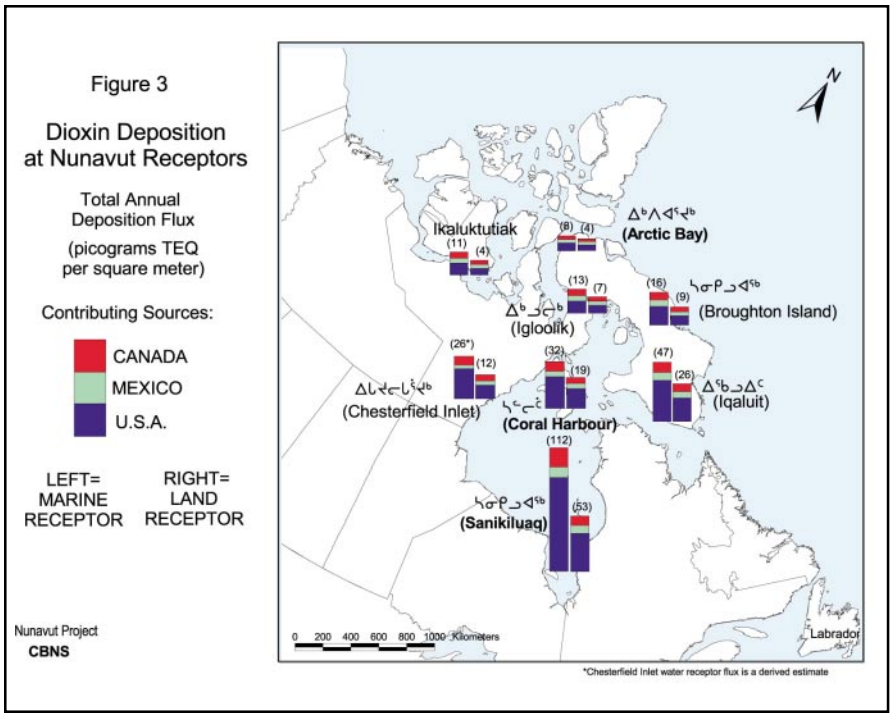


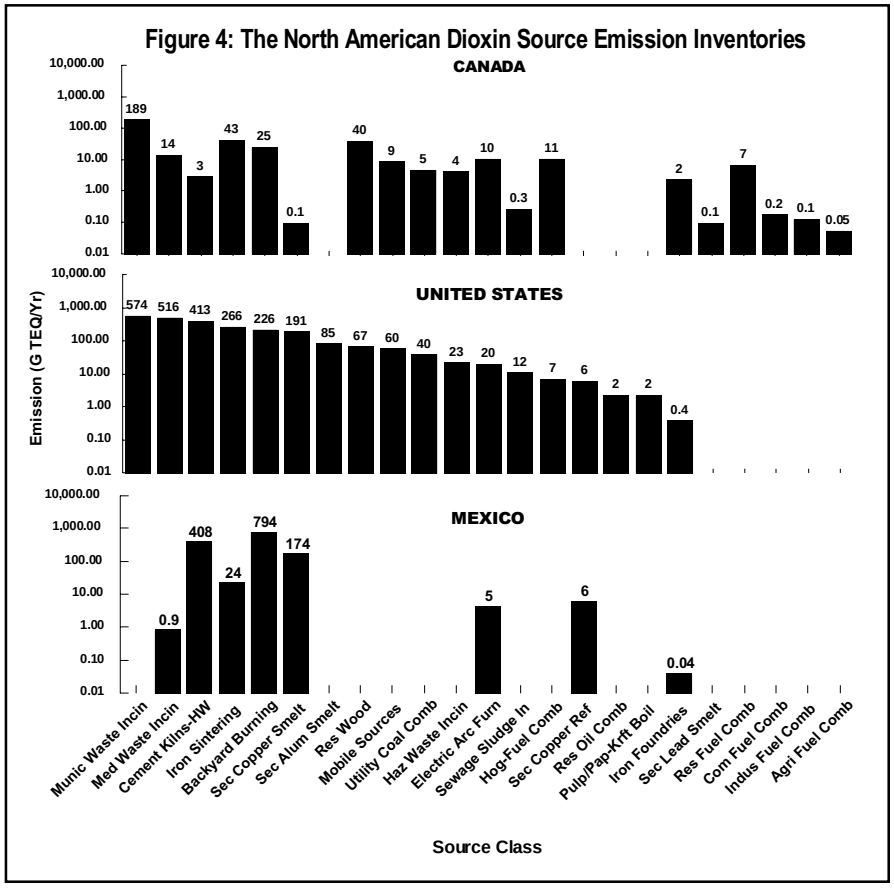
Figure 3: The heights of the bars are representative of the annual deposition flux at the adjacent marine and land receptors at each of the Nunavut sites. Deposition flux (picograms TEQ per square meter) values are in parentheses.

cinogenic potency relative to that of the most potent congener, 2,3,7,8-TCDD.)

