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

Final Report to the
North American Commission for Environmental Cooperation

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The North American Commission for Environmental Cooperation (NACEC) was established by Canada, Mexico and the United States to help build cooperation among the NAFTA partners in the protection of their shared environment, with a particular focus on the opportunities and challenges presented by continent-wide free trade.

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Finally, we are grateful to the Inuit, who, through the extraordinary efforts of the Tungavik Federation of Nunavut to establish Nunavut, created as well the *Nunavut Atlas*, which as been an essential aid to our work.

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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.

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[2] 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 model assumes that the dioxin is emitted as four-gram "puffs" at four-hour intervals from each

[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 U.S. EPA.

[2] Copies of the full report in its original language (English) are available from the NACEC Secretariat.

source and tracks their location and dioxin content, which are recorded at one-hour intervals (using NOAA meteorological data) (see Figure 2.1). 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 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 U.S. inventories that were obtained from Environment Canada and U.S. 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 Nunavaut 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 3.9), 4,713 grams TEQ, Canadian sources account for 364 grams TEQ, U.S. 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 carcinogenic potency relative to that of the most potent congener, 2,3,7,8-TCDD.)

The dioxin sources within Nunavut are responsible for only a 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 3.1), 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 percent 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 3.1, reveal considerable geographic variation. The deposition flux (picograms TEQ of dioxin per square 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 U.S. 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-burning in a U.S. county or a Mexican municipality. As shown in Figure 2.6, 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 2.7). 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 Figure 3.6D. 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 (7^{th}) 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.) The highest-ranked Mexican sources are a secondary copper smelter (31^{st}), an iron sintering plant (40^{th}) and a cement kiln burning hazardous waste (41^{st}).

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.

The distance between the dioxin sources in the total North American inventory and several representative receptors is shown in Figure 3.4. 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 3.4 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 3.12 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 3.9) 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 U.S. 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 3.15A 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 U.S. 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 3.1). There is 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.

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 the HYSPLIT air transport model 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.

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 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 two alternative 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 U.S. 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 U.S.-Mexican border area. It is likely, therefore, that the U.S. 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.

1. Introduction

Recent studies have detected increased levels of dioxin and other persistent organic pollutants in the indigenous population, Inuit in particular, in the polar region of North America. Although only minimal sources occur in the region, dioxin has been detected in the Inuit territory, Nunavut, in major land-based (caribou) and marine (ringed seal, polar bear) food chains (Jensen *et al.* 1997, 200-219; Herbert *et al.* 1996, 195-204; Norstrom *et al.* 1990, 66:1-19). Dioxin concentrations in Inuit mothers' milk are twice the levels observed in southern Quebec (Jensen *et al.* 1997, 352), an apparent consequence of the dioxin content of the indigenous diet. That diet is rich in animal fat, in which dioxin tends to concentrate.

The term "dioxin" is commonly applied to a group of 210 substances dioxin (polychlorinated dibenzo-p-dioxin and polychlorinated dibenzofuran, PCDD/PCDF), similar in their molecular structure but which differ in the number and arrangement of their chlorine atoms. Certain individual members of the group, or congeners, have similar biological effects, which include increased incidence of cancer and damage to the development of the endocrine, immune and nervous systems. Only 17 of the 210 possible dioxin congeners are toxic, and these differ considerably in their potency. The toxic potency of the dioxin congeners is commonly expressed in terms of Toxicity Equivalency Factor (TEF), i.e., the toxic potency (with respect to carcinogenicity) of a given congener relative to that of 2,3,7,8-tetrachloro-dibenzo-p-dioxin (2,3,7,8-TCDD), which is the most toxic congener in this respect. The overall toxicity of a mixture of congeners can be expressed quantitatively by using their respective TEFs to compute the amount of 2,3,7,8-TCDD that is equivalent in its toxicity to that of the mixture. This quantity is expressed as the Toxic Equivalent Quotient (TEQ). Dioxin congeners are not produced intentionally. However, they are frequently produced when chlorinated organic substances, for example chlorine-containing plastics, are burned or when chlorine is present in any combustion process.

It is now known that dioxin is readily airborne at the source and is then spread by advection, dispersion and diffusion, becoming deposited *en route*. It is also known that human exposure to dioxin is almost entirely (98 percent) through animal food, especially fat (U.S. EPA, 1994), and that airborne dioxin enters such food chains via plant life (CBNS and NEEPC, 1998). In the Arctic, the avenue of entry to the major land-based food chain is chiefly lichen, mosses and shrubs; dioxin enters the marine food chain through algae, which flourish in early spring when sunlight begins to penetrate the sea ice in arctic waters.

Since there is no way to protect lichen or marine algae from airborne dioxin, preventive action must be directed to the distant sources that emit it. For that purpose, the sources must be identified and their separate impacts on these ecological receptors estimated. Moreover, since the sources are very numerous (there are more than 5,000 individual point sources of dioxin in the United States and Canada), they must be ranked with respect to their contribution to the contamination level at the receptors. Remedial action can then be directed to the relatively few sources that are the major contributors.

While measurements of the concentrations of airborne pollutants in the ecological receptors, food chain components, and people are essential to the establishment of levels of exposure, such data

do not identify the sources. However, this goal can be approached by using an air transport model to track the pollutant from each of the sources to the receptors. There is a need, therefore, to determine how such a model can identify the sources at which remedial measures will be most effective in reducing exposure in the Arctic, by ranking them with respect to their contribution to the dioxin deposited on the receptors.

The foregoing considerations serve to define the purpose of this project. It is designed to test the efficacy of the HYSPLIT air transport model, as a means of ranking the North American sources of airborne dioxin with respect to their contribution to the amount of dioxin deposited on ecologically vulnerable receptors in the Inuit territory, Nunavut.

2. Procedures

2.1 Temporal Considerations

The design of this project is governed by certain unavoidable constraints regarding the time periods to which several types of data and analytical operations apply. First, it should be noted that although with respect to levels of exposure, the time period of greatest interest is the current one, the requisite data are not concurrently available. In particular, the development of the necessary inventories of dioxin emission sources is a time-consuming process, creating an unavoidable lapse between the assembly of the database and its use. Thus, once the inventory is completed and in use, changes—for example, modifications in sources' emissions control systems—are likely to occur that only later become known. An additional time constraint affects the operation of the air transport model, which can only be run *after* the necessary weather data have been collected and entered into it.

In this project, the new set of global weather data used in the model HYSPLIT-4 began in July 1996, so that the resulting analysis of the air transport of the dioxin emitted by the sources annually necessarily pertained to the period July 1, 1996 through June 30, 1997. We therefore endeavored to establish Canadian, U.S. and Mexican source inventories that also pertained to this period of time. An inventory available from Environment Canada (1999) that characterized the status of sources in 1997 was suitable for this purpose. In the case of Mexico, it was necessary to assemble an inventory *de novo* and it was designed to cover 1996-1997. The only existing inventory available for the United States, assembled by U.S. EPA, was based on conditions in 1995. However, in connection with an earlier project (CBNS/NEECP, 1998) we had modified this inventory with respect to major source classes such as municipal and medical waste incinerators and cement kilns, to reflect their status in 1996. Finally, in this connection it should be noted that there was an unusually high incidence of changes in operational status in these source classes during the project period. This was chiefly due to the establishment of more stringent EPA emission regulations for these major source classes.

2.2 The Air Transport Model

The model used in this study is the latest version of the HYSPLIT (Hybrid Single-particle Lagrangian Integrated Trajectory) air transport model originally developed by the National Oceanic and Atmospheric Administration (NOAA) to track the movement of inorganic radionuclides, which CBNS had earlier adapted to dioxin (CBNS, 1995). For the purpose of the

Nunavut project, NOAA kindly supplied us with the latest version, HYSPLIT-4, which is designed to operate with NOAA's global meteorological archive, and therefore covers all of North America from the southern border of Mexico to the North Pole. Dr. Mark Cohen at NOAA shared with us his latest adaptations of HYSPLIT-4 to organic trace pollutants. The NOAA archive incorporates meteorological data for a three-dimensional grid 190x190 km apart horizontally, with 14 atmospheric layers vertically (up to 12,000 meters), tabulated at six-hour intervals. Ekaterina Radeva, of Environment Canada, kindly prepared daily snow depth and ice cover data on a 1°x1° grid and the NOAA 190 km x 190 km grid. Since our U.S./Canadian source inventory applies to 1996, with some 1997 updates, and the NOAA global weather data are only available since July 1996, we have chosen July 1, 1996 through June 30, 1997 as the project's study year.

The model computes the transport, degradation and deposition of material emitted by a source at a given geographical location (designated by latitude and longitude), by estimating the atmospheric behavior of the emitted material, typically in the form of discrete "puffs." In this project the dioxin generated by each source was assumed to be emitted as four-gram puffs at four-hour intervals over the one-year study period (see Figure 2.1). Thus, 2,190 puffs were emitted from each source; they were tracked and their location and dioxin content recorded at one-hour intervals until the dioxin concentration reached negligible levels. The original puffs are split into multiple puffs when they disperse over more than one computational grid and are tracked individually. The computational time necessary to model these processes is strongly affected by the number of puffs being tracked, for each puff's movement and behavior must be calculated separately. The model includes algorithms that calculate the rates of degradation of dioxin congeners (largely through reaction with OH radicals) as affected by solar flux, cloud cover and season, and that also calculate rates of deposition at designated receptors in wet and dry conditions.

The model was run with 105 standard (hypothetical) source points suitably distributed in Mexico, the United States and Southern Canada (see Figure 2.2). These runs estimated, for each standard point, the fraction of a unit amount (one gram) of emitted dioxin that is deposited at each of the receptors (i.e. the Air Transport Coefficient, ATC). The runs were carried out for each of four representative congeners, and a separate program ("Transfer Coefficient," TRANSCO, developed earlier by Dr. Mark Cohen, then at CBNS) was then used to interpolate from these results the ATC values for the remaining array of 17 toxic dioxin congeners and eight homolog groups. TRANSCO also includes a spatial interpolation program, which estimated the ATC values for the numerous *actual* sources from the values of the four nearest standard points and their geographic orientation relative to the receptor. These actual ATC values multiplied by the actual source emissions given by the inventory predicted the amounts of the dioxin emitted from each of the actual sources that are deposited at each of the receptors.

The HYSPLIT-3 dioxin air transport model has been evaluated by comparison with month-long dioxin measurements at three sites in Vermont and Connecticut in August/September 1996 (CBNS/NEEPC, 1998). Dr. Cohen has compared HYSPLIT-4 with those measurements and with

Figure 2.1 HYSPLIT Air Transport and Deposition Model

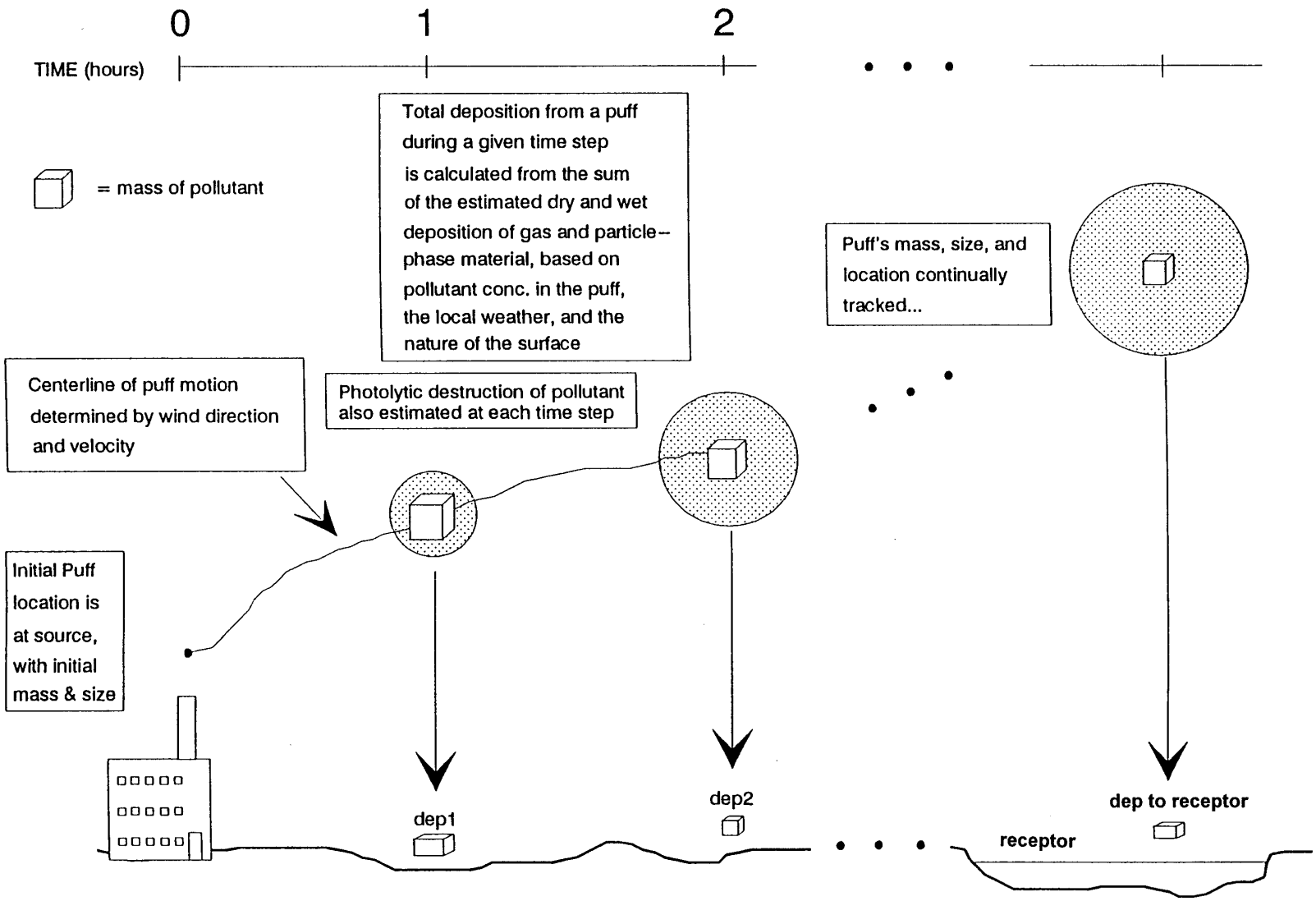
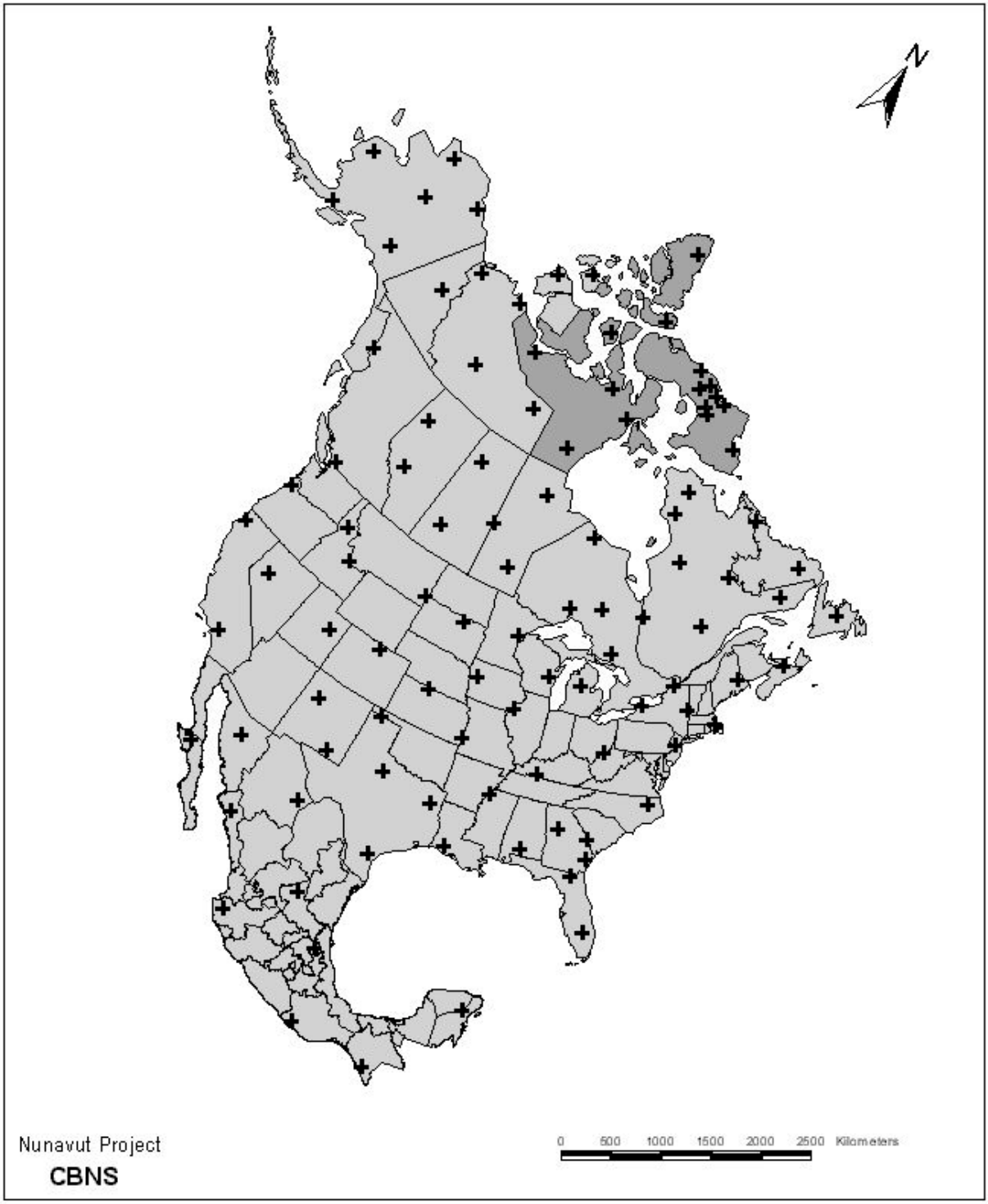


FIG. 2.2 STANDARD (HYPOTHETICAL) SOURCE POINTS



measurements in Nova Scotia and New Brunswick made by Environment Canada. These evaluations of the model are presented in the Appendix.

The question of the feasibility of applying the HYSPLIT model to airborne dioxin transport to Nunavut from the rest of North America, the purpose of the project, raised several major issues that have not been encountered in earlier studies.

- The study area is more than twice as large as that encountered in our previous studies. As a result of the extended area and time of air transport, which can be as much as two weeks from sources in Mexico, emission tracking times are extended, requiring more computation time. This factor, together with the very large number of sources (44,098), creates very large data files, complicating processing, analysis and quality control.
- Since the model operated over a large range of latitudes, adjustments in the model were needed to accommodate the considerable seasonal changes, for they significantly affect deposition and degradation. For example, seasonal changes dramatically affect the nature of ground cover and therefore the efficiency of deposition. Snow cover increases the receptivity of tundra to deposition by covering bare ground and rocks, which are resistant to deposition, with the receptive surface of snow. Extensive ice coverage results in less deposition to marine receptors than to open water. Snow scavenging is more effective than rain in removing organic pollutants, due to snowflakes' larger surface area. Destruction of dioxin by hydroxyl radical and photochemical reactions is greatly affected by solar angle and flux, which are very different in the Arctic than they are in lower latitudes.

The issues raised by arctic conditions and longer range transport for HYSPLIT modeling, and modifications made in order to resolve them, are discussed in further detail in the Appendix.

2.2.1 Computer runs

The computer runs have been optimized with respect to processing time, the size of the input/output files and accuracy of results. In practice this depends largely on the number of standard source points, computational grid, timing factors, computer algorithm efficiency, and number of puffs to be kept track of. Test runs were carried out to determine the effect of the number of puffs tracked and length of the time step on the accuracy of results and running time. In the present project, we carried out a one-year run for each of the 105 standard points, for each of the four selected congeners, a total of 420 runs.

2.3 Inventories

2.3.1 Requirements

For use with the air transport model, the geographic location (latitude and longitude) and the rate of dioxin emission for each known source are essential. However, apart from the relatively few facilities for which actual dioxin emission measurements are available, emission is estimated from capacity or throughput data and an appropriate emission factor. The latter is derived from the available emission measurements and ideally takes into account the influence of the facility's operational characteristics and type of air pollution control system. Typically the emission factor is expressed as annual amount of dioxin emitted per ton of throughput. Because of the

considerable uncertainty involved in this procedure, the emission factors and hence the emission rates are estimated as high and low values, which generally may range up to two orders of magnitude. As a result, this same range affects the modeled estimates of dioxin deposition. This report is based on mid-point values. The full ranges of key parameters are given in the Appendix.

Certain sources cannot be localized because they are mobile (e.g., diesel trucks) or are too numerous to be individually identified (e.g. backyard trash burners). In these cases, emission estimates are based on the estimated number of sources in a convenient unit area, and their collective location is represented by the area centroid. Examples of the dioxin emissions from such area-based sources are the total emissions of diesel trucks operating in a given U.S. county, or the emissions from the estimated amount of backyard trash burning in a Mexican municipality. The source classes that comprise the dioxin emission inventories for Canada, the United States and Mexico and their basic characteristics are shown in Table 2.1.

2.3.2 Approach

Our approach to the preparation of dioxin emission inventories is necessarily conditioned by the requirements of this project. The cardinal condition is that the inventory must serve as an essential input into the model, the efficacy of which was to be assessed in the project. The major task to which the air transport model was devoted, ranking the individual sources of dioxin with respect to their relative contributions to the amounts of dioxin deposited on the receptors, was suggested by the results of certain recent studies. These ranked dioxin sources in the United States and Canada with respect to their contributions to deposition and/or air concentration at several types of receptors: the five Great Lakes (CBNS, 1995), a series of dairy farms in Vermont and Wisconsin, and several dioxin monitoring stations in the United States and Canada (CBNS/NEEPC, 1998).

These studies lead to a basic conclusion: relatively few of the sources account for most of the emissions and most of the deposition at the receptors. Thus, in a combined inventory of dioxin sources in the United States and Canada (1996), 92 percent of the total annual emissions were due to only six of 23 classes of sources: municipal waste incinerators, medical waste incinerators, cement kilns burning hazardous waste, secondary copper smelters, iron sintering plants, and backyard trash burners (CBNS/NEEPC, 1998). Similar relationships have been observed in a number of European dioxin inventories (UNEP, 1999). Relatively few of the individual sources dominated deposition at the receptors as well. In the dairy farm study, of a total of 24,644 individual and area sources in the United States and Canada, only 200 (0.8 percent) accounted for 90 percent of the dioxin deposition on a dairy farm in northern Vermont; only nine individual sources (0.004 percent) accounted for 60 percent of the deposition at this receptor. In the earlier Great Lakes study, where the receptors were much larger, this effect is less striking but nevertheless significant: for example, of 1,329 sources, only 100 (7.5 percent) accounted for 95 percent of the dioxin deposited on Lake Michigan. Such data emphasize the value of ranking the sources relative to their impact on the receptors as a means of identifying the sources toward which remedial action can be most effectively directed.

Table 2.1: Characteristics of Dioxin Sources

SOURCE CLASS NUMBER	SOURCE CLASS NAME	NUMBER OF SOURCES												ANNUAL THROUGHPUT (10^{12} G/YR OR VEH-KM/YR)			DIOXIN EMISSION FACTORS (10^{-12} G TEQ PER G OR VEH-KM OF THROUGHPUT)		
		CANADA			USA			MEXICO			TOTAL								
		POINT	AREA	TOTAL	POINT	AREA	TOTAL	POINT	AREA	TOTAL	POINT	AREA	TOTAL	CAN	USA	MEX	MIN	AVG	MAX
1	MSW	87		87	167		167			0	254	0	254		31.64		9.98	31.57	99.83
2	MWI	203		203	2,200		2,200	24		24	2,427	0	2,427		0.95	0.01	169.23	535.10	1,691.95
12	Cement-K	18		18	112		112	29		29	159	0	159		71.23	22.95	2.76	8.72	27.56
13	Fe-S	2		2	9		9	1		1	12	0	12		0.11	0.01	7.57	23.93	75.67
20	BB		268	268		2,035	2,035		4,808	4,808	0	7,111	7,111		1.61	5.65	44.42	140.44	444.09
3	Sec-Cu-Sm	1		1	4		4	3		3	8	0	8		0.24	0.22	246.99	780.99	2,469.27
14	Sec-Alum-Sm			0	45		45			0	45	0	45		2.26		11.98	37.89	119.80
7	Wood		2,173	2,173		6,258	6,258			0	0	8,431	8,431		31.07		0.68	2.16	6.83
8	Mobil-S		8,034	8,034		6,280	6,280			0	0	14,314	14,314		3.90		4.89	15.47	48.90
6	Coal		29	29		1,176	1,176			0	0	1,205	1,205		756.94		0.02	0.05	0.17
10	HWI	961		961	265		265			0	1,226	0	1,226	NO	4.20		1.70	5.39	17.04
15	EAF	14		14	237		237	19		19	270	0	270	DATA	38.49	8.66	0.15	0.52	1.84
5	SSI	9		9	145		145			0	154	0	154	AVAILABLE	1.68		2.21	6.97	22.06
21	Hog-Fuel-C	10		10	222		222			0	232	0	232		13.77		0.16	0.52	1.64
4	Sec-Cu-Ref			0	6		6	6		6	12	0	12		0.36	0.37	5.36	16.95	53.59
19	Res-Oil			0		2,955	2,955			0	0	2,955	2,955		0.03		0.03	0.08	0.26
17	PP-Krft			0	166		166			0	166	0	166		80.74		0.01	0.03	0.09
16	GIF	184		184	157		157	33		33	374	0	374		3.56	0.38	0.01	0.11	3.35
23	Sec-Ld-Sm	4		4			0			0	4	0	4						
25	Res-Fuel-C		1,476	1,476			0			0	0	1,476	1,476					NO	
26	Com-Fuel-C		1,323	1,323			0			0	0	1,323	1,323					DATA	
27	Ind-Fuel-C		876	876			0			0	0	876	876					AVAILABLE	
28	Ag-Fuel-C		1,057	1,057			0			0	0	1,057	1,057						
TOTAL		**1,493**	**15,236**	**16,729**	**3,735**	**18,704**	**22,439**	**115**	**4,808**	**4,923**	**5,343**	**38,748**	**44,091**						
COUNT		**11**	**8**	**19**	**10**	**4**	**19**	**6**	**1**	**19**	**19**	**19**	**19**	**0**	**14**	**7**	**14**	**14**	**14**

Table 2.1A: Source Class Identification

NUMBER	CODE	DESCRIPTION
1	MSW	Municipal Solid Waste Incinerators
2	MWI	Medical Waste Incinerators
12	Cement-K	Cement Kilns
13	Fe-S	Iron Sintering Plants
20	BB	Backyard Trash Burning
3	Sec-Cu-Sm	Secondary Copper Smelters
14	Sec-Alum-Sm	Secondary Aluminum Smelters
7	Wood	Commercial Wood Combustion
8	Mobil-S	Mobil Sources
6	Coal	Commercial Coal Combustion
10	HWI	Hazardous Waste Incinerators
15	EAF	Electric Arc Furnaces
5	SSI	Sewage Sludge Incinerators
21	Hog-Fuel-C	Hog-Fuel Boilers
4	Sec-Cu-Ref	Secondary Copper Refiners
19	Res-Oil	Residential Oil Combustion
17	PP-Krft	Kraft Liquor Boiler
16	GIF	Grey Iron Furnaces
23	Sec-Ld-Sm	Secondary Lead Smelters
25	Res-Fuel-C	Residential Fuel Combustion
26	Com-Fuel-C	Commercial Fuel Combustion
27	Ind-Fuel-C	Industrial Fuel Combustion
28	Ag-Fuel-C	Agricultural Fuel Combustion

In general, it has been found that the performance of the model is quite robust in its evaluation of source/receptor relationships, for example, with respect to the expected effects of source/receptor distance and of geographic orientation to the prevailing weather pattern. In contrast, model estimates of the amounts of dioxin deposited at receptors are less precise. This is due in part to uncertainties about the completeness of the inventory and considerable variance in emission factors and hence in emission rates. It is also due to uncertainties of model parameters, especially those affecting deposition rates. However, the relative values of deposition at different receptors are robust, since the uncertainties have about the same proportional effect on all receptors. These observations suggest several practical guidelines in the development of source inventories for use in air transport models that are designed to assess source/receptor relationships:

- Since relatively few types of sources dominate overall emissions and deposition, and in any case the model's estimates of absolute deposition values are inherently uncertain, for the purpose of ranking sources the inventory may be quite serviceable if it covers 75 to 90 percent of the likely emissions.
- On the other hand, it is important to include in the inventory those types of sources that are known to be the largest contributors to overall emissions and deposition. If such sources are omitted, rankings will be severely distorted, hindering the main purpose of the exercise, which is to direct remedial action toward the most important sources.
- At the same time, for the reasons cited above, a considerable range of uncertainty in the absolute value of a source's rate of dioxin emission is tolerable (and in any case is generally unavoidable), since it will apply more or less equitably to all sources and hence have relatively little effect on their ranking.
- Finally, at this stage of our knowledge it is appropriate to regard a dioxin emission inventory as work in progress, to be improved for each successive project to which it is applied. As a corollary, it is useful at each stage in an inventory's development to make an effort to estimate the major emissions, in order to at least provide a basis for further improvements, for example, in inventories and emission factors.

In the present project, these considerations suggest that the model-estimated dioxin deposition at the Nunavut receptors should not be used to directly estimate the resultant health hazard. That information can be far more effectively derived from actual dioxin measurements of environmental samples, the dietary intake, and body burden. On the other hand, these considerations also suggest that the model-based data can be used to rank the sources with respect to their relative contributions to the amounts of dioxin deposited on the Nunavut receptors, even if their estimated rates of dioxin emission are inherently uncertain, so that the measurements and remedial tasks can be reduced to feasible dimensions.

2.3.3 Canada

Environment Canada (EC) has published an inventory of dioxin sources as of 1997 that was made available to us in electronic form (Environment Canada, 1999). The inventory includes a total of 16,729 emission rate estimates sources in 19 classes, representing a total of 1,493 point sources and 15,236 area sources (see Table 2.1). A few of these source classes overlapped with

source class categories in the U.S. inventory, and adjustments were made to avoid double counting (see Appendix). In addition, since EC had not yet completed an analysis of backyard waste burning, we prepared such an analysis for inclusion in the Canadian inventory. The methodology used for this purpose is described in the Appendix and is summarized briefly in what follows.

Backyard waste burning is the practice, common in rural areas of Canada and the United States (in areas not served by centralized waste collection) of disposing of household waste in a burner generally made of a suitably aerated steel drum. As indicated by earlier inventories, the combustion of residential waste in specially designed commercial incinerators is the largest single source of dioxin emissions in Canada and the United States, and indeed in all industrialized countries. Several studies have shown that dioxin is also emitted by backyard waste burners, and at relatively high rates because they lack the emission control systems that are commonly installed in incinerators (Riewe, 1992; Lemieux *et al.,* 2000).

The amount of dioxin emitted annually from backyard waste burners in Canada was estimated from demographic data (which distinguished between rural and urban populations on the basis of population density), data on *per capita* production of residential waste, and an emission factor developed in a recent U.S. EPA study of the combustion of household waste in barrel burners (Lemieux *et al.,* 2000). Assumptions regarding operational conditions of backyard burners are also based on this U.S. EPA study. The outcome of this analysis is an estimate of the amount of dioxin emitted annually from the backyard burners in each Canadian postal zone.

2.3.4 United States

The United States dioxin emission inventory is largely based on that produced by U.S. EPA and made available to us in electronic form. (This inventory in part reflects an ongoing exchange of inventory information between U.S. EPA and CBNS.) However, we have added several classes of sources that were lacking in the U.S. EPA inventory: iron sintering plants, electric arc furnaces, coal-burning power plants and backyard trash burning. The methodology used to estimate dioxin emissions from backyard burning is described in detail in the Appendix, and is similar to that briefly summarized in section 2.2.3 above. The inventory consists of 18 source classes representing a total of 22,439 sources, of which 3,735 are point sources and 18,704 are area sources (see Table 2.1).

2.3.5 Mexico

The dioxin emission inventory for Mexico represents a unique problem. In contrast with Canada and the United States, where the respective government agencies, EC and U.S. EPA, have produced essentially complete inventories, in Mexico the Instituto Nacional de Ecologia (INE) has only recently begun this process. As a result, while it was necessary to make certain additions to the U.S. and Canadian inventories, in the case of Mexico the CBNS contribution to the inventory was much more extensive. This effort is worthy of some note, since it represented, to our knowledge, the first time this task has been undertaken with respect to a developing country. Accordingly, in what follows, our approach to this task and the methods used to accomplish it are discussed in some detail.

2.3.5.1 Approach

Based on the precepts outlined in section 2.3.2 above, our aim was to develop an inventory that included the source classes that were expected to be the *major* contributors to dioxin emissions in Mexico. The identity of these sources can be readily deduced from what is known about *existing* inventories, for example, that the bulk of the dioxin emissions is due to combustion of domestic waste, that is, waste produced by households, commercial and medical establishments and institutions. As indicated earlier, sources that burn domestic waste, together with cement kilns that burn hazardous waste, secondary copper smelters, and iron sintering plants encompass nine-tenths of the dioxin emissions from industrialized countries such as the United States. Moreover, in a less industrialized country like Mexico, the production of domestic waste, which is chiefly linked to population size rather than industrial activity, will be even more dominant. It follows, therefore, that the crucial element of the Mexican inventory was the combustion of domestic waste.

Accordingly, we limited our request for information to the Mexican authorities to this major category plus cement kilns, secondary copper smelters, and iron sintering plants. The data requested were: facility name and location, design capacity, throughput, type of air pollution control equipment installed, and dioxin emission measurements, if any. The INE response indicated that there were no municipal waste incinerators operating in Mexico and that 24 medical waste incinerators had recently been installed (see Table 2.1). We received data with varying degrees of completeness on these source categories. In addition, it was possible to obtain basic data on several other industrial source classes from industry publications and the U.S. Department of Commerce. None of the foregoing information included actual dioxin emission data; data on facility capacity were available in all cases. As a result, we were required to develop plausible assumptions regarding the missing data from what was known about analogous facilities in the United States and Europe. The procedures followed to carry out this approach are briefly summarized below and are described in more detail in the Appendix. The overall inventory is shown in Table 2.1.

