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Importance of accurate trophic level determination by nitrogen isotope of amino acids for trophic magnification studies: A review

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ABSTRACT

During the last several decades, persistent organic pollutants and metals cause great concern for their toxicity in organisms as well as for their bioaccumulation and/or trophic transfer through the food chains in ecosystems. A large number of studies therefore have focused on the trophic levels of organisms to illustrate food web structure, as a critical component in the study of pollutant dynamics and biomagnification. The trends in biomagnification of pollutants in food webs indeed provide fundamental information about the properties and fates of pollutants in ecosystems. The trophic magnification supports the establishment of a reliable trophic structure, which can further aid the understanding of the transport and exposure routes of contaminants in accumulation and risk assessments. Recently, efforts to interpret the food web structure using carbon and nitrogen stable isotope ratios have contributed to better understanding of the fate of pollutants in the ecosystem. However, it is known that this isotope analysis of bulk ones has many weaknesses, particularly for uncertainties on the estimate of trophic levels and therefore of magnification factors for studied organisms, enough to support a regulatory interpretation. In this review, we collate studies that investigated biomagnification characteristics of pollutants in aquatic ecosystems, along with calculated trophic magnification factors. Moreover, we introduce a novel approach, compound-specific stable isotope analysis of nitrogen in amino acids, to establish reliable food web structures and accurate trophic levels for biomagnification studies. This method promises to provide sound results for interpreting the influence of the pollutant in organisms, along with their bioaccumulation and magnification characteristics, as well as that in ecosystem.

1. Introduction

One of the significant issues relating to the environmental pollution studies would be characterizing the risks of pollutants to organisms, particularly humans and other biota at the top of the food chain (Mackay et al., 2016; Ross and Birnbaum, 2003; Zenker et al., 2014). Those concerns are based on the fact that pollutants or xenobiotics can accumulate in organisms and be transferred through the food chain. In the middle of the 20th century, the cases observed in the book *Silent Spring* by Rachel Carson (dichloro diphenyl trichloroethane, DDT) and the presence of Minamata disease in Japan (mercury, Hg) showed the repercussions of bioaccumulation and magnification as xenobiotics were transferred to the top predators in a food web. With increasing recognition of the dietary pathways that determine body burden, bioavailability, and the effects of pollutants in marine organisms, estimates of bioaccumulation of pollutants and their transfer in the food web (trophic transfer) have received much attention (Wang and Fisher, 1999; Wang and Rainbow, 2008). Biomagnification is the process by which organisms with high trophic levels (TLs) show greater concentrations of a pollutant than those seen at the source (Russell et al., 1999; Walters et al., 2011; Wang et al., 2017). The behavioral properties of pollutants in the environment and in organisms are important because accumulation and trophic transfer might enhance the risks to an ecosystem by increasing bioavailability,

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even if not all forms of a pollutant are directly associated with toxic results. Thus, it is generally considered important to explain the fate of pollutants in the environment by describing their properties, particularly on bioavailability, persistence, and degradability (Alava and Gobas, 2012; Zenker et al., 2014). The results of some studies on pollutants that have transferred through a food chain are used as data to predict hazards to the ecosystem and humans (Alave and Gobas, 2012; Franklin, 2016; Ross and Birnbaum, 2003; Zenker et al., 2014). Furthermore, whether a particular pollutant is magnified or diluted in the food chain is a significant factor in setting management priorities, although uncertainties in those determinations remain an issue (Mackay et al., 2016).

Many studies have shown a clear route for pollutants in a food chain by showing the trophic relationships with accumulated concentrations, and they have done so using several approaches (Barwick and Maher, 2003; Fortibuoni et al., 2013; Munoz et al., 2017; Walters et al., 2011; Watanabe et al., 2008; Zhou et al., 2016). The biomagnification factors presented in those studies are based on information about structures between predator and prey relations, which allow predictions about whether or not a particular pollutant can be transferred and magnified through a particular food chain (Connolly and Pedersen, 1988; Oliver and Niimi, 1988). Thus, reliable food chains and the TL of each organism are the most important background information needed to demonstrate biomagnification in an ecosystem. In most biomagnification studies, the accumulation of exogenous materials (e.g., pollutants) is determined based on concentrations in various organisms and the TL of those organisms in their ecosystem (Barwick and Maher, 2003; Fortibuoni et al., 2013; Munoz et al., 2017; Walters et al., 2011; Watanabe et al., 2008; Zhou et al., 2016). In an early study on the food web structures in aquatic environments, Issacs (1973) suggested that little biomagnification was observed in marine ecosystems because the food chain was more unstructured than that in terrestrial ecosystems, say with a wide range of available prey of various species and ages and with relatively great variations in concentrations and distributions of pollutants in a dynamic aquatic system. However, more recently, many examples of the biomagnification of pollutants in marine environments have been increasingly evidenced from the TL analyses; such as Hg (Atwell et al., 1998), hexachlorobenzene (HCB), DDTs, and polychlorinated biphenyls (PCBs) (Corsolini and Sara, 2017), butyltins (Fortibuoni et al., 2013), organochlorine compounds (Hoekstra et al., 2003), Cu and Zn (Jara-Marini et al., 2009), and polybrominated diphenyl ethers (PBDEs) (Kelly et al., 2008).