The dioxin sources within Nunavut are responsible for only a very small fraction of the airborne dioxin that is deposited on Nunavut. For example, based on the modeled estimates of deposition at a typical land receptor, Broughton Island, the total dioxin deposition flux from all North American Sources is 8.90 picograms TEQ per square meter, of which Nunavut sources account for only 0.01 picograms TEQ per square meter, or 0.11 percent. An estimate of this ratio, more broadly based on deposition at all eight land receptors (although more approximate) yields a similar result. Based on the geographic distribution of the model-estimated deposition flux at the eight Nunavut land receptors (see Figure 3), the total annual deposition on the Nunavut area (land plus water), two million km^2, is approximately 37 grams TEQ. Hence, even if *all* of the dioxin emitted by local sources (0.12 grams TEQ) were deposited on Nunavut, it would represent only 0.32 percent of the amount deposited from all North American sources. The exposure of the Nunavut environment to airborne dioxin is therefore almost entirely due to outside sources. A preliminary estimate shows that the amount of the deposited dioxin that originates from sources outside North America is between 2 and 20 percent of the total deposition in Nunavut. In effect, the North American sources outside of Nunavut are responsible for almost all of the dioxin deposited on that territory.

The model's estimates of the amounts of dioxin deposited at each of the Nunavut receptors, which are shown in Figure 3, reveal considerable geographic variation. The deposition flux (picograms TEQ of dioxin per square

Figure 4: The Canadian dioxin source inventory is based on one prepared for 1997 by Environment Canada, except for the inventory for backyard burning, which was prepared by CBNS. The US inventory is based on one prepared for 1995 by US EPA, updated to 1996/97 by CBNS, with added inventories for backyard burning, iron sintering plants, and several metallurgical processes. The Mexican inventory was prepared by CBNS, based on data provided by the Instituto Nacional de Ecología *(INE) and commercial sources.*



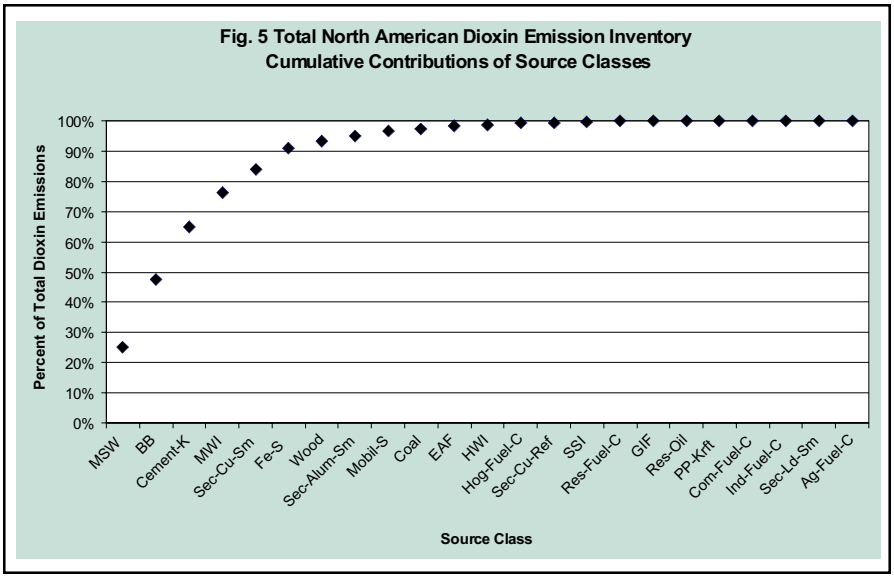


Figure 5: In this plot the emission values for all North American sources, in each source class, are ranked by their respective contributions to the total North American dioxin emission inventory.

meter) at the southernmost receptor, Sanikiluaq, is about 10 times greater than it is at the most northern receptor, Arctic Bay, which is about 1500 km more distant from the intense sources in the United States. Marine receptors uniformly receive more deposition than adjacent terrestrial receptors because dioxin is more efficiently deposited onto water than land.