2.3.5.2 Residential waste combustion

INE provided us with a recent analysis of the residential waste disposal system in Mexico prepared by the Secretaria de Desarollo Social (SEDESOL, 1999). This included data on the amounts of this waste disposed of in different ways; average *per capita* production of residential waste; waste composition in the five regions of Mexico; fraction of the waste stream collected and disposed of to sanitary landfills; fraction disposed of by “informal” means. It was then possible, from this information and census data, to generate an overall pattern of waste disposal, which is shown in Figure 2.3. In 1998 Mexico produced 30.7 million t (metric tonnes) of residential waste per year at the average rate of 0.85 kg/capita/day. Of this total, an estimated six percent is recycled; half of the non-recycled waste (14.5 million t) is collected and transported to sanitary landfills; the remaining material (14.5 million t) is not collected but disposed of “informally.” We have therefore assumed that only this last segment of the waste is subject to burning.

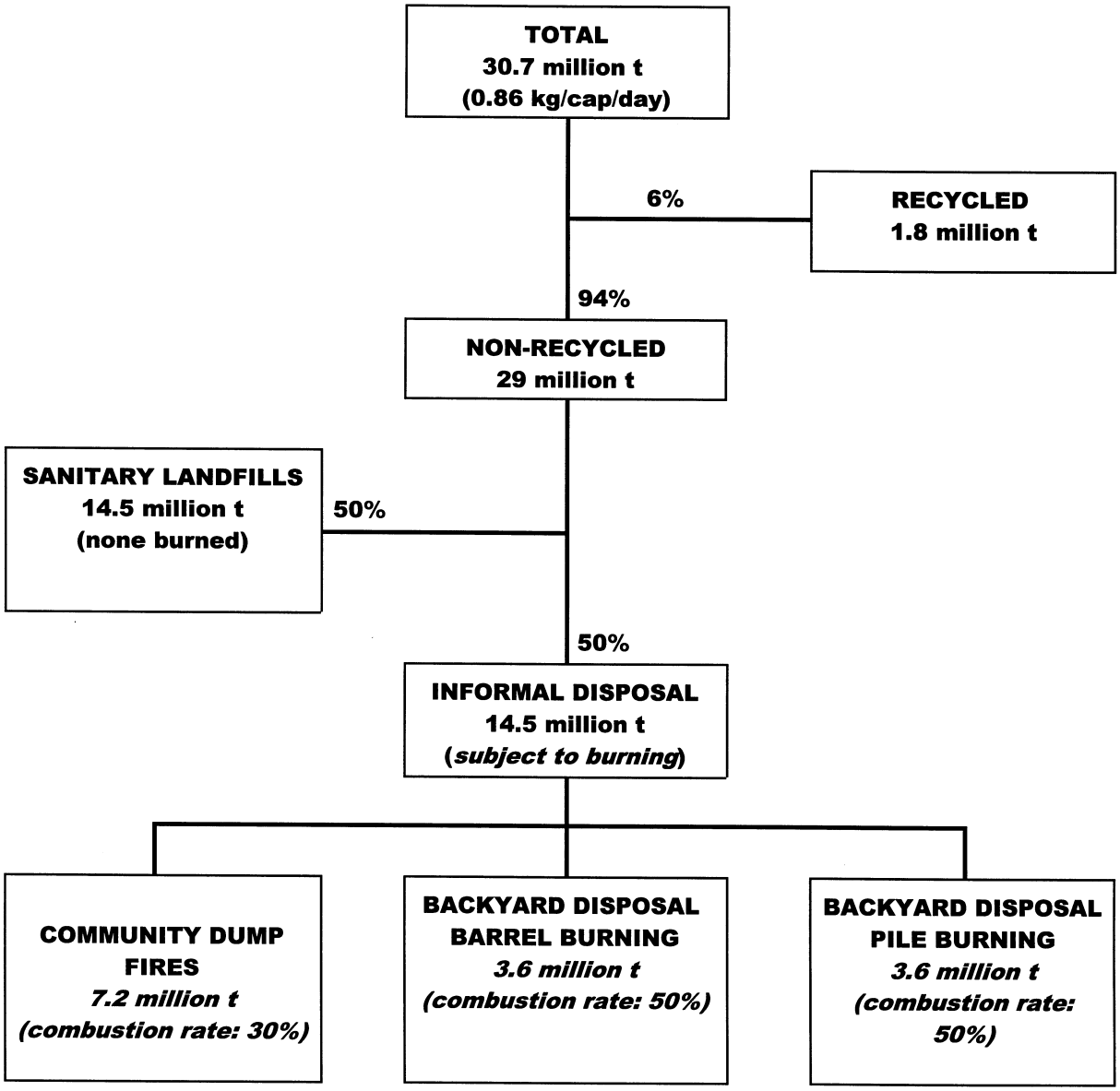
The issue, then, is to estimate what fraction of the informally disposed of waste is burned and the dioxin emission factor appropriate to the method of combustion. On the national scale, to our knowledge, there is only anecdotal information available about how residential waste is disposed of in areas that lack a central collection and disposal system. In such areas, householders may carry their waste to a communal unsupervised dump where, at intervals, the accumulated material is set on fire, deliberately or by accident; alternatively, householders may discard their waste on their own property, generally burning it at intervals. Although the total amount of waste disposed of in this way can be estimated for a given area from *per capita* waste production data and population density, there is no known information on the fraction of the disposed waste that is actually combusted.

In response to this situation, we adopted two approaches to the problem. First, with respect to the national estimate of the combustion of residential waste, we arbitrarily assumed that the waste subject to burning was consigned equally to communal dumps and backyard disposal. As shown in Figure 2.3, according to the SEDESOL study, 47 percent of the municipal solid waste was subject to burning. Based on limited studies of combustion in these situations, it was assumed that 30 percent of the waste consigned to a dump was actually combusted, while 50 percent was combusted in backyard burning. In sum, based on this scenario, we assumed that 20 percent (40 percent of 30.7 million metric tons) of the national domestic waste stream was *actually combusted*. The most detailed study of household waste burning (i.e., excluding commercial incinerators) was based on steel drum backyard burners (Lemieux *et al.,* 2000). From those results (modified to account for the method used in that study to account for non-detect dioxin values) (Cleverly, 2000), we applied a dioxin emission factor of 0.14 micrograms TEQ per kilogram of waste *actually combusted*. (Emission factors for conventional sources, such as incinerators, are based on fuel throughput, not the amount combusted.) As noted in Figure 2.3, the SEDESOL study assumed that 14.5 million metric tons of the waste stream was “informally” disposed and therefore subject to burning. Of this amount, we assumed that 40 percent, or 5.8 million metric tons, was actually combusted. Applying an emission factor of 0.14 micrograms TEQ of dioxin per kilogram of waste yielded dioxin emissions of 794 g TEQ per year from this source.

A second approach to this problem was designed to explore how, in a situation in which half of the national domestic waste disposal is “informal,” it might be possible to assess the amount of this waste that is subject to burning and hence likely to emit dioxin. For this purpose, in collaboration with Dr. Lizbeth Lopez Carrillo, of the Instituto Nacional de Salud Publica in Cuernavaca, Mexico, we designed a survey that was administered by interviewers to 397 householders in the State of Morelos. The survey form (see Appendix) was designed to elicit a sequential series of responses leading ultimately to the respondent’s personal estimate of the amount of their own household’s waste that was subject to burning. The results are summarized in Table 2.2. The survey covered households in three types of municipalities: urban (278), semi-urban (59), and rural (60). The survey showed that backyard burning occurred in all three types of municipalities, although twice as much of the waste was burned in rural areas as in either urban or semi-urban areas. Overall, 191,408 kilograms, or 28.2 percent, of the total amount of the waste generated by the 397 households surveyed (678,320 kilograms) was subject to being

Figure 2.3

MUNICIPAL SOLID WASTE DISPOSAL IN MEXICO



t = metric tons

Table 2.2: Residential Trash Management Practices in the State of Morelos – Results of a 1999 Survey (n=397)

SURVEY SUBJECT	POPULATION						
	URBAN		SEMI-URBAN		RURAL		TOTAL QUANTITY
	QUANTITY	PERCENT	QUANTITY	PERCENT	QUANTITY	PERCENT	
Number of households surveyed	278	70.03	59	14.86	60	15.11	397
Estimated trash quantity generated by the surveyed households **(kilograms/year)** (1)	474,326	69.93	100,666	14.84	103,328	15.23	678,320
Number of households discarding their trash through curbside collection program	208	71.97	49	16.96	32	11.07	289
Estimated trash quantity managed through curbside collection program and landfill disposal **(kilograms/year)**	354,891	71.90	83,604	16.94	55,108	11.16	493,604
Number of households discarding their trash through informal pick up and disposal techniques	70	65.42	10	8.41	28	26.17	108
Estimated trash quantity managed through informal waste management practices **(kilograms/year)**	119,435	64.66	17,062	9.24	48,220	26.10	184,716
Number of households engaging in backyard burning to discard their household trash	49	46.23	26	24.53	31	29.25	106
Estimated quantity of residential trash that is subject to backyard burning **(kilograms/year)**	114,047	59.58	29,666	15.50	47,694	24.92	191,408
Estimated quantity of residential trash that is actually combusted during backyard burning **(kilograms/year)**	57,024	59.58	14,833	15.50	23,847	24.92	95,704
Estimated total annual dioxin emissions from backyard burning (grams TEQ/year) (2)	**0.0080**	59.58	**0.0021**	15.50	**0.0033**	24.92	**0.0134**

Notes:

(1) The calculation of the waste quantity is based on the following assumptions: (a) The waste generation rate is on average .96 kilograms per person per day; (b) The average household size in the Central region of Mexico is approximately 5 persons per household. The two assumptions were derived from the Mexican Census and government data on residential waste generation rates and management practices (SEDESOL, 1999). The calculation on the yearly generation of trash by the households that participated in the survey was based on the following algorithm:
[.964 (kg/person/year * 4.85 persons/household * 365 days per year = 1,706 kilograms of trash per household per year.] Finally, multiplying the waste generation rate per household per year by the number of households surveyed yields the estimated trash quantity generated by the surveyed households.

(2) The computation of the annual dioxin emissions from informal waste burning is based on the following assumptions: (a) The combustion rate of residential trash subjected to informal waste burning is approximately 50 percent; (b) The emissions factor is 140 nanograms of dioxin TEQ per kilogram of waste combusted. Thus, the calculation of the TEQ is based on the following algorithm: [yearly trash quantity in kilograms that is being combusted during informal waste burning * emissions factor 140 ng TEQ/kg of combusted material / 1.E+09 = grams TEQ/year].

burned. The difference between this result and the result given by the national scenario described above (47 percent) provides a measure of the range within which the true value may fall.

The overall annual dioxin emission due to backyard waste burning estimated from the national scenario, 794 grams TEQ, represents the largest element (56.2 percent) in the total emissions from Mexico, 1,412 grams TEQ. If the results of the Cuernavaca survey apply to the nation as a whole, the actual figure may be lower than this estimate. The geographic distribution of the emissions due to backyard waste burning among the municipalities of Mexico, based on the national estimate, is shown in Figure 2.4.

Based on certain assumptions, it was possible to make a rough approximation of dioxin emissions from a group of point sources in Mexico. The relevant procedures are briefly summarized below and are presented in more detail in the Appendix.

Medical Waste Incinerators: INE provided us with information on 24 facilities. This included location (by municipality) and capacity in kg of fuel per hour. Running time was estimated from data on the U.S. medical waste incinerator inventory. It was assumed that the Mexican facilities operated 1,321 hours per year, based on the weighted average of all U.S. facilities. A similar approach was used to adopt a range of emission factors for the Mexican facilities from the emission factors characteristic of the U.S. incinerators (see Appendix for details). The overall estimated dioxin emission from medical waste incinerators is 0.9 g TEQ per year.

Iron Sintering Plants: From industrial literature (*Iron & Steel Works of the World*, 1994), it was learned that there is a single such facility operating in Mexico; its location and capacity were provided. We assumed a capacity utilization of 67 percent, leading to a throughput of approximately 1.1 million tons per year. Emission factors derived from measurements at a number of German plants were adopted (Batz, 1996). (See Appendix for details.) The overall estimated dioxin emissions from these facilities is 24 g TEQ per year.

Cement Kilns: From information provided by F. Bejarano, we compiled a list of 29 cement plants that were operating in 1996-97. As of 1996, 20 plants had a temporary or full permit to use hazardous waste as an auxiliary fuel in the cement production process. It was therefore assumed that these facilities burned hazardous waste in 1996, while the remaining nine facilities without such permits were assumed to use conventional (non-hazardous) fuels in their production process. Throughput was estimated from the total production capacity of the industry apportioned to the 29 plants according to their size. Dioxin emission factors were derived from test data of U.S. facilities. The computation of total yearly dioxin emissions from the 20 facilities burning hazardous waste amounts to 387 grams TEQ compared to 21 grams TEQ that were emitted by nine cement plants that do not use hazardous waste as a fuel. In sum, the study estimated that the 29 Mexican cement plants combined emitted 408 grams TEQ in 1996 into the air. (See Appendix for details.)

Secondary Copper Smelters/Refiners: According to the Directory of Copper Mines and Plants (International Copper Study Group, 1997), there were three secondary copper smelters and six copper refiners operating in Mexico in 1996/97. The data provided were: facility name and location (municipality), and processing capacity as of 1997. Capacity utilization factors recommended earlier by the U.S. Bureau of Mines (before this agency was abolished) were employed: 0.9 for secondary smelters and 0.6 for refiners. U.S. dioxin emission factors for such plants were applied to the resultant throughputs. These procedures yielded annual dioxin

emission estimates: 174 grams TEQ for secondary copper smelters, and six grams TEQ for refiners (see Appendix for details).

Electric Arc Furnaces: From the journal *Iron & Steelmaker* (*Iron & Steelmaker*, 1996), 19 steel electric arc furnaces were identified in Mexico. Data provided included facility name and location (municipality), number of furnaces, facility design capacity, and other technical data. Total production of steel by Mexican electric arc furnaces was obtained from the American Iron Ore Association (AIOA, 1997); 9.55 million metric tons in 1995. Based on this estimate and an average capacity utilization of 0.88, it was estimated that these facilities produced a total of 8.7 million metric tons of steel in 1995/96. Dioxin emission factors for similar facilities in Germany were applied (Batz, 1996), yielding total annual dioxin emissions of five grams TEQ (see Appendix for details).

Grey Iron Foundries: According to the *Casting Source Directory* (*Casting Source Directory 1996-1997*), there were 33 grey iron foundries in Mexico in 1995. Data provided included name, location (municipality), and throughput (assuming 1995 values would apply to 1996 as well). Dioxin emission factors available from German facilities (Batz, 1996) were applied to yield an estimated annual emission of 0.04 grams TEQ for the 33 Mexican facilities (see Appendix for details).

The locations of the point sources discussed above are shown in Figure 2.5.

2.3.6 The North American inventories

The characteristics of the source classes in each of the three North American inventories are summarized in Table 2.1. Together, they comprise 44,091 sources, of which 5,343 are point sources and 38,748 are area sources. As shown in Table 2.3, annually, the total source inventory emits 4,713 grams TEQ, 364 grams TEQ (7.7 percent) from Canadian sources, 2,937 grams TEQ (62.3 percent) from U.S. sources, and 1,412 grams TEQ (30 percent) from Mexican sources. Figure 2.6 describes the emissions from the various source classes in each of the three national inventories. While the airborne emissions from the separate source classes vary over five orders of magnitude, only six of the 23 source classes account for 91 percent of the total emission: municipal solid waste incinerators, backyard trash burners, cement kilns burning hazardous waste, medical waste incinerators, secondary copper smelters, and iron sintering plants (see Figure 2.7). The combustion of domestic waste (in incinerators and backyard burning) accounts for more than half of the total emissions.

The effects of these factors are also evident in a comparison of the Canadian, U.S. and Mexican inventories. The emissions from the six dominant source classes in these categories are shown in Figure 2.8. In Mexico there are no reported municipal waste incinerators, so that, as already indicated, whatever burning does occur takes place “informally,” and is here classified as backyard trash burning. These emissions are significantly higher than they are in both Canada and the United States because, as noted earlier, the emission factor is quite high compared to that of the incinerators that burn residential waste in those countries (but not in Mexico). The high emissions of dioxin from cement kilns in Mexico may be an artifact of the worst-case scenario in which we assumed that all of the facilities were burning hazardous waste.

Figure 2.4: GEOGRAPHIC DISTRIBUTION OF DIOXIN EMISSIONS FROM INFORMAL ("BACKYARD") BURNING OF MUNICIPAL SOLID WASTE IN MEXICO

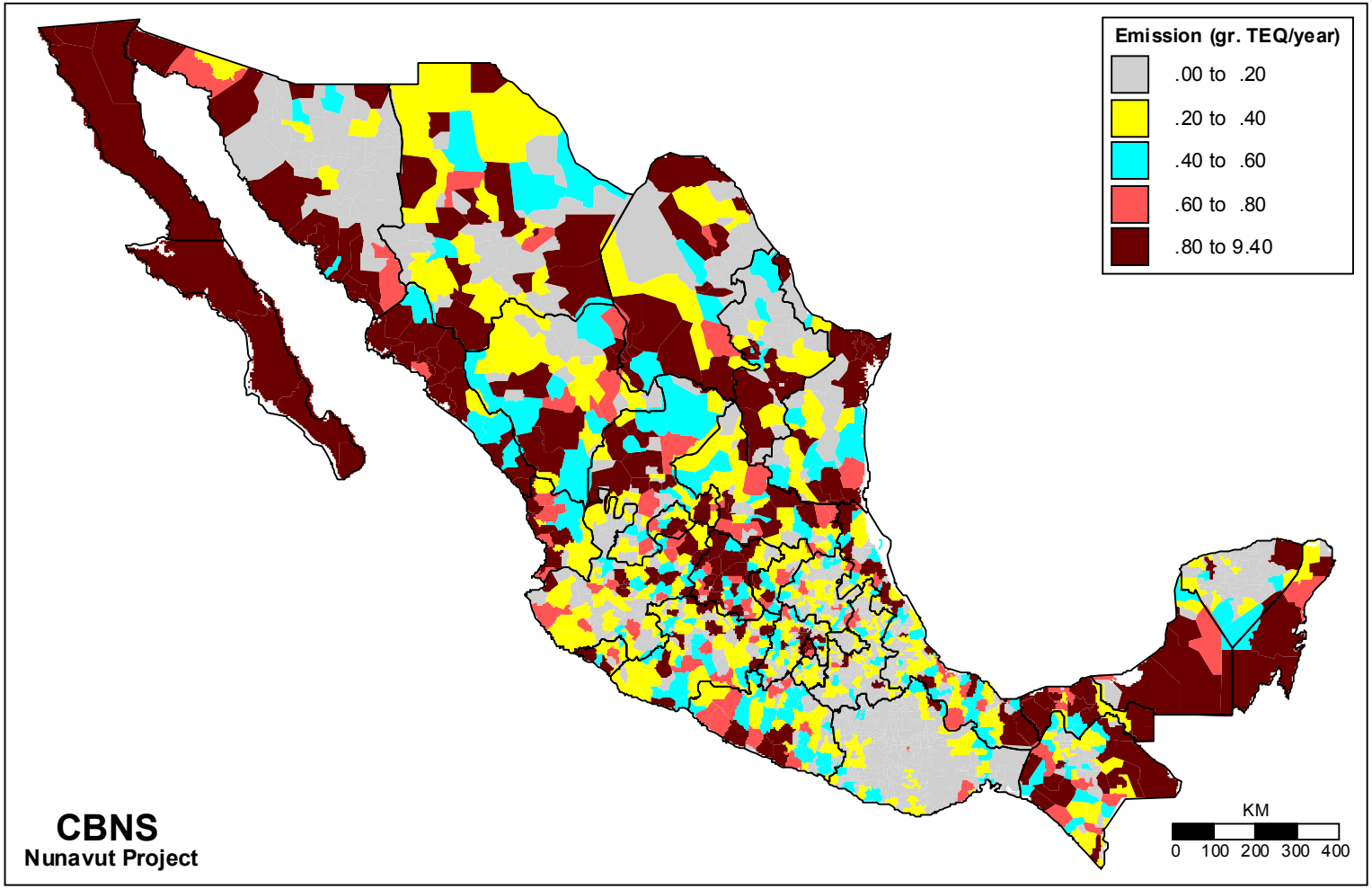


Figure 2.5: LOCATION OF MAJOR POINT SOURCES

OF DIOXIN EMISSIONS IN MEXICO (n=115)

Table 2.3: Cumulative Contribution of Dioxin Source Classes to Total National Emission Inventories

	CANADA			US			MEXICO			TOTAL		
SOURCE CLASS	**G TEQ/yr**	**%**	**Cum %**	**g TEQ/yr**	**%**	**Cum %**	**g TEQ/yr**	**%**	**Cum %**	**g TEQ/yr**	**%**	**Cum %**
MSW	189	52.1	52.1	999	34.0	34.0				1188	25.2	25.2
MWI	14	3.9	56.0	516	17.6	51.6	0.9	0.1	0.1	531	11.3	36.5
Cement-K	3	0.8	56.7	413	14.1	65.6	408	28.9	29.0	824	17.5	54.0
Fe-S	43	11.8	68.5	266	9.1	74.7	24	1.7	30.7	334	7.1	61.0
BB	25	7.0	75.5	226	7.7	82.4	794	56.2	86.9	1,045	22.2	83.2
Sec-Cu-Sm	0.1	0.0	75.5	191	6.5	88.9	174	12.4	99.2	365	7.8	91.0
Sec-Alum-Sm				85	2.9	91.8				85	1.8	92.8
Wood	40	11.0	86.6	67	2.3	94.1				107	2.3	95.1
Mobil-S	9	2.4	89.0	60	2.1	96.1				69	1.5	96.5
Coal	5	1.3	90.3	40	1.4	97.5				45	1.0	97.5
HWI	4	1.2	91.5	23	0.8	98.3				27	0.6	98.0
EAF	10	2.9	94.3	20	0.7	99.0	5	0.3	99.6	35	0.7	98.8
SSI	0.3	0.1	94.4	12	0.4	99.4				12	0.3	99.1
Hog-Fuel-C	11	2.9	97.3	7	0.2	99.6				18	0.4	99.4
Sec-Cu-Ref				6	0.2	99.8	6	0.4	99.997	12	0.3	99.7
Res-Oil				2	0.1	99.9				2	0.05	99.7
PP-Krft				2	0.1	99.99				2	0.05	99.8
GIF	2	0.6	97.9	0.4	0.01	100.0	0.04	0.003	100.0	3	0.06	99.8
Sec-Ld-Sm	0.1	0.03	98.0							0.1	0.002	99.8
Res-Fuel-C	7	1.9	99.9							7	0.1	99.99
Com-Fuel-C	0.2	0.05	99.99							0.2	0.004	99.996
Ind-Fuel-C	0.1	0.03	99.99							0.1	0.003	99.999
Ag-Fuel-C	0.1	0.01	100.0							0.1	0.001	100.0
TOTAL	**364**	**100.0**	**n/a**	**2,937**	**100.0**	**n/a**	**1,412**	**100.0**	**N/a**	**4,713**	**100.0**	**n/a**
COUNT	**19**	**n/a**	**n/a**	**18**	**n/a**	**n/a**	**8**	**n/a**	**n/a**	**23**	**n/a**	**n/a**

Figure 2.6: The North American Dioxin Source Emission Inventories

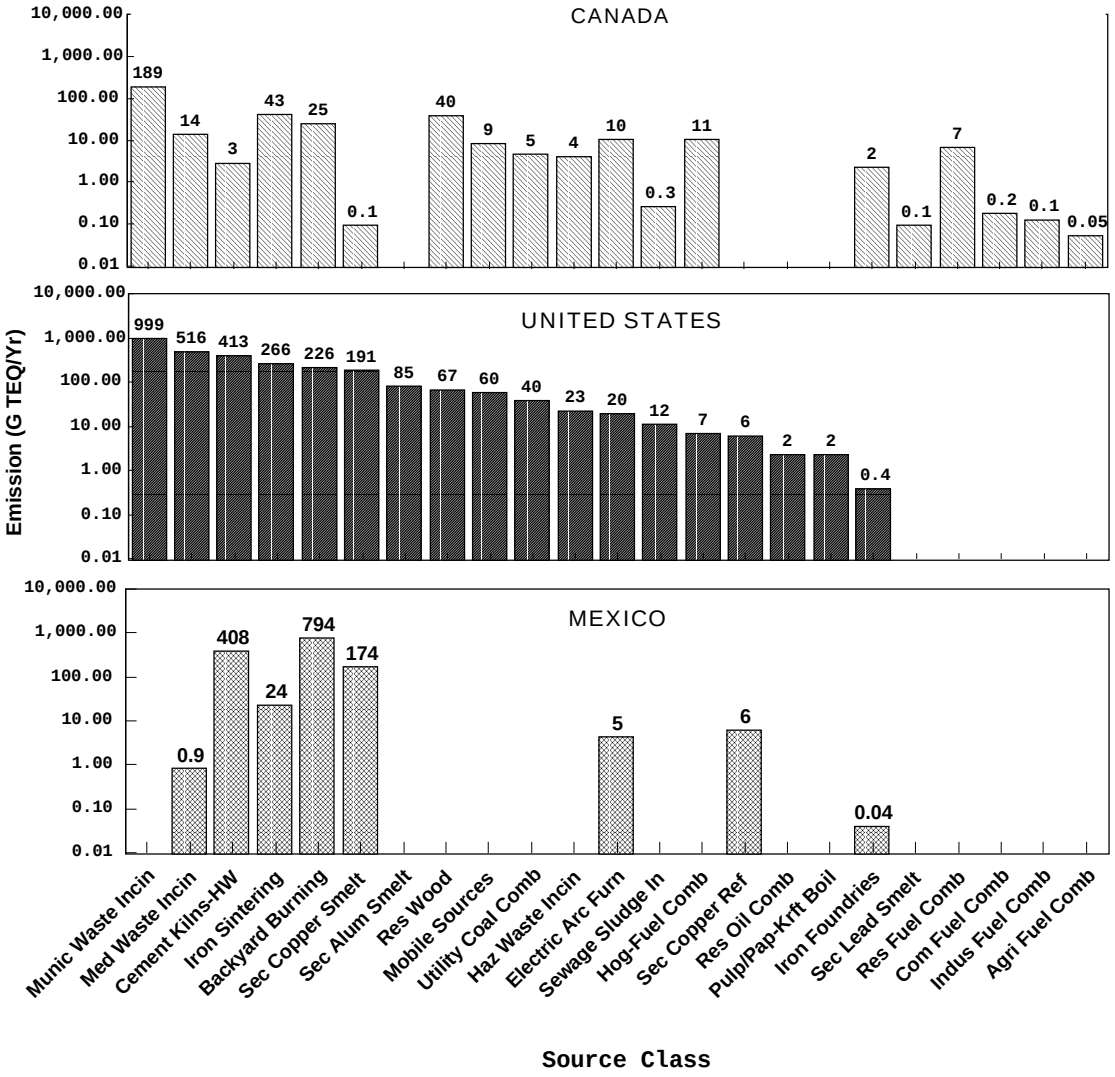


Fig. 2.7 Total North American Dioxin Emission Inventory
Cumulative Contributions of Source Classes

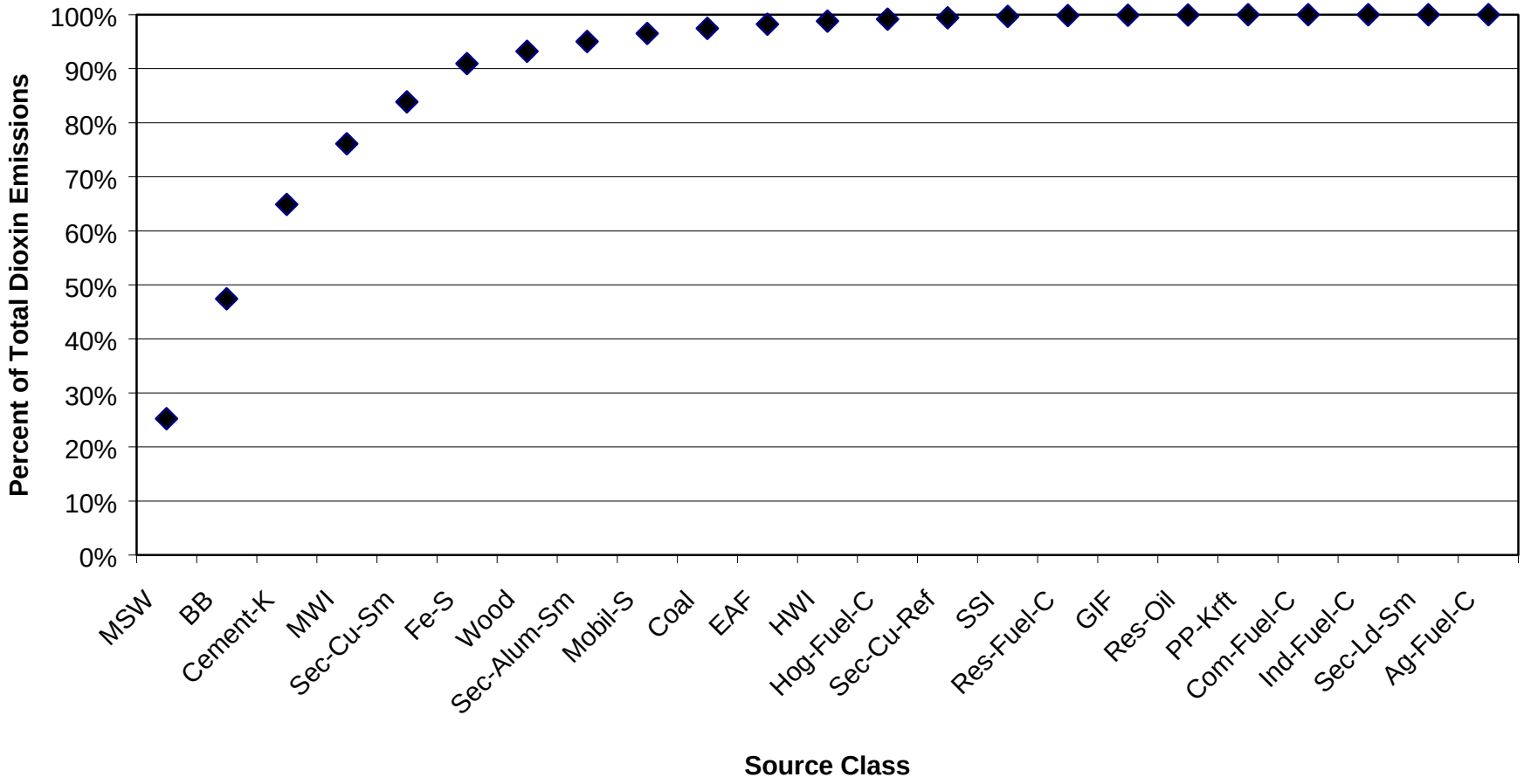
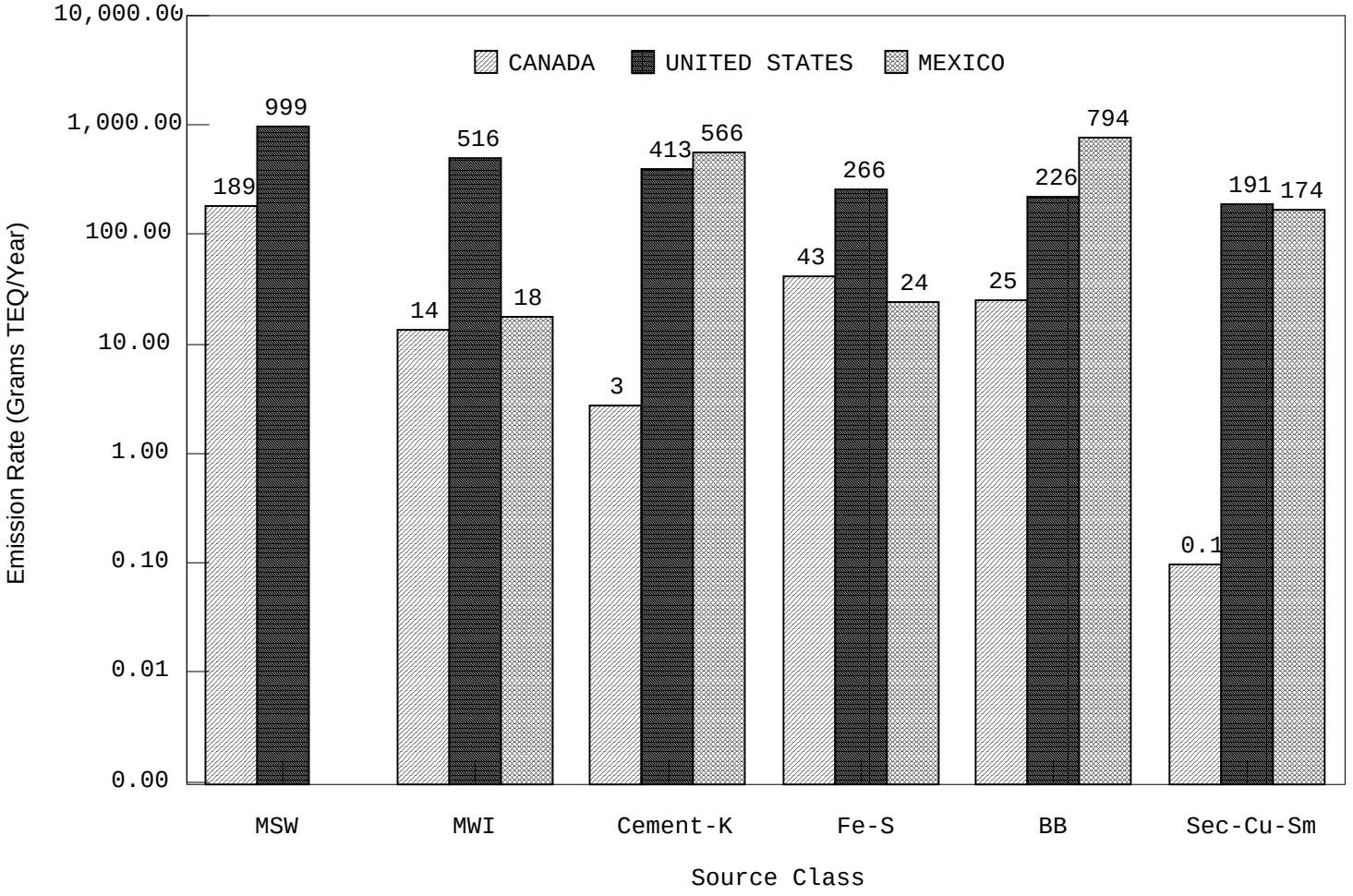


Figure 2.8: Comparative Rates of Dioxin Emission from Major Sources in Canada, United States and Mexico



2.3.7 Comparative inventories

The deposition of airborne dioxin on Nunavut is an example of a global process that carries semivolatile pollutants such as dioxin and PCBs from sources throughout the northern hemisphere toward the Arctic. The present data, for the North American component of this overall process, offer an initial opportunity to compare the dioxin inventories of countries that differ in their systems of production and hence in their origins of anthropogenic pollutants such as dioxin. In Table 2.4, the overall annual dioxin emissions from Canada, the United States and Mexico are compared with those of a series of other countries that are included in a recent compilation of inventories prepared by the United Nations Environment Programme (UNEP, 1999). Table 2.4 also compares the dioxin emissions *per capita* and per GDP.

