Quantitative Structure Activity Relationships for Predicting the Bioaccumulation of POPs in Terrestrial Food-Webs

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Abstract

K_{OW} based QSARs are used to assess the bioaccumulation potential of thousands of commercial chemicals in Canada and internationally. The QSARs, which are based on information from aquatic organisms, identify chemicals with a log $K_{OW} > 5$ to have a potential to biomagnify in food-chains. This study investigates whether K_{OW} based QSARs are also effective in identifying biomagnifying chemicals in terrestrial food-chains. First, a terrestrial bioaccumulation model is developed and used to hypothesize the general relationship between the chemical's octanol-air and octanol-water partition and its biomagnification potential. Secondly, field observations of the bioaccumulation of persistent organic pollutants in wolves are used to test the hypothesis and explore the fundamental differences between QSARs for bioaccumulation in aquatic and terrestrial food-chains. The results indicate that (i) QSARs for bioaccumulation in terrestrial food-chains should include both octanol-air (K_{OA}) and octanol water partition coefficients (K_{OW}); (ii) chemicals with a log $K_{OA} >$ approximately 5 can biomagnify in terrestrial food-chains if log $K_{OW} > 2$ and the rate chemical transformation or metabolism is low; (iii) biomagnification factors in terrestrial food-chains are much greater than those in aquatic food-chains; (iv) biomagnification factors of very hydrophobic substances (log $K_{OW} > 7$) in terrestrial biota do not drop off with increasing K_{OW} as has been observed in aquatic biota. The relevance of these findings is that current regulations and protocols may misidentify (i) low K_{OW} but high K_{OA} chemicals as having no bioaccumulation potential and (ii) very hydrophobic (log $K_{OW} > 8.5$) which appear not to biomagnify in aquatic organisms but have the potential to biomagnify in terrestrial food-chains. Considering that 67.9% of the approximately 12 000 organic chemicals on Canada's Domestic Substances List exhibit high K_{OA} but low K_{OW}, this represents a major gap in our methods for screening bioaccumulative substances.

1 Introduction

Quantitative Structure Activity Relationships (QSARs) play an important role in the management of Persistent Organic Pollutants (POPs). For example, in Canada QSARs are being used to categorize the approximately 23 000 chemicals on the Domestic Substances List in terms of their persistence, bioaccumulation potential and toxicity as part of provisions under the Canadian Environmental Protection Act (CEPA) [1]. With regard to the bioaccumulation criteria, the *Persistence and Bioaccumulation Regulations* of CEPA state that if the Bioaccumulation Factor (BAF) or the Bioconcentration Factor (BCF) exceeds 5000 or the logarithm of the octanol-water partition coefficient (K_{OW}) of the chemical substance exceeds 5, the bioaccumulation criterion is exceeded. The regulations further stipulate that a reliable BAF takes precedence over a BCF, which in turn takes precedence over a log K_{OW}. The intent of the regulations is to identify substances that are "bioaccumulative". These are chemicals that biomagnify in food-chains resulting in concentrations in predators that exceed those in their prey and which consequently exhibit a biomagnification factor (BMF) larger than 1.0.

Since empirical bioaccumulation and bioconcentration data are unavailable for the great majority of the substances on the DSL, the categorization for bioaccumulation relies heavily on the use of K_{OW} based QSARs. In countries that are signatories of the UNEP Long Range Transboundary Air Pollutants Protocol [2] similar K_{OW} based QSARs and criteria are used to assess the bioaccumulation potential of organic substances [3, 4]. K_{OW} based QSARs are also used to assess the toxicity of chemicals.

The reason for the success of the octanol-water partition coefficient in assessing the bioaccumulation as well as the toxicity of organic chemicals is that the octanol-water partition coefficient is to a first degree a good descriptor or model of the water-to-organism exchange of organic chemicals in aquatic organisms. As a first approximation, organic chemicals partition into the lipids and organic matrices of organisms in a similar fashion as they partition between water and octanol. A wealth of empirical data

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support this basic model although a number of modifying factors such as metabolism, growth, fecal egestion and reproductive factors have also been identified [e.g. 5].