Because of its source-to-receptor tracking capability, the HYSPLIT model can identify the major contributing sources responsible for the dioxin deposited at each of the receptor areas. Overall, the greatest contribution to dioxin deposition in Nunavut is due to US sources: 70–82 percent, depending on the receptor. Canadian sources contribute 11–25 percent, and Mexican sources five to ten percent. Moreover, only a very small percentage of the total source inventory is responsible for most of the dioxin deposition. For example, at a typical land receptor, Coral Harbour, only 19 sources (four ten-thousandths of the inventory) are responsible for 35 percent of the deposition. Of those 19 sources, 17 are located in the United States and two are located in Canada.

The North American national dioxin inventories include a total of 44,091 sources, of which 5,343 are individual facilities such as trash-burning incinerators, and 38,748 are area sources such as backyard trash-burn-

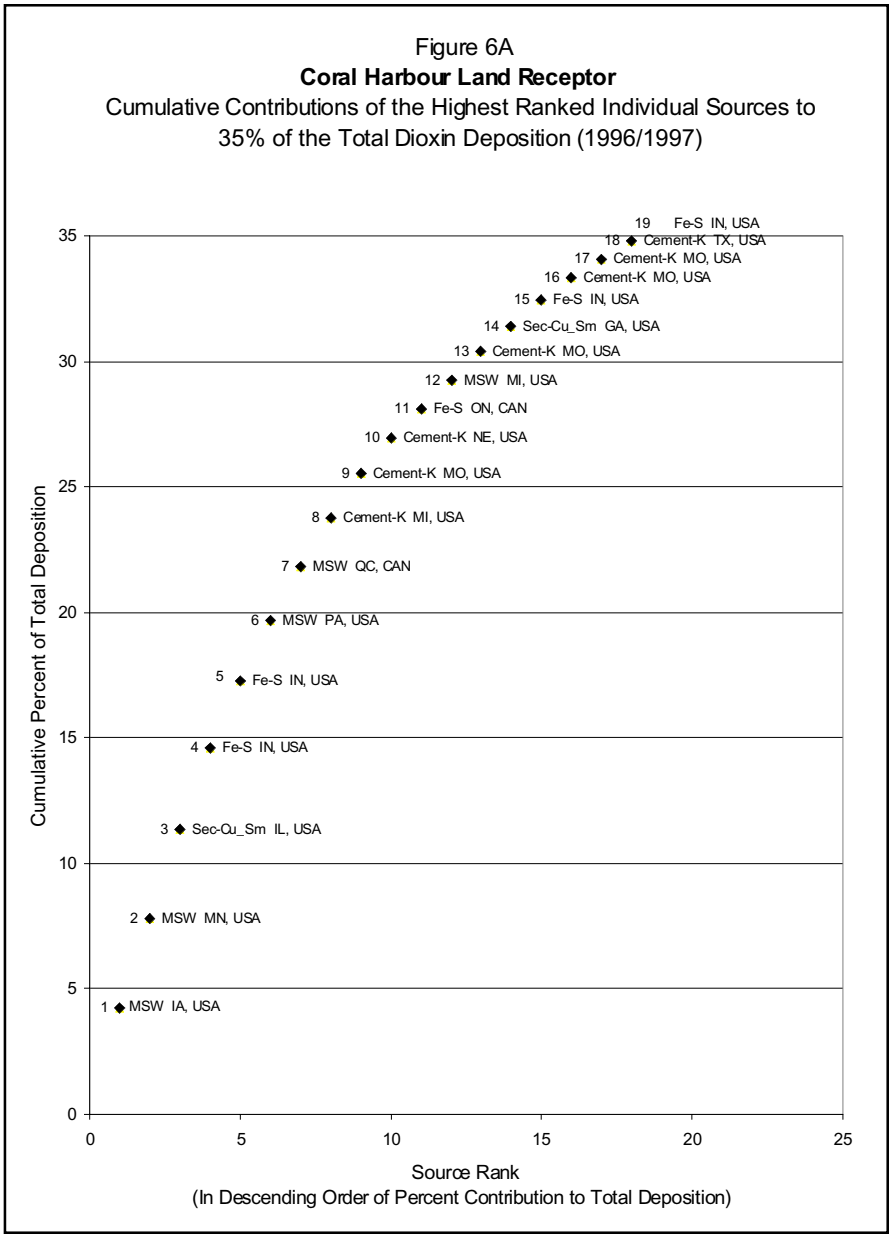


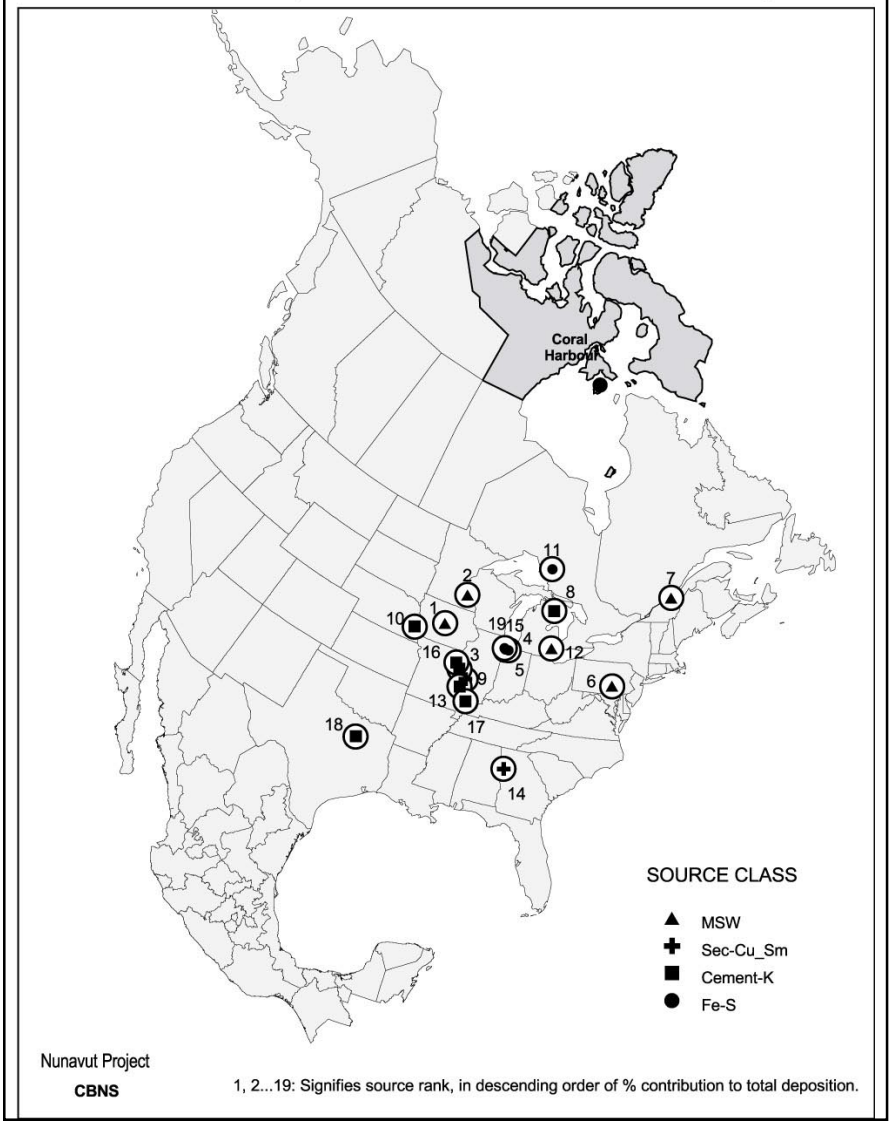
Figure 6A: The individual sources, identified by state and county, are plotted, in descending order, according to their percentile contribution to the total annual dioxin deposition at the Coral Harbour land receptor. Together, these sources account for 35% of the total deposition at the receptor.

ing in a US county or a Mexican municipality. As shown in Figure 4, these sources fall into 23 classes. Only three of these classes—municipal waste incinerators, backyard trash burning, and cement kilns burning hazardous waste—account for two-thirds of the total dioxin emission, and only six classes account for 90 percent of the total emissions (see Figure 5). Only a very small proportion of the 44,091 North American sources accounts for most of the dioxin deposited at the Nunavut receptors. For example, at a typical land receptor, Coral Harbour, 0.04 percent of the sources account for 35 percent of the total deposition, 0.15 percent account for 50 percent of the total deposition, 1.54 percent account for 75 percent of the deposition, and 6.87 percent for 90 percent of the deposition.

