

# Susceptibility of Human Populations to Environmental Exposure to Organic Contaminants

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Environmental exposure to organic contaminants is a complex function of environmental conditions, food chain characteristics, and chemical properties. In this study the susceptibility of various human populations to environmental exposure to neutral organic contaminants was compared. An environmental fate model and a linked bioaccumulation model were parametrized to describe ecosystems in different climatic regions (temperate, arctic, tropical, and steppe). The human body burden resulting from constant emissions of hypothetical chemicals was estimated for each region. An exposure susceptibility index was defined as the body burden in the region of interest normalized to the burden of the same chemical in a reference human from the temperate region eating an average diet. For most persistent chemicals emitted to air, the Arctic had the highest susceptibility index (max 520). Susceptibility to exposure was largely determined by the food web properties. The properties of the physical environment only had a marked effect when air or water, not food, was the dominant source of human exposure. Shifting the mode of emission markedly changed the relative susceptibility of the ecosystems in some cases. The exposure arising from chemical use clearly varies between ecosystems, which makes an understanding of ecosystem susceptibility to exposure important for chemicals management.

## Introduction

Human exposure to organic pollutants is highly variable in different regions of the world (1). It has been shown, however, that pollutant concentrations in humans and other top predators are not necessarily directly related to the levels of emissions into the environment in which they live. For instance, the levels of many POPs in indigenous populations in the Arctic, an environment with low emissions of these chemicals, by far exceed the levels found in populations living in temperate regions with higher POP emissions (2). The variability in human exposure suggests that different ecosystems have a different susceptibility to contaminant exposure in top predators.

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Environmental mass balance models can be used to study the complex interplay between chemical transfer within and between the environmental compartments and the organisms living there. Several models have been developed for predicting chemical fate in the environment as a function of the chemical partitioning properties, persistence, and environmental conditions (see summary in ref 3). Also, a number of bioaccumulation models have been developed to study the behavior of various organic chemicals in different organisms and food chains (e.g. refs 4–8). Linking environmental fate and bioaccumulation models can facilitate the understanding of the complex chemical journey from emissions to top predators for chemicals with different intrinsic properties in different ecosystems. Model derived continent specific human intake fractions for a number of organic compounds have been reported to vary in general by a factor 5 to 10 between continents, mainly due to variations in population density and agricultural production intensity (9). The low spatial resolution of these measures, however, does not capture the differences in exposure of subpopulations following regional emissions. Regional scale exposure of humans living on local food (i.e., a traditional diet) was considered in an initial comparison of the Arctic and the temperate European environments (10). Assuming equilibrium partitioning in the physical environment, identical emissions of persistent compounds yielded concentrations in humans that were up to ~3 orders of magnitudes higher in the Arctic compared to temperate Europe. This provides preliminary insight into the susceptibility of the Arctic to contaminant exposure in top predators, but we are unaware of assessments of the susceptibility of other ecosystems, of how the susceptibility is influenced by mode of emission and chemical degradability, or of the environmental characteristics that most strongly influence the susceptibility.

To address these issues, we here compare the susceptibility of a number of generic ecosystems to environmental exposure to hypothetical organic contaminants. The concentrations in humans resulting from unit emissions to the ecosystem are estimated by means of linked dynamic environmental fate and bioaccumulation models. Contaminants with a broad range of partitioning properties are explored, and the differences in susceptibility are related to the properties of the physical environment as well as the structure and characteristics of the food webs. A worst case scenario approach is taken in the sense that local food only is considered. Initially, the chemicals are assumed to be emitted to air and perfectly persistent. Thereafter, the assessment is repeated for labile chemicals. Finally, the influence of mode of emission on relative susceptibility is explored for a selection of the ecosystems.