One classic methodology for estimating TL analyzes the concentrations of cesium (Cs) and potassium (K), because K, an essential element, is fairly constant in tissue, whereas Cs occurs in organisms only by accumulation (Campbell et al., 2005; Young and Mearns, 1979). Other studies used an approach that recognizes nutritional levels using the stable isotope ratio for nitrogen ($^{15}N/^{14}N$, $\delta^{15}N$) (Peterson and Fry, 1987). The method using $\delta^{15}N$ for trophic analysis was extended and strengthened researchers' ability to estimate TL in complex ecosystems (Peterson and Fry, 1987). Since the 1980s, the analysis of $\delta^{15}N$ value has become a powerful tool for estimating prey-predator relationships in ecology and has been widely utilized to determine biomagnification. For example, one previous study reported that the results based on $\delta^{15}N$ values could reveal more reliable connections among the organisms in pelagic ecosystem compared to other methods (Hansson et al., 1997). They also demonstrated that $\delta^{15}N$ -based interpretation can determine the complex diets of zooplankton and mysids (Hansson et al., 1997). This approach has broadened to include stable isotope ratio and specific compounds in organisms that can provide more specific interpretations when establishing TLs (Chikaraishi et al., 2014; Sackett et al., 2015).

Here, we reviewed recent progress in studying the bioaccumulation and biomagnification of pollutants in aquatic environments. The parameters affecting bioaccumulation and trophic transfer are also discussed for further understanding. In particular, we consider research on trophic position estimates by use of ^{15}N stable isotope ratio, emphasizing the implications of TL analyses when studying biomagnification in a diverse ecosystem.

2. Case studies on the biomagnification of organic chemicals and metals

Biomagnification is the increasing concentration of toxic chemicals (e.g., persistent organic pollutants (POPs) and metals) in the tissues of organisms at successively higher TLs in a food web (Fig. 1). A biomagnification potential of pollutants is one of the important indices when evaluating its biological persistence and prioritizing chemicals of concern in the environment (Borgå et al., 2012). The biomagnification factor (BMF) and trophic magnification factor (TMF) are commonly used to assess the biomagnification potential of toxic organic chemicals (Franklin, 2016). The BMF represents the relative increase in concentration of a contaminant in single predator–prey relationships, whereas the TMF is the average factor of change in concentration of a contaminant per TL across a whole food chain. TMF is generally held to be the most reliable tool for assessing the magnitude of biomagnification (Borgå et al., 2012; Gobas et al., 2009). TMF values can be calculated from the regression slope (b) between TLs and the log concentrations of contaminants in the organisms ($TMF = 10^b$) (Borgå et al., 2012; Franklin, 2016) (Fig. 1). In the respect to organic pollutants, Gobas et al. (2009) demonstrated that if the TMF value > 1, the corresponding chemical is biomagnified through the food chain. Bioaccumulative (B) characteristic is one of the significant factor for categorizing priority substances together with persistent (P) and toxic (T) features. In the Stockholm Convention on POPs and other national risk assessment programs (e.g., European Commission), many thousands of commercial chemicals have been evaluated based on P, B, and T-assessment (UNEP, 2001). In this context, the TMF value can be used as a useful criterion for assessing whether a substance is “bioaccumulative” in the outline of B-assessment framework (Gobas et al., 2009). However, TMFs should be used and applied with caution because their values are affected by various abiotic and biotic factors in the given system (Borgå et al., 2012; Franklin, 2016).

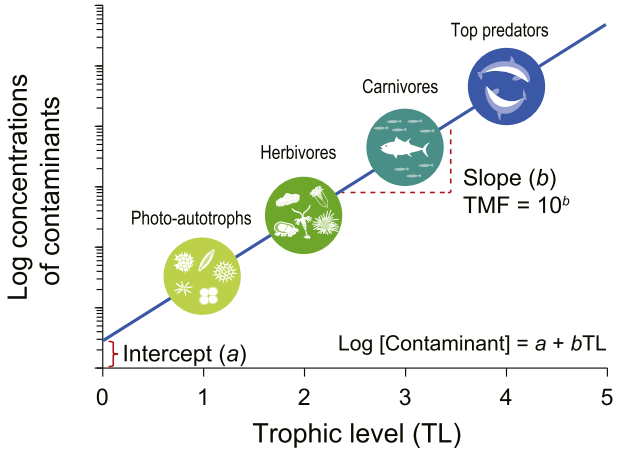

Fig. 1. A scheme of biomagnification and calculation of the trophic magnification factor (TMF) (modified from Borgå et al., 2012).