With respect to the countries of North America, two results stand out. The *per capita* annual dioxin emissions are relatively similar, 13,335, 11,809, and 17,379 picograms TEQ *per capita* for Canada, the United States and Mexico respectively. Yet with respect to emissions relative to GDP, 595, 472, and 5604 micrograms TEQ per $1 million GDP, respectively, the Mexican value is nearly 10 times higher than the Canadian and U.S. values. Indeed, Mexico ranks first in this respect among all the listed countries, while Canada and the United States are ranked 9th and 11th respectively. This is a consequence of the relatively low GDP *per capita* in Mexico, about one-seventh of the Canadian and U.S. figures—which is characteristic of developing countries. In sum, because the amount of domestic waste generated, and hence the dioxin it emits when burned, is more closely linked to population than GDP, this source dominates emissions in all three countries. In Mexico, nearly all of it is burned informally and the emission factor is particularly high in comparison with the municipal waste incinerators that are used in the United States and Canada, which adds to the overall effect.

While we have included the UNEP inventory data in Table 2.4, they are not entirely comparable to the North American data, which unlike the UNEP data are based on a common procedure. Nevertheless, this exercise emphasizes the importance of such comparative analyses of dioxin emission inventories, for, as exemplified by our Mexican inventory, an understanding of the structure of existing inventories from industrial countries can generate insights that facilitate the production of inventories in developing countries in ways that are suitable to their technical resources.

Table 2.4: Relation of National Dioxin Emission to Population and Gross Domestic Product (GDP)

COUNTRY	1995 POPULATION		1995 GDP		1996/97 TOTAL EMISSION		EMISSION PER CAPITA		EMISSION PER GDP		GDP PER CAPITA	
	NUMBER	RANK	MILLION 1990 CONSTANT DOLLARS	RANK	QUANTITY Grams TEQ/Yr	RANK	QUANTITY Nanograms TEQ/Yr	RANK	QUANTITY Micrograms TEQ/Yr	RANK	CONSTANT 1990$	RANK
Australia	16,850,540	8	348,006	7	150	11	8,902	11	431	12	20,653	12
Austria	7,795,786	13	175,848	13	29	15	3,720	15	165	15	22,557	8
Belgium	9,978,681	11	208,129	12	661	5	66,241	1	3,176	3	20,857	11
Canada	**27,296,859**	**7**	**612,233**	**6**	**364**	**8**	**13,335**	**7**	**595**	**9**	22,429	**9**
Denmark	5,146,469	16	142,492	14	39	14	7,578	13	274	13	27,687	2
France	56,634,299	5	1,262,307	4	873	4	15,415	6	692	8	22,289	10
Germany	77,782,677	4	1,801,381	3	334	9	4,294	14	185	14	23,159	7
Hungary	10,374,823	10	31,743	15	112	12	10,795	9	3,528	2	3,060	15
Japan	125,570,246	2	3,187,475	2	3,981	1	31,703	3	1,249	6	25,384	4
Mexico	**81,249,645**	**3**	**251,949**	**9**	**1,412**	**3**	**17,379**	**5**	**5,604**	**1**	3,101	**14**
Slovak Republic	5,274,335	15	13,413	16	42	13	7,963	12	3,131	4	2,543	16
Sweden	8,587,353	12	235,214	10	22	16	2,562	16	94	16	27,391	3
Switzerland	6,873,687	14	228,310	11	181	10	26,332	4	793	7	33,215	1
The Netherlands	13,060,115	9	314,815	8	486	7	37,213	2	1,544	5	24,105	6
United Kingdom	56,352,200	6	1,043,933	5	569	6	10,097	10	545	10	18,525	13
United States	**248,709,873**	**1**	**6,220,830**	**1**	**2,937**	**2**	**11,809**	**8**	**472**	**11**	25,012	**5**
TOTAL	**757,537,588**		**16,078,078**		**12,192**							
AVERAGE	**47,346,099**		**1,004,880**		**762**		**17,209**		**1,405**		**20,123**	

2.4 Receptors

The following criteria were used to select appropriate receptor areas: (a) that they serve as avenues of entry of airborne dioxin into Inuit food chains; (b) that they are representative of the three major ecozones in the Inuit territory, Nunavut: Southern Arctic, Arctic Cordillera, and Northern Arctic; c) they cover the three administrative regions: Kitikmeot, Kivalliq (Keewatin), and Bafin (Qikiqtaaluk); and d) that they are representative of the geographic extent of Nunavut.

The chief land-based food chain that supports the Inuit diet is lichen-caribou. Lichens absorb their nutrients largely from airborne materials and are a major source of food for caribou, which is important in the Inuit diet. The chief marine-based food chain is algae-crustaceans-fish (chiefly cod)-seal-polar bear, whale; these marine animals are major components of the Inuit diet. The avenue of entry, algae, chiefly occur under land-attached ice, which generally extends to about 50 km from the coast (Bergmann, 1999).

Based on these considerations, we define receptors that will conduct airborne dioxin into the Inuit diet as (1) land areas in which caribou are plentiful and are regularly hunted by Inuit, and (2) marine areas within about 50 km of the coastline in which seal, polar bear and whales are plentiful and hunted by Inuit. Trout and Arctic char are also important in the Inuit diet. Since the freshwater streams and lakes in which they occur are abundantly distributed in the land areas, estimates of deposition on these areas will be representative of the level of dioxin contamination of these fish.

The area encompassed in the newly established Inuit territory, Nunavut, is described in considerable detail in the Nunavut Atlas (Riewe, 1992). It includes detailed maps for each of the 57 sectors of the territory; one set of maps describes the occurrence of land-based and marine wildlife, and the second set outlines the areas in which the Inuit hunt, fish, and trap wildlife. Based on this information, we have selected eight such sectors as the location of receptors; they are identified by the name of a nearby Inuit community. These are shown in Figure 2.9. Together, these sectors are representative of most of the area of Nunavut. They range from latitude ("lat") 56^o (Sanikiluaq, n i r l x34) to lat 74^o (Arctic Bay, w4Wx3J4) and from longitude ("long") -60^o (Broughton Island, 3r r3b3Jx34) to long -120^o (Ikaluktutiak). All three arctic ecozones are represented as well.

In each sector we have identified a land-based receptor area and a marine (land-attached ice) receptor area of the order of 10-20,000 km^2. An example is shown in Figure 2.10. The Atlas sectors in which the receptors are located are described below.

2.4.1 Arctic Bay (w4Wx3J4)

This sector includes the Border Peninsula of north central Baffin Island; it is in the Northern Arctic ecozone with a high arctic ecoclimate. The vegetative cover is very sparse, consisting of moss and low-growing shrubs. The plateau slopes gently southward, ranging from 2500 to 1000 feet above sea level. There is an Inuit settlement (w4Wx3J4) at Arctic Bay. Seal and walrus are extensively hunted in the coastal areas, as are polar bears in the winter. Narwhales are hunted in the summer. There is relatively little caribou hunting. Marine receptor: lat 72.70, long -85.08. Land receptor: lat 72.66; long -83.28.

Figure 2.9

Nunavut Dioxin Deposition Receptors

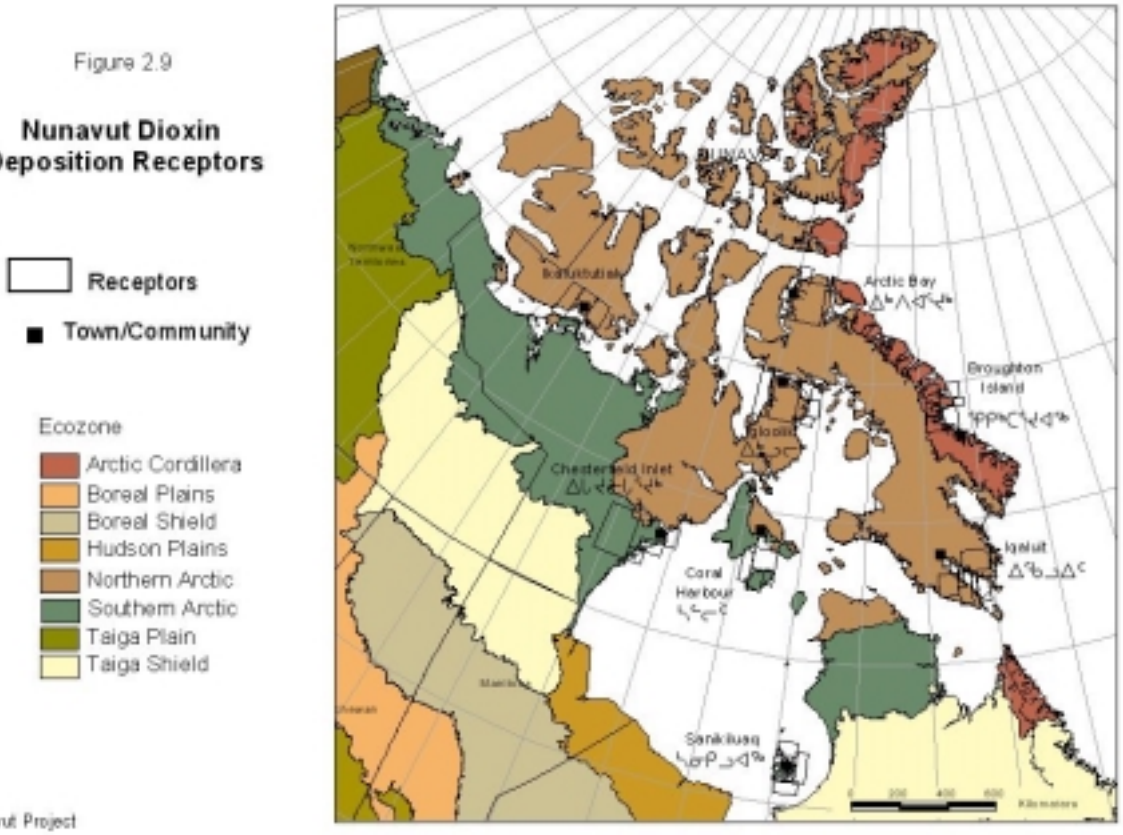


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Figure 2.10

Coral Harbour

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Receptor Polygons

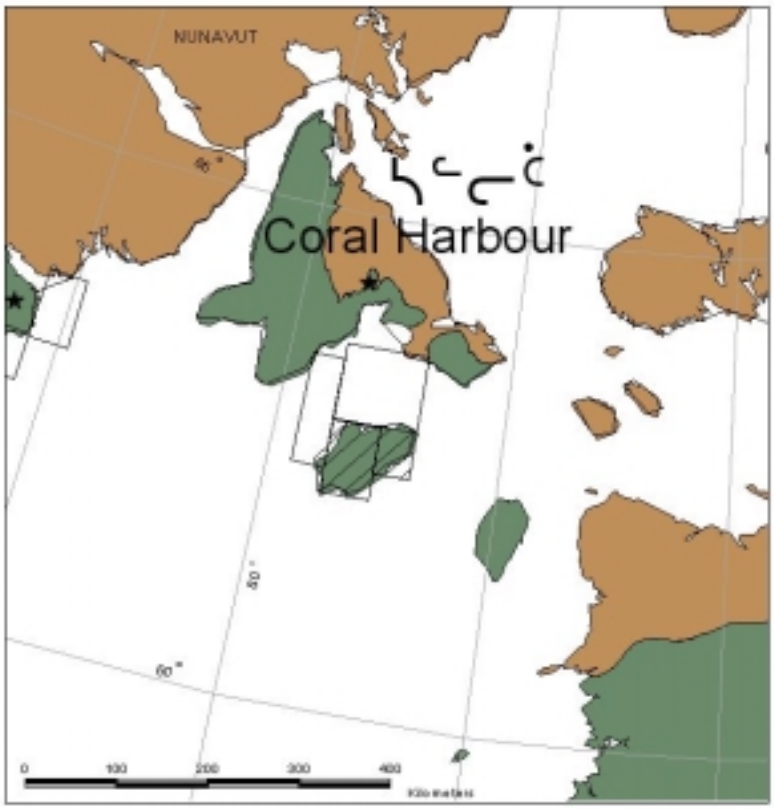
Land Receptor

Marine Receptor

★ Community of Coral Harbour

Ecozone

- Arctic Cordillera
- Boreal Plains
- Boreal Shield
- Hudson Plains
- Northern Arctic
- Southern Arctic
- Taiga Plain
- Taiga Shield



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2.4.2 Broughton Island (3rr3b3Jx34)

This sector is on the east coast of Baffin Island. It lies in the Northern Arctic and Arctic Cordillera ecozones. The northeastern part of the sector is hilly, rising to heights of 5000-6000 feet above sea level. The western part is typical tundra, where caribou are plentiful. There are seal, walrus, polar bear and whale in the coastal area, which are extensively hunted by Inuit from the Broughton Island (3rr3b3Jx34) and Clyde River (vq3gŽW4) communities; these are, respectively, south and north of the sector. Marine receptor: lat 69.11, long -66.39. Land receptor: lat 68.74, long -69.11.

2.4.3 Chesterfield Inlet (wZJoZ}J4)

Chesterfield Inlet is a sector on the northwest coast of Hudson Bay where three Inuit communities, Chesterfield (wZJoZ}J4), Rankin Inlet (vq3Oi6) and Whale Cove (trC3Jx6), are located. It lies in the Southern Arctic ecozone. The ecoregion is classified as having a low arctic ecoclimate, with a cover of shrub tundra vegetation. The region contains areas of permafrost. Wetlands make up 25-50 percent of the area. The land area is populated with caribou and wolf and is heavily used by Inuit from the local communities and other more distant ones for harvesting caribou, trapping Arctic fox, and fishing for char and trout. The entire coastal area is extensively used for hunting seal, polar bear, walrus, waterfowl, and migrating white and beluga whales. Figure 2.10 is a map of this sector, as an example of the location of the land and marine receptors within the sector. Marine receptor: lat 62.88, long -91.50. Land receptor: lat 62.90, long -94.42.

2.4.4 Coral Harbour (n9o5)

Coral Harbour is on the largest island in Hudson Bay, Southampton Island. This receptor is in a sector that includes the southern third of Southampton Island and Coats Island. While the northeast portion of Southampton Island is in the Northern Arctic ecozone, the remainder and Coats Island are in the Southern Arctic ecozone. The region has a low arctic ecoclimate, with a nearly continuous cover of low arctic shrub tundra vegetation. Elevation is less than 300 feet above sea level. Wildlife include polar bear, seal, walrus, whale, caribou, waterfowl and small game. Inuit at Coral Harbour hunt caribou, waterfowl, seal, walrus, polar bear and whale and fish for arctic char. Marine receptor: lat 63.07, long -83.21. Land receptor: lat 62.55, long -82.84.

2.4.5 Igloolik (w4lo4)

This region lies in the Northern Arctic ecozone and has a mid-arctic ecoclimate. Vegetation is sparse and discontinuous, dominated by shrubs. Rocky areas rise to about 1,650 feet above sea level. Most of the region is underlain by permafrost. There are two Inuit communities in the sector: Igloolik (w4lo4) and Hall Beach (niC/4). There is extensive hunting of polar bear, seal, walrus, and several types of whale and some caribou hunting. Trout and arctic char are caught in lakes and rivers. Marine receptor: lat 69.12, long -83.37. Land receptor: lat 69.03, long -83.69.

2.4.6 Ikaluktutiak

This sector includes the southern third of Victoria Island and is in the Northern Arctic ecozone. It has a low arctic ecoclimate, with a nearly continuous cover of dwarf tundra vegetation. The terrain of the southern third of Victoria Island slopes gently to the southwest. Permafrost is deep

and continuous. Inuit at Ikaluktutiak hunt caribou, muskox, seal and waterfowl extensively. There is intensive fishing for lake trout and whitefish in a chain of lakes in the northern part of the sector. Marine receptor: lat 68.70, long -106.26. Land receptor: lat 69.47, long -106.26.

2.4.7 Iqaluit (w3v l w5)

This sector is at the southern end of Baffin Island. It is in the Northern Arctic ecozone and is classified as having a mid-arctic ecoclimate. Elevations range from 700 feet above sea level at the southwestern coast to 3000 feet at the northeastern coast. In the lower elevations, there is nearly continuous shrub tundra vegetation. In the upland areas, vegetation is discontinuous dwarf tundra. There are two Inuit communities in the sector: Iqualuit (w3v l w5), which is now the capital of Nunavut, and Lake Harbour (r7uD6). Inuit hunt caribou throughout the area and hunt seal, walrus, polar bear and whale in Frobisher Bay and the coastal land-attached ice areas. Marine receptor: lat 62.89, long -67.07. Land receptor: lat 63.00, long -67.13.

2.4.8 Sanikiluaq (n i r l x34)

These receptors comprise the Belcher Islands, which are situated off the southeast coast of Hudson Bay; although well outside its contiguous boundary, these islands are officially part of Nunavut. They consist of numerous elongated islands separated by narrow channels. The community of Sanikiluaq (n i r l x34) is located on a central island. The islands are in the Southern Arctic ecozone; the ecoclimate is high sub-arctic and falls along the latitudinal limit of tree growth. Tall shrub and tundra are common. Land rises to a maximum of about 400 feet above sea level. There is intensive hunting for seal and polar bear; beluga whales are heavily hunted as well. Marine receptor: lat 56.24, long -78.93. Land receptor: lat 56.23, long -79.26.

3. Results

3.1 Data Output

The data yielded by the air transport model that best represent the ecological exposure of the receptors to airborne dioxin are the estimates of deposition. These are expressed as the mid-range deposition flux over the one-year test period: picograms TEQ per square meter per year ($pg/m^2/yr$). As noted earlier, the receptors are adjacent land and marine areas at each of the eight sites. Dioxin may be deposited in the form of dry vapor or particulates and, alternatively, in these forms but carried down by rain or snow. Within the model, deposition is defined as the amount of airborne dioxin that settles on the land or water and becomes attached to surface material. On land receptors, dioxin may be deposited on soil and rocks or vegetation or, in season, on snow and ice. On marine receptors, dioxin may deposit on surface water or, in season, on snow or ice. The model does not take into account the subsequent fate of the dioxin after it is deposited, for example, revolatilization of vapor adsorbed on plant material. However, at the low temperatures common to the Arctic, revolatilization of deposited dioxin will be negligible except perhaps during the height of the brief summer.

In sum, deposition flux is an estimate of the amount of dioxin that enters a marine or land receptor area and is potentially available to ecological uptake processes, initially by plant life. Since plant life is the entry point to both terrestrial and marine food chains, deposition is the

dominant process that results in the exposure of the local food system—and hence on the Inuit who depend on it—to dioxin.

The model output also provides estimates of the concentration of airborne dioxin at the level of 10, 1000, 5000 and 10000 meters above the surface, expressed as picograms TEQ per cubic meter of air (pg TEQ/m^3). The model uses airborne concentrations in its calculation of deposition. Very little exposure to dioxin occurs through inhalation; for that reason, airborne concentration data are not directly relevant to ecological exposure. In this study, these data are only used to compare model estimates with actual measurements of airborne dioxin, made at several stations in Canada (see Appendix).

3.2 Deposition at Receptors

Figure 3.1 describes the deposition flux at each of the sites for both land and marine receptors. The same data are displayed in Table 3.1 to describe the relative contributions of the sources in the three countries to deposition at the various Nunavut receptors. Certain useful generalizations can be drawn from these data. First, deposition to the marine receptors averages twice the deposition to the adjacent land receptors. This is a common phenomenon and is due to the high receptivity of water to dioxin in the particulate form in comparison to land, where only a fraction of particulate dioxin coming into contact with vegetation and other surfaces will remain in place.

Second, there is a gradient in deposition with latitude; for example, deposition at the southern-most receptor, Sanikiluaq, is about 10 times greater than at Arctic Bay, the northern-most receptor. There is a similar west to east gradient in deposition; thus, the deposition flux at Broughton Island, the eastern-most site, is about twice as great as it is at the western-most site, Ikaluktutiak. These gradients reflect the geographic and meteorological influences on the relationship between the receptors and the major sources of dioxin (see section 3.4 below). The deposition values of the different receptors are reliable despite uncertainties about the precise amounts of deposition at each of them, which generally have the same effect on all the receptors.

Finally, as shown in Figure 3.2, the contribution of the emissions from the several countries to deposition at a typical Nunavut land receptor, Coral Harbour, differ considerably. The bulk of the deposition flux, 82 percent, is due to U.S. sources; Canadian sources contribute 11 percent and Mexican sources seven percent. The contributions to the deposition at the Coral Harbour marine receptor are 78 percent, 17 percent, and five percent respectively.

It is also of interest to compare the various source classes with respect to their proportional contributions to both emissions and to deposition at a typical receptor. This is shown, in the case of the Coral Harbour land receptor, in Figure 3.3. The depositions at the receptor are approximately proportional to the emissions from each of the source classes. This is equally true of the emissions from sources in Canada, the United States and Mexico, despite their considerably different average distances from Nunavut. This result is in contrast with an earlier study of air transport of dioxin from U.S. and Canadian sources to dairy farms in Vermont and Wisconsin (CBNS/NEEPC, 1998). For example, at a farm in southeastern Wisconsin, while emissions from municipal waste incinerators accounted for 48 percent of total emissions from all

Figure 3.1

Dioxin Deposition at Nunavut Receptors

Total Annual Deposition Flux

(picograms TEQ per square meter)

Contributing Sources:

CANADA
MEXICO
U.S.A.

LEFT= MARINE RECEPTOR

RIGHT= LAND RECEPTOR

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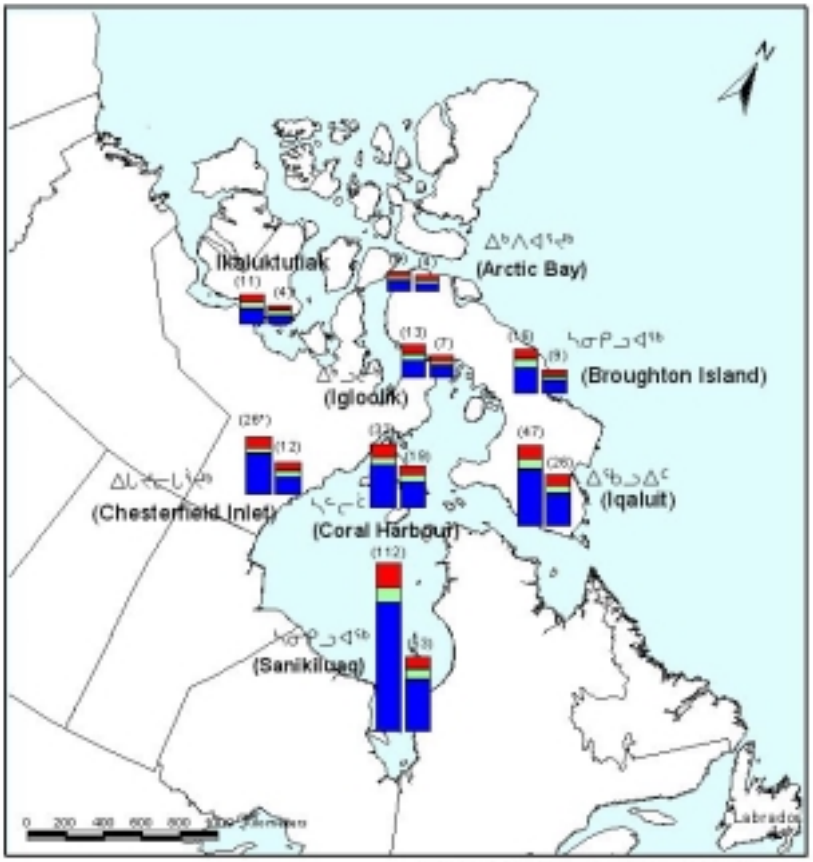


Table 3.1. Contribution of Sources in Canada, USA and Mexico to Dioxin Deposition Flux at Nunavut Receptors Annual Rate August 1996-June 1997

Receptor	Type	Deposition Flux (pg TEQ/m^2-year*)				Percent TEQ		
		Total	CAN	USA	MEX	CAN	USA	MEX
Ikaluktutiak	marine	11.3	2.8	7.9	0.6	25.1	69.9	5.0
	land	4.5	0.9	3.3	0.3	19.5	73.2	7.3
Chesterfield Inlet**	marine	26.3	5.5	19.4	1.4	20.8	74.0	5.2
wZJoZ}J4	land	11.7	1.8	9.1	0.8	15.2	78.1	6.8
Coral Harbour	marine	32.2	5.4	25.2	1.6	16.8	78.3	4.9
n9o}	land	19.2	2.2	15.8	1.3	11.4	82.0	6.6
Sanikiluaq	marine	111.9	16.1	90.5	5.4	14.3	80.8	4.8
nirlx34	land	53.5	5.7	43.5	4.2	10.7	81.4	7.9
Broughton Island	marine	16.2	2.7	12.3	1.2	16.6	75.7	7.7
3rr3b3Jx34	land	8.9	1.3	6.8	0.8	14.5	76.2	9.2
Igloolik	marine	13.4	2.5	10.1	0.8	18.4	75.4	6.2
w4lo4	land	7.0	1.0	5.5	0.6	14.2	77.8	8.0
Iqaluit	marine	46.7	7.8	36.5	2.5	16.6	78.1	5.2
w3vlw5	land	25.9	3.5	20.8	1.6	13.6	80.3	6.1
Arctic Bay	marine	7.9	1.4	5.8	0.6	18.3	73.9	7.8
w4Wx3J4	land	4.0	0.6	3.0	0.4	14.2	75.8	10.1

*These are mid-range estimates. High and low values due to range of emission factors are shown in the Appendix.

**The Chesterfield Inlet (wZJoZ}J4) marine receptor deposition flux is a derived estimate.

Figure 3.2 Contribution of Sources in Canada, United States and Mexico to Dioxin Deposition at Coral Harbour Receptors

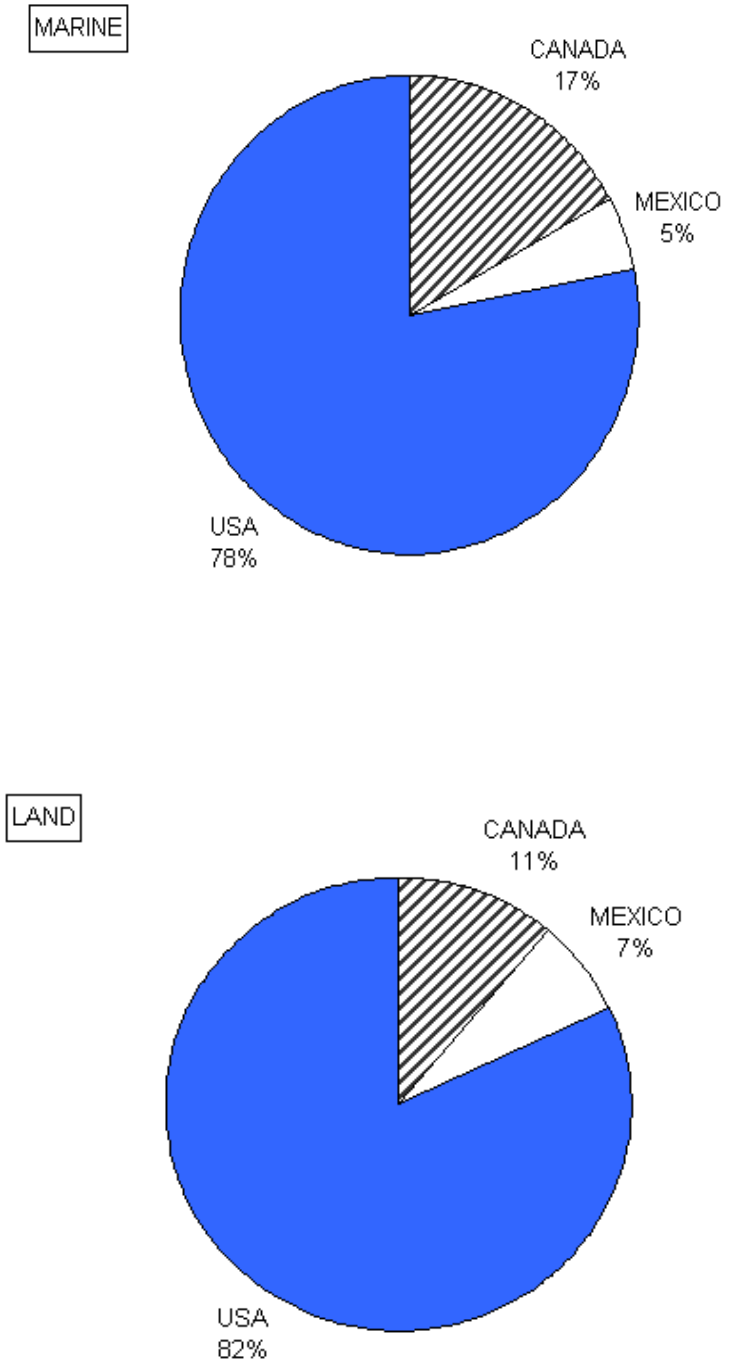
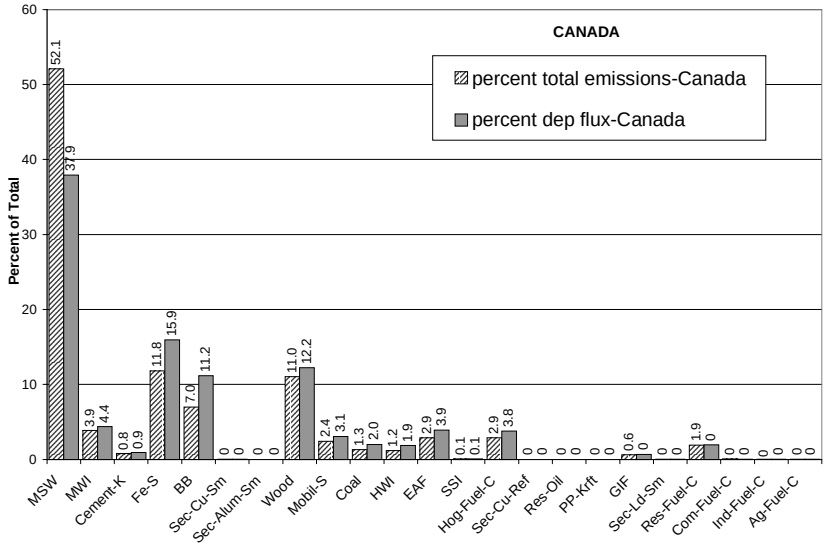
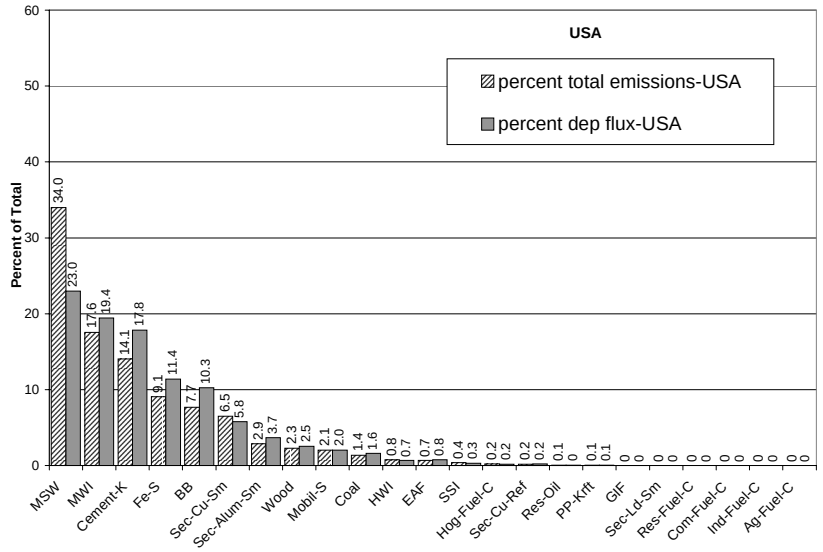
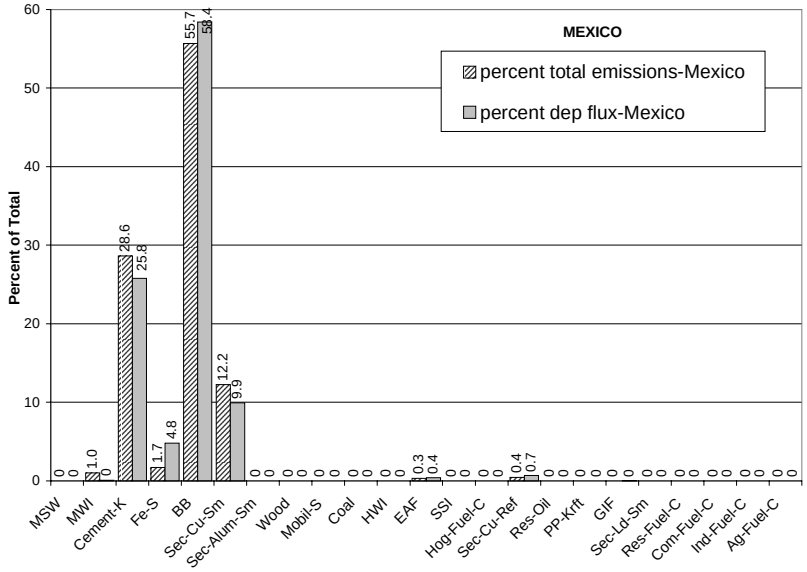


Fig. 3.3 DIOXIN SOURCE CLASS PERCENT OF EMISSIONS DEPOSITION FLUX







sources, they represented only 39 percent of the total deposition at the farms. On the other hand, with medical waste incinerators the relationship was reversed; emissions accounted for 12 percent of the total, while deposition accounted for 18 percent of the total. These results reflected the fact that the farm was generally closer to medical waste incinerators than it was to municipal waste incinerators. In contrast, Nunavut receptors are so distant from *all* major sources, so that differences in the location of the various sources tend to be minimized by the much larger transport distances.