## Method

**Models.** Two fugacity based box models, CoZMoPOP2 and ACC-HUMAN, were employed to simulate the environmental fate of organic chemicals in different ecosystems and their subsequent bioaccumulation in humans living in these regions. CoZMoPOP2 is a dynamic multimedia fate and transport model (MFTM) of a coastal environment. It consists of a drainage basin (forest, soils, fresh water) and several marine compartments (estuarine, coastal, open and deep water) (11). Alterations made to the model (e.g., higher spatial resolution of soil compartments, restricted temperature variability in groundwater and sediments, and a refined numerical differential equation solver) have been summarized in the Supporting Information. ACC-HUMAN is a dynamic food chain model that predicts bioaccumulation in

**TABLE 1. Qualitative Description of the Parameters Characterizing Each Ecosystem<sup>a</sup>**

	temperate	arctic	tropical island	tropical forest	cold steppe	warm steppe
<b>environmental conditions</b>						
temperature	M	L	H	H	L	H
seasonality	H	H	L	L	M	M
precipitation	M	L	H	H	L	L
wind	H	H	M	L	H	H
atmospheric aerosol fraction	M	L	M	M	L	L
soil thickness	H	L	M	M	L	L
soil organic carbon content	M	H	M	M	L	L
forest coverage	M	-	H	H	L	L
fraction nonarable land	L	H	L	L	M	M
fraction arable land	H	L	M	M	M/H	M/H
forest biomass	M	L	H	H	L	L
water coverage	M	H	H	L	L	L
<b>biotic conditions</b>						
grass yield	H	-	-	-	L	L
grass/vegetable growth rate	M	-	H	H	L	L
grass/vegetable transpiration rate	M	-	H	H	L	L
cow/steer grass ingestion rate	H	-	-	-	L	L
cow lactation rate	H	-	-	-	L	L
steer lipid content	H	-	-	-	L	L
steer weight	H	-	-	-	L	L
steer age at slaughter	L	-	-	-	M	M
human diet	mixed/veg/fish					
dairy products	M/-/-	-	-	-	M	M
beef	M/-/-	-	-	-	H	H
fish	M/-/H	-	H	H	-	-
vegetables	M/H/M	-	M	M	L	L
seal blubber	-	H	-	-	-	-

<sup>a</sup> L: low, M: moderate, H: high.

an agricultural (grass, milk cows, and beef cattle) and a marine food web (zooplankton, planktivorous fish, and piscivorous fish), both of which lead to the human as the top predator (6). To expand the ACC-HUMAN food chain, two submodels were added: the seal model described in ref 12, and a vegetable model that was recently developed and linked to the original ACC-HUMAN (13). Chemical fate in the physical environment was calculated using the expanded CoZMoPOP2, and the predicted fugacities in the exposure media were used as input for the bioaccumulation model, which then predicted the human body burden.

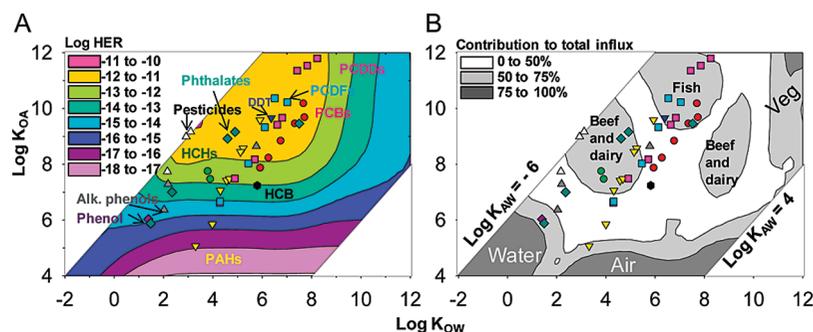
**Ecosystem Parameterization.** Six hypothetical regions were created and named temperate, Arctic, tropical island, tropical forest, cold steppe, and warm steppe. These regions were based on corresponding authentic regions located in various climate zones: southern Sweden, the Canadian Arctic Archipelago, the Seychelles, the Amazon, the Mongolian steppe, and the Sahelian steppe, respectively. Each region was combined with a food chain reflecting the diet of a population eating exclusively regionally produced food. Complete reliance on regionally produced food is not a typical scenario, but the use of a hypothetical regionally produced diet allowed an assessment of the maximum effect of regional properties on human exposure. In addition, a vegetarian diet and a fish-rich diet were considered for the temperate region, resulting in 8 different region/food chain combinations, which are referred to as *ecosystems* in the following. For parametrization, the point of departure was the default parameter values in the CoZMoPOP2 and ACC-HUMAN models, which had been parametrized for the southern Baltic region (14) and for an average diet in southern Sweden (6), respectively (see Tables S1 and S2 for the full parametrization of both models). A limited number of parameters were varied to differentiate between the ecosystems. Each ecosystem was characterized by environmental parameters such as climate, hydrology, and environmental media composition and by biotic characteristics such as food chain structure, organism physiology, and human diet composition (see Tables S3 and