The data generated by the air transport model can be used to rank the individual dioxin sources with respect to the amounts that *each* of them contributes to the dioxin deposited at *each* of the receptors. Consequently, the few individual sources that are responsible for most of the deposition can be identified by ranking the entire list of sources with respect to their contribution to the amount of dioxin deposited at the receptor. The 19 highest-ranked individual sources that contribute to 35 percent of the dioxin deposited at the Coral Harbour land receptor are identified in Figures 6A and 6B. The six highest-ranked sources are in the eastern half of the United States: three are municipal waste incinerators, two are iron sintering plants, and one is a secondary copper smelter. The highest-ranking Canadian source (7th) is a municipal waste incinerator in Quebec. (However, this reflects its status in 1996–97; since then, modifications have significantly reduced the facility's emissions and consequently its deposition ranking as well.) No Mexican sources appear in the top 35 percent. The highest-ranked Mexican sources are a secondary copper smelter (31st), an iron sintering plant (40th) and a cement kiln burning hazardous waste (41st).

Figure 6B

Highest-Ranked Individual Sources That Contribute to 35% of Total Dioxin Deposition at Coral Harbour Land Receptor



The amount of airborne dioxin deposited on Nunavut receptors depends on the amount emitted from the sources and the efficiency with which the emitted dioxin is transported to the receptor. The efficiency factor, the Air Transport Coefficient (ATC), is expressed as the fraction of a unit amount emitted from the source that is deposited on the receptor. Consequently:

Deposition Flux at Receptor = Emission from Source x **ATC**

In turn, ATC depends on the source-receptor distance and on the weather pattern en route. The emission data for each of the sources provided by the dioxin inventory and the deposition flux data generated by the model for each of the receptors have been used to analyze the effect of each of the three factors—i.e., emission, source-receptor distance, and weather pattern en route.

Figure 6B: The locations of the 19 highest-ranked sources, accounting for 35% of the total deposition at the receptor. The numbers indicate the source ranking with respect to its percentile contribution to deposition.

Figure 7 Dioxin Emissions and Deposition as a Function of the Distance of Sources from Selected Nunavut Land Receptors

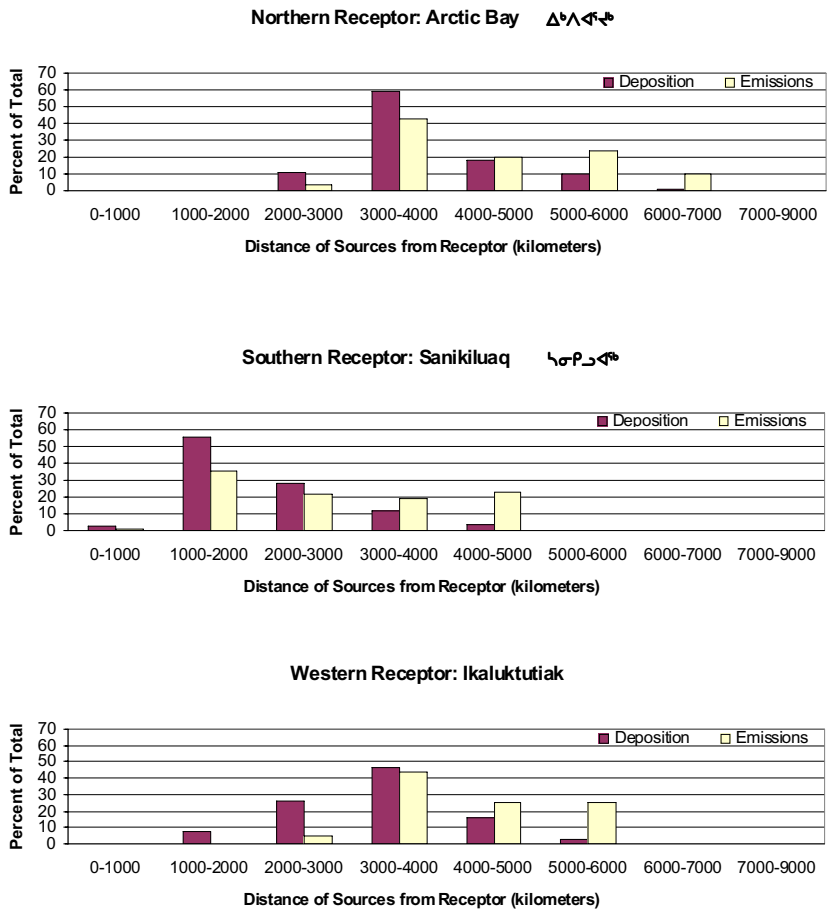


Figure 7: These data were prepared by segregating the total inventory of sources into a series of 1000-km concentric zones with respect to their increasing distance from the indicated receptor. The bars represent, as a percent of their total values, the emissions of all sources within each concentric zone and their relative contribution to the total deposition flux at the receptor.