3.3 The Effect of Source-Receptor Distance on Deposition

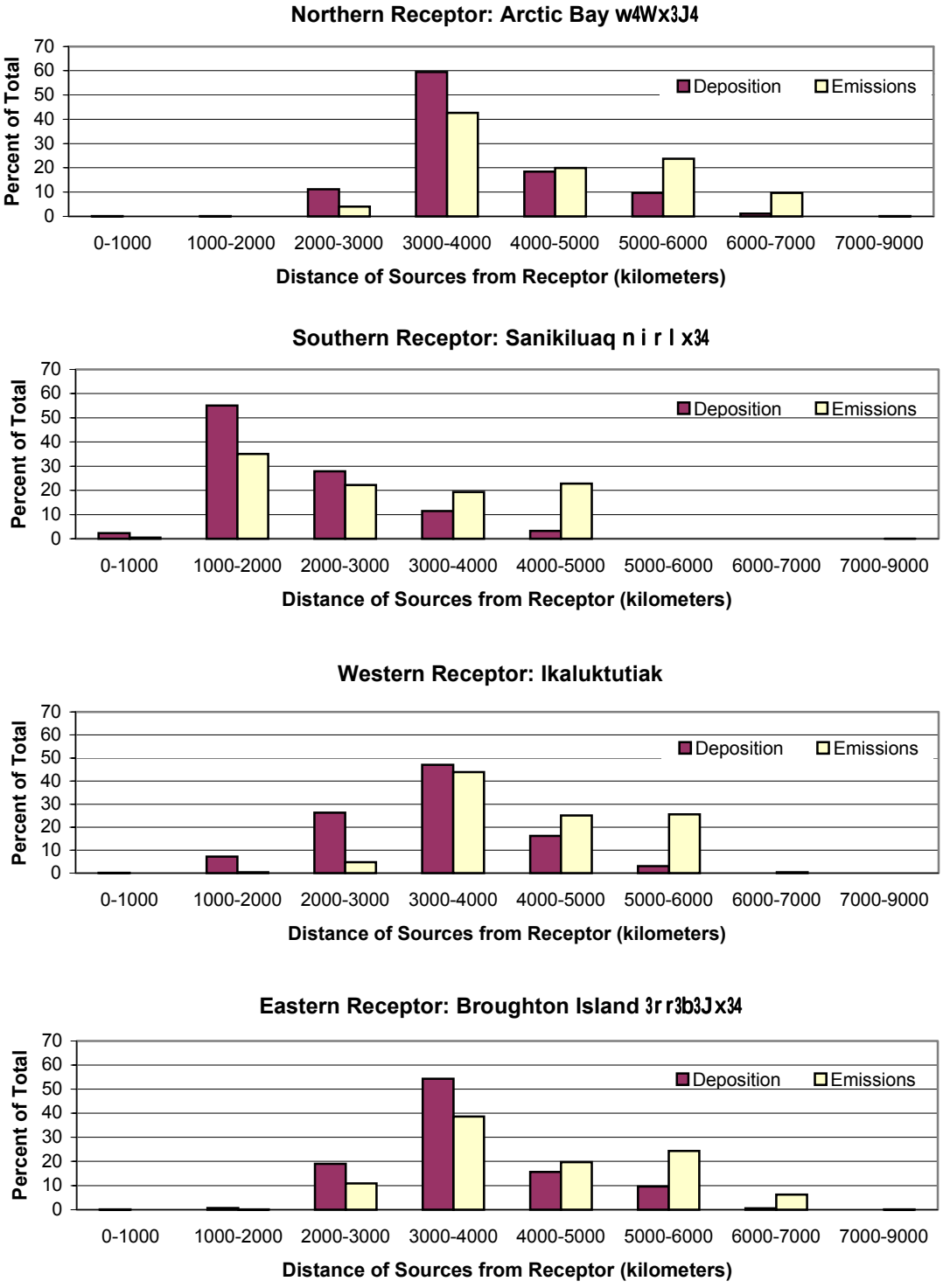
With the land receptor at Arctic Bay as the center point, the total inventory of sources was segregated into a series of 1,000 kilometer concentric zones with respect to their increasing distance from the receptor. It is then possible to estimate, for the sources located within each distance zone, the total amount of dioxin they emitted and their relative contribution to the total deposition flux at the receptor. In Figure 3.4, for four representative receptors, these data are expressed as the percentage of the dioxin emitted by all sources, that is due to the sources within each of the concentric distance zones, and as the percentage of the total deposition flux at the receptor that originates from the sources in each of the distance zones.

The two upper bar graphs in Figure 3.4 represent the data for the most northern receptor, Arctic Bay, and the most southern one, Sanikiluaq. The distribution of the source emissions with distance from the receptors is similar in both instances except that in the case of Arctic Bay, the pattern is shifted by about 2,000 km in distance. Thus, the distance range in which the largest percentage of source emission occurs is at 3,000 to 4,000 km from the Arctic Bay receptor, and 1,000 to 2,000 km from the Sanikiluaq receptor; the 2,000 km difference represents the distance between the two receptors, which is essentially devoid of dioxin sources. This is in keeping with the fact that both receptors receive most of their airborne dioxin from the same area, the eastern half of the United States, due south of both receptors and subject to the same overall direction of air transport.

The variation of the percentage of the total deposition at these receptors with source-receptor distance reflects the typical exponential decline in the efficiency of air transport with distance. This is shown in the relationship between the relative percentages of emission from the sources and deposition at the receptors. Thus, while the relative percentage of emissions from the three zones most distant from the Sanikiluaq receptor are about equal, the percentage of deposition at the receptor declines about ten-fold over these zones. This effect of source-receptor distance is also evident in the ten-fold differences in deposition flux between these two receptors that was noted earlier. As expected, air transport from the sources closest to the receptors is more efficient, as shown in Figure 3.4 by the excess, in the short-range zones, of the percentage of deposition over the percentage of emission due to the sources in those zones.

In Figure 3.4, the two lower bar graphs represent the effects of source-receptor distance on the percentages of emissions and deposition for two receptors at the same latitude, about 500 km south of Arctic Bay: Broughton Island and, 1500 km to the west, Ikaluktutiak. The variation of source emissions and deposition at the receptors with source-receptor distance are similar and resemble the Arctic Bay pattern. However, the percentage of the total deposition at Ikaluktutiak

Figure 3.4 Dioxin Emissions and Deposition as a Function of the Distance of Sources from Selected Nunavut Land Receptors



in the shorter distance ranges (1,000- 2,000 and 2,000-3,000 km) is relatively high in comparison with Arctic Bay. This reflects the fact that Ikaluktutiak, the most western receptor, is closest to sources in western Canada and, in addition, that there is an appreciable west-to-east weather pattern at that latitude. This effect is reduced at Broughton Island, which is more distant from the western sources. (See section 3.5, below.)

A notable feature of these results is that they illustrate the vulnerability of receptors to the deposition of airborne dioxin despite their considerable distance from the sources. Thus, the three receptors in the contiguous area of Nunavut, Arctic Bay, Broughton Island and Ikaluktutiak, receive 63 to 78 percent of their deposited airborne dioxin from sources that are 3,000 to 5,000 kilometers distant.

3.4 The Contributions of Different Sources to Deposition

As noted earlier, the total North American inventory consists of 44,091 identified sources. The basic datum computed by the air transport model is the deposition flux over the one-year test period at *each* of the 16 receptors that is due to *each* of these sources. In order to classify this large list of sources with respect to their relative impact on a receptor, and hence with respect to their importance in any remedial effort, it is useful to rank them with respect to the amounts of dioxin they deposit on the receptors.

Initially, the total list of sources was classified into categories that represent a source class and country (e.g., deposition due to all municipal waste incinerators in the United States). There are 45 such source categories; their contribution to the cumulative total deposition at the Coral Harbour land receptor is shown in Figure 3.5. The results show that the six highest-ranking categories, which together account for 72 percent of the total deposition, are in the United States. Only two U.S. source classes, municipal and medical waste incinerators, account for nearly 35 percent of the total deposition. The highest ranked Canadian category (ranked sixth) is municipal waste incinerators. The highest ranked Mexican source category is backyard trash burning (ranked seventh). Nearly 90 percent of the total deposition is due to only 12 source categories; of these, eight are U.S. sources, two are Mexican, and two are Canadian.

These data provide an outline of the regulatory measures that can be targeted in each country to efficiently reduce the emissions from the sources that are responsible for the dioxin emissions deposited in Nunavut. In the United States this would be accomplished by targeting remedial action on municipal waste incinerators, medical waste incinerators, cement kilns burning hazardous waste, iron sintering plants, backyard trash burners, secondary copper smelters, and aluminum smelters. In Canada, municipal waste incineration is the most important source class, and some iron sintering plants would need to be targeted as well. In Mexico, emissions from backyard trash burners and cement kilns burning hazardous waste would be most important targets. (These policy considerations are discussed in more detail in section 5, below.)

Despite the very large number of *individual* North American sources that contribute to the deposition of airborne dioxin at the Nunavut receptors, most of the deposition is due to a very *small* number of sources. This is shown in Table 3.2, using deposition at the Coral Harbour land receptor as an example. Thus, 35 percent of the deposition is due to only 19 sources (0.04 percent of the total number); 50 percent is due to 64 sources (0.15 percent); 75 percent is due to 680

sources (1.37 percent); 90 percent is due to 3,031 sources. The last 10 percent of the deposition is due to 41,060 sources, each of which make an exceedingly small contribution to the total deposition.

Finally, since remedial action of such point sources often must be taken facility by facility, it is useful to characterize the individual sources that are responsible for a large enough fraction of the total deposition to serve as a substantial start in an overall remedial program. For this purpose, the individual sources, each identified by location and class, have been ranked in descending order with respect to their percent contributions to the total amount of dioxin deposited at each of the eight Nunavut land receptors. In Figures 3.6A-H, the resulting data are presented in two ways: a cumulative curve of the contributions of the highest-ranked individual sources to 35 percent of the total deposition at the receptor; and a map showing the locations of each of these ranked sources. These figures serve to identify and characterize the *individual* sources that are responsible for a major part of the dioxin deposited at the Nunavut receptors, and hence, the sources toward which remedial action can be directed most effectively. Only an exceedingly small fraction of the 44,091 sources account for 35 percent of the deposition at the receptors (land). The number varies from 19 at Coral Harbour to 39 at Ikaluktutiak, ranging from 0.04 to 0.08 percent of the total number of sources. These major contributors to the dioxin deposited at the receptors are chiefly located in the eastern half of North America, extending as far south as a municipal waste incinerator in southern Florida and a secondary copper smelter in central Mexico. However, the major contributors to deposition at the two most western ones, Ikaluktutiak and Chesterfield Inset, are sources in western Canada, Alaska, the U.S. northwest, California, and western Mexico. As noted in section 3.5 below, the geographic distribution of the major sources that contribute to 35 percent of the deposition received by the receptors reflects the impact of weather patterns and source-receptor distance on the efficiency of dioxin air transport.

As can be seen from the maps shown in Figure 3.6, only four source classes (municipal solid waste incinerators, secondary copper smelters, cement kilns burning hazardous waste, and iron sintering plants) account for 35 percent of the deposition at most of the receptors. Again, the most western receptors are an exception; seven source classes are represented at Chesterfield Inlet and nine at Ikaluktutiak.

Although the bulk of the sources that account for 35 percent of the dioxin deposition at the Nunavut receptors are located in the United States, ten Canadian and two Mexican sources contribute as well.

The ranking assigned to any individual source with respect to its contribution to dioxin deposition at a given receptor depends on its emission rate and the relevant ATC value. As noted in section 2.3.1, there is a significant range of uncertainty in the individual source emission rates, which is inherent in the procedures used to assemble the national source inventories. As a result, in some cases, the rank order may be affected to some degree. Accordingly, in Figures 3.6A-H it can be expected that while the identified individual sources are reliably included in the group responsible for 35 percent of the deposition at the receptor, their exact order in the ranking may be less certain.

Figure 3.5 Cumulative Contributions of the 45 Source Class/Country Categories to Dioxin Deposition at Coral Harbour (n9oʖ) Land Receptor

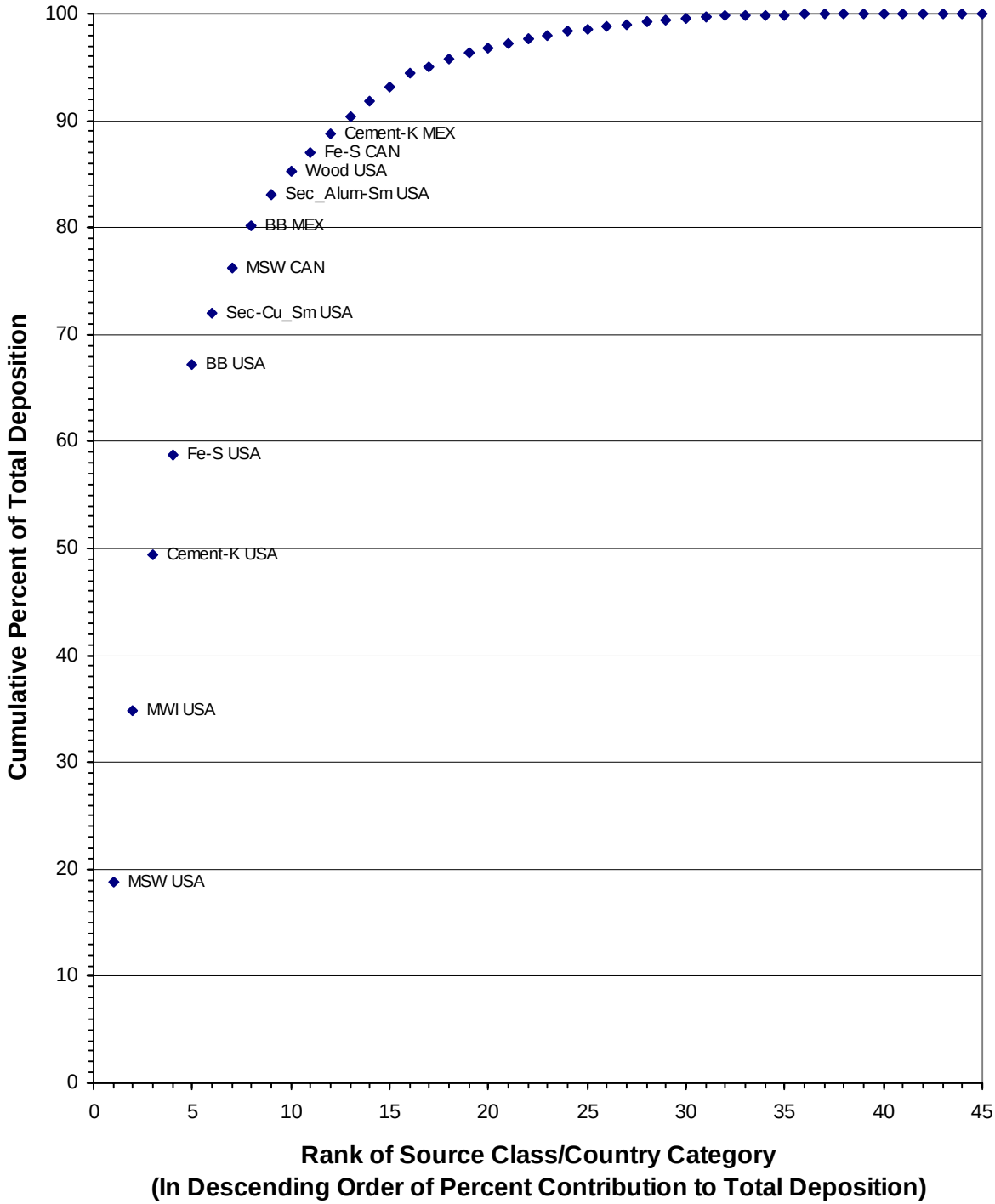
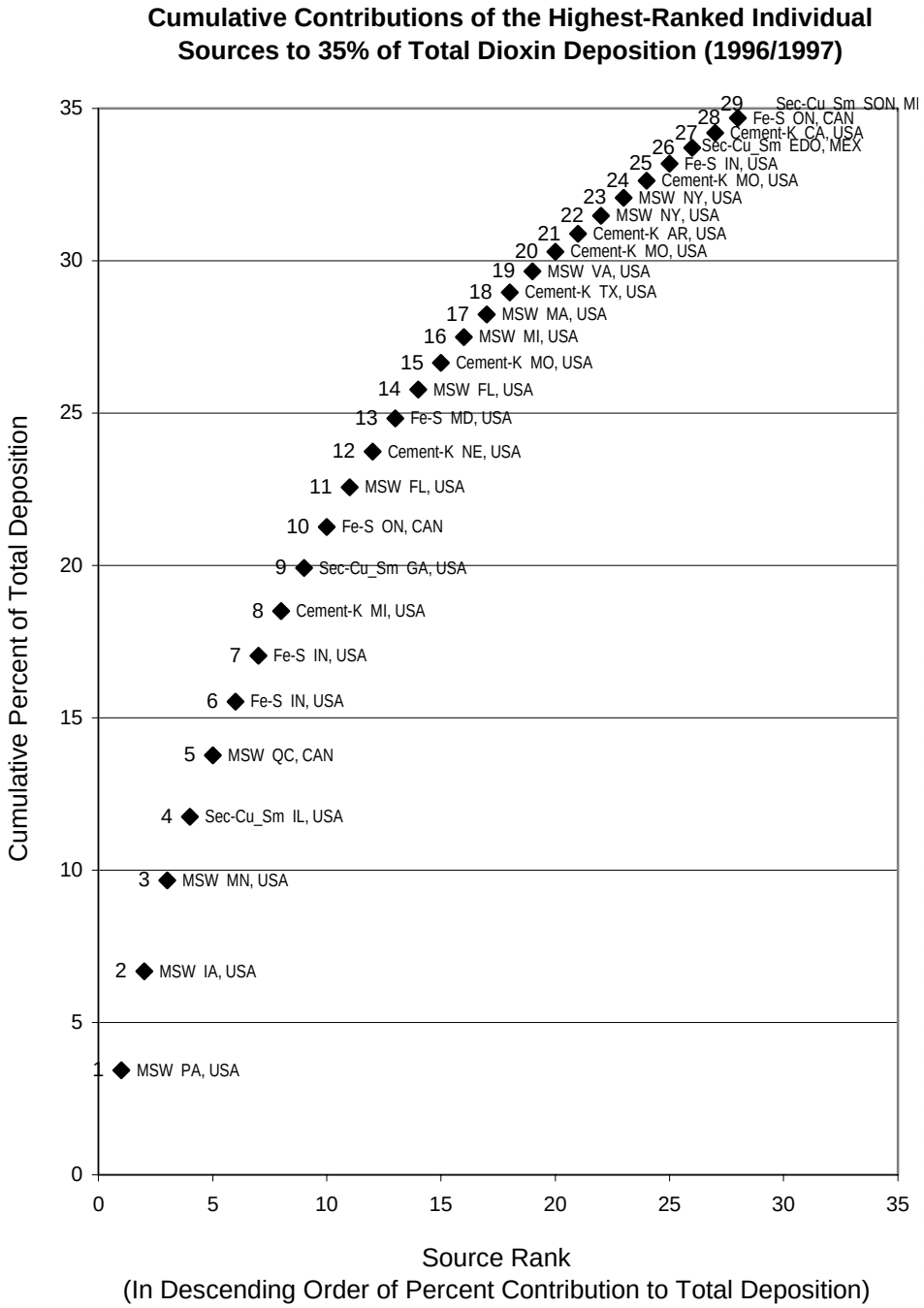


Table 3.2. The Relation Between the Cumulative Percent of Total Dioxin Deposition at Coral Harbour Receptors and the Number and Percent of Sources Contributing to It

Cumulative Percent Deposition	Number of Sources							
	Land Receptor				Marine Receptor			
	CAN	USA	MEX	TOTAL	CAN	USA	MEX	TOTAL
Top 35	2	17	0	19	3	17	0	20
Top 50	6	50	8	64	11	50	4	65
Top 75	124	493	63	680	150	442	45	637
Top 90	334	2,461	236	3,031	423	2,395	190	3,008
Top 99	1,464	9,143	1,653	12,260	1,661	9,176	1,459	12,296
Top 100	16,729	22,439	4,923	44,091	16,729	22,439	4,923	44,091
	Percent of Total							
Top 35	0.00	0.04	0.00	0.04	0.01	0.04	0.00	0.05
Top 50	0.01	0.11	0.02	0.15	0.02	0.11	0.01	0.15
Top 75	0.28	1.12	0.14	1.54	0.34	1.00	0.10	1.44
Top 90	0.76	5.58	0.54	6.87	0.96	5.43	0.43	6.82
Top 99	3.32	20.74	3.75	27.81	3.77	20.81	3.31	27.89
Top 100	37.94	50.89	11.17	100.00	37.94	50.89	11.17	100.00

Figure 3.6A Arctic Bay Land Receptor



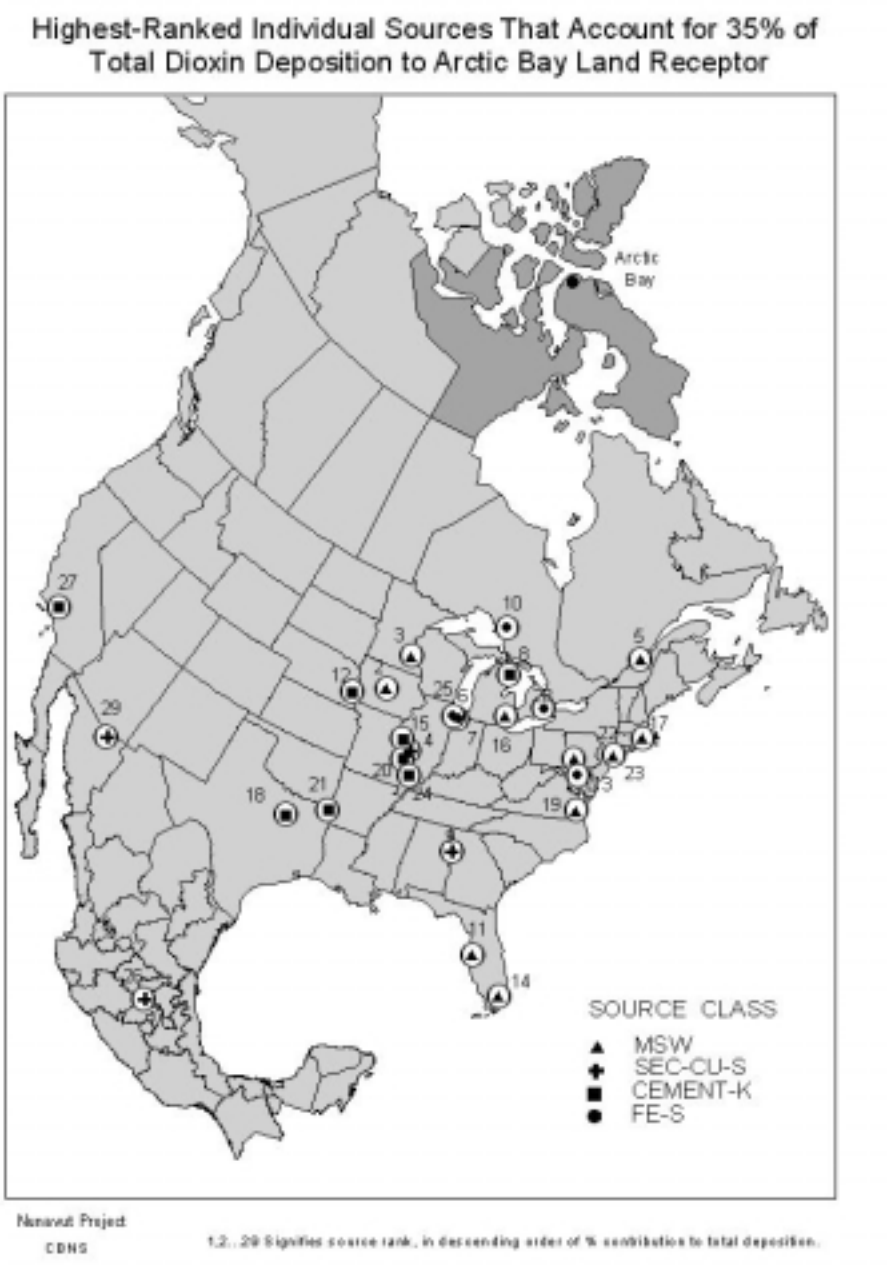
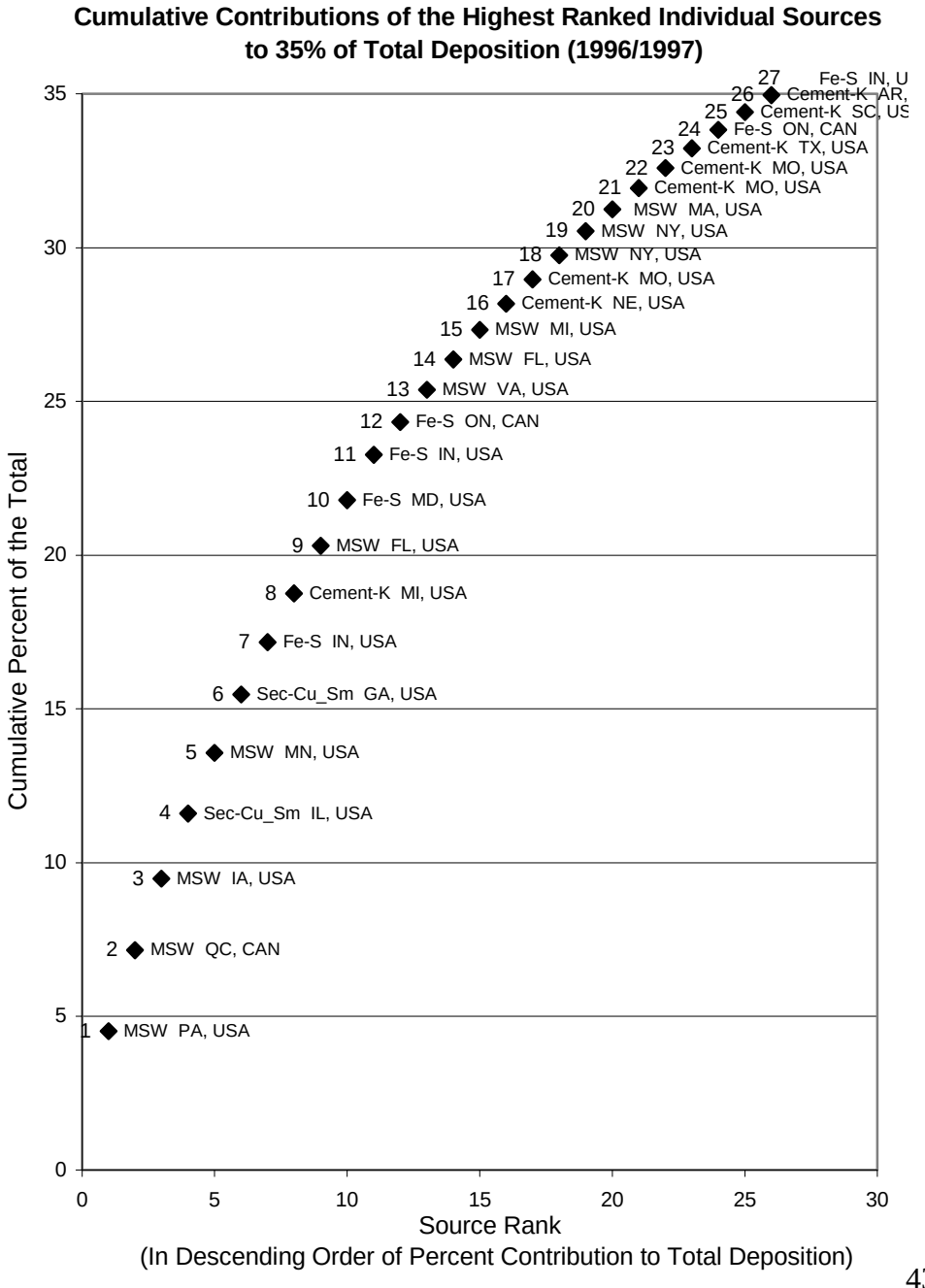


Figure 3.6B Broughton Island Land Receptor



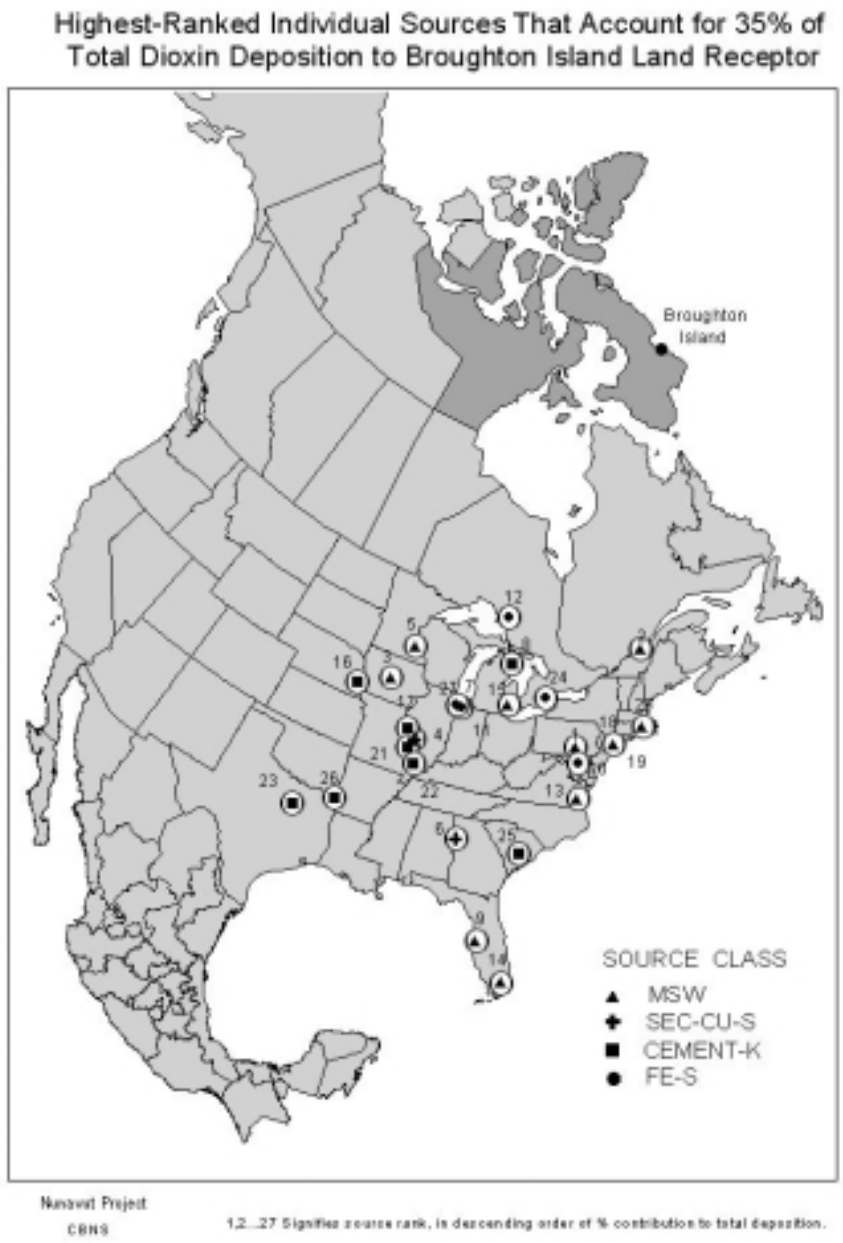
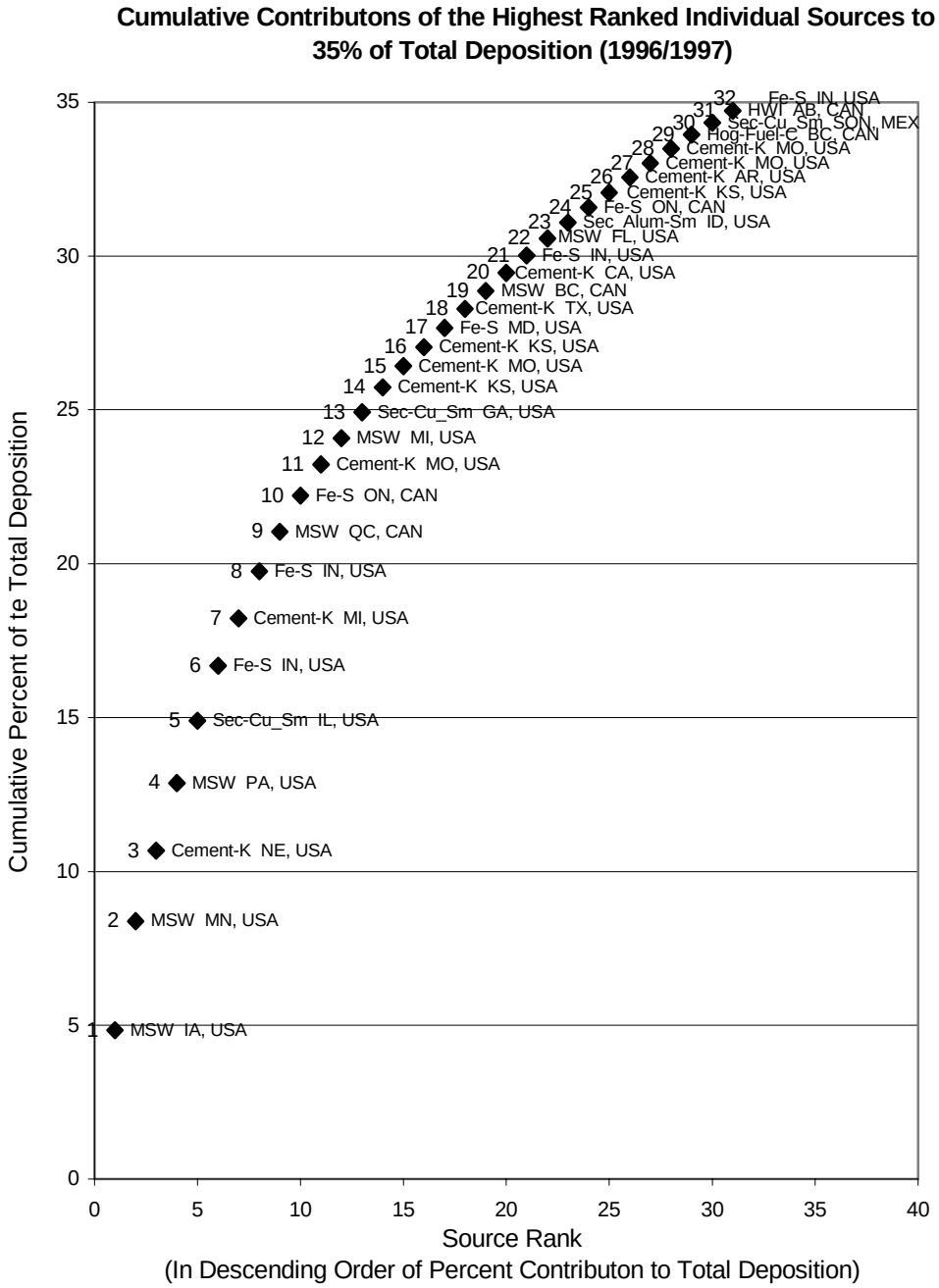