S4). A qualitative description of the key parameters is presented in Table 1.

**Hypothetical Chemicals.** The simulations were performed using hypothetical chemicals with a wide range of partitioning properties. The chemicals were assigned octanol-air and octanol-water partition coefficients ( $\log K_{OA}$  and  $\log K_{OW}$ ) ranging from 4 to 12 and -2 to 12, respectively, in steps of 0.5 log units. Due to model stability limitations, the range for the log air-water partition coefficient ( $\log K_{AW} = \log K_{OW} - \log K_{OA}$ ) was restricted to -6 to 4 in all regions except for the cold steppe where the lower boundary was set to -5.

Two sets of these hypothetical chemicals were created, one set assumed to be perfectly persistent in all environmental media and biota, and a second set that was labile. For the labile chemicals, the transformation half-lives in the major compartments of the physical environment were arbitrarily set equal to the POP persistence criteria (see Table S5). In addition, the degradation half-life in humans and mammals was arbitrarily set to 30 days, while that in fish was set to 450 days based on evidence of slower biotransformation in poikilotherms compared to homeotherms (15). Other physical chemical properties were held constant (see Table S5).

**Emission Scenarios.** Chemical fate was calculated for each region and compound (persistent and labile) for a 75 year period during which there were constant emissions to air of 1 tonne of chemical per year. There was no advection of chemical into the region (although advection out was considered); advection into the region would have the same consequence for the predicted exposure as emissions into the same medium. All regions had the same area, although the land/water surface area ratio and the volumes of the soil and water compartments varied (see Table S2). The predicted fugacities in the various compartments (air, surface soil, fresh water, and marine water) were used as input for the bioaccumulation model. For a selection of regions (temperate, tropical forest, tropical island, and warm steppe) emissions to soil or water were also simulated. The model



**FIGURE 1.** Chemical partitioning space plots displaying **A)** the human to emissions ratio (*HER*) for a 25 year old woman on a mixed diet and living in the temperate region and **B)** the maximum contribution of a single exposure vector to the total uptake flux plotted as a function of the log octanol–air ( $\log K_{OA}$ ) and octanol–water ( $\log K_{OW}$ ) partition coefficients at 25 °C. The positions of a number of environmentally relevant contaminants in the chemical partitioning space are indicated.

end point was the chemical body burden of a 25 year old woman born 50 years after emissions had started and who was nursing her first child. This body burden was normalized to the total accumulated emissions (here 75 tonnes for all chemicals) to obtain the human body burden to emissions ratio (*HER*) of each ecosystem.

## Results and Discussion

Figure 1 (panel A) shows the *HERs* for a woman in the temperate region eating a mixed diet, plotted as a function of the chemical partitioning properties. Unless stated otherwise, the figures in this study refer to persistent chemicals emitted to air. The *HERs* ranged from just below  $10^{-18}$  for the most volatile chemicals (low  $K_{OA}$ ) to nearly  $10^{-11}$  for compounds with  $\log K_{OW} < \sim 8$  and  $\log K_{OA} > \sim 8$ , a range which includes many pollutants of environmental concern.