The distance between the dioxin sources in the total North American inventory and several representative receptors is shown in Figure 7. In each case there are virtually no emissions from sources less than 1000 km from the receptor. Except for Sanikiluaq, the southernmost receptor, most of the sources are 3000 or more kilometers distant. Figure 7 also shows that the efficiency of source-to-receptor transport, as evidenced by the ratio of emission to deposition, decreases sharply with source-receptor distance.

The geographic distribution of the Air Transport Coefficient can be mapped by computing the ratio, deposition/emission, for each group of sources located within a pattern of 100x100 km grids. Figure 8 compares such ATC maps for the two receptors that differ most in their amounts of dioxin deposition flux—Sanikiluaq and Arctic Bay (53 picograms TEQ per square meter and 4 picograms TEQ per square meter at their land receptors, respectively). Comparison of these maps with the geographic distribution of emissions (see Figure 2) serves to explain the difference in deposition. At Sanikiluaq, relatively high ATC values, $5x10^{-15}$ or more (i.e., high transport efficiency) extend over the entire area of the United States. For that reason, the very intense dioxin emissions, especially from the eastern half of the United States, are efficiently transported to Sanikiluaq, resulting in the high deposition flux level. In contrast, the $5x10^{-15}$ ATC zone for transport to Arctic Bay barely reaches into the US high emission area. There is efficient air transport to Arctic Bay from western Canada, but since that area has relatively few, small sources, little dioxin is carried to the receptor and deposition is low.

The effect of only the weather pattern on dioxin deposition at the receptor can be singled out by examining variations in the ATC map with time (of the three factors that influence deposition—source emissions, source-receptor distance, and the weather pattern—only the latter varies with time). Figure 9 shows the successive monthly ATC maps for the Ikaluktutiak land receptor, together with the monthly model-estimated deposition values. Nearly half of the total annual dioxin deposition (4.5 picograms TEQ per square meter) occurs in only two months, September and October. In comparison with the rest of the year, these months are characterized by weather patterns that efficiently carry dioxin from the area of intensely emitting US sources to Ikaluktutiak.

The available evidence, though limited, suggests that the estimated levels of airborne dioxin deposited at the Nunavut receptors may significantly affect the levels of dioxin in the Nunavut food chain. Fortuitously, an earlier study had been made of dioxin content in the tissue of caribou in herds at locations adjacent to several of the Nunavut receptors, which, according to the project results, exhibit an east-to-west (declining) gradient in deposition (see Figure 3). There is

Figure 8

Annual Dioxin Deposition Air Transport Coefficients to Arctic Bay & Sanikiluaq Land Receptors