A crucial question that has received little attention in the literature is whether the QSARs that were derived based on studies of bioaccumulation and toxicity in aquatic organisms can also be used to assess bioaccumulation and toxicity of chemical substances in terrestrial biota and humans. Unlike aquatic organisms, humans and terrestrial organisms are not dependent on exchange with the water for their respiratory needs. The bioaccumulation behavior of organic chemicals in terrestrial organisms may therefore be less related to K_{OW} than the bioaccumulation in aquatic biota. The octanol-air partition coefficient K_{OA} can be expected to be a better structural property as it better describes the organism-to-air exchange.

The question whether K_{OW} based QSARs are a good model for terrestrial mammals and humans is important because the intent of the current regulations in Canada and international protocols is to act as a safety net by identifying those substances that may be harmful to human and environmental health. It is important to stress that many of the environmental effects of now regulated organic pollutants such as PCBs and DDT were strongest and most evident in higher organisms such as birds and marine mammals rather than in aquatic organisms such as fish.

It is the objective of this paper to explore the applicability of K_{OW} based QSARs to assess the bioaccumulation behavior of organic chemicals in terrestrial organisms. Current regulations and the UNEP protocol [2–4] identify chemical substances to be "bioaccumulative" if the K_{OW} of the chemical substance exceeds 100000. A chemical substance is considered bioaccumulative if it biomagnifies in the food-chain and exhibits biomagnification factors greater than 1. This study analyzes the differences between QSARs for the bioaccumulation of hydrophobic organic chemicals in aquatic and terrestrial biota. To accomplish this, we first present a terrestrial bioaccumulation model to hypothesize the general relationship between the chemical's octanol-air and octanol-water partition coefficients and its biomagnification potential. We then present field observations of the bioaccumulation of persistent organic pollutants in wolves to test the hypothesis and explore the fundamental differences between QSARs for bioaccumulation in aquatic and terrestrial food-chains. Finally, we explore the implications of our findings for current regulations and international protocols regarding bioaccumulative substances.

2 Theory

When exploring the applicability of K_{OW} based QSARs for bioaccumulation, it is useful to briefly revisit their theoretical basis. The underlying assumption of K_{OW} based QSARs is that most hydrophobic organic chemicals can relatively easily pass through biological membranes via passive diffusion. When absorbed, organic chemicals are in many cases quickly distributed within the organisms and partition predominantly in the lipids. As a result, one can (in a simplified manner) view an organism as a single compartment of lipid, which exchanges chemical substances with the ambient water via passive diffusion [6]. This process resembles a partitioning process between octanol (a surrogate for lipids) and water [6].

An important difference between terrestrial and aquatic organisms is that the respiring medium is air rather than water. Uptake of contaminants in terrestrial organisms is from the diet and inhalation. For POPs, the diet is typically the main route of uptake [7, 8]. Elimination is predominantly via respiration to the air, urinary excretion, fecal egestion, bile excretion, growth dilution, milk excretion and metabolism. Elimination of contaminants into respired air involves organism-to-air exchange and can be expected to correlate with the lipid-air or octanol-air partition coefficient K_{OA}. Elimination into urine and bile involves exchange between the organism and water and is related to the octanol-water partition coefficient. Fecal egestion and milk excretion (in female animals) involves chemical exchange between organic media and can be represented by lipid-to-organic matter partition coefficients. The relationship between the chemical's properties and its bioaccumulation potential is therefore complex and involves relationships with octanol-air, octanol-water and octanol-organic matter partitioning properties. To explore these relationships it is useful to derive a model of the bioaccumulation of persistent organic chemicals in terrestrial organisms.

Figure 1 presents a conceptual diagram of a relatively simple model of the bioaccumulation of POPs in terrestrial organisms. If it is assumed that dietary uptake is the main route of exposure (as is the case for many POPs), one can define a steady-state biomagnification factor as (BMF) as

$$BMF = C_{Biota}/C_{Diet} = k_{Diet}/(k_{Air} + k_{Urine} + k_{Bile} + k_{Feces} +$$
$$k_{Milk} + k_{Growth} + k_{Metabolism}) \tag{1}$$

Where C_{Biota} and C_{Diet} are the steady-state chemical concentrations (mol/m³).