Figure 3.6C Chesterfield Inlet Land Receptor



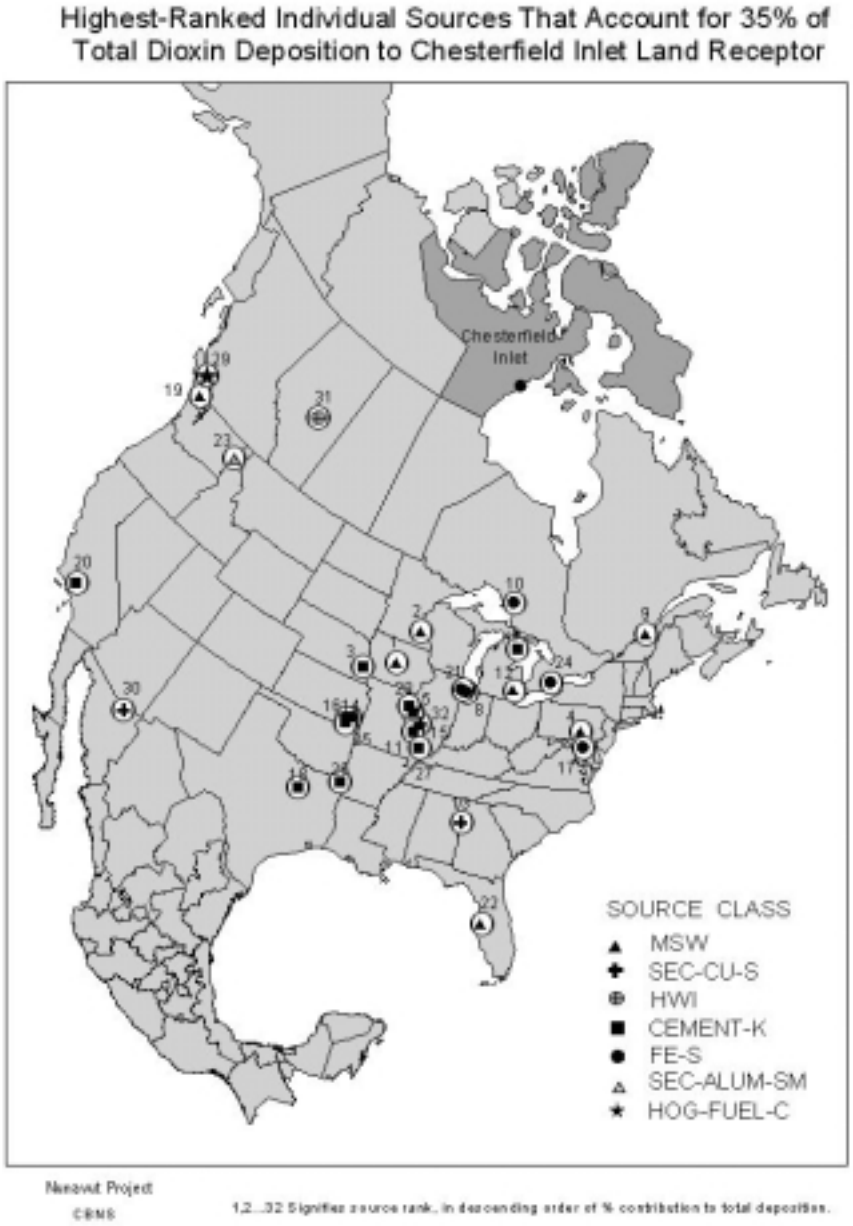


Figure 3.6D Coral Harbour Land Receptor

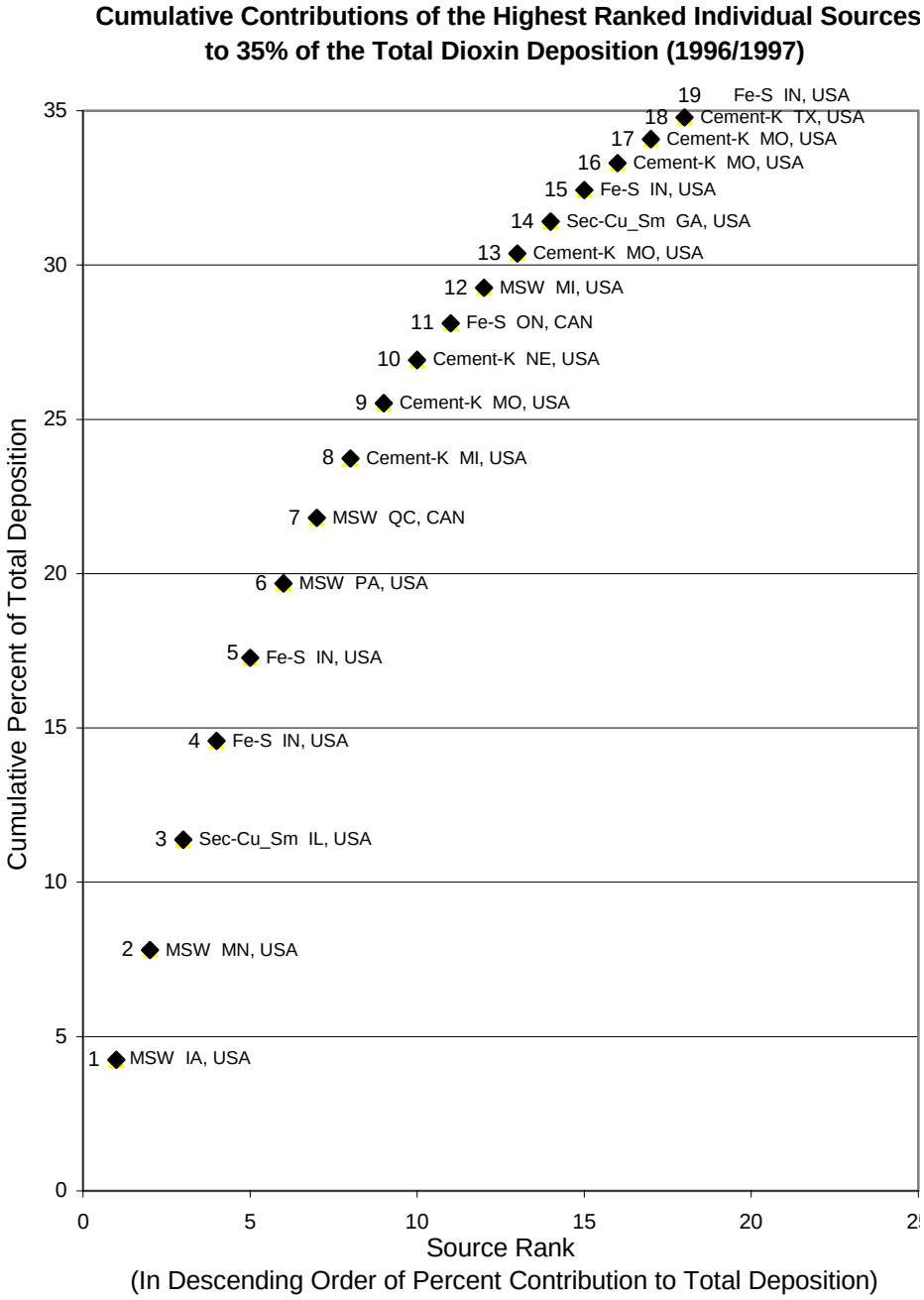


Figure 3.6E Igloolik Land Receptor

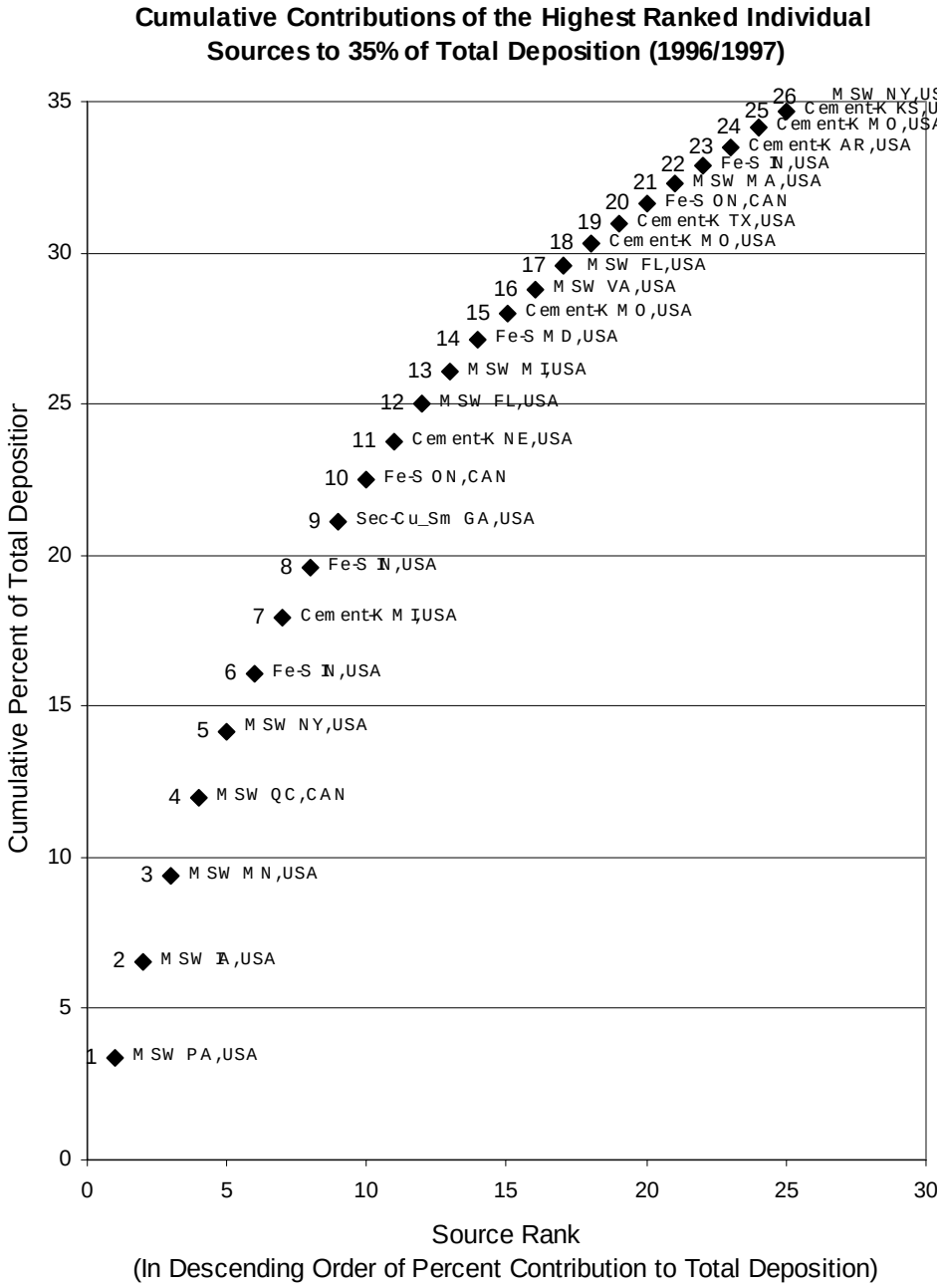
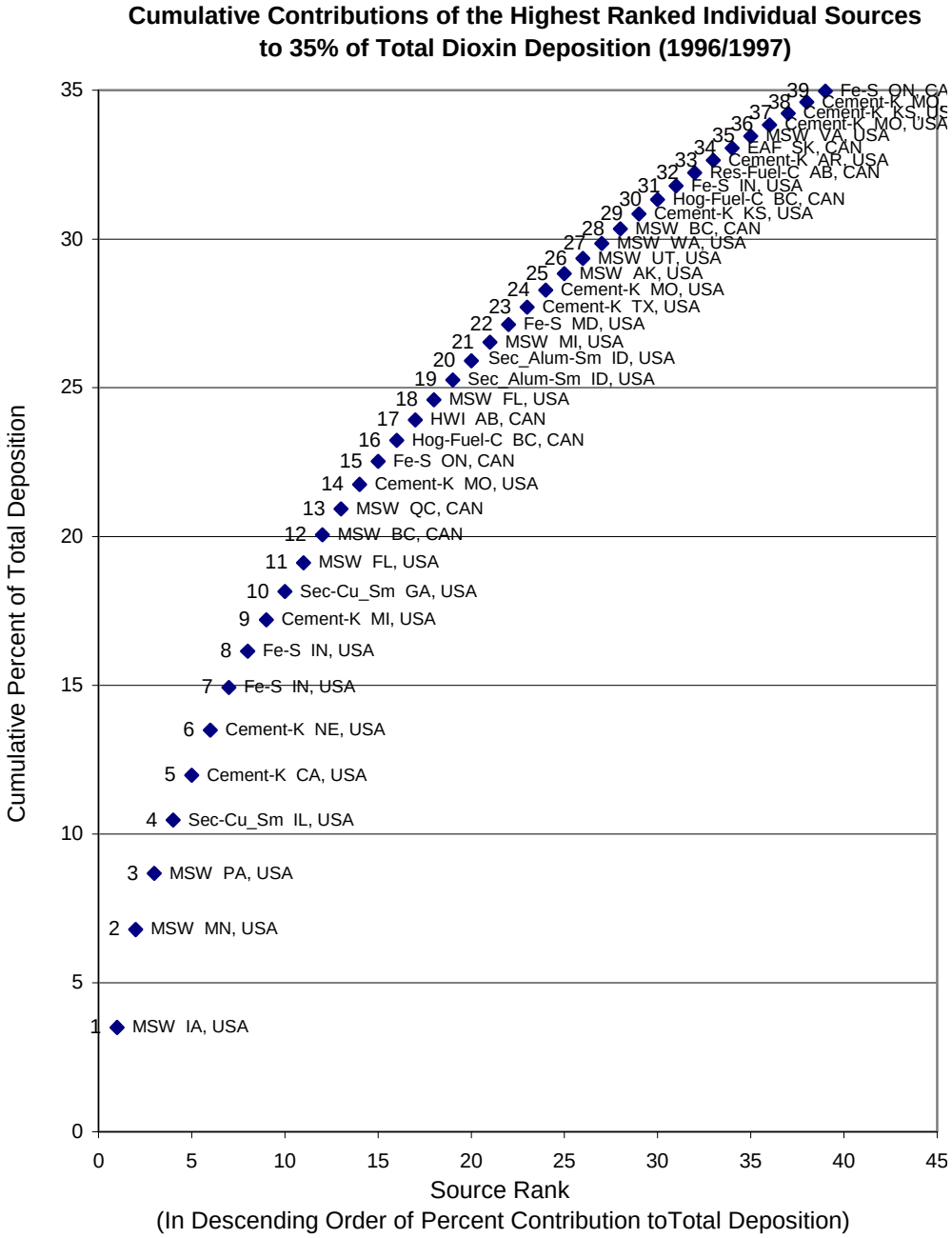


Figure 3.6F Ikaluktutiak Land Receptor



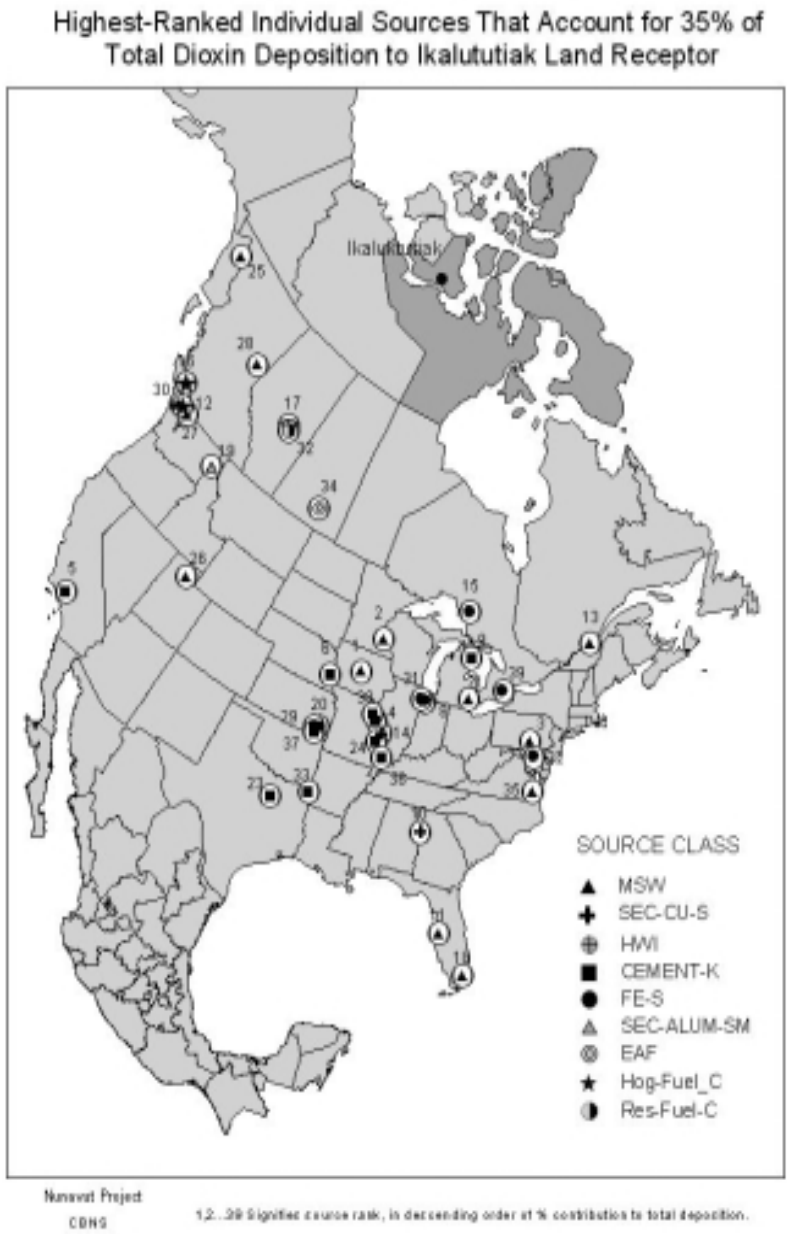
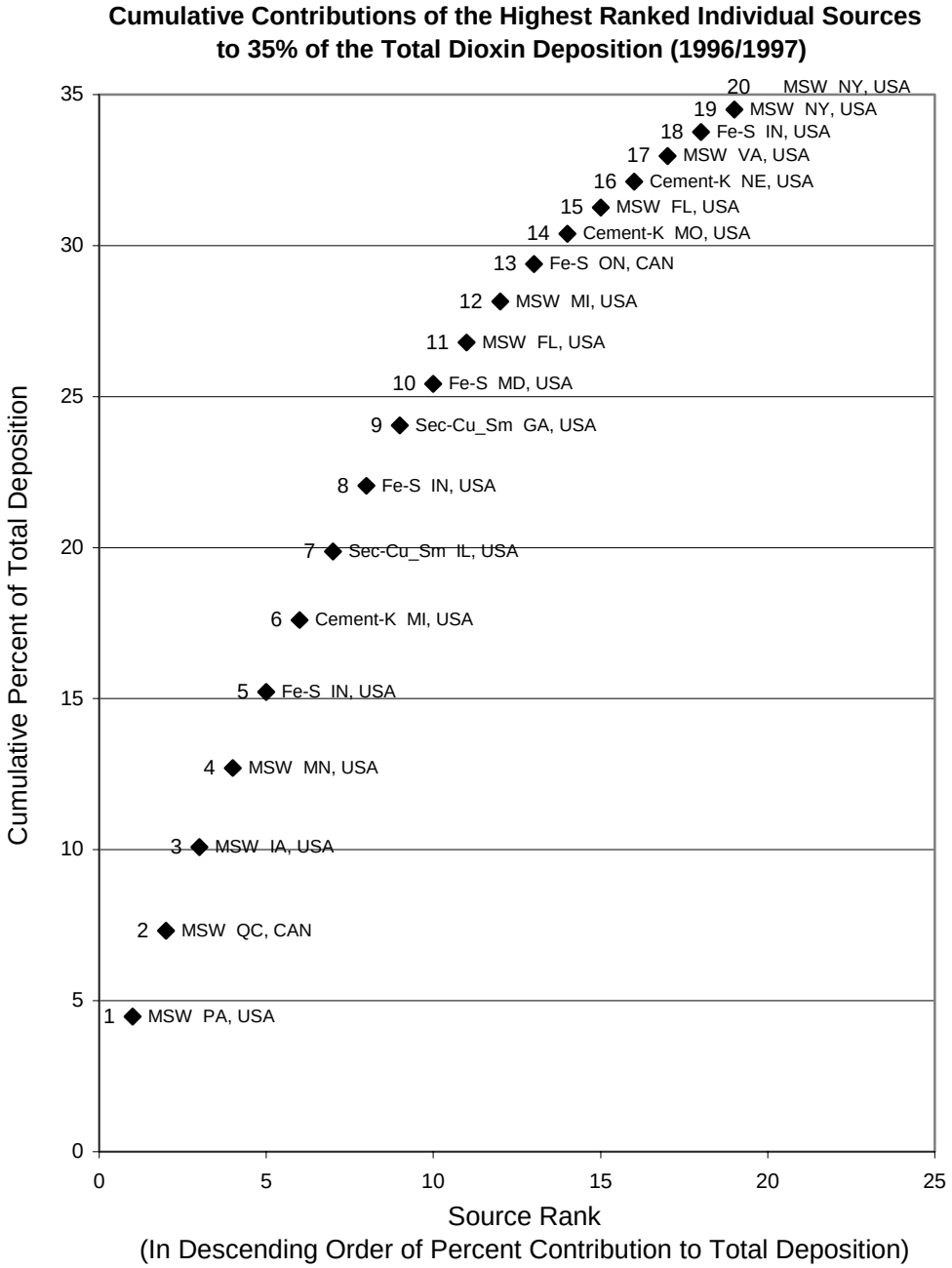


Figure 3.6G Iqaluit Land Receptor



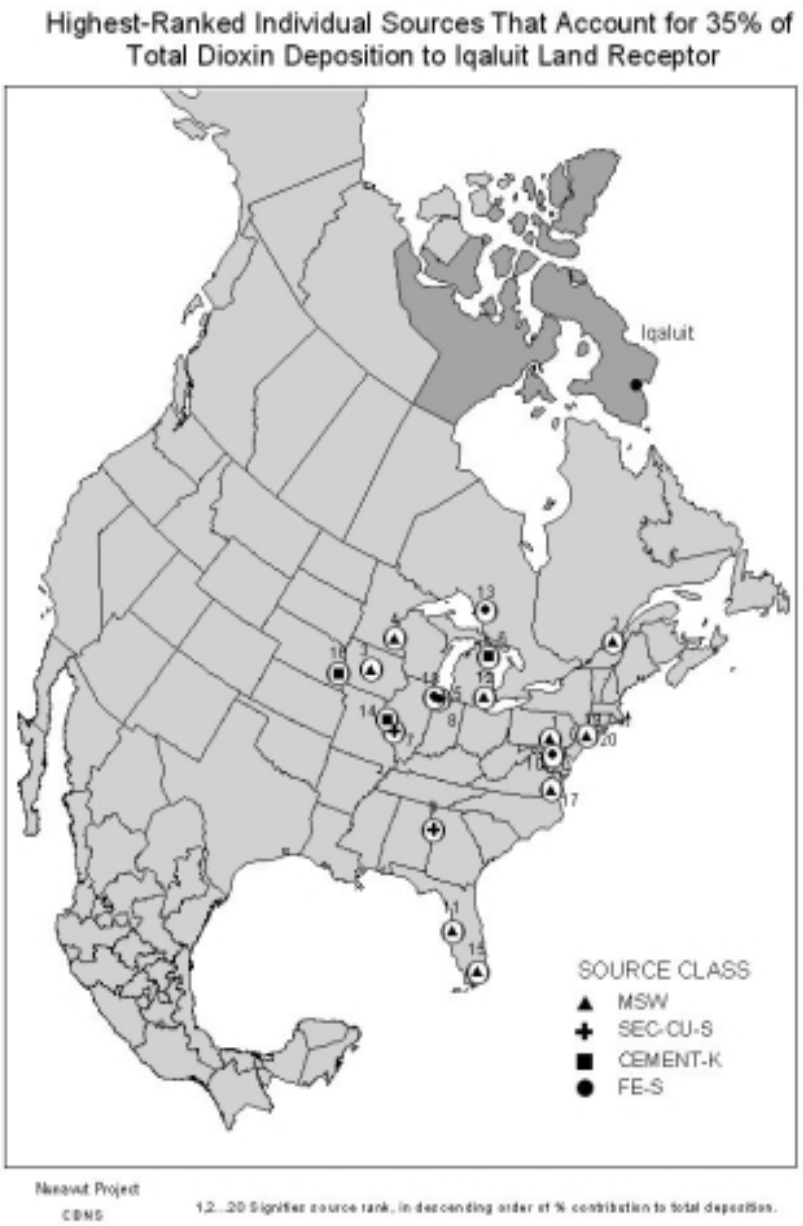
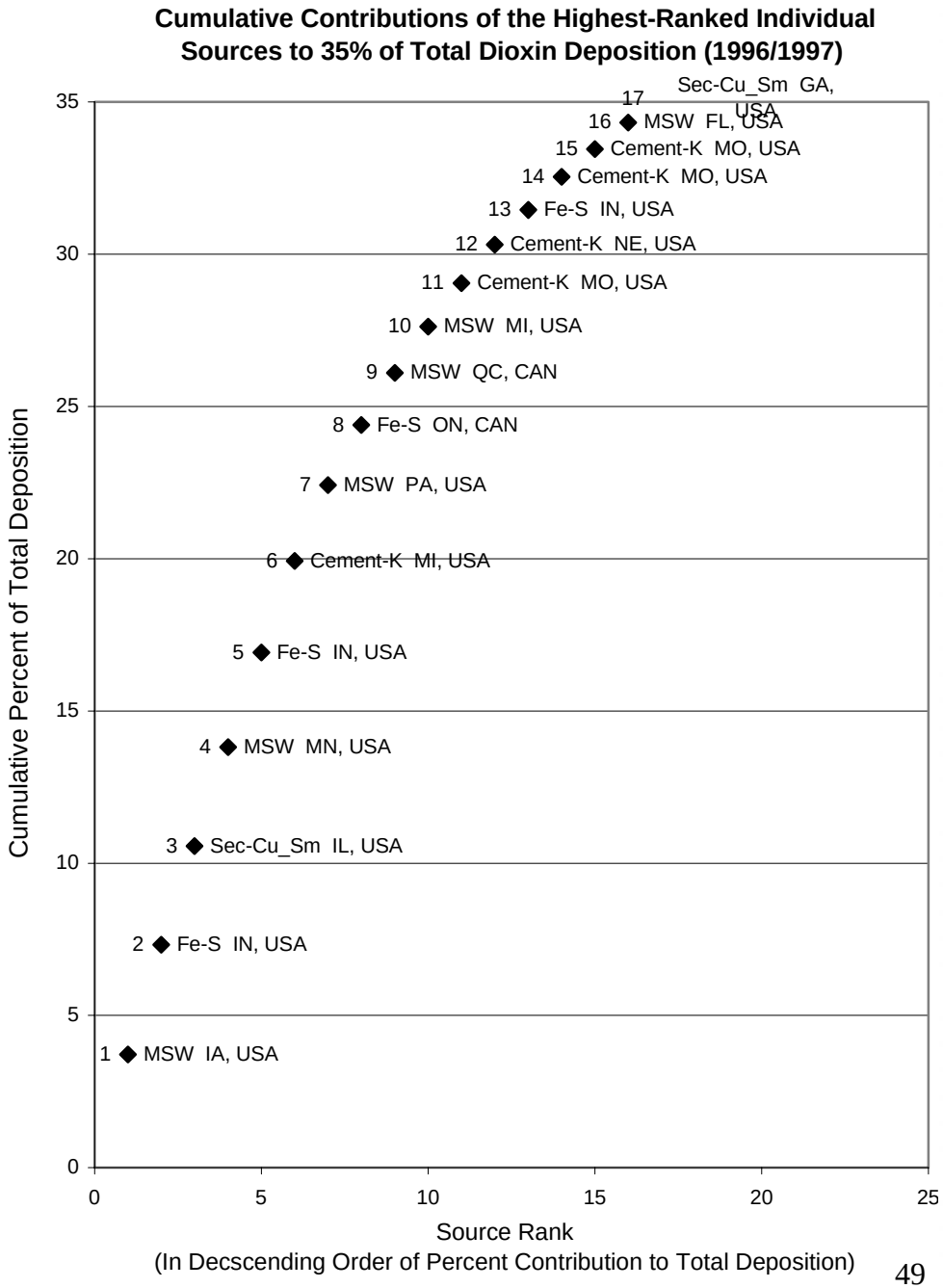


Figure 3.6H Sanikiluaq Land Receptor



3.5 Analysis of Source/Receptor Relationships

The preceding sections quantify the relative contributions of different sources and categories of sources to the amounts of dioxin deposited at the Nunavut receptors. They show that these amounts vary among the eight receptor sites and also, at the same site, between land and marine receptors. While these data suffice to rank the sources with respect to their contribution to the exposure of the receptors to airborne dioxin, they do not explain the physical basis for these differences. That issue is considered in what follows.

Several major factors determine the amount of dioxin emitted from a specific source that is deposited at a particular receptor: the rate at which dioxin is emitted by the source; the geographic distance between the source and the receptor; the wind direction and velocity *en route*; the rate at which dioxin is destroyed and deposited *en route*; the frequency and intensity of precipitation at the receptor and its physical characteristics. The fate of airborne dioxin as it travels from source to receptor is affected by meteorological conditions as well: temperature will affect vapor/particle partitioning, and since these two states differ in their deposition rate, will influence overall deposition as well; rain and snow will tend to increase deposition rate, especially of dioxin in the particle phase both *en route* and at the receptor itself. Finally, all of the factors that influence the fate of airborne dioxin will be affected by the duration of transport from source to receptor, which depends on the distance traveled; this in turn depends on the *geographic* source-to-receptor distance as well as the wind direction and velocity. The distance traveled may be considerably greater than the geographic source-receptor difference, since wind directions are likely to vary considerably *en route*.

This complex set of processes is conveniently encompassed in terms of transport efficiency, which is expressed as the fraction of the dioxin emitted by a source that is deposited at the receptor, i.e., the Air Transport Coefficient (ATC). The amount of dioxin emitted by the source that is deposited at the receptor (the model output) can be expressed as:

Amount deposited at receptor = ATC x amount emitted by source.

3.5.1 The relation among source emission, the air transport coefficient, and deposition at the Ikaluktutiak land receptor

To illustrate how the interaction between the source emission rate and the efficiency of dioxin air transport crucially determines the impact of an individual source on a specific receptor, we discuss here, as an example, the effect of different sources on deposition at the Ikaluktutiak land receptor. For this purpose, we consider the relative effects of the 39 highest-ranked sources that account for 35 percent of the dioxin deposition on this receptor.

Figure 3.7A shows the location of these sources, color-coded to reflect their respective rates of dioxin emission, and marked to show their ranking *with respect to this factor.* The highest emissions are exhibited by sources generally southeast of Ikaluktutiak, in the Midwest and eastern region of the United States, as far south as Florida. The map also shows that there are a number of relatively small sources southwest of Ikaluktutiak in Alaska, the U.S. Northwest, and western Canada. The numerous sources in the eastern half of the United States include all but one of the sources ranked first to 28th in emission rate. The source ranked 24th is in California.

Figure 3.7B is a map of the same 39 sources, ranked with respect to their *percent contribution to the total deposition* at the receptor. There are significant changes in the ranking of most of the sources in comparison with their emission ranking. All of the sources in the western regions of Canada and the United States are ranked higher in their contribution to deposition at the receptor than they are in emission rate. The reverse is true among the sources in the eastern region of the United States. For example, the two sources in Florida ranked first and second in emissions are ranked 18^{th} and 11^{th} with respect to their contribution to dioxin deposition at Ikaluktutiak. Since, as indicated above, the amount of dioxin deposited at the receptor is the product of the amount emitted by the source and the Air Transport Coefficient, such changes in ranking reflect differences in the efficiency of source-to-receptor air transport (i.e., ATC) among the various sources.