The differences in *HERs* between chemicals are related to the potential of the different exposure vectors to transfer chemicals to humans. Figure 1 (panel B) shows the relative contribution of the individual uptake pathways to the total uptake flux. Animal foods dominated the uptake for the chemicals with the highest *HERs*. Several studies have shown that animal fat is the major source of dietary exposure to persistent hydrophobic compounds like hexachlorobenzene (HCB), polychlorinated biphenyls (PCBs), polybrominated diphenyl ethers (PBDEs), and polychlorinated dibenzo-p-dioxins/dibenzofurans (PCDD/DFs) (16–21). *HERs* and the dominant uptake pathways for the other ecosystems are presented in the Supporting Information in Figures S1 and S2, respectively. The variations in *HERs* between the ecosystems are discussed in the following sections.

**Exposure Susceptibility Index.** The influence of the ecosystem properties on exposure to a chemical was evaluated by normalizing the chemical's *HER* in each ecosystem of interest to the *HER* of the same chemical in a reference ecosystem. This parameter was termed the *exposure susceptibility index (ESI)*. An *ESI* > 1 implies that the human body burden will be higher in the ecosystem of interest than in the reference ecosystem, given identical emissions. The temperate environment with a mixed diet was chosen as the reference ecosystem, as this is the kind of ecosystem for which the most information on organic contaminant fate and bioaccumulation is available.

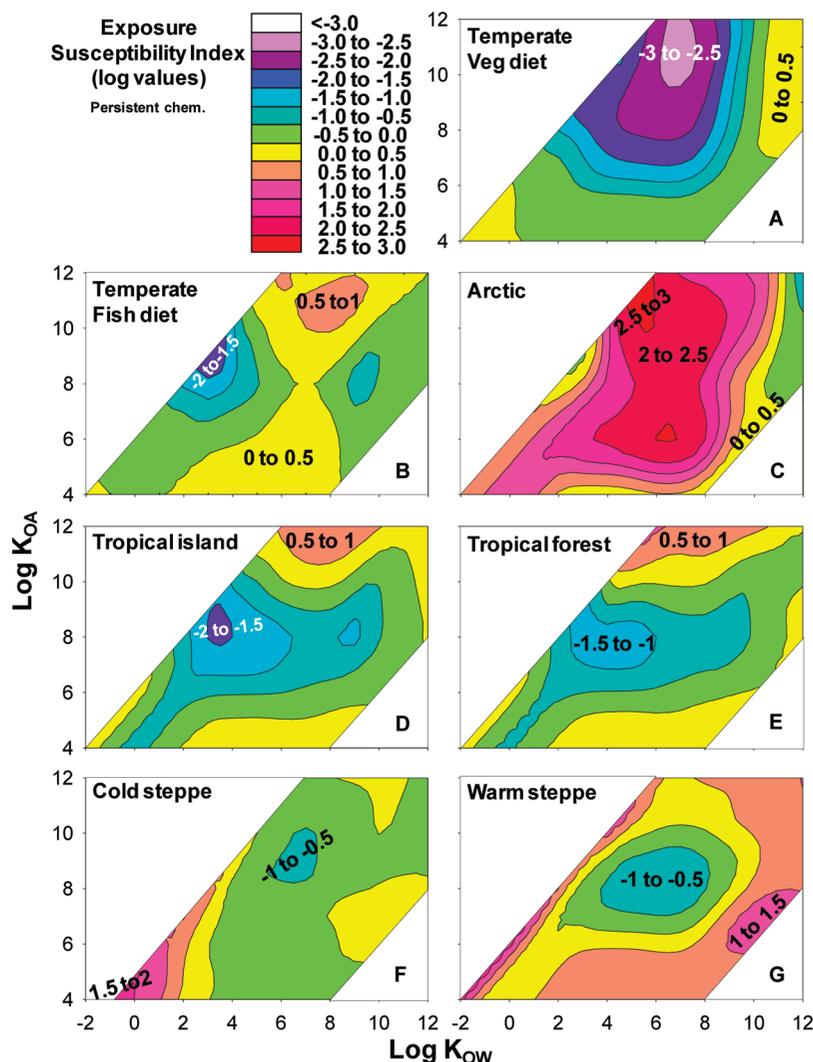
The *ESI* of the different ecosystems to persistent chemicals emitted to air are illustrated as a function of  $\log K_{OW}$  and  $\log K_{OA}$  in Figure 2. The variability in *ESI* was considerable, ranging from 0.002 to 520. The most susceptible ecosystem was the Arctic, where *ESI* was  $\gg 1$  for nearly all chemicals (panel C). A high *ESI* was also exhibited for highly water-soluble compounds in the cold steppe and all chemicals in the warm steppe except for those in the middle of the chemical partitioning space (panels F and G). The least