The dietary uptake rate constant k_{Diet} can be expressed as:

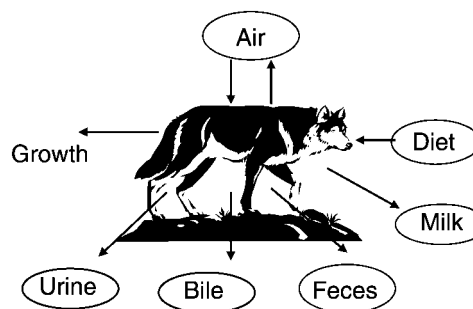$$k_{Diet} = E_{Diet} \cdot G_D/V_B \tag{2}$$

Figure 1. A conceptual model of the bioaccumulation process of organic chemicals in terrestrial biota.

Where E_{Diet} is the dietary uptake efficiency, G_D is the feeding rate (m^3/d) and V_B is the weight of the organism (m^3). The respiratory elimination rate constant k_{Air} can be expressed as:

$$k_{Air} = E_{Air} \cdot G_A/V_B \cdot L_B \cdot K_{OA} \qquad (3)$$

Where G_A is the respiration rate (m^3/d), V_B is the weight of the organism, L_B is the lipid content of the organism, and K_{OA} is the octanol-air partition coefficient. The urinary excretion rate constant is

$$k_{Urine} = G_U/V_B \cdot L_B \cdot K_{OW} \qquad (4)$$

where G_U is the urinary excretion rate (m^3/d) and K_{OW} is the octanol-water partition coefficient. The fecal excretion rate constant is

$$k_{Fecal} = G_F/V_B \cdot K_{BF} \qquad (5)$$

where G_F is the fecal excretion rate (m^3/d) and K_{BF} is the organism-to-feces partition coefficient (kg wet weight organism/kg wet weight feces). The bile excretion rate is

$$k_{Bile} = G_B/V_B \cdot L_B \cdot K_{OB} \qquad (6)$$

Where G_B is the bile excretion rate (m^3/d) and K_{OB} is the octanol-bile partition coefficient which can be expressed as a function of K_{OW}, i.e. $K_{OB} = K_{OW}/\beta$ where β represents the degree to which bile fluids exceed the solubility of contaminants over that in water. The milk excretion rate constant can be expressed as

$$k_{Milk} = G_M/V_B \cdot L_B \cdot K_{OM} \qquad (7)$$

where G_M is the milk excretion rate (m^3/d) in female animals and K_{OM} is the octanol-milk partition coefficient. In male animals k_{Milk} is zero.

In the BMF model, k_{Growth} (1/d) is the growth dilution rate constant. It does not represent a true elimination pathway. However, an increase in body mass has the effect of "diluting" or lowering the internal concentration and can be represented as an elimination route. The metabolic transformation rate constant $k_{Metabolism}$ represents the metabolic transformation rate of the parent compound. Metabolic transformation lowers the biomagnification potential of chemicals. The model does not account for any accumulation of metabolite(s).

3 Methodology

3.1 Model calculations

To explore the relationship between the biomagnification potential of organic compounds and their octanol-water and octanol-air partitioning properties, we have parameterized

Table 1. Parameters for the bioaccumulation model of POPs in arctic wolves.

Model Parameter	Value
Weight V_B	80 kg [11, 12]
Lipid Content L_B	0.12 [11, 12]
Respiration Rate G_A	20 000 L/d
Feeding Rate G_D	2.1 kg/d [11, 12]
Urine excretion rate G_U	1.0 L/d
Bile Excretion rate G_B	0.3 L/d
Fecal excretion rate G_F	0.66 kg/d [11, 12]
Milk excretion rate G_M	0 L/d
Growth rate constant	0 kg/kg.d
Air uptake efficiency	30%
Dietary uptake efficiency	90%
K_{BF}	50
β	10 (estimated)

the model to adult male wolves (*Canis lupus*) of 3 years and older. One of the advantages of selecting these animals is that k_{Milk} and k_{Growth} are zero as the animals do not grow significantly at that age. Also, $k_{Metabolism}$ was set to zero as we are primarily interested in persistent organic pollutants that do not undergo biotransformation at a significant rate. These assumptions simplify the model allowing us to focus on relationships between the BMF and physical-chemical properties. Data to parameterize the model were obtained from a number of sources [9–12] and are summarized in Table 1. It is interesting to note that the model parameters for the wolves are comparable to those for adult human males. Model calculations were performed for chemicals with a log K_{OW} between 0.5 and 15 and a log K_{OA} between 0.5 and 15.