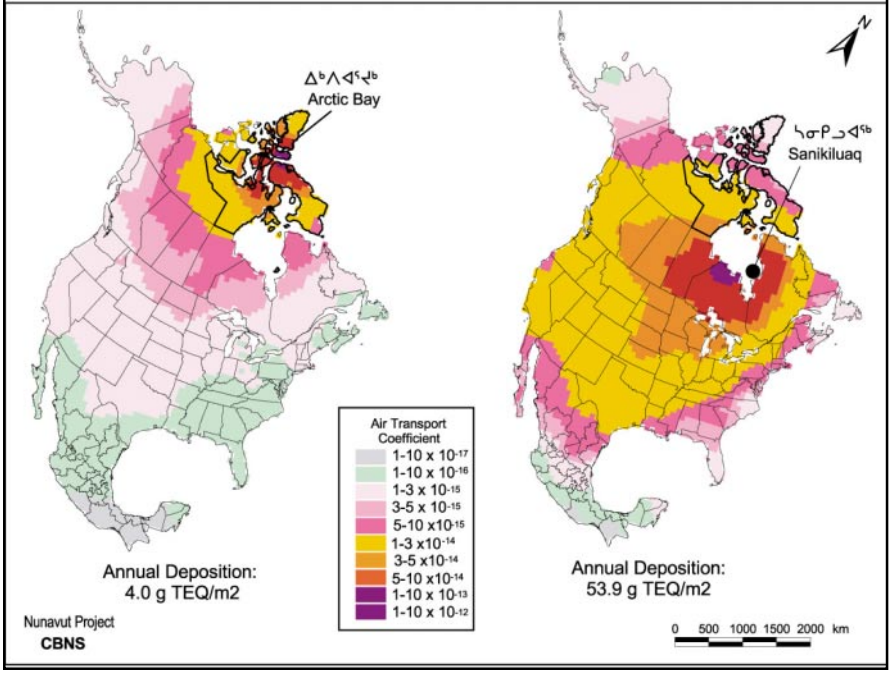


Figure 8: The maps represent the geographic distribution of the ratio: deposition at receptor/source emission, i.e., the Air Transport Coefficient (ATC). The model estimated the deposition, at the given receptor, of the fraction of a unit amount of dioxin (one gram) emitted from each of the 2,988 "sources" created by the same 100x100 km grid that was used to map the actual source emissions shown in Figure 2. Modeled estimates are for the one-year project period.

a comparable gradient in the dioxin levels in the caribou of the nearby herds. This suggests that the differences in the dioxin content of the local biota reflect comparable differences in the level of airborne dioxin deposited at the adjacent receptors.

Policy Considerations

The foregoing observations and conclusions are relevant to several current policy issues. If the levels of dioxin exposure are judged to be a threat to human health and environmental quality, then the basic goal of environmental policy is to remedy this hazard by reducing or, preferably, eliminating exposure. Since there is no feasible way to protect food chains from the deposition of airborne dioxin, such a remedy must be directed at the sources. Alternatively, human exposure can be reduced by avoiding foods containing animal fat—a recourse that, certainly in Nunavut, would clash with the transcendent importance of the indigenous diet in Inuit culture. Consequently, if remedial action is to be taken, the Inuit face the daunting task of defining and implementing a policy that would act effectively on the dioxin emissions

Figure 9

Monthly Dioxin AirTransport Coefficients & Deposition Flux (pg TEQ/m2) to Ikaluktutiak Land Receptor (July 1996-June 1997)

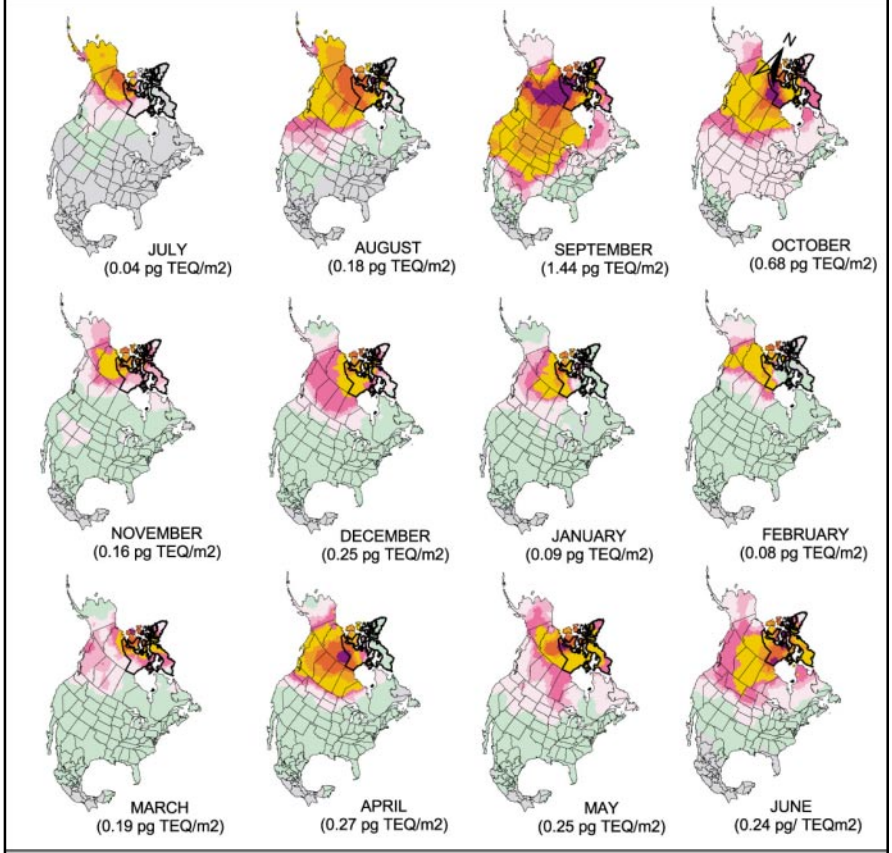


Figure 9: These maps were prepared in the same manner as Figure 8, except that the modeled values are for the separate successive months of the one-year project period. The July deposition value is low and does not represent a full month of activity. This is because the project period began on 1 July 1996 and, especially for the most distant sources, up to three weeks is required for dioxin to reach the receptors.