susceptible system was the temperate vegetarian where the *ESIs* of all chemicals were close to or below 1 (panel A). The *ESI* was also comparatively low in the ecosystems with fish eating communities (panels B, D, and E). To understand the reasons for this variability in ecosystem susceptibility to chemical exposure, the influences of the properties of the physical environment (i.e., chemical fate) and of the food web (i.e., bioaccumulation) were explored separately.

**Influence of the Physical Environment on Susceptibility to Exposure.** The influence of the characteristics of the physical environment on *ESI* was first examined by comparing the ecosystems with identical food chains and dietary habits. This was the case for the temperate/fish diet and the two tropical ecosystems. As evident from Figure 2 (panels B, D, and E) the *ESI* plots for these three ecosystems exhibit similar patterns. When the *ESI* of the tropical ecosystems was calculated using the temperate/fish diet as the reference, the values ranged between 0.1 and 10 (Figure S3). This shows that the broad range in the characteristics of the physical environment between the temperate, tropical island, and tropical forest regions had only a modest influence on human exposure.

The two steppe regions also had identical food chains and dietary habits. Their *ESI* values (Figure 2, panels F and G) reveal a greater influence of environmental conditions (i.e., for low  $\log K_{OA}$  chemicals), in particular for the portions of the chemical partitioning space where the major uptake pathways were directly related to concentrations in the environmental media (e.g., breathing and drinking, see Figure S2). The inhabitants of the cold steppe were particularly susceptible to highly water-soluble chemicals which were concentrated in the relatively small and cold freshwater compartment. In the warm steppe, the concentrating effect of the relatively small water volume in this environment was counteracted by the greater partitioning from water to air at high temperatures. This is reflected in the lower *ESI* for water-soluble chemicals and higher *ESI* for volatile compounds in the warm steppe compared to the cold steppe region.

To assess the influence of the physical environment in the Arctic, the ecosystem with the highest *ESI*, the quotient between the freely dissolved concentration in the marine water of the Arctic and the temperate regions was calculated (see Figure S4). For most of the chemical partitioning space, the concentration in the marine water (the dominant exposure medium for bioaccumulation of the majority of compounds in the Arctic ecosystem, see Figure S2) was around three (max 15) times higher in the Arctic ecosystem than in the temperate. This difference is small compared to the *ESI* (Figure 2, panel C). Hence, for the Arctic system as well as for most chemicals in the tropical and steppe systems, the characteristics of the physical environment play a relatively small role in determining susceptibility to chemical



**FIGURE 2.** Exposure susceptibility index (*ESI*) of the different ecosystems to persistent chemicals emitted to air. This index is the human body burden to accumulated emissions ratio (*HER*) for a 25 year old woman from the specified ecosystem normalized to the *HER* for the temperate environment/mixed diet ecosystem. The log of the index is plotted as a function of the chemical's log octanol-air and log octanol-water partition coefficients (log  $K_{OA}$  and log  $K_{OW}$ ) at 25 °C.

exposure. The properties of the food web are the primary determinant of the *ESI*.