3.2 Field Observations

Field observations of the biomagnification factor BMF of a range POPs in male and female wolves of arctic Canada are documented in [7]. For the purpose of this analysis, we will only refer to BMFs observed in adult (3 years and older) male wolves from the Bathurst range. These animals feed almost exclusively on barren ground caribou (*Rangifer tarandus*) [9, 10]. The BMFs were expressed as the ratio of lipid normalized concentrations in the wolves and the caribou as explained in [7] and plotted versus K_{OW} and K_{OA}. The BMFs and the physical chemical properties that were used are documented in Table 2.

4 Results

4.1 Model calculations

Figure 2a illustrates the relationship between the BMF and K_{OW} as determined by the terrestrial biota bioaccumulation model. It shows that for chemicals of low K_{OA} (i.e. log K_{OA} between 1 and approximately 5), the BMF is less than 1.0

Table 2. Biomagnification factors (kg/lipid/kg lipid) of some hydrophobic organic substances in arctic wolves from 3 locations (i.e. Inuvik, Bathurst Inlet and Cambridge Bay, respectively) reported in [7] in relation to chemical's octanol-water K_{OW} and octanol-air partition K_{OA} coefficient. N/A = not available due to non-detectable concentrations.

Chemical Compound	Log K_{OW}	Log K_{OA}	BMF (Inuvik)	BMF (Bathurst Inlet)	BMF (Cambridge Bay)
β-HCH	3.81	8.17	28	37	3.3
1,2,4,5 Tetrachlorobenzene	4.70	5.84	N/A	6.9	1.6
Pentachlorobenzene	5.03	6.50	3.2	5.7	1.1
Hexachlorobenzene	5.50	7.11	2.2	6.5	0.9
PCB-153	6.92	10.0	28	24	3.0
PCB-170/190	7.46	10.8	N/A	110	13
PCB-180	7.50	10.8	110	93	8.0

and there is no or little relationship between the BMF and K_{OA}. For these substances, respiration is the main route of elimination. Hence, the elimination rate and the BMF, which follows a reciprocal relationship with the respiratory elimination rate constant, are predominantly related to K_{OA} rather than K_{OW}. When K_{OA} increases above 5, respiration becomes increasingly less important as a route of elimination. For these higher K_{OA} substances, the lower K_{OW}

substances (i.e. log $K_{OW} \leq 3.5$) are predominantly eliminated in urine and bile. The higher K_{OW} substances are very poorly eliminated into air, urine and bile. In absence of metabolism, fecal egestion rate is the only significant route of elimination. Since the fecal egestion rate constant is smaller than the dietary uptake rate constant, these high K_{OW} and high K_{OA} substances have the potential to biomagnify and produce BMFs > 1. For substances of high K_{OW} for which elimination to aqueous media are insignificant, the BMF is not expected to relate to K_{OW}. The model calculations illustrate that persistent (i.e. unmetabolizable) compounds with a log $K_{OA} > 5$ can be expected to be bioaccumulative (i.e. BMF > 1) even if the chemical's K_{OW} is low, e.g. less than 5. Only, when log K_{OW} falls below 2, combined elimination to air, bile and urine is large enough to cause the BMF to drop below 1.0.

