Controls on the Trophic Magnification Factor of Organic Chemicals in Aquatic Foodwebs

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1. Introduction

The trophic magnification factor (TMF) of a chemical in a food web is determined from the slope of a regression between lipid-normalized chemical concentrations in biota and the trophic position of the sampled biota; the biomagnification factor (BMF) is the ratio between lipid-normalized chemical concentratons in a preditor species and its prey [1,2]. Measured TMF greater than 1 has been proposed as the top-tier of a framework for assessing the bioaccumulation potential of chemicals [1]. TMF greater than 1 will be observed when the average BMF between each trophic level of a food web is greater than 1. Therefore, the TMF can be viewed as a field-measured BMF where the measurements have been conducted – and thereby averaged – across several trophic levels.

The BMF of chemicals at each trophic step in an aquatic foodweb is determined by a balance between competing rates of uptake and elimination of the chemical that can be described by characteristic times or half-times for uptake and elimination. All of the relevant process rates in an aquatic foodweb are joint properties of the chemical and the system made up of the predator fish, its food, and the water that they are both imersed within. The most interesting case is when the time-scale for uptake of the chemical is short relative to the timescale for elimation from the organism because this leads to BMF greater than 1, and potentially to TMF greater than 1 if it is the case on-average for the entire foodweb.

Here, we have used a process-based model of bioaccumulation of chemicals by fish from food and water to analyze the kinetic controls on the uptake and elimination of chemicals with a wide range of hydrophobicities and susceptibility to biotransformation. Our goal is to identify the processes that control whether BMF is greater than 1 for organic chemicals with different properties. We then extrapolate from BMF to TMF, and identify cases where TMF is controlled by processes that are determined mostly by chemical properties, and cases where it is more heavily influenced by properties of the environmental sysem.

2. Materials and methods

We modeled BMFs using the Arnot & Gobas fish bioaccumulation model [3]. We coded the model in a spreadsheet and used VBA code to model steady-state bioaccumulation by fish for substances that cover a range of combinations of octanol-water partition coefficent (log K_{OW}) and rate constant for biotransformation. A broad range of combinations of log K_{OW} from –2 to 12, and a range of rate constants for whole-body biotransformation by fish of 0.00001 – 10000 day^{-1} was modeled, and the modeled BMFs and uptake and removal process rates were collected.

3. Results

Modeled BMFs and the dominant processes that remove chemicals from fish over the entire range of chemical properties are shown in Figure 1. The model identifies chemicals with biotransformation rate constants less than 0.1 day^{-1} and ($4.5 < \log K_{OW} < 7.5$) as having BMF > 1, and thus having the potential to have TMF >1 (Figure 1A). Different elimination processes are dominant at the boundaries of the region of chemicals that fall in this range (Figure 1B); gill elimination dominates for chemicals with lower log K_{OW} and biotransformation dominates for chemicals with higher biotransformation rate constants. For substances with log K_{OW} above 7.5 two processes limit BMF: growth dilution and slow kinetics of uptake through the gastrointestinal tract.

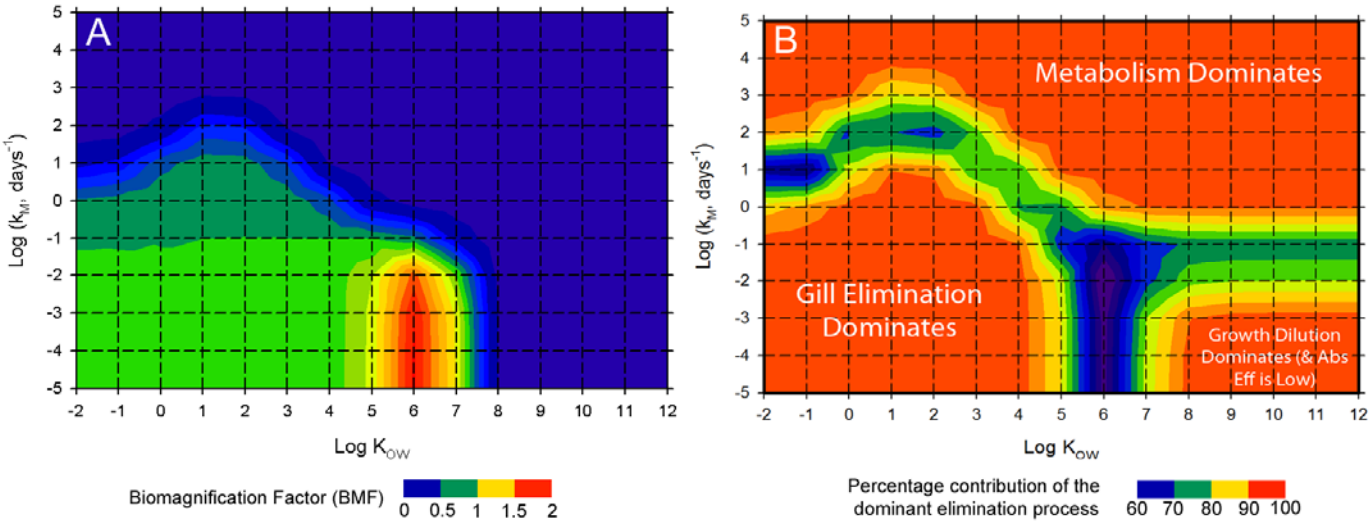

Figure 1: (A) – Modeled biomagnification factor in the Arnot & Gobas model [3] for chemicals with 10 orders of magnitude of variability in biotransformation rate constant (vertical axis) and 12 orders of magnitude variability in hydrophobicity (horizontal axis). Chemicals with combinations of properties in the yellow and red regions have BMF > 1 and potential to have TMF > 1 in aquatic foodwebs. **(B)** – Percentage contribution of the dominant elimination process to the modeled total elimination of chemicals from fish. In most of the chemcal space one process dominates total removal, but in the region where BMF > 1 there is no single dominant process.

4. Discussion & Conclusions

It is interesting to consider the implications of the kinetic controls at the boundaries of the range of chemical properties where BMF > 1 is calculated by the model. At the lower log K_{OW} boundary the dominant controlling process is elimination of chemical through gills, which is mostly dependent on the hydrophobicity of the chemical. The biotransformation rate constant, which is a joint property of the fish and the chemical, is the dominant control on BMF at the upper horizontal boundary. At the upper log K_{OW} boundary BMF is controlled first by the rate at which fish in the system are growing, and then at higher log K_{OW} by the low absorption efficiency of highly hydrophobic chemicals.

The different natures of the processes controlling BMF have implications for the variability in TMFs that can be expected when comparing field values from two or more systems. Near the lower log K_{OW} boundary variability in TMFs in different systems will be driven by variability in gill elimination between species. At the upper boundary of biotransformation rate constant the potential variability between species and between systems is poorly characterized. Finally, at the upper boundary of log K_{OW} there is clearly large variability between species and between aquatic systems in the growth rate of fish and other aquatic biota. Therefore, we should expect high variability in TMF values determined in different systems for chemicals with log K_{OW} above 7, with lower values in systems where growth rates are higher.

5. References

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Acknowledgement – This research was funded by the European Chemical Industry Council (CEFIC) Long-range Research Initiative (LRI) grant number ECO-15.