**Influence of the Properties of the Food Web on Susceptibility to Exposure.** The influence of bioaccumulation on ecosystem susceptibility to chemical exposure was first explored by assessing the three temperate ecosystems that differed only in food chain structure (mixed diet, vegetarian diet, and fish-rich diet, Table 1). The *ESIs* of the temperate/vegetarian diet and temperate/fish diet ecosystems are displayed in Figure 2, panels A and B (note that the temperate/mixed diet ecosystem was the reference). Compared to the woman on a mixed diet, the vegetarian woman was between ~10 and 400 times less exposed to chemicals with log  $K_{OW} < 9$  and log  $K_{OA} > 6$  (Figure 2 panel A). As shown in Figure S2, for a mixed diet it is dairy products, beef, and fish that are the dominant exposure pathways for persistent chemicals with these partitioning properties (panel A, see also Figure 1B), while for a vegetarian diet it is vegetables (panel B). The reason for the low *ESIs* in the temperate/vegetarian ecosystem was thus the generally lower potential of vegetables to accumulate these hydrophobic chemicals compared to cattle and fish.

The woman on a fish rich diet accumulated up to 4 times higher body burdens of persistent chemicals with log  $K_{OW}$  6 to 9 and log  $K_{OA} > 9$  (Figure 2B). This is the portion of chemical partitioning space where fish is the major exposure vector

in the reference ecosystem (Figure 1B) and hence the higher fish consumption more than compensated for the absence of dairy products and meat in the diet (Table 1). Elevated levels of persistent PCB congeners in human tissues have been related to high fish consumption in several studies (22–24), in particular highly chlorinated (and thus more hydrophobic) congeners (25, 26), as well as PCDDs/DFs (27). The fish rich diet ecosystem showed particularly low *ESI* values for log  $K_{OA}$  7 to 10 and log  $K_{OW} < 4$  as well as log  $K_{OW}$  8 to 10. In this portion of the chemical partitioning space, dairy and beef are the major exposure vectors in the reference ecosystem (Figure 1). The absence of these foods in the fish rich diet explains the low *ESI* values. The low *ESI* values in these portions of the partitioning space are also the key features of the *ESI* plots for the tropical ecosystems (Figure 2D,E). This is due to the same factor, the absence of milk and meat in the diet.

As concluded in the previous section, the characteristics of the physical environment did not explain the high susceptibility of the Arctic ecosystem to exposure to persistent contaminants (Figure 2C). This is in agreement with a previous modeling study of Arctic bioaccumulation potential (10). The major difference between the Arctic food web model compared to the temperate, apart from the absence of beef/dairy and vegetables, was the presence of a seal in the marine food web. For all chemicals of log  $K_{OW} > 2$ , seal blubber was

the dominant exposure vector (Figure S2). A long lifetime and high body temperature, ingestion rate, and dietary absorption efficiency combined with a slow depuration rate makes the seal a highly potent magnifier of persistent organic contaminants. Elevated PCB concentrations have been found in the breast milk and blood (up to 11 and 37 times, respectively) of Canadian populations living on a high fish or traditional Inuit diet compared to control groups (28, 29).

**Labile Chemicals.** Figure S5A plots the  $HER$  of the labile chemicals ( $HER_{\text{labile}}$ ) divided by the  $HER$  of the analogous persistent chemicals ( $HER_{\text{persistent}}$ ). For the labile chemicals, a lower total mass of chemical remained in the environment, and consequently the  $HER_{\text{labile}}/HER_{\text{persistent}}$  quotient was always  $<1$ . The relative decrease in  $HER_{\text{labile}}$ , however, was related to the major exposure vectors. Chemicals that were mainly transferred via inhalation and drinking showed little decrease ( $\sim 10$  times lower), whereas the decrease was large (up to  $10^{5.5}$  times lower) for compounds for which the major exposure pathways passed through several organisms capable of metabolizing the chemicals. The strong influence of biotransformation on bioaccumulation has been demonstrated in other studies (30, 31).