Figure 2b shows the same BMF data as in Figure 2a but now expressed relative to K_{OA}. It shows a strong relationship between the BMF and K_{OA} for substances with lower K_{OA}, for which respiration is an important route of elimination. However, for substances with high K_{OA} (log $K_{OA} > 5$), K_{OW} becomes a secondary factor. As in Figure 2a, high K_{OA} and K_{OW} substances exhibit no significant elimination to air or to urine and bile, causing the fecal egestion to be only significant route of elimination, hence resulting in biomagnification.
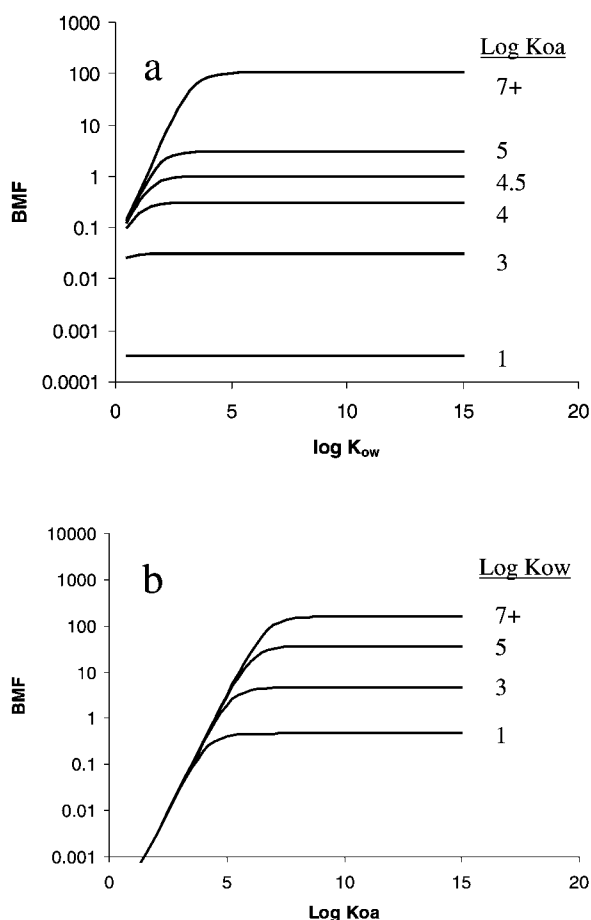
4.2 Field Observations

Figure 3 shows field observed biomagnification factors in male wolves in relation to K_{OW} (a) and K_{OA} (b). It shows that the BMF varies from 3 to approximately 160 and increases with increasing K_{OW} and K_{OA}. The BMF does not show a maximum and a decline for very hydrophobic substances with high K_{OW} and K_{OA} as has been observed for the BMF in fish [e.g. 13, 14]. The BMF shows a reasonable correlation with K_{OW} ($r^2 = 0.533$), but a stronger correlation with K_{OA} ($r^2 = 0.768$). Figure 4 shows that within the homologous series of PCBs and chlorobenzenes there is a strong correlation between K_{OW} and K_{OA}. This implies that both K_{OW} and K_{OA} are good descriptors for the BMF. However, this correlation disappears when chemicals of different chemical make-up are included and K_{OA} and K_{OW} no longer
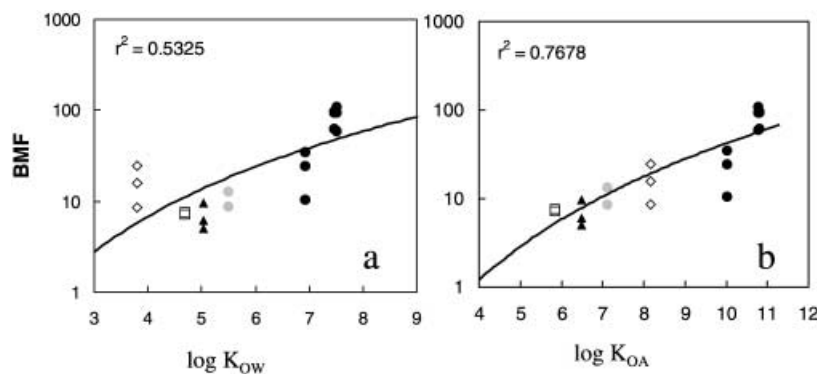
Figure 2. Relationship between the biomagnification factor (BMF) and K_{OW} (a) and K_{OA} (b) as predicted by the terrestrial bioaccumulation model.