The ATC (which is a dimensionless ratio) for dioxin air transport between each of the 39 sources and the Ikaluktutiak receptor can be computed from the relationship:

$$ATC = Deposition/Emission$$

Figure 3.7C maps the 39 sources, now ranked with respect to their ATCs for transport (and deposition) to Ikaluktutiak. (Here the color code is identical with that used in maps of the overall geographic distribution of ATC values, shown in Figures 3.12 to 3.15B, below, in order to facilitate comparison with Figure 3.7C.) In Figure 3.7C the ATCs tend to fall into fairly distinct geographic groups. The sources southeast of Ikaluktutiak in the eastern region of the United States, and in the eastern part of the U.S. Midwest, are characterized by relatively low ATCs. A group of sources generally south of this receptor, in the western region of the U.S. Midwest, have intermediate ATCs. The sources southwest of the receptor (which are relatively close to it) in western Canada, the U.S. Northwest and California, have the highest ATCs. Such assessments of air transport efficiency reflect the joint effect of source-to-receptor distance and the nature of the intervening weather patterns. The influence of source-receptor geographic distance can be seen in the group of sources southwest of Ikaluktutiak, in which the ATC value decreases sharply with distance in that direction.

To illustrate the role of geographic orientation, and hence of weather pattern, on the efficiency of air transport, it is useful to examine the ATCs of a group of sources that are approximately equidistant, geographically, from the Ikaluktutiak receptor. As indicated in Figure 3.7C, for this purpose the sources that lie in a 1000 km zone with a radial distance of 3100 ! 500 km from Ikaluktutiak have been identified. In Table 3.3, the ATC of each of these 17 sources is shown, together with its longitude, which indicates the source's geographic orientation relative to the receptor. The relationship between the ATCs and the longitudes of the 17 sources is plotted in Figure 3.8. It is evident that, within a reasonable range of variation (due to the sources' actual distances from the receptor within the 1000 km-wide zone), ATC varies significantly with longitude. The average ATC for the six sources southwest of the receptor ($0.0075x10^{-12}$) is about five times greater than the average ATC for the nine sources southeast of the receptor ($0.0015x10^{-12}$). Moreover, there appears to be a progressive order of magnitude increase in ATC with increasing longitude (i.e., westward).

Figure 3.7A
Dioxin Emissions Due to the Highest-Ranked Sources (39) Contributing to 35% of the Total Dioxin Deposition at Ikaluktutiak Land Receptor.

(Numbers show emission rank)

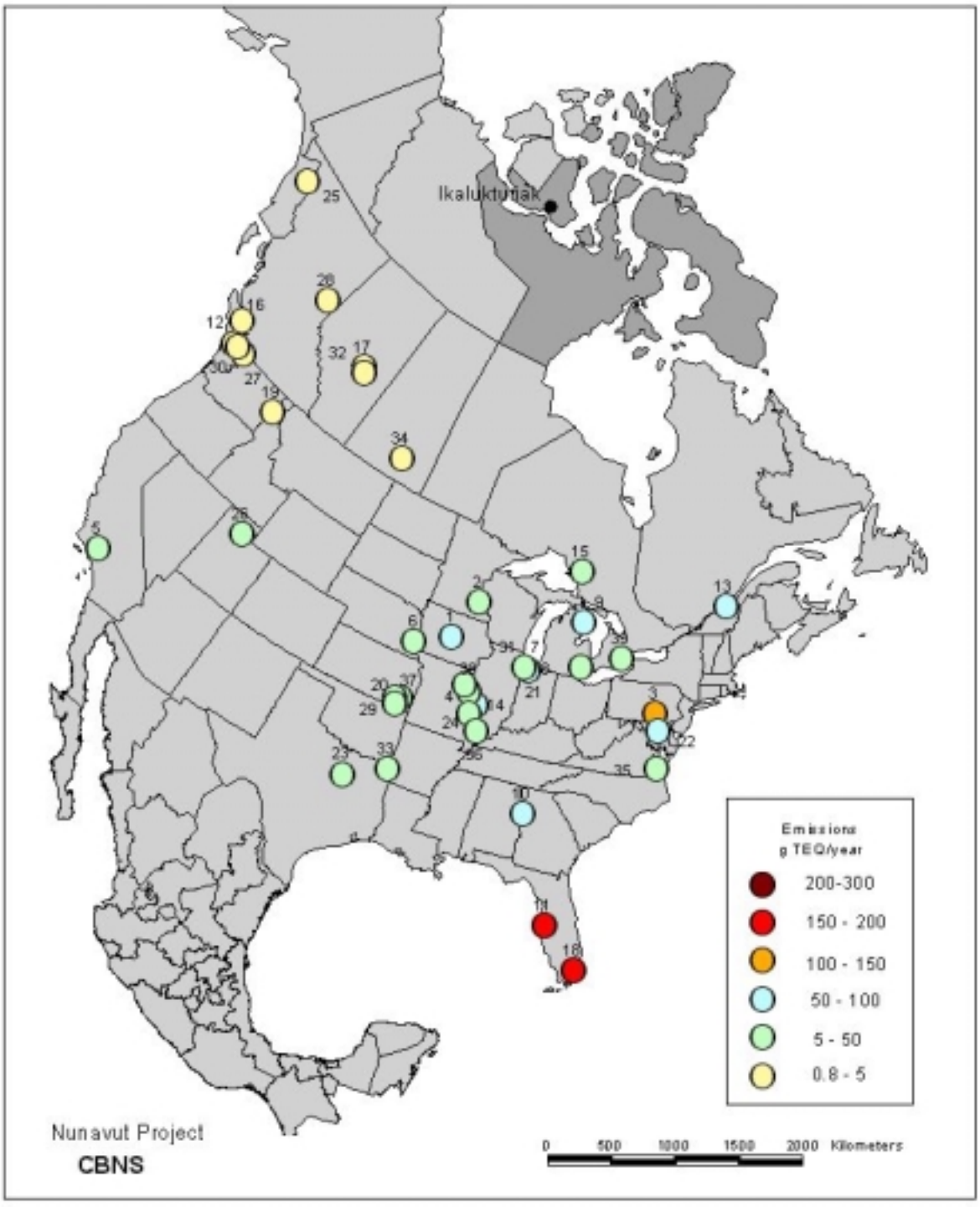


Figure 3.7B
Dioxin Deposition Due to the Highest-Ranked Sources (39) Contributing to 35% of the Total Dioxin Deposition at Ikaluktutiak Land Receptor.
(Numbers show deposition rank)

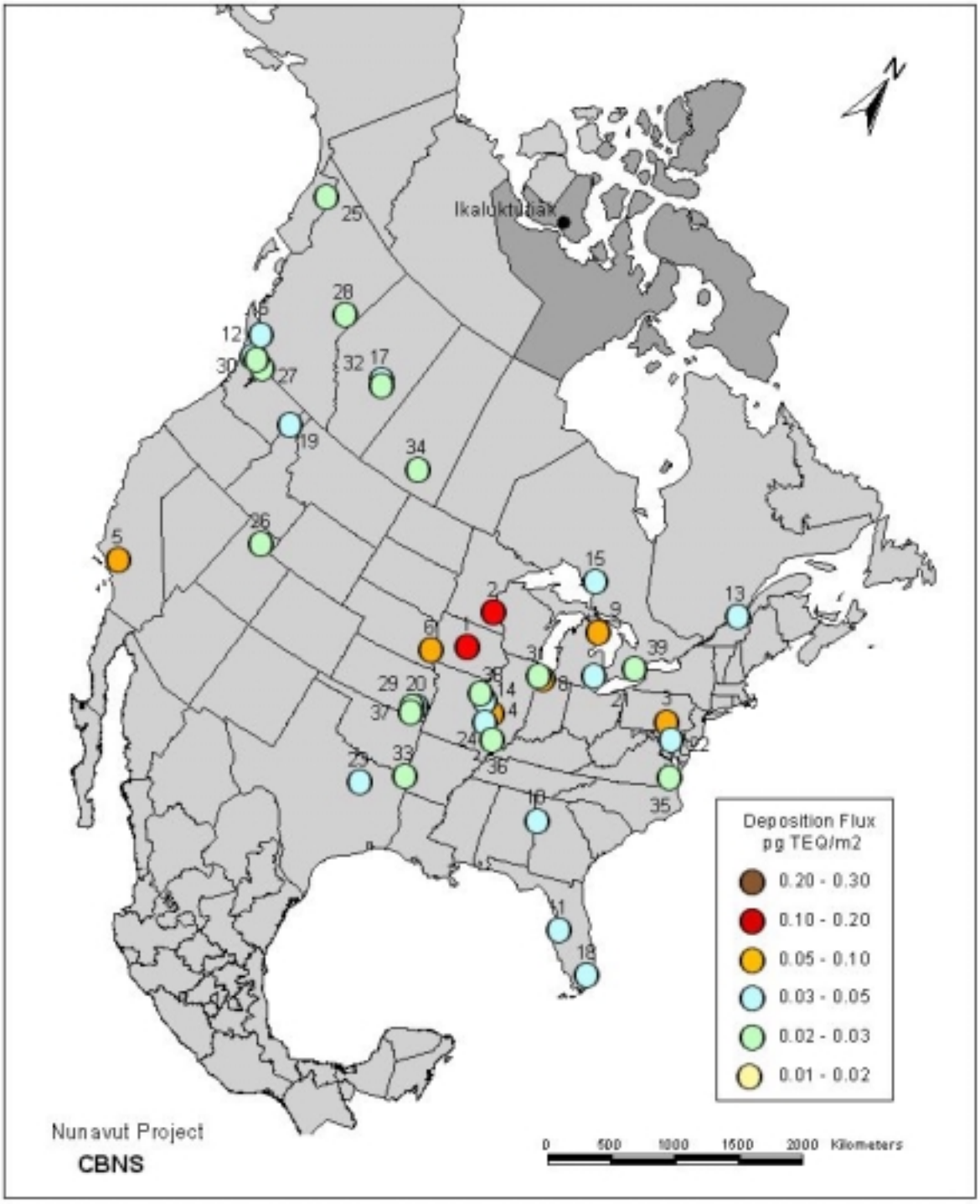


Figure 3.7C
Air Transport Coefficients of the Highest-Ranked Sources (39)
Contributing to 35% of the Total Deposition at Ikaluktutiak Land Receptor.
(Numbers indicate Air Transport Coefficient rank)

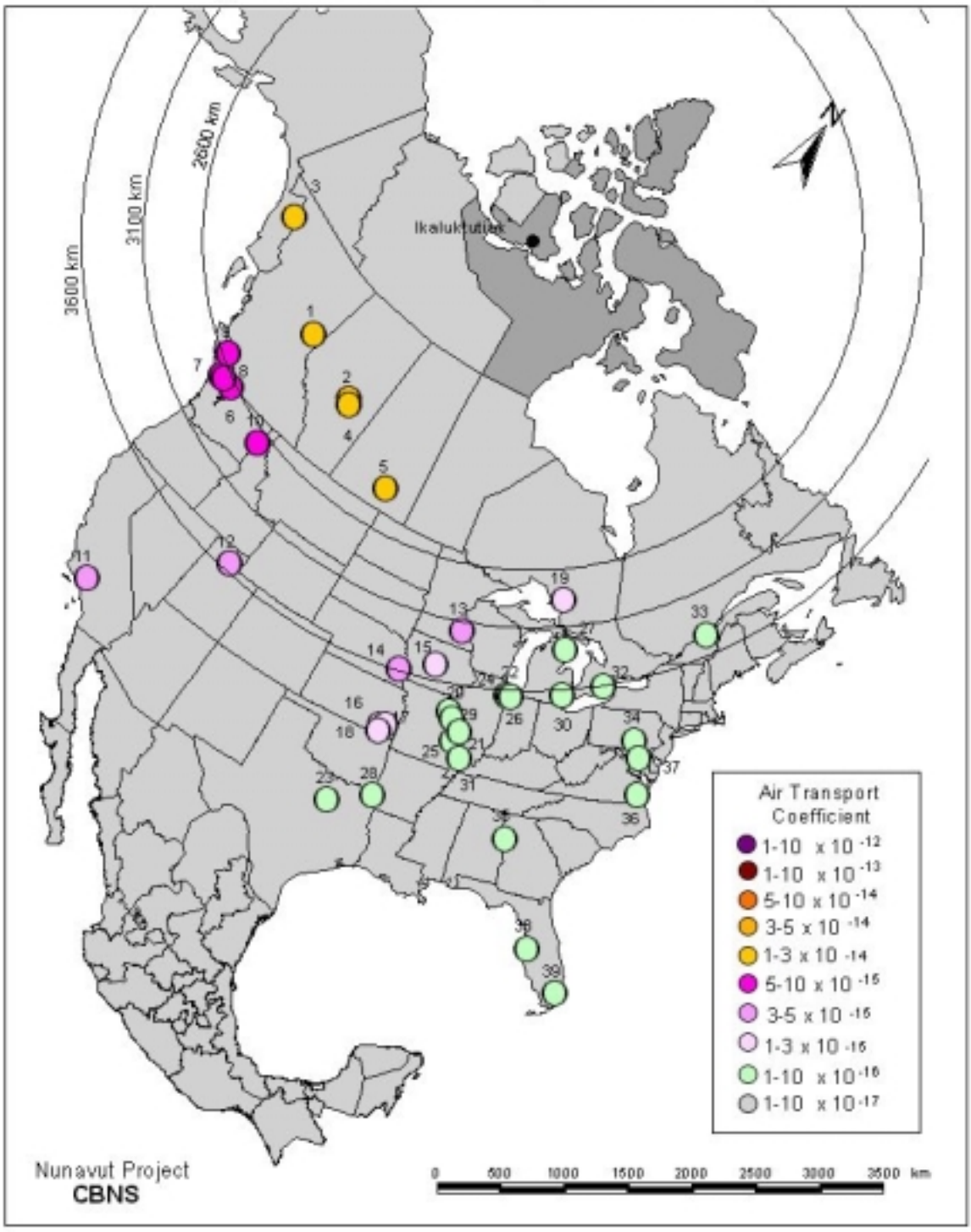


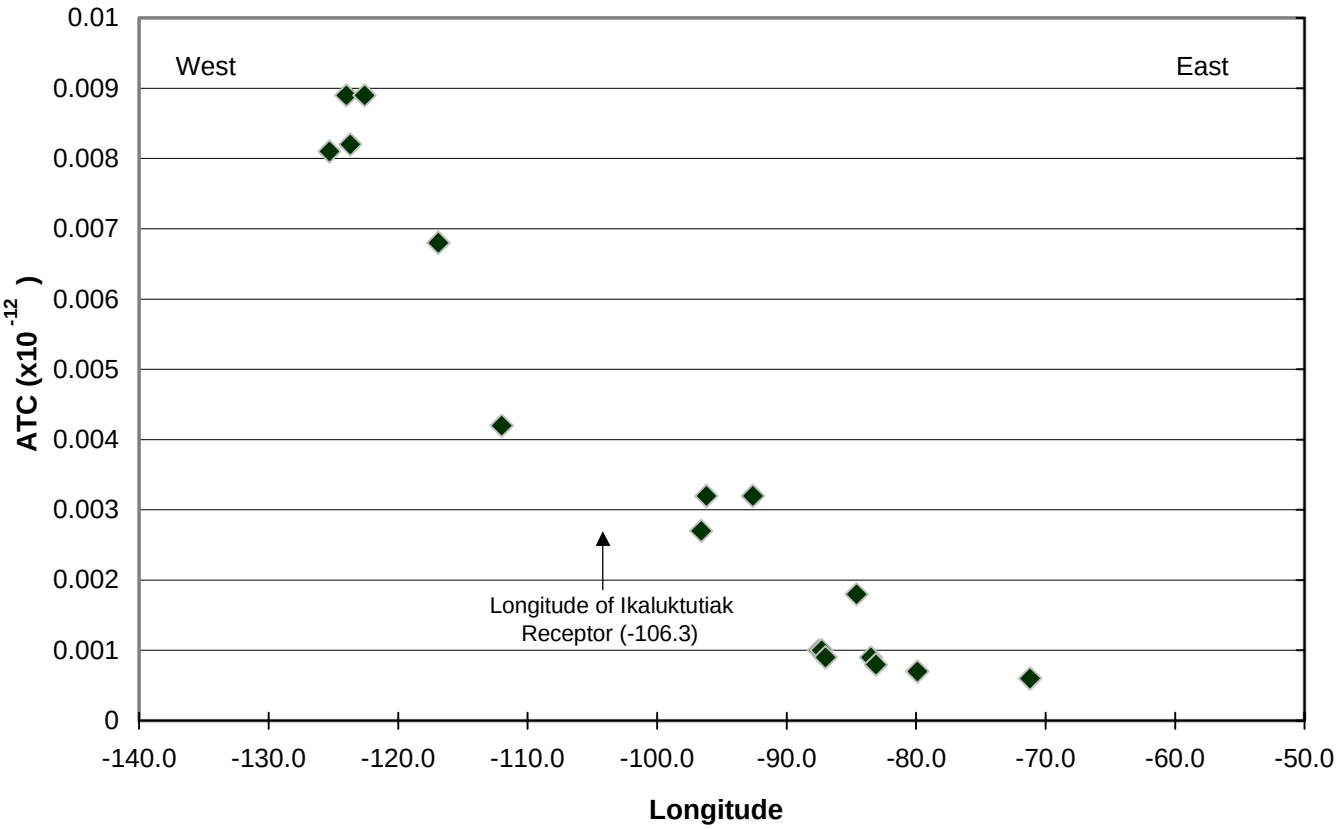
Table 3.3 Highest Sources Contributing to 35 Percent of Dioxin Deposition at Ikaluktutiak Land Receptor and Approximately Equidistant (3100 ! 500 km) from Receptor:

Relation between ATC and Longitude*

Source	ATC ($x10^{-12}$)	ATC Rank	Longitude
MSW, WA-USA	0.0089	6	-122.6
MSW, BC-Can.	0.0089	7	-124.0
Hog Fuel, BC-Can.	0.0082	8	-123.7
Hog Fuel, BC-Can.	0.0081	9	-125.3
Sec. Al. Sm., ID-USA	0.0068	10	-116.9
MSW, UT-USA	0.0042	12	-112.0
Average	**0.0075**		
MSW, MN-USA	0.0032	13	-92.6
Cem.K., NE-USA	0.0032	14	-96.2
MSW, IA-USA	0.0027	15	-96.6
Fe.S., ON-Can.	0.0018	19	-84.6
Fe.S., IN-USA	0.0010	22	-87.5
Fe.S., IN-USA	0.0010	24	-87.3
Fe.S., IN-USA	0.0009	26	-87.0
Cem.K., MI-USA	0.0009	27	-83.5
MSW, MI-USA	0.0008	30	-83.1
Fe.S., ON-Can.	0.0007	32	-79.9
MSW, QC-Can.	0.0006	33	-71.2
Average	**0.0015**		

*Longitude of Ikaluktutiak land receptor: -106.3

Figure 3.8 Relation Between Air Transport Coefficient (ATC) and Longitude for Highest Sources that Contribute to 35% of Dioxin Deposition at Ikaluktutiak Land Receptor and are Aproximately Equidistant (3100±500 km) from Receptor



Thus, there appears to be a significant variation in the *weather-dependent* component of the efficiency of dioxin air transport from the various sources to the Ikaluktutiak receptor. In particular, there appear to be clearly distinguishable weather patterns that, with different degrees of intensity, carry airborne dioxin from sources southeast, south and southwest of this receptor. As noted in Section 3.5.2.2 below, this conclusion is confirmed by monthly maps of ATCs for air transport between Ikaluktutiak and a general array of source sites.

3.5.2 A generalized analysis of source-receptor relations

As a means of more generally demonstrating the interactions among emissions from *all* of the sources, air transport efficiency, and the resulting deposition of dioxin at all of the receptors, the relevant data on these factors have been collated on a common polar stereographic 100x100 kilometer grid. Thus, each grid zone is treated as an individual source, with the total dioxin collective output of all the separate sources within the zone emitted from its centroid.

3.5.2.1 The geographic distribution of dioxin emissions

In Figure 3.9 the annual emissions from the entire North American dioxin inventory are plotted on the grid; the sum of the annual emissions of all the sources in each grid zone are color-coded to indicate the total grams TEQ of dioxin emitted annually (1996-97) in that zone. Certain features of this map are noteworthy. First, it is evident that the area of Nunavut is entirely free of sources that emit more than 0.01-0.1 gram TEQ, and there appears to be only one such source within 500 km of Nunavut's border. In sum, with respect to *local sources*, Nunavut is a virtually dioxin-free territory. Second, the map clearly depicts the high concentration of dioxin sources in the eastern half of the United States, with particularly intense corridors of sources along the entire eastern coast extending to Nova Scotia, in the Midwest, and between Minnesota and Texas. Finally, the intense level of dioxin emission from Mexican sources, especially in the central region, is largely due to backyard trash burning, which accounts for about half of the country's total emissions. This necessarily reflects population density.

While Figure 3.9 is representative of the geographic distribution of the emissions from 44,091 North American dioxin sources, it is useful to compare it with the distribution of the most intense of these numerous sources. This is shown in Figure 3.10, which maps the location of the highest-ranked sources that account for 35 percent of the dioxin emissions in North America. Together, these sources account for 23-35 percent of the dioxin deposition, depending on the receptor. It is apparent that these large sources are chiefly responsible for the dominant emissions from the eastern half of the United States. None of such large sources are in the section of the United States west of the Minnesota-Texas line. There are a number of large sources in Mexico, most of them cement kilns burning hazardous waste. However, as noted earlier, the qualitative estimates of the Mexican sources should be regarded as preliminary, for they are significantly less certain than the emission estimates for U.S. and Canadian sources.

3.5.2.2 The geographic distribution of source to receptor transport efficiency (ATC)

It is of interest to plot the geographic distribution of the efficiency of dioxin transport from *hypothetical* source points evenly distributed throughout North America. This provides a general

Figure 3.9

Geographic Distribution of Annual Dioxin Emission from North American Sources, 1996-1997

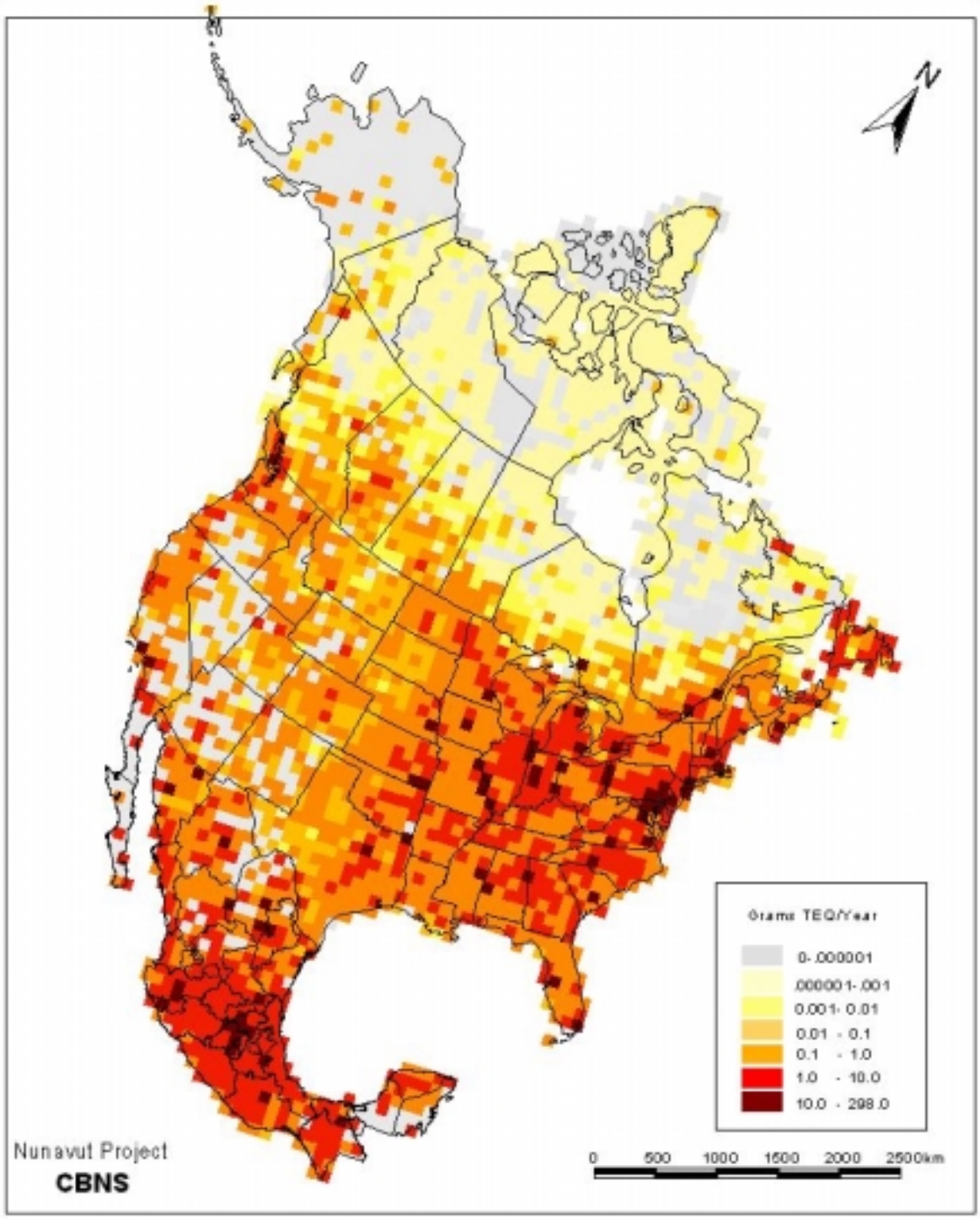
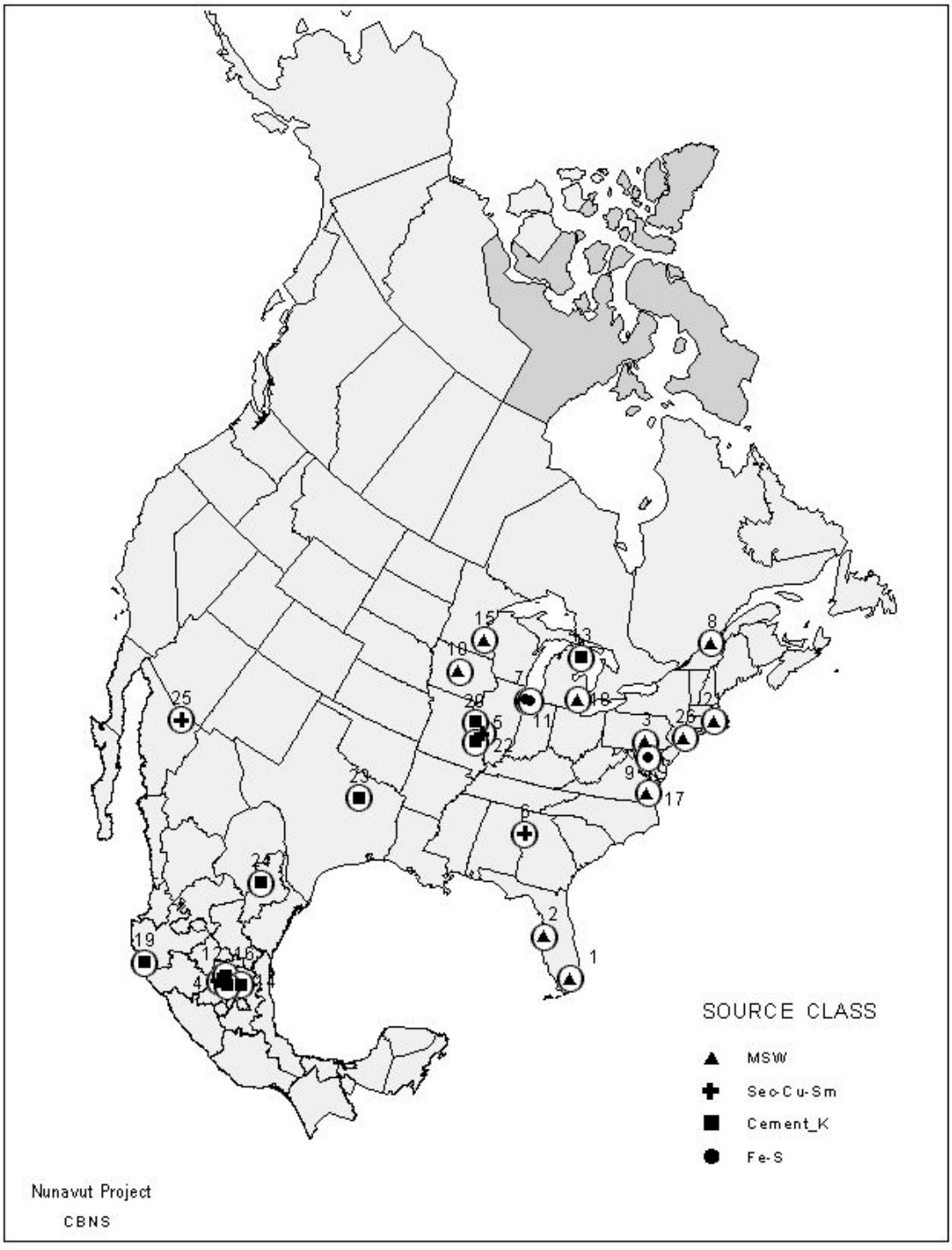


Figure 3.10

Highest-Ranked Individual Sources that Account for 35% of Total Dioxin Emissions



map that predicts the ATC value for a source located anywhere in North American to any one of the selected Nunavut receptors. For this purpose, the model estimated the deposition, at a given receptor, of the fraction of a unit amount of dioxin (one gram) emitted from each of the 2,988 hypothetical sources uniformly distributed geographically on the same 100x100 km grid that was employed to map the *actual* source emissions shown in Figure 3.8.

Figure 3.11 illustrates the effect of the atmospheric fate on the Air Transport Coefficient of two individual dioxin congeners, TCDD and OCDD, that differ in their behavior during air transport. Of the two congeners, OCDD is more attached to particles and hence less prone to degradation *en route*, and, for the same reason, more readily deposited to receptors. Dioxin congeners that are attached to particles are more easily removed and deposited by precipitation and are also more efficiently deposited into water. Both of these effects tend to increase the efficiency of air transport and hence the transport distance that results in a given ATC value. Thus, while the zone ATC=1-3x10^{-14} for TCDD transport extends from the Nunavut receptor at Coral Harbour to the U.S.-Canadian border, in the OCDD map that zone extends much further, to the northern border of Texas. (Given the long transport distances between the sources and the Nunavut receptors, the fraction of the emitted dioxin that is deposited at the receptors is very small.) The succeeding ATC maps, Figures, 3.12 to 3.15, are based on the emission of a unit amount of dioxin expressed as TEQ and therefore accounts for the behavior of the entire array of PCDD/PCDF congeners.

Figure 3.12 compares the ATC maps of the most northern land receptor, Arctic Bay, and the most southern land receptor at Sanikiluaq. The maps define successive zones, centered around the receptor, of progressively smaller values of ATC so that the most distant zones, for example in Mexico or Florida, represent the smallest fraction of the unit emission that is deposited at the receptor. Thus, in the map for deposition at Sanikiluaq the ATC value declines from 1x10^{-12} for sources in northern Quebec closest to the receptor (about 500 km), to 1x10^{-17}, or five orders of magnitude lower, for the sources in southern Mexico some 4,500 km distant. This exponential reduction in ATC with air transport distance is commonly observed and arises largely from the effect of diffusion and dispersion of the original amount of dioxin emitted at the source on the airborne dioxin concentration. The concentration decreases exponentially with increased transport time; hence, *en route* deposition decreases proportionally as well.

Figure 3.12 helps to account for the order of magnitude difference in the dioxin deposition at Sanikiluaq and Arctic Bay: 53 pg TEQ/m^2 at the Sanikiluaq land receptor and 4 pg TEQ/m^2 at the Arctic Bay land receptor. At each receptor deposition is the product of the rate of dioxin emission from the source and the ATC value characteristic of the source's geographic location, summed for all sources. Thus, deposition at the receptor is maximized when the geographic locations of high rates of emission and high values of ATC coincide. As can be seen in Figure 3.12, the eastern half of the United States, where the bulk of the North American dioxin emissions originate, is characterized by high ATC values; most of that area is characterized by ATCs of 1-5x10^{-14}. In contrast, for air transport to Arctic Bay this same area is characterized by much lower ATCs, between 10^{-15} and 10^{-16}. Part of this difference in the ATC values of these two receptors is due to source-to-receptor distance; Arctic Bay is about 1500 km more distant from the eastern half of the United States than Sanikiluaq.