The  $ESI$  values of the labile chemicals are plotted in Figure S5B. A comparison with the  $ESI$  for the persistent chemicals (Figure 2) shows that the  $ESI$  of a given labile chemical in an ecosystem did not differ from the  $ESI$  of the analogous persistent chemical in the same ecosystem by more than a factor of 10. In other words, the relative difference in chemical fate and bioaccumulation between two ecosystems is relatively insensitive to whether the chemical is perfectly persistent or labile. The Arctic ecosystem was a notable exception; the  $ESI$  was  $>500$  times lower for labile compounds with  $\log K_{\text{OW}}$  of 4 to 5 and  $\log K_{\text{OA}}$  of 9 to 11. The presence of the seal in the Arctic food web provided an extra biotransformation filter compared to the reference ecosystem. This resulted in the strong susceptibility of the Arctic ecosystem to exposure to persistent chemicals being virtually eliminated for labile chemicals. We note that this assessment is limited to one set of transformation rates; a particularly fast rate in one compartment or organism could give different conclusions.

**Influence of Mode of Emission.** The influence of mode of emission on susceptibility to exposure was explored in several experiments that are described in detail in the Supporting Information. Several salient findings were as follows:

When chemicals were emitted to freshwater, the  $ESI$  of the tropical forest increased by up to 10000 times for chemicals with  $\log K_{\text{OW}} > 4$ , when compared to emissions to air. The  $ESI$  was very high, achieving values in excess of 10000. The explanation was that the fish in the tropical forest ecosystem were exposed in the freshwater compartment, while the fish in the temperate ecosystem were exposed in the marine compartment, where dilution of the emissions to water was much greater. The dilution of the chemical in the media responsible for food web exposure is a significant factor influencing the  $ESI$ .

Emissions to freshwater in the warm steppe illustrated a different effect. The  $ESI$  decreased for chemicals with  $\log K_{\text{OW}} > 7$  compared with emissions to air. Redirecting emissions from air to water strongly reduced the exposure of the agricultural food chain in both the warm steppe and the temperate environment, while increasing the exposure of the aquatic food chain. However, because the steppe diet did not include fish, it was only affected by the reduced exposure of the agricultural food chain, which resulted in a lower  $ESI$ . Hence, changing mode of emission can affect  $ESI$  when the dominant exposure pathways differ between the target and the reference ecosystem, and when one of the

unique exposure pathways is reduced by changing the mode of emission.

An increase in a unique exposure pathway can also be caused by changing the mode of emission. When the mode of emissions in the tropical forest ecosystem was changed from air to soil, the  $ESI$  decreased by about a factor of 10 for chemicals with  $\log K_{\text{OA}} > 10$  and  $\log K_{\text{OW}}$  of 6 to 8. This was due to the increased exposure via the agricultural food chain as a result of soil ingestion by livestock. However, because the diet in the tropical forest did not include meat or dairy products, human exposure increased only in the reference (temperate) ecosystem.

Changing the mode of emission to soil in the tropical island ecosystem resulted in a large increase in  $ESI$  (up to  $\sim 870$  times) for chemicals with  $\log K_{\text{OW}} < 3$ . The primary exposure vector for these chemicals was water, and the chemicals were entering the water from the soil. Since the land surface area was much smaller in the tropical island ecosystem than in the temperate, the concentrations in soil arising from the emissions were much higher in the former. This resulted in the higher  $ESI$  when the chemicals were emitted to soil instead of air. This is an example of how dilution (here in soil) can indirectly affect exposure (here via water) and susceptibility to exposure.

These examples illustrate that the impact of shifting mode of emission varies considerably between the ecosystems, and hence that the mode of emission can strongly influence the susceptibility ranking of different ecosystems.

**Implications for Chemicals Management.** This modeling exercise illustrates that the differences in ecosystem susceptibility to chemical exposure are sometimes large. Emission of a certain amount of a compound possessing a given combination of chemical properties into different ecosystems can yield human body burdens that differ by several orders of magnitude. Note also that the concept of exposure susceptibility is applicable to top predators other than humans. This suggests that the use of generic models for exposure assessment in chemical regulation can be problematic. Instead, models should be tailored to the ecosystem of interest. Otherwise errors of several orders of magnitude could occur, both in estimates of the magnitude of exposure as well as the relative exposure between chemicals.