Figure 3. Observed relationship between the biomagnification factor (BMF) and K_{OW} (a) and K_{OA} (b) for PCB congeners (●), hexachlorobenzene (⊙), pentachlorobenzene (▲), tetrachlorobenzene (□) and β-HCH (◇) in adult (3 + years old) wolves (*Canis lupus*) feeding on barren ground caribou of the Bathurst range.
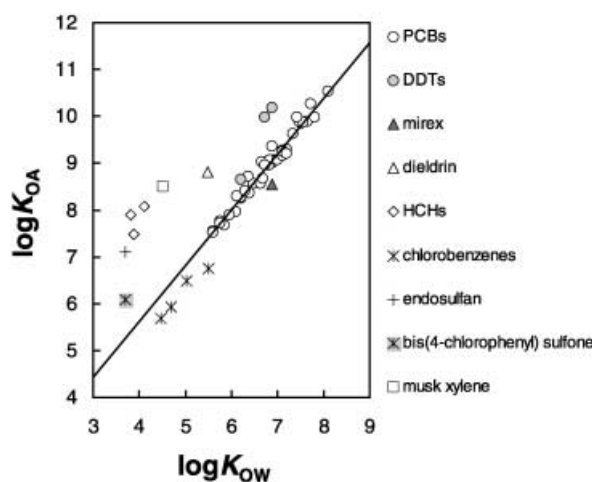

Figure 4. Correlation between K_{OW} and K_{OA} for the chemicals (i.e. some PCBs, chlorobenzenes, β-HCH, dieldrin, mirex, DDT, endosulfan and bis-4-chlorophenylsulfone) included in the field study.

correlate. For the chemicals included in the study, K_{OA} provides a better correlation than K_{OW}. However, as the model indicates BMFs are related to both K_{OW} and K_{OA}

(Figure 2). Figure 3 illustrates that chemicals with log K_{OW} as low as 3.5 can biomagnify in wolves and suggests that substances with log K_{OA} as low as 4 can biomagnify in wolves if they are not metabolized at a significant rate.

5 Discussion

QSAR: The model calculations and field observations are in good agreement with regards to the general relationship between the BMF and the octanol-water and octanol-air partition coefficients. The data indicate that the biomagnification potential of organic chemicals in terrestrial food-chain is controlled by K_{OW} and K_{OA}, but that over a large range of K_{OW} values (i.e. log K_{OW} > approximately 2), the occurrence of biomagnification potential can be reasonably well assessed by K_{OA}. This provides us with an opportunity to explore the question whether QSARs derived for bioaccumulation in aquatic food-chains can be used and depended on to identify bioaccumulative substances in terrestrial food-chains. To aid this discussion, we have plotted the biomagnification QSAR for the aquatic environment (data from Ref. 13) and the terrestrial environment
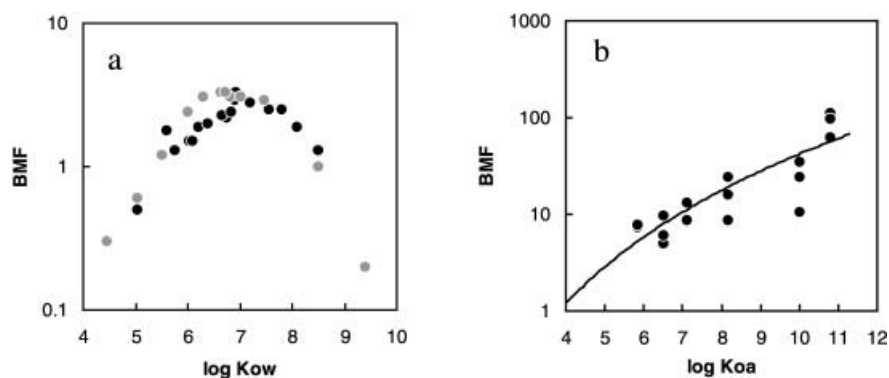

Figure 5. A comparison of QSARs for biomagnification in (a) aquatic organisms (empirical data for juvenile rainbow trout (●) [13] and model predictions (⊙) according to [5]) and (b) terrestrial organisms (data for adult wolves [7]).

in Figure 5. This Figure points out a number of differences between the QSARs. First, while the BMF in aquatic organisms correlates well with K_{OW} because of the importance of animal to water exchange of contaminants, the data illustrate that K_{OA} is generally a better predictor of the BMF due to the importance of animal-to-air exchange. This implies that a categorization of the bioaccumulation potential of organic chemicals in terrestrial organisms and possibly humans requires a different approach than that for aquatic organisms. Fortunately, there is an increasing number of reliable K_{OA} data for organic substances in the literature and methods for the calculation of K_{OA} are available as well [15, 16].