Figure 3.11

Annual OCDD & TCDD Deposition Air Transport Coefficients to Coral Harbour, Land Receptor

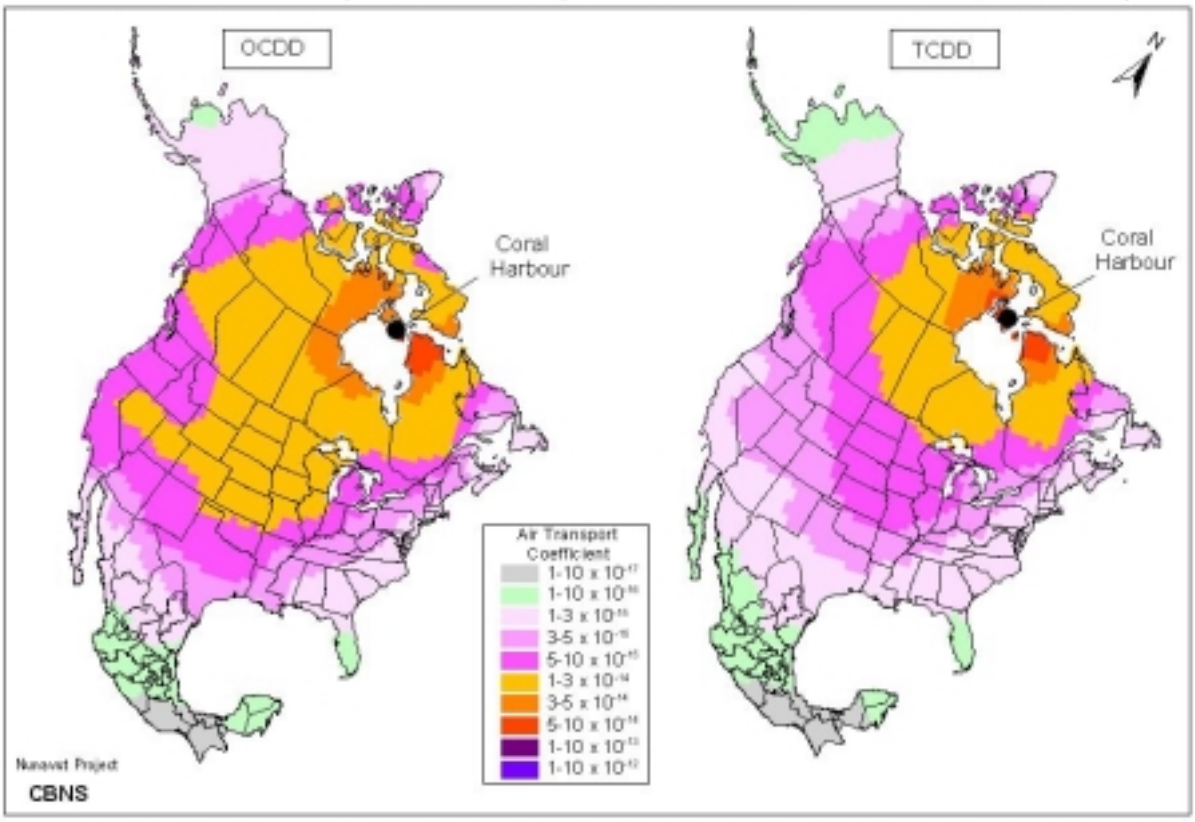
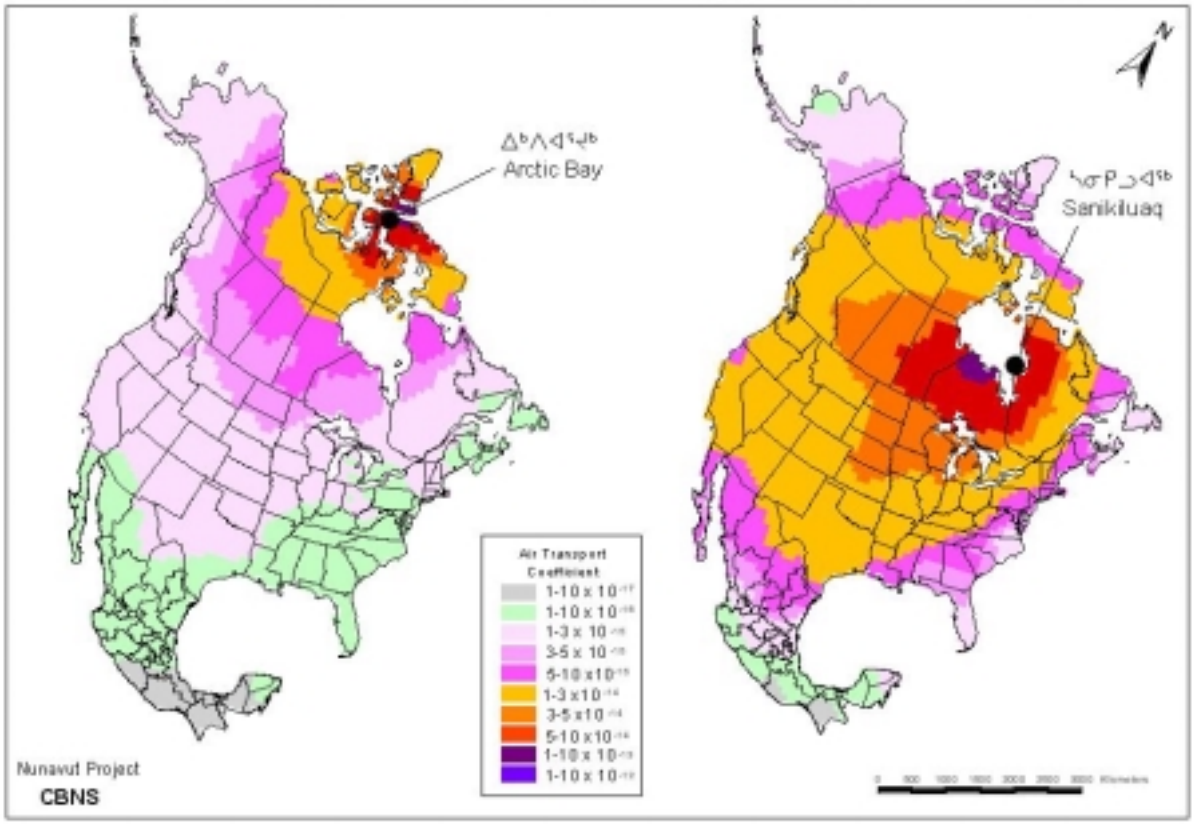


Figure 3.12

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



In Figure 3.12 the ATC zones depicted are average values for the one-year period July 1, 1996-June 3, 1997. As noted earlier, the ATC values represent the combined effect of the geographic source-to-receptor distance and of the intervening weather pattern. While the source-to-receptor distance is of course constant over time, the weather pattern is not, varying as it does even hourly. Accordingly, the *changes* that occur in the ATC map over time represent the effect of the *en route* weather pattern alone on the efficiency of air transport. These temporal changes will in turn lead to a parallel effect on the dioxin deposition flux at the receptor. Thus, by computing the ATC on a *monthly* basis, it is possible to analyze the degree to which the weather pattern *alone* influences deposition at the receptor. The results are illustrated by the maps in Figures 3.13A and B, which depict the monthly geographic distribution of ATC values, using the same color code employed in Figure 3.12, as well as the deposition flux during each month. (Note that deposition for July 1996 is artificially low; although the model operation begins on July 1, some time must elapse, which is as much as two weeks for Mexican sources, before dioxin emitted on that date reaches the receptor.)

Figure 3.13A, which describes monthly dioxin air transport to the Sanikiluaq land receptor, clearly reflects seasonal changes in the ATC that result in corresponding variations in the monthly deposition flux. In those months—August to December—in which the higher ATC zones, of the order of 10^{-14} or more, reach as far south as Mexico and, in particular, cover the area of intense dioxin emissions in the eastern half of the United States, the monthly deposition flux is correspondingly high (average: 6.8 pg/m^2). Conversely, in January and February, when only the lower ATC zones, 1-3x10^{-15} or less, cover the area of intense emissions, the deposition flux is lowest, 1.01 and 0.46 pg TEQ/m^2 respectively. The average deposition for the six-month period January-June, when only part of the area of intense emissions is affected by high ATCs, is only 2.4 pg TEQ/m^2.

Figure 3.13B describes the monthly variation in ATC zones for dioxin transport to the Arctic Bay land receptor. As expected from Figure 3.12, the ATC zones are highly constricted in range in comparison with Sanikiluaq. Although the values of deposition flux are an order of magnitude lower than those at the Sanikiluaq receptor and therefore less certain, there is a general correspondence between relatively high deposition values (for example, in September, October and December) and the presence of ATC values of 1-3x10^{-15} or more in areas of high dioxin emissions.

Figure 3.14 compares the ATC maps for the most western receptor, at Ikaluktutiak, and the most eastern receptor, at Broughton Island. There is a significant increase in air transport efficiency to Broughton Island from the eastern region of the United States (where dioxin emissions are intense) as compared with that characteristic of Ikaluktutiak. On the other hand, the zone for ATC=3-5x10^{-15} on the Ikaluktutiak map extends further south into the western United States. In general, the weather system favors the transport of dioxin from the relatively weakly emitting sources in the western part of Canada and the United States to Ikaluktutiak and favors transport from the intensely emitting sources in the eastern United States to Broughton Island. As a result, deposition at Broughton Island land receptor (9 pg TEQ/m^2) is about twice that at the Ikaluktutiak land receptor (4 pg TEQ/m^2).

Figure 3.13 A

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

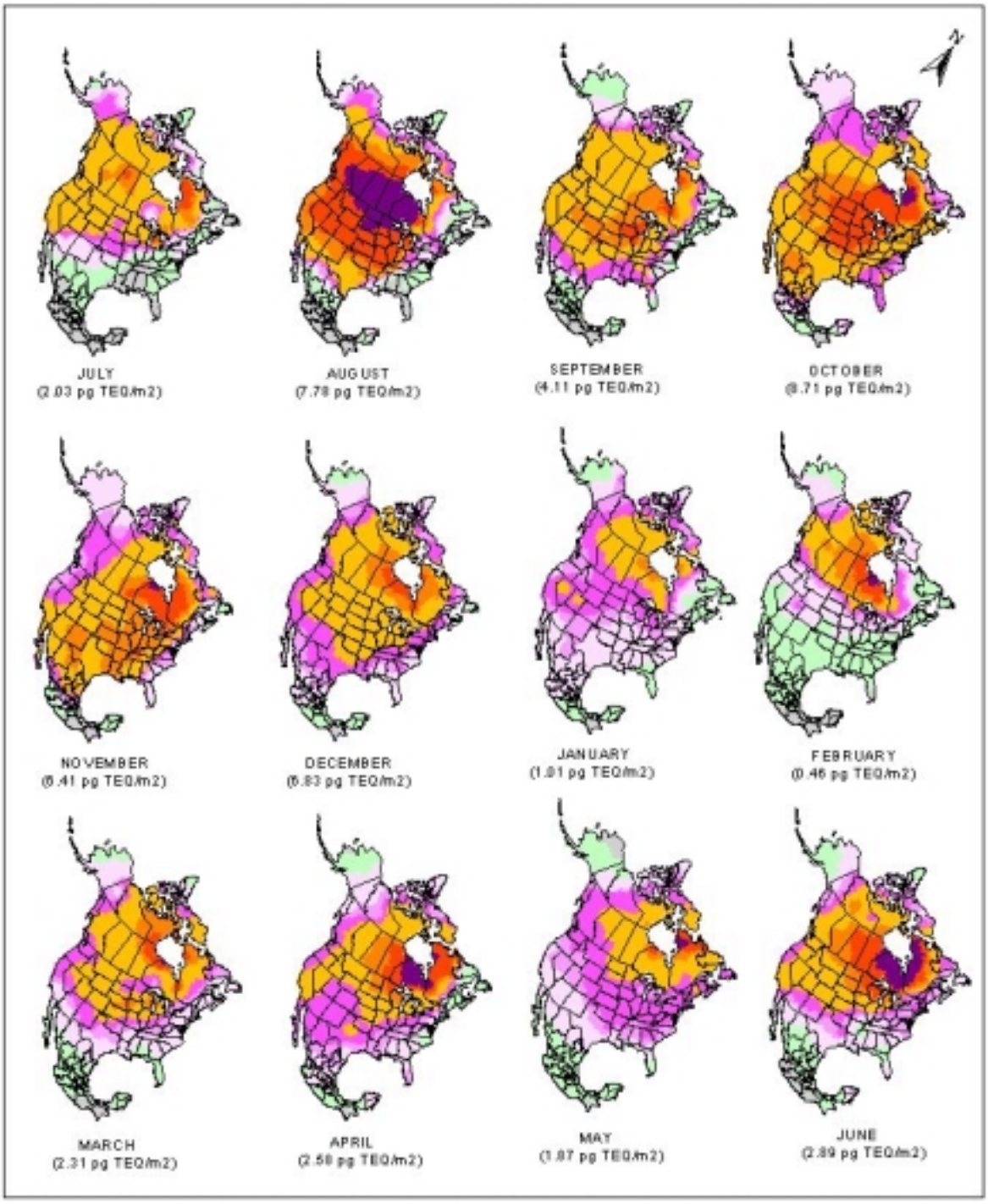


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Figure 3.13 B

Monthly Dioxin Deposition Air Transport Coefficients & Deposition Flux (pg TEQ/m2) to Arctic Bay Land Receptor (July 1996-June 1997)

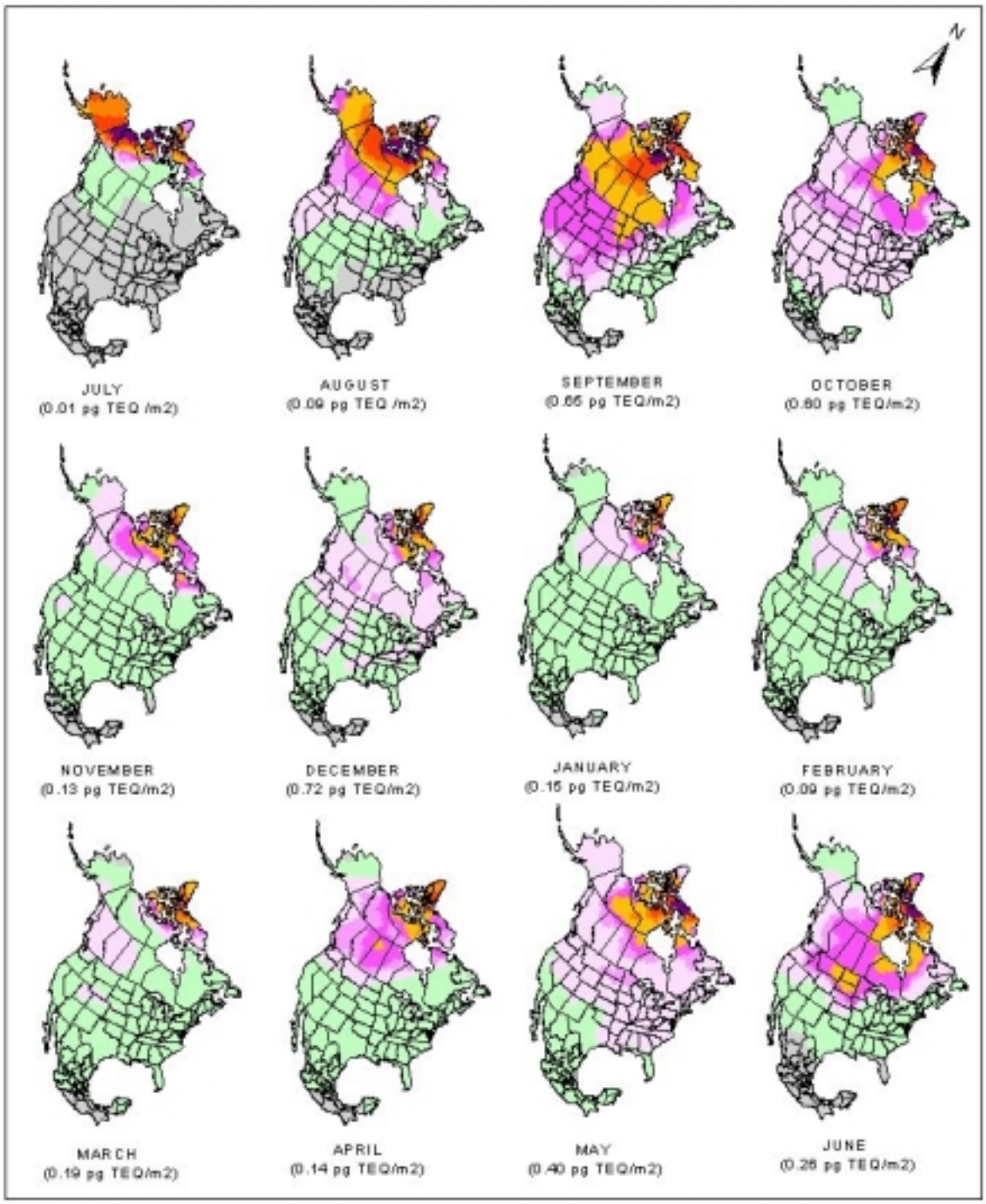

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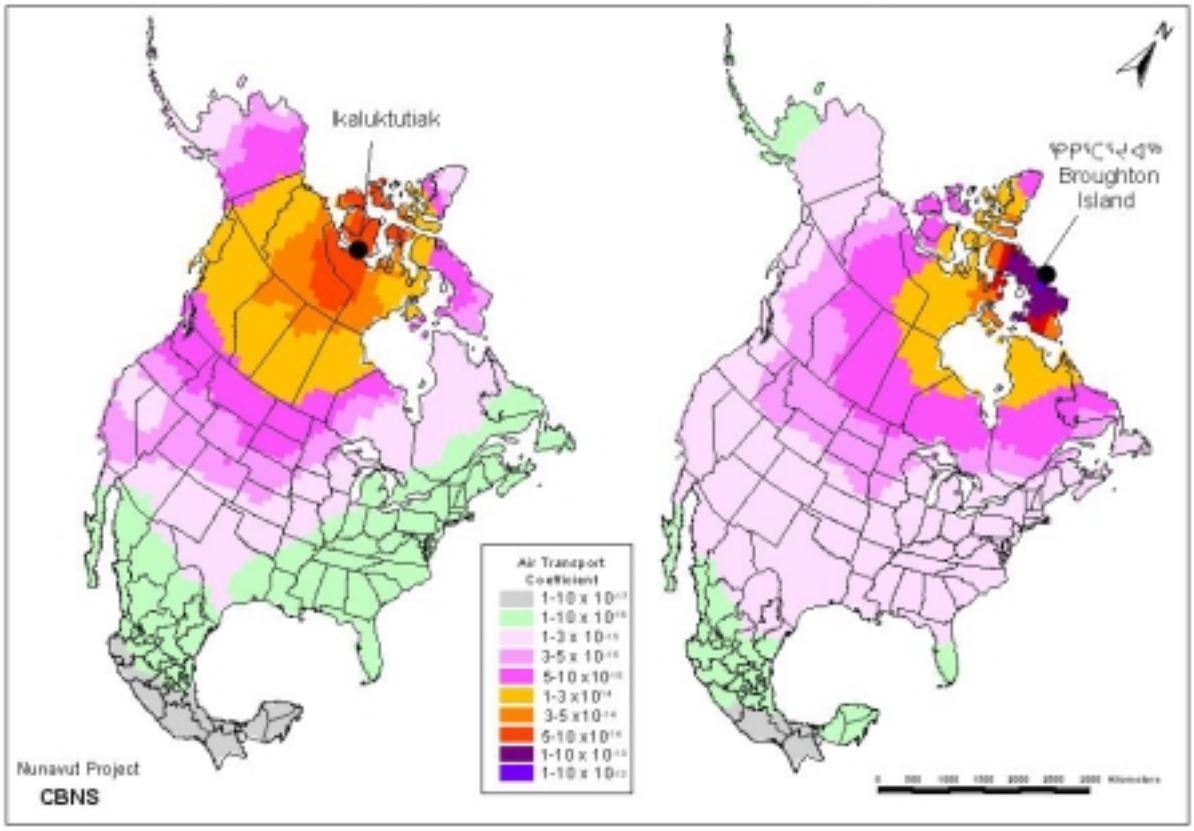
Figure 3.14

Annual Dioxin Deposition Air Transport Coefficients to Ikaluktutiak & Broughton Island Land Receptors



Figures 3.15A and B present the monthly ATC maps and deposition flux for the receptors at Ikaluktutiak and Broughton Island. As indicated earlier in Section 3.5.1, an analysis of the ATC values for transport from individual sources equidistant from the Ikaluktutiak receptor suggests that there is a strong weather-related gradient of increasing air transport efficiency from east to west. The monthly ATC maps for Ikaluktutiak (see Figure 3.15A) and the accompanying deposition values support that conclusion. In every month there are relatively high ATC values extending southwest of the receptor to varying distances, indicative of a generally prevailing southwesterly wind direction toward the receptor. This weather pattern favors dioxin transport from sources in western Canada, Alaska and the U.S. northwest. However, these sources have generally low rates of emission and will therefore contribute relatively little to deposition at the receptor. In all but two months—September and October—the ATC values in the U.S. Midwest and eastern region are very low, in the order of 10^{-17} to 10^{-16}, limiting the deposition from the heavily emitting sources there. During the remaining months the amounts of dioxin deposited at the receptor are very low, ranging from 0.08 to 0.27 pg/m^2. (The deposition in July 1996, 0.04 pg TEQ/m^2, is excluded because it was artificially low early in the month due to the time required for dioxin emitted at the start of the project period, July 1, 1996, to reach the Nunavut receptors.) Significantly, the highest of these values—0.27, 0.25, and 0.24—occur in April, May and June, when the zone of relatively high ATC values extends to several states, Minnesota, Iowa and Michigan, where intense dioxin sources are located. Finally, only in September and October does the ATC zone for 1-3x10^{-15} or greater extend over nearly the entire eastern half of the United States, thereby facilitating transport to Ikaluktutiak from the region of highest dioxin emissions. Consequently, the deposition at the receptor in these two months—1.44 pg TEQ/m^2 in September and 0.67 pg TEQ/m^2 in October—is qualitatively greater than the values during the rest of the year. These two months account for more than half of the total deposition during the year**.**

Thus, the monthly maps of air transport of dioxin to the Ikaluktutiak receptor, which necessarily reflect *only* changes in the concurrent weather pattern (source-receptor distance and rates of source emissions being constant), confirm the analysis based on the relation between ATC values and the longitude of sources that are equidistant from the Ikaluktutiak receptor described in Figure 3.8 and Table 3.3. Both sets of data illustrate the robustness of the HYSPLIT model as a means of analyzing the complex relationships that govern the impact of individual sources on the deposition of dioxin at a receptor, even when exceptionally long air transport distances are involved.

At Broughton Island, as expected, the deposition flux values are highest—for example, in May, September, October, December and January—when the high ATC zones cover the areas, especially eastern United States, where dioxin emission rates are high.

3.5.2.3 The geographic distribution of source contributions to dioxin deposition at the receptors

In Figure 3.16 the sources in each of the grid zones are coded to indicate the amount of their collective emitted dioxin that is deposited, per square meter, at the receptors at Sanikiluaq and Arctic Bay. Of all the Nunavut receptors, Sanikiluaq receives the highest annual deposition flux, 53 pg TEQ/m^2 land, 112 pg TEQ/m^2 marine. This reflects the combined effect of its relatively

Figure 3.15 A

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

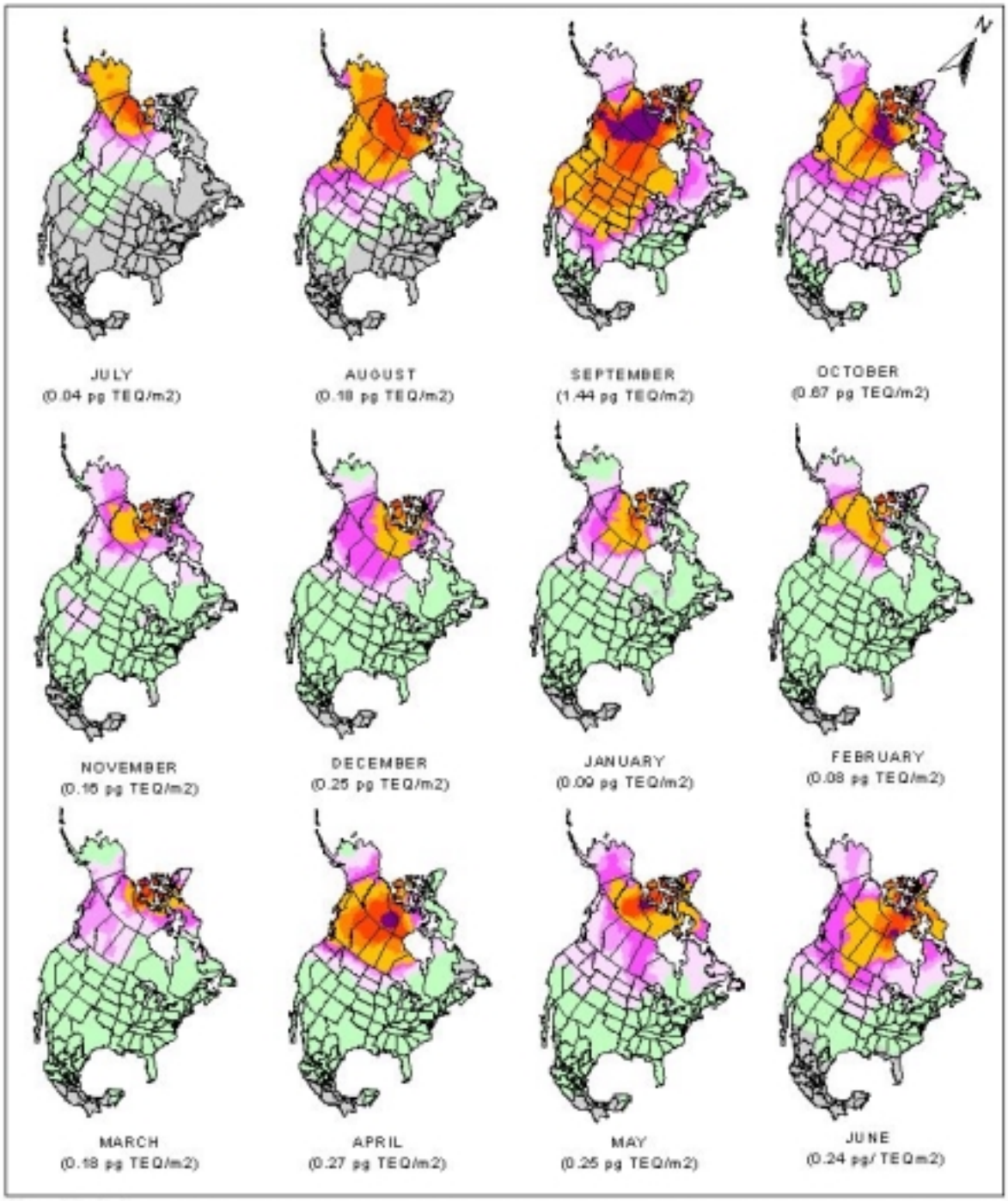


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Figure 3.15 B

Monthly Dioxin Deposition Air Transport Coefficients & Deposition Flux (pg TEQ/m2) to Broughton Island Land Receptor (July 1996-June1997)

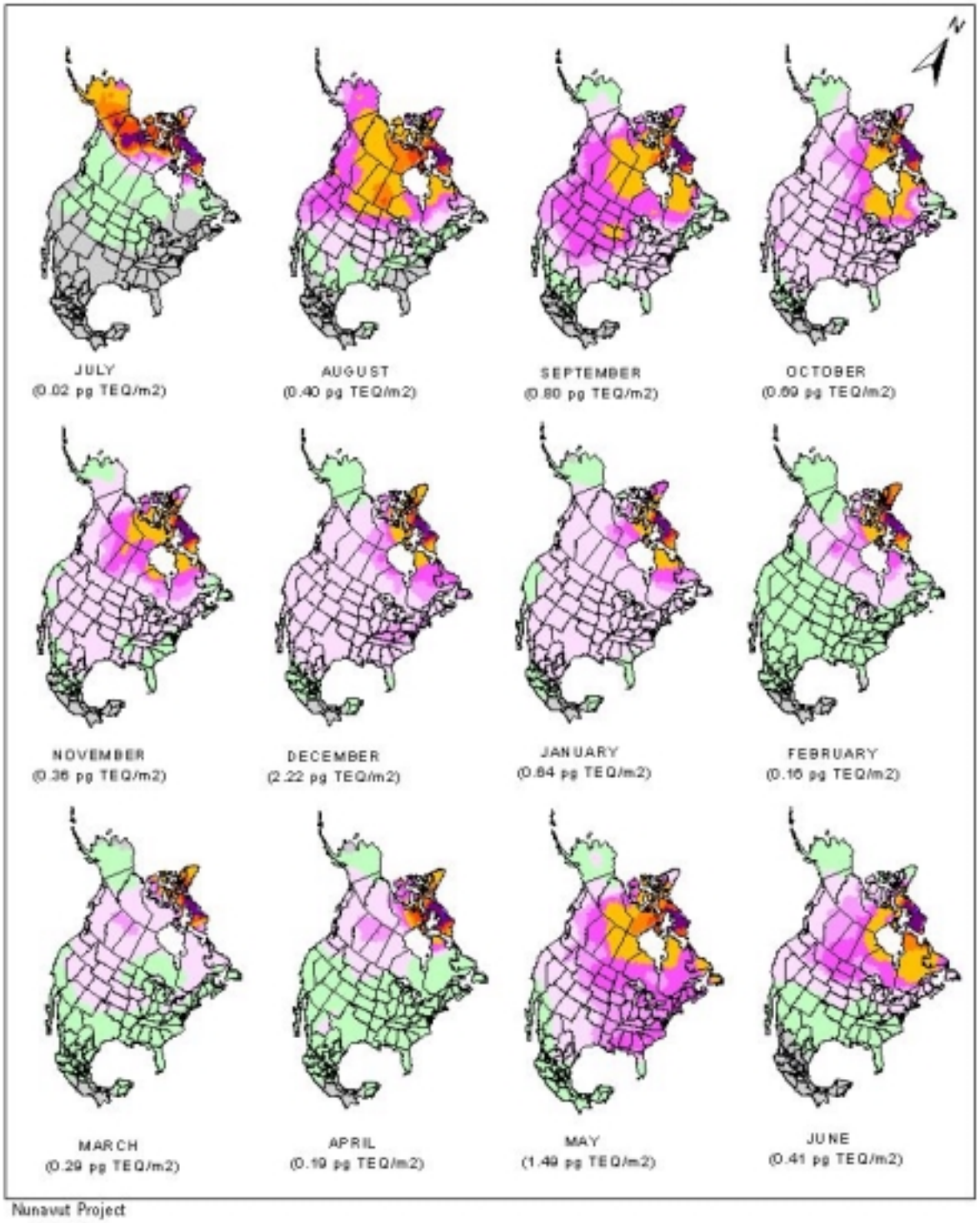

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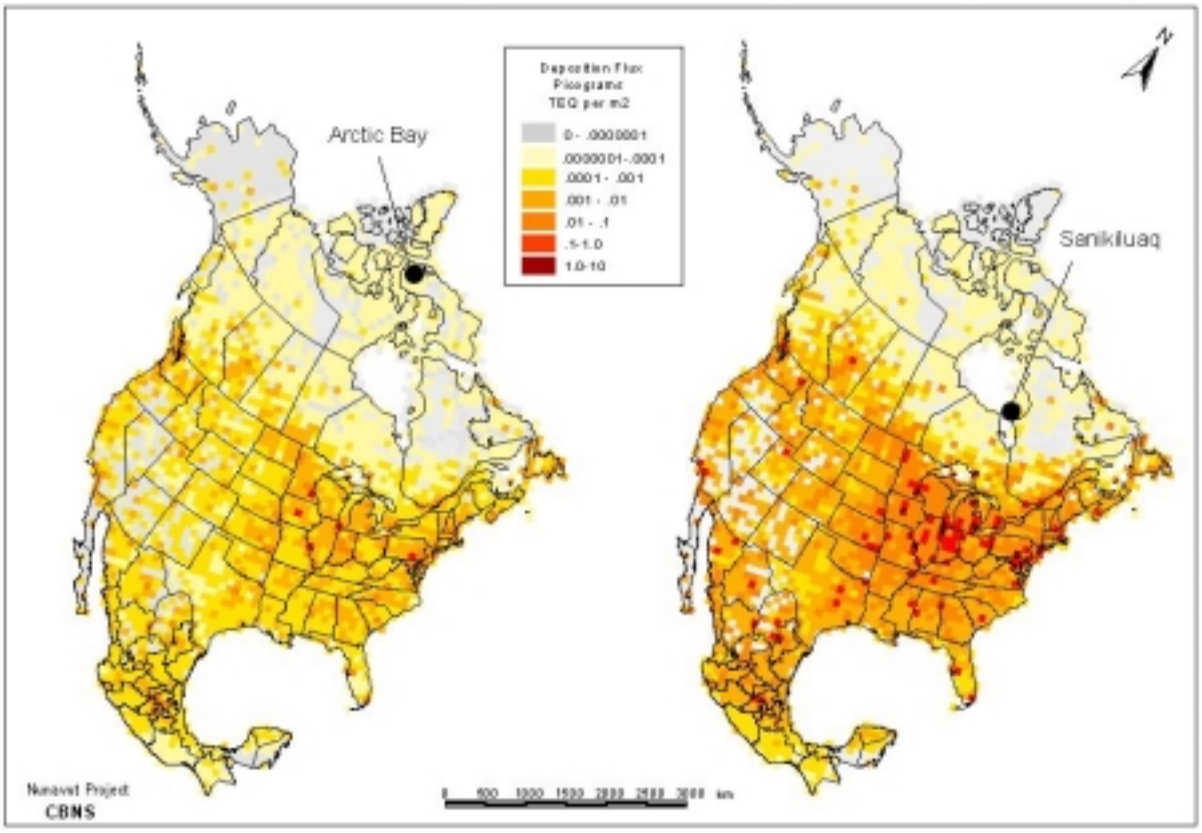
Figure 3.16

Dioxin Source Contributions to Deposition Flux at Arctic Bay and Sanikiluaq Land Receptors



close proximity to the region of intense source emissions in the United States and southern Canada (see Figures 3.9 and 3.10) to the south, and an ATC that efficiently transports emissions from as far south as the Gulf of Mexico (see Figure 3.12). As a result, Sanikiluaq receives most of its airborne dioxin from the high concentration of intense sources in the eastern half of the United States (see Figure 3.9).

In contrast, the receptor at Arctic Bay, which, along with Ikaluktutiak, has the lowest deposition flux of all the Nunavut receptors, is about 2,000 km more distant than Sanikiluaq from the intense sources of dioxin in the eastern half of the United States. As shown in Figure 3.12, air transport is correspondingly less efficient, although chiefly from the south. Thus, while both of these receptors receive most of their airborne dioxin from the region of intense source emissions in the Midwest and eastern United States and Canada, the 2000 km difference in their respective distance from these sources results in a more than 10-fold difference in their exposure to the airborne dioxin that the sources emit.