As discussed in the previous sections, several factors influence ecosystem susceptibility to chemical exposure. When persistent chemicals were emitted to air, the most important property affecting this susceptibility was the structure of the food web, whereas the characteristics of the physical environment played a minor role except for highly water-soluble or volatile compounds that were not transferred via the food chain. The presence of long-lived, warm blooded predators in the food web is one feature that is likely to result in a high  $ESI$ .

It has been shown that biotransformation is a more important predictor of bioaccumulation in humans than partitioning properties (31). However, for ecosystem susceptibility (the relative bioaccumulation in an ecosystem compared to the reference temperate ecosystem), this parameter was in most cases less important. This is because the impact of biotransformation in one ecosystem was usually matched by a similar impact of biotransformation in the reference ecosystem.

Mode of entry had a stronger influence on ecosystem susceptibility than chemical persistence. Two important mechanisms for this were differences in chemical dilution related to mode of emissions and selective influencing of exposure pathways that were uniquely dominant in either the target ecosystem or the temperate ecosystem. Hence, one cannot readily conclude that if an ecosystem is highly susceptible to exposure to a chemical released into medium

x, that it will also be highly susceptible when the chemical is released into medium y.

To assess the robustness of the conclusions of this study, the uncertainty in the model predictions must be considered. In an uncertainty assessment of 236 chemicals in a chemical fate and exposure model it was concluded that the variance of predicted human daily dose was largely attributable to chemical-specific input parameters, while landscape characteristics made a minor contribution (32). In calculating the ESI the influence of most chemical-specific input parameters cancels out through the normalization to the reference scenario, and hence the major source of uncertainty is largely eliminated. Uncertainty in model predictions also arises from model uncertainty. Model uncertainty will not affect many of the major conclusions in this study, particularly those with transparent explanations (e.g., the influence of diet, the role of warm-blooded predators in the food chain, the influence of mode of emission, and the influence of biotransformation). However, model uncertainty could have a significant impact on specific details of the results. For instance, there is still considerable uncertainty in important processes for the fate and bioaccumulation of high  $K_{OW}$  compounds, which could influence conclusions about the dominant exposure vectors and ESI in this region of the figures.

There are several readily apparent applications of the concept of ecosystem susceptibility to chemical exposure. One is in deciding where chemicals are produced and used. It may be prudent to limit such activities in ecosystems that are highly susceptible to exposure. This is particularly relevant for chemicals that are persistent in the environment and that thus should be managed based on their exposure hazard. A second is in choosing the regions for chemical monitoring programs and prioritizing regulatory activities. Here it might be wise to focus on particularly susceptible ecosystems and to use the information on critical exposure pathways to help select monitoring matrices.

The results of this study also give an indication of how changes in some parameters related to climate (i.e., temperatures, storm intensities, and precipitation) might affect exposure. They suggest that any major effects of climate on exposure to contaminants are likely to be indirect, via modifications of food chain structure (e.g., elimination of marine mammals in the Inuit diet, changes in the balance between fish/meat/dairy and other foods in the human diet). The modeling principles presented could be used to explore these issues more directly.

This work shows that the complexity of environmental fate and bioaccumulation leads to great variability in human exposure between ecosystems. Hence, an exposure assessment for one ecosystem cannot be readily extrapolated to others. For this an understanding of the ecosystem susceptibility to chemical exposure is required, whereby the contribution of regionally produced food to the diet should be considered.

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### Supporting Information Available

Tables presenting model parametrization and physical-chemical properties of the hypothetical chemicals and chemical space plots displaying human to emissions ratios (HERs) and dominant exposure vectors for all ecosystems, environmental concentration ratios (normalized to corresponding temperate environmental concentrations), HERs of labile compounds normalized to persistent compounds,

ESIs of labile chemicals, ESIs for a selection of ecosystems with emissions to soil or freshwater, and resulting dominant exposure vectors. This material is available free of charge via the Internet at <http://pubs.acs.org>.

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