Secondly, the QSARs for aquatic organisms generally indicate that substances with a log $K_{OW} > 5$ have the potential to biomagnify in aquatic food-chains. The bioaccumulation criteria in the TSMP, which identify substances to be bioaccumulative if their K_{OW} exceeds 10^5 is in good agreement with these QSARs. However, the model calculations and observed data for the wolves suggest that chemicals with a log K_{OW} perhaps as low 2 can biomagnify in terrestrial food-chains as long as K_{OA} exceeds approximately 5 and the chemical is not metabolized at a significant rate. This indicates that the bioaccumulative potential (in absence of metabolism) of many hydrophobic organic chemicals can be successfully assessed from the chemical's K_{OA}. The findings also indicate that the CEPA regulations in Canada and UNEP's LRTAP, which identify substances to be potentially bioaccumulative if log $K_{OW} > 5$, can be expected to erroneously categorize many lower K_{OW} (but high K_{OA}) substances that do not have a biomagnification potential in aquatic food-chains but do in terrestrial food-chains. These "lower K_{OW}-high K_{OA}" substances can be bioaccumulative in terrestrial food-chains if they are not metabolized at a significant rate. In addition to our study, there are a number of examples illustrating the bioaccumulative potential of lower K_{OW} chemicals in mammalian food-chains. For example, BMFs of 7.6 and 2.0 were reported for ΣHCH (log $K_{OW} = 3.81$) in ringed seals (Arctic cod/blubber) [8] and beluga whales (Arctic cod/blubber) [17]. Also, α-endosulphan (log $K_{OW} = 3.83$) has been observed to biomagnify in beluga whales and in ringed seals [17].

Third, Figure 5 illustrates that the degree of biomagnification can be much greater in the terrestrial food-chains than in aquatic food-chains. BMFs in fish and aquatic invertebrates generally range between 2 to 10. BMFs of POPs in wolves, birds and marine mammals are generally an order of magnitude greater than those in aquatic organisms. This implies that persistent chemicals are much more strongly magnified in terrestrial food-chains than in aquatic food-chains. This may be one of the reasons why some of the effects of certain POPs (e.g. DDT, PCBs) were first observed and are most evident in higher trophic level terrestrial organisms.

Fourth, Figure 5 shows that the BMF for aquatic organisms exhibits a maximum at a log K_{OW} value of about 7. Further increases in K_{OW} appear to reduce the BMF.
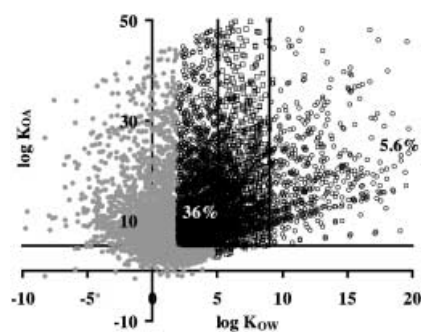

Figure 6. Relationship between K_{OW} and K_{OA} for approximately 12 000 organic compounds on the Canadian Domestic Substances List. The graph identifies the percentage of low K_{OW} (i.e. log $K_{OW} < 5$) substances, high K_{OW} substances (log K_{OW} between 5 and 9) and very hydrophobic chemicals (log $K_{OW} > 9$). The horizontal line at a log K_{OA} of 5 identifies substances that have a biomagnification potential if not metabolized at a significant rate.

Substances with a log K_{OW} exceeding approximately 8.5 or 9 do not appear to have a biomagnification potential. One of the factors contributing to this behavior is that for high log K_{OW} substances, the dietary uptake efficiency in fish tends to drop with increasing K_{OW}. Figure 5 shows that a similar maximum of the BMF is not observed in wolves. This may be explained by the observation that, in contrast to fish, the dietary uptake efficiency in mammals and also in birds does not show a similar magnitude of reduction in the dietary uptake efficiency with increasing K_{OW} or K_{OA}. This is an important characteristic of the bioaccumulation of POPs in terrestrial food-chains as various methods of bioaccumulation categorization advocate that very hydrophobic organic chemicals with a log K_{OW} greater than 9 or 10, should not be considered bioaccumulative. Figure 5 suggests that it would be a mistake to categorize these very hydrophobic substances as being non-bioaccumulative as they do demonstrate a very high bioaccumulation potential in terrestrial food-chains.