produced, collectively, by 44,091 sources, nearly all of them thousands of kilometers away in other jurisdictions.

The magnitude of this problem is considerably reduced by the basic finding that the preponderance of the airborne dioxin deposited in Nunavut originates from an extremely small fraction of the sources. Remedial action directed toward these major sources can be guided by strategic policies. One of these is based on the regulatory approach common to most countries' environmental agencies: standards of allowable emissions are set for different source classes (e.g., municipal waste incinerators). In this case, exposure to deposited dioxin could be addressed, for example at Coral Harbour, by calling for more rigorous standards that could virtually eliminate emissions from only three classes of US sources (municipal and medical waste incinerators, and cement kilns burning hazardous waste); this would reduce current exposure at Coral Harbour by 49 percent. In general, based on such data, developed for each of the receptors, Nunavut remedial policy could be targeted toward those relatively few source class/country categories that offer the best return in remedial action for the effort made to accomplish it.

An alternative approach to remedial policy can be directed toward specific individual sources rather than classes of sources subject to national regulations. Such a direct appeal to the operators of a particular facility and/or the people of the local community has the advantage of avoiding the intricacies and delays inherent in international—and even national—administrative actions. Thus, in the example of Coral Harbour, total exposure to deposited dioxin could be reduced by 35 percent if only 19 individual sources—most of them in the United States—could be induced to virtually eliminate their emissions.

Conclusion

It is believed that this project is the first effort to describe source-to-receptor dioxin air transport on a continental scale, and its results are therefore particularly relevant to the proposed United Nations Treaty on Persistent Organic Pollutants, of which dioxin is a major component. By demonstrating the feasibility of tracking airborne dioxin from enumerated sources to specific receptors on a continental scale, the results provide a useful methodological infrastructure suitable to the international policies that the Treaty negotiations seek to develop. For example, the finding that secondary copper smelters and cement kilns burning hazardous waste in Mexico and Texas are among the top dioxin contributors to deposition in the Arctic indicates that these sources are likely to deposit dioxin at much higher rates in the US-Mexican border area. It is likely, therefore, that the US sources are exposing Mexican dairy farms—and the milk they produce—to dioxin and that Mexican sources have a similar effect on Texas dairy farms. Such instances of transboundary toxic contamination of an essential food emphasize the importance of the proposed treaty.

These results reinforce the precept that, given the difficulties of compiling source inventories and the limited resources available for this purpose, especially in developing countries, it would be helpful to establish a common set of priorities to guide this task. Thus, quite workable inventories can be restricted to the six to eight classes that comprise the preponderant source emissions. Together with the assembly of a common database of confirmed emission factors, this approach could considerably simplify the development of useful dioxin source emission inventories. Experience in assembling a preliminary inventory of dioxin sources in Mexico suggests that informal burning of domestic waste (i.e., "backyard trash burning") may be the single most important source of airborne dioxin in developing countries.

In sum, the results of this project confirm that the atmospheric and ecological processes that carry airborne dioxin from its numerous sources, through terrestrial and marine food chains, to human beings, is a problem of continental, if not global, dimensions. To meet this challenge, analytical methods and remedial policies must be established on that scale as well.

For more information...

The full report, *Long-range Air Transport of Dioxin from North American Sources to Ecologically Vulnerable Receptors in Nunavut, Arctic Canada,* by Barry Commoner, Paul Woods Bartlett, Holger Eisl and Kimberly Couchot of the Center for the Biology of Natural Systems (CBNS), Queens College, City University of New York, in its original language (English) is available electronically on the NACEC web site <http://www.cec.org> or from: North American Commission for Environmental Cooperation, 393, rue Saint-Jacques Ouest, Bureau 200, Montréal (Québec) H2Y 1N9 Canada, Tel: (514) 350-4300; Fax: (514) 350-4319; E-mail: info@ccemtl.org