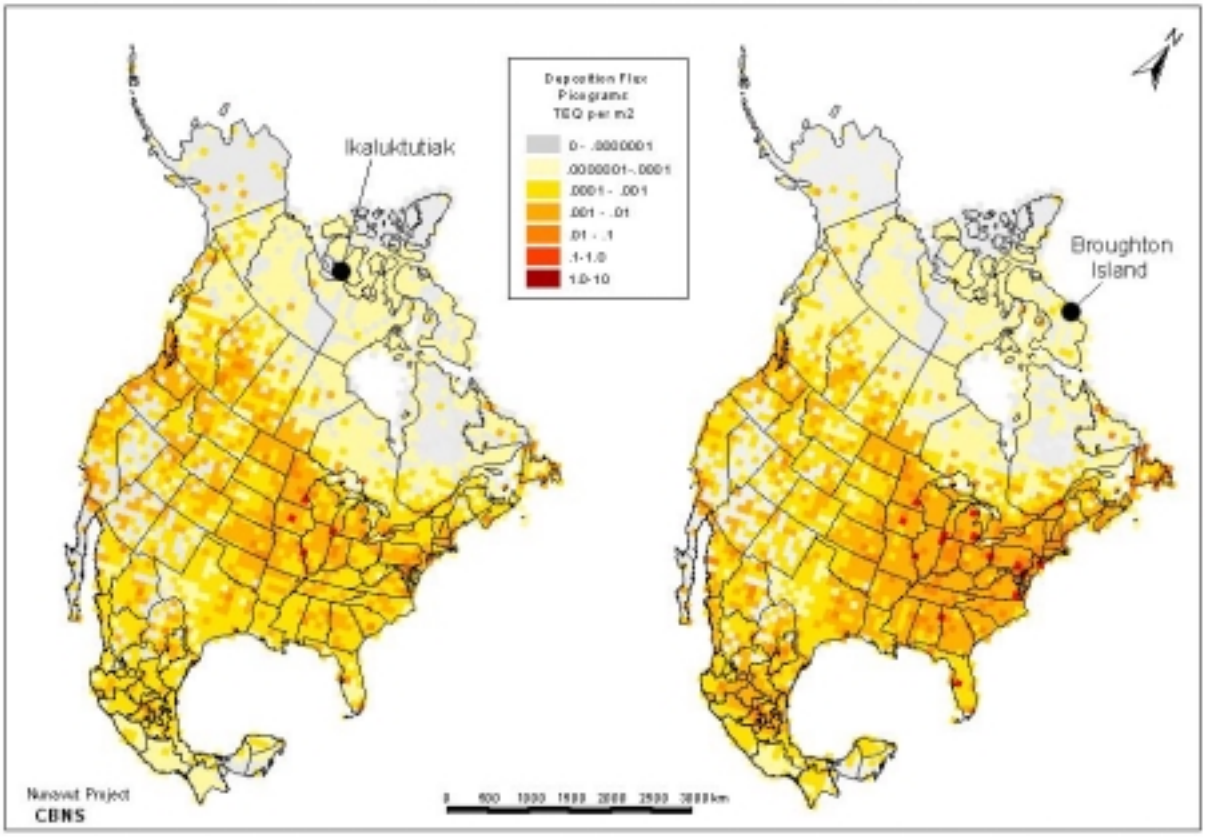
As indicated earlier, there is a west-to-east gradient in deposition flux at the receptors, which is apparent in those at approximately latitude 69, Ikaluktutiak at the extreme west and Broughton Island at the extreme east. This effect is also evident in the relevant maps of source contributions to these receptors (see Figure 3.17). Thus, almost all the intense sources in the eastern half of the United States contribute 0.01-0.1 picograms TEQ/m^2 annually to Broughton Island, and some contribute 0.1-1.0 pg TEQ/m^2. In contrast, the sources in this same region contribute much less to the deposition flux at Ikaluktutiak; most of them contribute 0.0001-.001 pg TEQ/m^2, and those that contribute at higher levels are much fewer than they are in the Broughton Island map. On the other hand, the sources southwest of the Ikaluktutiak receptor in western Canada and, to a degree, those in Minnesota, Iowa and Nebraska are relatively strong contributors to deposition at this receptor.

In sum, the maps of source contributions to deposition flux indicate that dioxin emitted by the numerous sources in the eastern half of the United States is more efficiently transported to Broughton Island than it is to Ikaluktutiak. On the other hand, with respect to the western sources in Canada and the United States, air transport to Ikaluktutiak is more efficient than it is to Broughton Island. But this relatively efficient transport from the western sources has little impact on deposition flux at Ikaluktutiak because emissions from these sources are relatively weak.

The foregoing analysis of the factors that influence the deposition of dioxin emitted from North American sources on the receptors at Arctic Bay, Sanikiluaq, Ikaluktutiak and Broughton Island appears to apply as well to the remaining Nunavut receptors. Thus, the influence of the relative distances of Sanikiluaq and Arctic Bay from the intense sources of dioxin in the eastern half of the United States applies as well to the intervening receptors, Coral Harbour and Igloolik, which exhibit intermediate amounts of deposition. Similarly, the gradient of rising ATCs with increasing westward longitude, derived from an analysis of the relation of equidistant sources to the Ikaluktutiak receptor serves to explain the west-to-east gradient in deposition that applies quite generally. This deposition gradient is exhibited not only by the Ikaluktutiak, Igloolik, Broughton Island series, but by the Chesterfield Inlet, Coral Harbour, Iqaluit series as well.

Figure 3.17

Dioxin Source Contributions to Deposition Flux at Ikaluktutiak and Broughton Island Land Receptor



3.6 The Contribution of Nunavut Sources to Dioxin Deposition on the Nunavut Territory

This issue has been analyzed in several ways. First, even if all of the 0.12 grams TEQ dioxin emitted from Nunavut sources were deposited on the total area of Nunavut, this would amount, at the most, to an average deposition flux of 0.06 picograms TEQ per square meter or only 0.1 to 1.5 percent of the modeled receptor deposition flux from all North American sources. Second, the availability of a high density of close-in standard source points near the Broughton Island land receptor enabled an estimate of the contribution of dioxin sources within Nunavut to total deposition flux at that receptor; only 0.01 picograms TEQ per square meter, or 0.11 percent of the deposition was due to Nunavut sources. Finally, a comparison based on an estimate of deposition on the total area of Nunavut gave a quite similar result. For this purpose, the total area of Nunavut was divided into three sections, corresponding to the locations of the eight receptor sites and the deposition in each section was computed from its area and the average model-estimated deposition flux at the relevant land receptors. The dioxin deposition on the total area of Nunavut is 37 grams TEQ per year. In comparison, the total dioxin emissions from all Nunavut sources is 0.12 grams TEQ per year. If this entire amount were deposited on Nunavut, it would contribute only 0.32 percent of the total deposition. It is evident that only a very small fraction of the airborne dioxin deposited on Nunavut originates from sources within the Territory.

3.7 The Impact of Non-North American Sources of Dioxin

The design of this project assumes that North American sources are chiefly responsible for the deposition of airborne dioxin in Nunavut and we have made a preliminary effort to verify this assumption. To this end, we included standard (hypothetical) source points in the Eastern Hemisphere in the HYSPLIT runs that estimated the Air Transport Coefficients for transport from standard points in North America to the Nunavut receptors. In order to maximize the efficiency of transport from the standard points in Europe and Asia, we chose to use for this purpose the Nunavut receptor that is closest to them: Arctic Bay. To further maximize transport efficiency, the ATC values were estimated for OCDD, the dioxin congener which, because of its properties, is most efficiently transported. The results, which are plotted in Figure 3.18, show that the most efficient Air Transport Coefficients to Arctic Bay from non-North American sources are of the order of $1x10^{-17}$. These highest ATC values for sources outside of North America are equivalent to the *lowest* North American ATC values, for example for sources in southern Mexico and Florida. In Table 3.4 the total dioxin emissions for various countries outside North America, as given in the recent UNEP report (UNEP, 1999), are multiplied by the range of the highest Eastern Hemisphere ATC values ($1x10^{-17}$ to $1x10^{-16}$), shown in Figure 3.18, as a way of assessing the upper limit of the effect of non-North American sources on deposition at the Arctic Bay receptor. As shown in Table 3.4, the sum of the resultant deposition flux values for all these non-North American sources ranges from $0.075x10^{-17}$ to $0.75x10^{-16}$ pg TEQ/m^2/year. This represents 1.9 to 19 percent of the deposition flux at the Arctic Bay land receptor from North American sources, 4 pg TEQ m^2/year. However, given the measures we have taken to maximize this computation, the actual deposition from non-North American sources is more likely to be the lower of these values. In sum, Nunavut is almost entirely exposed to airborne dioxin emitted by sources located outside of Nunavut itself.

Figure 3.18 **Annual OCDD Deposition AirTransport Coefficients from Standard (Hypothetical) Source Points in Europe and Asia to Arctic Bay, Marine Receptor**

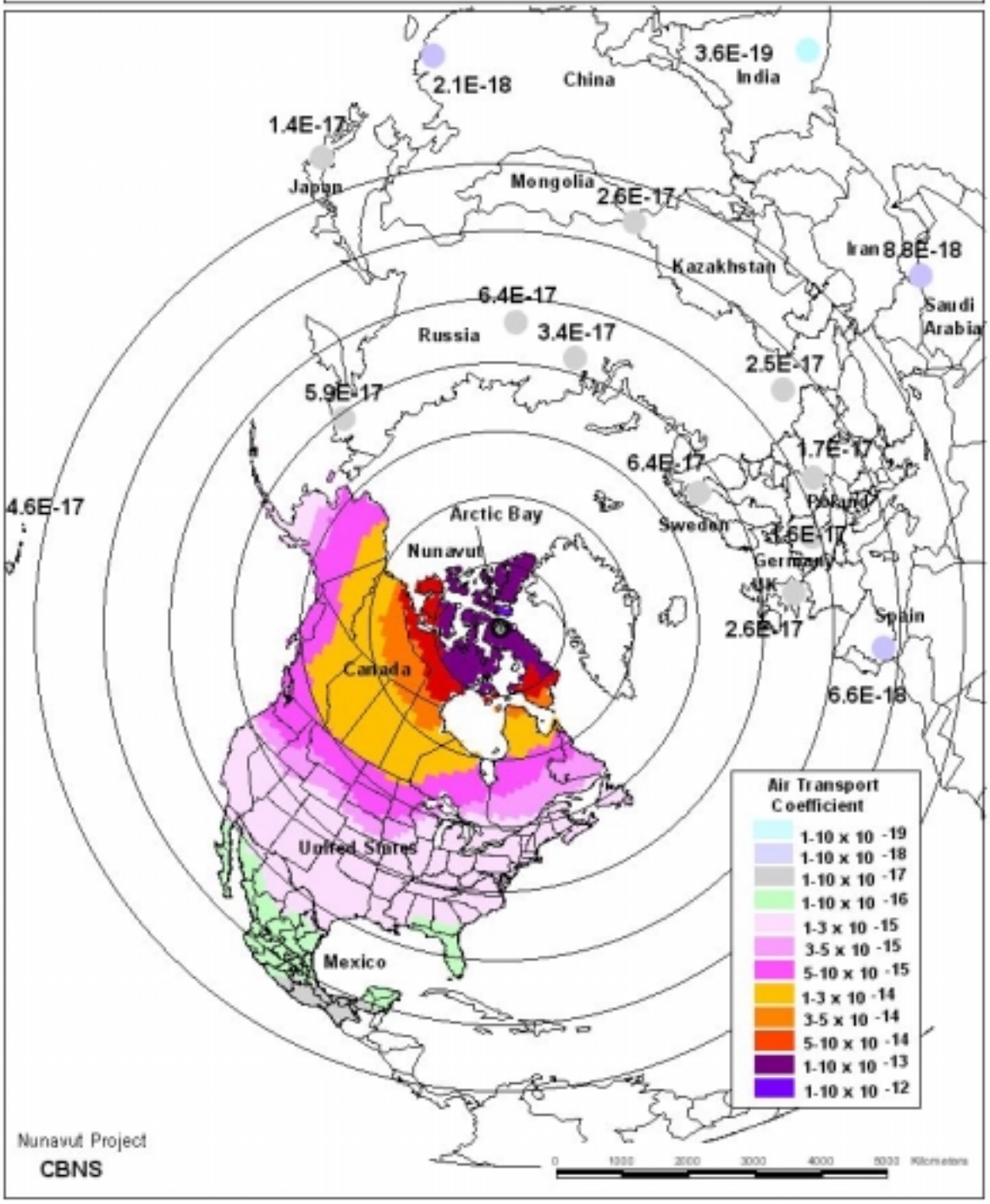


Table 3.4 Range of Possible Contributions of European and Asian Dioxin Sources to Deposition Flux at Arctic Bay Receptor

Country	Annual Emission (Grams TEQ/Yr)	Estimated Contribution to Receptor Deposition Flux (pg TEQ/m^2)	
		High ATC ($1x10^{-16}$)	Low ATC ($1x10^{-17}$)
Australia	150	0.0150	0.0015
Austria	29	0.0029	0.0003
Belgium	661	0.0661	0.0066
Denmark	39	0.0039	0.0004
France	873	0.0873	0.0087
Germany	334	0.0334	0.0033
Hungary	112	0.0112	0.0011
Japan	3,981	0.3981	0.0398
Slovak Republic	42	0.0042	0.0004
Sweden	22	0.0022	0.0002
Switzerland	181	0.0181	0.0018
The Netherlands	486	0.0486	0.0049
United Kingdom	569	0.0569	0.0057
Total	7,479	0.7480	0.0750

Note: These values are from runs not optimized for east-west hemispheric transport and represent the likely upper limit of ATC.

4. Conclusions

The results generated by the air transport model support a series of conclusions that specify the locations, classes, and individual identities of the sources; that assess the relative exposure of the various Nunavut receptors to airborne dioxin transported from these sources; that evaluate the meteorological factors that influence these source/receptor relationships; and that identify the relatively few sources that, if targeted for remedial action, could significantly reduce dioxin exposures in Nunavut. These conclusions are summarized below.

- Of the total of 44,091 North American dioxin sources, 16,729 (37.9 percent) are in Canada, 22,439 (50.9 percent) in the United States, and 4,923 (11.2 percent) in Mexico. Of the total amount of dioxin emitted by these sources during the one-year study period, 4,713 grams TEQ, those in Canada emitted 364 grams TEQ (7.7 percent), in the United States, 2,937grams TEQ (62.3 percent), and those in Mexico, 1,412 grams TEQ (30 percent). There are virtually no significant sources of dioxin within about 500 km of Nunavut.
- Of the 23 classes of North American dioxin sources, municipal waste incinerators emitted 25 percent of the total dioxin emissions; backyard trash burning, 22 percent; cement kilns burning hazardous waste, 17 percent; medical waste incinerators, 11 percent; secondary copper smelters, eight percent; and iron sintering plants, seven percent. Thus, only these six major classes of dioxin sources are responsible for 90 percent of the total North American emissions.
- The air transport model estimates the amounts of airborne dioxin emitted by each of the sources that is deposited on a specified Nunavut receptor. While sources from all three North American countries contribute to the deposition of dioxin at the Nunavut receptors, by far the greatest amount (70 to 82 percent, depending on the receptor) is due to U.S. sources; Canadian sources contribute 11 to 25 percent, and Mexican sources five to 11 percent. Only 0.2 percent of the dioxin deposited on Nunavut from all North American sources originates from sources within the boundary of Nunavut.
- The amounts of dioxin transported from North American sources and deposited in Nunavut vary significantly among the eight receptor sites. Deposition at Sanikiluaq, the southernmost receptor, is more than 10 times higher than it is at Arctic Bay, the most northern receptor. This is a consequence of the exponential decline in the rate of deposition with increasing distance from the sources, nearly all of which are south of Nunavut, due to dispersion, destruction and deposition of airborne dioxin during transport.
- The data generated by the air transport model allow us to rank the dioxin sources with respect to the amounts that each of them contributes to the dioxin deposited at each of the receptors in the one-year study period. Only a very small proportion of the 44,091 North American sources accounts for most of the dioxin deposited on the Nunavut receptors. At a typical Nunavut receptor, Coral Harbour, only 0.04 percent of the individual sources account for 35 percent of the total deposition; 0.10 percent of the

individual sources account for 50 percent of the total deposition, and 1.4 percent of the individual sources account for 75 percent of the total deposition at any of the receptors.

- The air transport model serves to identify the individual sources that are most responsible for the dioxin deposited at a Nunavut receptor. For example, 35 percent of the deposition at the Coral Harbour land receptor is due to only 19 individual sources. Of the 10 largest individual contributors, nine are U.S. facilities: three municipal waste incinerators in Minnesota, Iowa and Pennsylvania, three cement kilns burning hazardous waste in Michigan, Missouri and Nebraska, two iron sintering plants in Indiana, and a secondary copper smelter in Illinois. One Canadian municipal waste incinerator in Quebec (ranked seventh) is included as well.
- The amount of dioxin deposited on Nunavut receptors depends on the amount emitted from the sources and the efficiency with which the airborne dioxin is transported to the receptor. This is expressed as the fraction of a unit amount emitted from the source that is deposited at the receptor, i.e., the Air Transport Coefficient (ATC). The ATC value decreases sharply with the distance between the source and the receptor and is affected by the weather pattern *en route* and at the receptor as well. Of these two factors, only the weather varies over time, so that its influence can be assessed, for example, by means of monthly estimates of the ATC values. These show that dioxin deposition at the receptor is high when the weather pattern favors efficient transport from those areas of North America where the source emissions are most intense, in particular the eastern half of the United States.
- Based on some preliminary measurements of ATC values from locations in Europe and Asia and available European dioxin emission inventories, it is possible to make a rough estimate of the amount of airborne dioxin transported from these non-North American sources that is deposited at Nunavut receptors. This amount is between 1.9 and 19 percent of the deposition from North American sources, and most likely closer to the lower of these values. Thus, the problems created by the deposition of airborne dioxin in Nunavut originate in North America, and remedial action is an intrinsically North American responsibility.

5. Policy Implications

This project has been concerned with long-range transport of dioxin, which necessarily involves emission and deposition in places under different jurisdictions. This gives rise to policy issues that do not occur when both the sources and receptors are in the same country. It is pertinent to ask, therefore, to what extent the sources of dioxin emissions *within* Nunavut (primarily trash burning) contribute to the deposition at the Nunavut receptors. To this end, for the receptors at Broughton Island we modeled close-range dioxin transport from additional Nunavut source points. We found that only 0.01 picograms TEQ per square meter or 0.11 percent originated from Nunavut sources. We conclude, therefore, that the contribution of Nunavut sources to the deposition of airborne dioxin at Nunavut receptors is negligible and that, in practice, the policy issues relate to emissions and depositions in widely separated jurisdictions.

Since public policy on toxic pollutants is motivated by their possible effects on human health and wildlife, it is also useful to ask how the data produced by this study may relate to these effects. As noted earlier, without additional and more refined information it is not possible to translate our modeled estimates of dioxin deposition at the receptors into levels of exposure in wildlife or people. Nevertheless, the significant geographic variation in dioxin deposition does provide a possible link to comparable variation in ecological exposure. For example, the Canadian Arctic Contaminants Assessment Report (Canadian Arctic Contaminants Assessment Report, 1997) lists the results of a study of the dioxin content of caribou tissue in various arctic areas. The study included tissue samples taken from four herds in Nunavut (in 1991/92), of which three, Bathurst, Southampton Island and Lake Harbour, were, fortuitously, in areas close to our receptors. Table 5.1 compares the model-estimated dioxin deposition flux at these land receptors with the tissue dioxin concentrations in the nearby herd locations. Although there are only three comparable locations, the geographic variation in the dioxin content of caribou tissue samples and our estimates of dioxin deposition exhibit a similar trend, with both sets of values increasing from west to east. This suggests that the differences in the dioxin content of the local biota reflect comparable differences in the levels of airborne dioxin deposited at the nearby receptors. This relationship lends credence to the view that the modeled deposition data are applicable to the basic goal of environmental policy. If the levels of exposure to dioxin are judged to be a threat to

Table 5.1: Comparison of Dioxin Deposition at Nunavut Land Receptors with Tissue Dioxin Concentration in Caribou of Nearby Herds

Receptor	Dioxin Deposition Flux (pg TEQ/m^2/yr)	Herd Location	Dioxin Concentration ng TEQ/kg tissue
Ikaluktutiak	4	Bathurst	0.33
Coral Harbour n9o5	19	Southampton Island	0.85
*	—	Cape Dorset rNzw5	1.23
Iqaluit w3vlw5	26	Lake Harbour r7uD6	3.29

*There is no dioxin receptor near the location of the Cape Dorset caribou herd. Cape Dorset lies midway between the Coral Harbour and Ikaluktutiak receptors and its caribou dioxin concentration is included for completeness in demonstrating the west-to-east trend in this measure of dioxin exposure.

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 could be reduced to a degree by moderating consumption of 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 are faced with the daunting task of defining and implementing a policy that would effectively reduce the emissions collectively produced by 5,343 individual and 38,748 area sources, nearly all of them thousands of kilometers away, in other jurisdictions. The task is further complicated by the fact that there are considerable differences among the eight Nunavut receptor sites in the estimated level of dioxin deposition. Finally, the data generated by the model are themselves numerous and complex, involving 44,091 sources grouped in 23 classes, in three different countries. Nevertheless, despite these difficulties, it is possible to assemble relatively simple sets of facts that illuminate the feasibility of alternative policy strategies.

As already indicated, most of the dioxin deposition at the receptors is due to a very small proportion of the total number of sources. Beyond that strategic generalization, the data can be organized to address two alternative policy strategies. One strategy is based on the regulatory approach common to most countries' environmental agencies: standards of allowable emissions are set for different source classes, such as municipal waste incinerators or cement kilns burning hazardous waste. In this case, the Inuit community at Coral Harbour, for example, can learn from Table 5.2 that by addressing their need for relief from exposure to the annual dioxin deposition (on land) of 19.24 pg TEQ/m^2 only to the United States, and calling for more rigorous emission standards for only five classes of U.S. sources (municipal and medical waste incinerators, cement kilns burning hazardous waste, iron sintering plants, and backyard trash burners), their exposure to dioxin might be reduced by 67 percent, provided that the standard virtually eliminated emissions. By adding to their strategic aim improved regulation of municipal solid waste incinerators in Canada, and of informal trash burning in Mexico, the Coral Harbour community would be addressing 73 percent of their dioxin exposure, which, if eliminated, would reduce it to 5.2 pg TEQ/m^2. That would bring the level of exposure at the Coral Harbour land receptor to about the lowest level among all the Nunavut land receptors, which occurs at Arctic Bay and Ikaluktutiak. In sum, such data could be used by Inuit communities to target their remedial policy toward those source class/country categories that might offer the best potential return in reduced exposure to dioxin for their effort to accomplish it.

An alternative approach to policy is directed toward specific individual sources rather than categories of sources subject to national regulations. This policy depends more on direct appeal for action to the operators of a particular facility and/or the people of the local community than to the national environmental agency. Such a direct appeal has the advantage of immediacy, avoiding the intricacies and delays inherent in international, and even national, administrative actions. It has the disadvantage of dealing with the sources one by one. Thus, in the example

cited earlier in section 3.3, if the community of Coral Harbour adopted this approach, total exposure to dioxin could be reduced by 35 percent if 19 individual sources, again, most of them in the United States, could be induced to virtually eliminate their dioxin emissions. To go beyond that target sharply increases the overall effort needed; 680 sources must be targeted to reach a 75 percent reduction, and 3,031 sources to reach a 90 percent reduction. On the other hand, as shown by experience in the United States, public appeals for action on a particular source can often succeed by stimulating the necessary administrative response.

In this connection, it may be useful initially to direct such policy toward a small number of individual sources that appear to be responsible for the largest impact on the receptor, i.e. the sources that contribute most to the deposition of airborne dioxin on Nunavut. For this purpose, we have identified the 10 highest-ranked sources with respect to their *average* contribution to annual dioxin deposition at the eight Nunavut land receptors. Table 5.3 shows the contributions of each of these sources to deposition at each of the land receptors. The list includes four municipal solid waste incinerators, two secondary copper smelters, two cement kilns burning hazardous waste, and two iron sintering plants. All but one of these sources—a municipal solid waste incinerator in Quebec, Canada—are U.S. facilities. They range in emission rate from 21 to 148 g TEQ/year. Depending on the receptor, these 10 sources account for from 18 percent (at Ikaluktutiak) to 26 percent (at Coral Harbour and Sanikiluaq) of the total annual deposition from all North American sources.

Table 5.3 illustrates the relative roles of emission rate and ATC value in determining the source's contribution to the dioxin deposition flux at the receptor. Thus, the high total deposition flux at Sanikiluaq is due to relatively high ATC values, resulting from the proximity of this receptor to the major sources in southern Canada and the United States. At Ikaluktutiak, two sources, a cement kiln in Nebraska and a municipal waste incinerator in Pennsylvania, contribute about equally to deposition (0.07 and 0.08 pg TEQ per square meter, respectively) despite the considerable difference in their emission rates (21 and 148 grams TEQ per year, respectively). This results from the five-fold difference in these sources' ATC values (0.0032 and 0.0006 x 10^{-12}, respectively). These data have important implications for remedial policy. For example, it is equally important at Ikaluktutiak to reduce or eliminate dioxin emissions from both of these sources, despite the considerable disparity in their emission rates. Indeed, if it is recalled that the factors that govern the ATC value—source-receptor distance and the weather pattern en route—are not under human control, and that the Nunavut food chain cannot be protected from the deposition of airborne dioxin, it is apparent that remedial action must be directed toward emissions at the source.

It is important to note that, to a degree, such remedial action at the sources is already under way. For example, due to more stringent U.S. regulatory policies enforced since the 1996-97 study period have affected several of the sources listed in Figure 5.3. The Harrisburg, PA facility has been ordered to install new emission control equipment by December 2000; the Northern State Power facility in Redwing, MN is currently installing the required emission controls; and the Regie Intermun facility in Lewis, Quebec installed more effective emission controls in the fall of 1988 (To our knowledge all of the other sources listed in Table 5.3 are currently operating under the same conditions reported in 1996-97). In practice, the acquisition

of additional source information may be the most important initial step toward remedial action at the sources that contribute most to dioxin deposition on Nunavut receptors. As already noted, the major reason for uncertainty in estimating the contributions from individual sources is the wide range of the emission rates resulting from the very limited availability of up-to-date tests of actual dioxin emissions. The implementation of such tests might be the earlist outcome of identifying an individual source as a major contributor to dioxin deposition in Nunavut.

In sum, the project's results provide Inuit communities with the basic information about exposure to airborne dioxin needed to support the development of alternative remedial policies. Clearly, this database still needs to be strengthened, particularly by systematically relating the levels of dioxin deposition to dioxin concentration in the local marine and terrestrial food chains. In addition, it would be useful to confirm the present dioxin deposition data in a more recent year, when the weather pattern may be different, and with added receptors, in order to establish geographic trends more firmly. Such a study, coordinated with dioxin analysis of local food chain samples, would strengthen the case for remedial action to reduce, taken at the most important sources, the exposure of the Inuit to airborne dioxin.

Our experience in employing the nation dioxin inventories in this project suggests that there is a need for considerable improvement in this important element of transboundary airborne pollution. The results of this project clearly reinforce the precept that, given the difficulties of compiling them, and the limited resources available for the task (especially in developing countries), it would be helpful to establish a common set of priorities regarding source classes. Clearly, quite workable inventories can be restricted to the six to eight source classes that are responsible for most of the airborne dioxin emissions. Our effort to help establish an initial inventory of dioxin sources in Mexico suggests that informal burning of domestic waste may be the single most important source of airborne dioxin in developing countries.

Finally, the results of this project emphasize the importance of the proposed United Nations Treaty on Persistent Organic Pollutants, of which dioxin is a major component. The results show that the atmospheric and ecological processes that carry airborne dioxin from its sources, through the food chain, to human beings is a problem of continental, if not global, dimensions. Remedial policy, directed at the virtual elimination of the sources, must achieve this scale as well.

Table 5.2 Contributions of the 10 Highest-ranked Dioxin Source Class/Country Categories to Cumulative Percentage of Total Deposition Flux at Nunavut Land Receptors

Avg. Rank	Source Class/Country Category	Ikaluktutiak		Chesterfield Inlet		Coral Harbour		Sanikiluaq	
		Deposition Flux pg TEQ/m^2	Cum. %	Deposition Flux pg TEQ/m^2	Cum. %	Deposition Flux pg TEQ/m^2	Cum. %	Deposition Flux pg TEQ/m^2	Cum. %
	Total Dep. Flux	4.46		11.65		19.24		53.47	
1	MSW USA	0.82	18	2.28	20	3.63	19	9.86	18
2	MWI USA	0.58	32	1.81	35	3.07	35	8.50	34
3	Cem K USA	0.51	43	1.49	48	2.81	49	7.93	49
4	Fe-S USA	0.21	48	0.66	54	1.80	59	5.57	60
5	BB USA	0.51	59	1.32	65	1.62	67	4.12	67
6	MSW Can	0.19	63	0.43	69	0.83	72	1.61	70
7	BB Mex	0.20	68	0.47	73	0.74	75	2.48	75
8	Sec-Cu Sm USA	0.13	71	0.35	76	0.91	80	2.23	79
9	Sec-Alum Sm USA	0.14	74	0.33	78	0.58	83	1.73	82
10	Cement-K Mex	0.12	77	0.28	81	0.40	85	1.05	84
Avg. Rank	Source Class/Country Category	Broughton Island		Igloolik		Iqaluit		Arctic Bay	
		Deposition Flux pg TEQ/m^2	Cum. %	Deposition Flux pg TEQ/m^2	Cum. %	Deposition Flux pg TEQ/m^2	Cum. %	Deposition Flux pg TEQ/m^2	Cum. %
	Total Dep. Flux	8.90		7.03		25.89		4.00	
1	MSW USA	1.97	22	1.49	21	5.89	23	0.87	22
2	MWI USA	1.40	38	1.09	37	4.22	39	0.59	36
3	Cem K USA	1.02	49	0.86	49	3.21	51	0.45	48
4	Fe-S USA	0.61	56	0.49	56	2.27	60	0.25	54
5	BB USA	0.60	63	0.59	64	1.65	67	0.34	62
6	MSW Can	0.65	70	0.37	69	1.76	73	0.21	68
7	BB Mex	0.47	75	0.32	74	0.90	77	0.23	73
8	Sec-Cu Sm USA	0.38	80	0.27	78	1.17	81	0.15	77
9	Sec-Alum Sm USA	0.22	82	0.19	81	0.69	84	0.11	80
10	Cement K-Mex	0.17	84	0.19	83	0.55	86	0.14	82

Table 5.3: The Individual Sources that Contribute Most to the Deposition of Airbrone Dioxin on Nunavut Land Receptors:Contributions to the Separate Receptors

Facility: Name, Class and Location	Emission g/yr	Ikaluktutiak ATC (x10-12)	Ikaluktutiak Dep. Flux pg TEQ /m2 year	Arctic Bay ATC (x10-12)	Arctic Bay Dep. Flux pg TEQ /m2 year	Igloolik ATC (x10-12)	Igloolik Dep. Flux pg TEQ /m2 year	Broughton Island ATC (x10-12)	Broughton Island Dep. Flux pg TEQ /m2 year
Ames WTE, MSW, IA, USA	58	0.0027	0.16	0.0022	0.13	0.0039	0.22	0.0036	0.21
Ash Grove, Cement-K, NE, USA	21	0.0032	0.07	0.0022	0.05	0.0042	0.09	0.0036	0.07
Beth. Steel, Fe-S, IN, USA	57	0.0010	0.05	0.0011	0.06	0.0021	0.12	0.0023	0.13
Chemetco, Sec-Cu_Sm, IL, USA	96	0.0008	0.08	0.0009	0.08	0.0016	0.15	0.0020	0.19
Harrisburg, MSW, PA, USA	148	0.0006	0.08	0.0009	0.14	0.0016	0.24	0.0027	0.40
Lagarge, Cement-K, MI, USA	51	0.0009	0.05	0.0012	0.06	0.0025	0.13	0.0028	0.14
NSP, Redwing, MSW, MN, USA	45	0.0032	0.15	0.0026	0.12	0.0044	0.20	0.0039	0.17
Regie Intermun, MSW, QC, CAN	62	0.0006	0.04	0.0013	0.08	0.0029	0.18	0.0038	0.23
Southwire, Sec-Cu_Sm, GA, USA	82	0.0005	0.04	0.0007	0.06	0.0013	0.11	0.0021	0.17
USS, Fe-S IN, USA	66	0.0010	0.06	0.0011	0.07	0.0021	0.14	0.0023	0.15
Total Deposition Flux			0.78		0.84		1.57		1.88
Deposition Flux; all N. American Sources			4.46		4.00		7.03		8.90
Total Flux/N. American Flux (%)			18%		21%		22%		21%
Facility: Name, Class and Location	Emission g/yr	**Chesterfield Inlet** ATC (x10-12)	**Chesterfield Inlet** Dep. Flux pg TEQ /m2 year	**Coral harbour** ATC (x10-12)	**Coral harbour** Dep. Flux pg TEQ /m2 year	**Snikiluaq** ATC (x10-12)	**Snikiluaq** Dep. Flux pg TEQ /m2 year	**Iqaluit** ATC (x10-12)	**Iqaluit** Dep. Flux pg TEQ /m2 year
Ames WTE, MSW, IA, USA	58	0.0097	0.56	0.0141	0.82	0.0343	1.99	0.0124	0.72
Ash Grove, Cement-K, NE, USA	21	0.0128	0.27	0.0128	0.27	0.0324	0.68	0.0106	0.22
Beth. Steel, Fe-S, IN, USA	57	0.0031	0.18	0.0091	0.52	0.0292	1.67	0.0099	0.56
Chemetco, Sec-Cu_Sm, IL, USA	96	0.0025	0.24	0.0072	0.69	0.0181	1.74	0.0061	0.59
Harrisburg, MSW, PA, USA	148	0.0017	0.26	0.0032	0.47	0.0090	1.33	0.0079	1.16
Lagarge, Cement-K, MI, USA	51	0.0035	0.18	0.0073	0.37	0.0318	1.61	0.0122	0.62
NSP, Redwing, MSW, MN, USA	45	0.0091	0.41	0.0152	0.69	0.0383	1.73	0.0150	0.68
Regie Intermun, MSW, QC, CAN	62	0.0024	0.15	0.0066	0.41	0.0148	0.91	0.0119	0.73
Southwire, Sec-Cu_Sm, GA, USA	82	0.0012	0.10	0.0024	0.20	0.0051	0.42	0.0063	0.52
USS, Fe-S IN, USA	66	0.0032	0.21	0.0093	0.62	0.0293	1.93	0.0099	0.65
Total Deposition Flux			2.55		5.03		13.99		6.45
Deposition Flux; all N. American Sources			11.65		19.24		53.47		25.89
Total Flux/N. American Flux (%)			22%		26%		26%		25%

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