The main purpose of the bioaccumulation criteria under CEPA and UNEP's LRTAP is to act as a safety net to identify those substances that have a high bioaccumulation potential. The current criteria provide an adequate system to identify chemicals that biomagnify in aquatic food-chains. This is due to the fact that the criteria were based on the large amount of bioaccumulation information that is available for aquatic organisms such as fish and invertebrates. However, our analysis shows that the current criteria provide significant gaps in our ability to identify bioaccumulative substances in terrestrial food-chains. In particular we identify, low K_{OW} but high K_{OA} substances (i.e. chemicals with a log K_{OW} between 2 and 5 and log $K_{OA} > 5$) as a group of potentially bioaccumulative substances that are not identified by the current criteria. This is a major gap in our ability to screen for bioaccumulative substances. Figure 6 illustrates that 67.9% of the approximately 12 000 organic chemicals on Canada's Domestic Substances List exhibit high K_{OA} (i.e. log $K_{OA} > 5$) but low K_{OW} (i.e. log $K_{OW} < 5$). Of

334

these chemicals, 57% (or 4,151 chemicals) have a log K_{OW} between 2 and 5 and have the potential to biomagnify in terrestrial food-chains if they are not degraded and/or metabolized at a significant rate. These substances will currently be categorized as being non-bioaccumulative based on their K_{OW}. In addition, another 2.6% (or approximately 618 substances) of the most hydrophobic substances (log $K_{OW} > 9$, and all with a log $K_{OA} > 5$) can be misidentified as being non-bioaccumulative if aquatic K_{OW} based QSARs [18] are used to categorize chemicals on the DSL for bioaccumulation. Based on the current QSARs for the biomagnification in terrestrial organisms, these substances can be expected to have a very high bioaccumulation potential in terrestrial food-chains.

6 Conclusion

This paper presents empirical and theoretical evidence that indicates that the octanol-air partition coefficient (K_{OA}) is a crucial physical-chemical property controlling the potential of organic chemicals to biomagnify in terrestrial mammalian food-chains.

The data illustrate that organic chemicals with a log K_{OA} exceeding approximately 5, have an inherent biomagnification potential as long as the chemical's log K_{OW} exceeds approximately 2. Metabolic transformation, lactation, rapid growth and increases in fat reserves can cause the actual degree of food-chain biomagnification to be lower than the chemical's inherent biomagnification potential.

QSARs for biomagnification of organic chemicals in terrestrial food-chains differ in several aspects from QSARs in aquatic food-chains; i.e. (i) the magnitude of biomagnification in terrestrial food-chains is greater than that in aquatic food-chains; (ii) the biomagnification factors correlates better with K_{OA} than K_{OW}; and (iii) the BMF-QSAR for aquatic food-chains exhibits a maximum BMF for chemicals with a log K_{OW} of approximately 7 and a drop of BMF with increasing K_{OW}, while the BMF QSAR for terrestrial food-chains does not exhibit a decline in BMF with increasing K_{OA} for chemicals with extremely high K_{OA}.

Current bioaccumulation criteria in the UNEP protocol on Long Range Transboundary Air Pollutants as well as domestic legislation in Canada and other countries are appropriate for identifying the bioaccumulation potential of organic chemicals in aquatic food-webs but fail to identify chemicals with a biomagnification potential in terrestrial food-chains. We identify "*low K_{OW} but high K_{OA}*" substances (i.e. chemicals with a log K_{OW} between 2 and 5 and log $K_{OA} > 5$) as a group of potentially bioaccumulative substances that are not appropriately identified by the current criteria.

The inability of current bioaccumulation criteria to identify substances that have a biomagnification potential in food-chains is of serious concern given that 36% of the 12 000 organic chemicals on Canada's Domestic Substances List fall in the category of substances that have a high log K_{OA} (i.e. larger than 5) and a log K_{OW} between 2 and 5. These

substances will currently be categorized as being non-bioaccumulative based on their K_{OW}, but can be expected to biomagnify in terrestrial food-chains unless the chemicals are rapidly metabolized by organisms or excreted by other routes (e.g. lactation and growth dilution).

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