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Benthic Invertebrate Bioturbation Activity Determines Species Specific Sensitivity to Sediment Contamination

Tom V. van der Meer[1], *Milo L. de Baat*[1]*, *Piet F. M. Verdonschot*[1,2] *and Michiel H. S. Kraak*[1]

[1] *Department of Freshwater and Marine Ecology, Institute for Biodiversity and Ecosystem Dynamics, University of Amsterdam, Amsterdam, Netherlands,* [2] *Department of Freshwater Ecology, Wageningen Environmental Research, Wageningen, Netherlands*

Bioturbation activity of sediment-dwelling organisms promotes the release of contaminants across the benthic-pelagic ecosystem boundary, thereby affecting the exposure to and uptake of sediment associated contaminants at the sediment-water interface by themselves and the entire community around them. This way, bioturbation activity may contribute to species specific sensitivities to sediment associated compounds. Therefore we assessed, based on literature data, if invertebrate bioturbation activity determines species specific sensitivities to sediment contamination. For two metals, Ni and Cu, sufficient data were available to construct Species Sensitivity Distributions (SSD). The position of the species in the SSDs could indeed be linked to their bioturbation rate: the most active bioturbators being the most sensitive benthic invertebrates. Active bioturbators thus enhance their exposure and therewith their sensitivity to sediment associated toxicants. Moreover, active bioturbators can hence promote the release of sediment-associated contaminants across the benthic-pelagic ecosystem boundary, thereby stimulating delivery of contaminants from what is often the most polluted environmental compartment in freshwater ecosystems. It is concluded that trait based ecotoxicology offers a possibly potent tool for predicting sensitivity of benthic invertebrates and the benthic community to sediment-associated contaminants.

Keywords: benthic invertebrates, bioturbation, species specific sensitivity, sediment contamination, SSD

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***Correspondence:**
Milo L. de Baat
m.l.debaat@uva.nl

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INTRODUCTION

The largest group of animals making up the species rich benthic communities of freshwater ecosystems are invertebrates, consisting of many different taxa, like chironomids, amphipods, tubificids, and bivalves, that all perform different ecological roles (Covich et al., 1999, 2004; Hillebrand and Matthiessen, 2009). Accordingly, benthic invertebrates exhibit different ways of locomotion and different ways in which they process and rework sediments, due to differences in feeding mechanism and food acquisition (Mermillod-Blondin et al., 2002; Jonsson and Malmqvist, 2003; Nogaro et al., 2009). These ecological functional traits in turn influence the environmental conditions and sediment properties adjacent to the organisms (François et al., 1997; Gérino et al., 2003; Nogaro et al., 2009). In this way, benthic invertebrates alter and influence their own environment, as well as that of the entire community around them (Covich et al., 1999).

Consequently, benthic invertebrates may also affect the exposure to and uptake of sediment associated contaminants by the whole benthic invertebrate community.

Sediment contamination in freshwater ecosystems is a major environmental issue in industrialized countries. Over the past decades, contaminants like metals, pesticides, PAHs and pharmaceuticals ended up in water bodies. A considerable part of such contaminants accumulates in sediments, which act as a sink for hydrophobic compounds (Eggleton and Thomas, 2004). While the contaminant concentrations in the water column have decreased in many instances due to improved pollution- and runoff management, the often persistent sediment-associated contaminants remain (Dsa et al., 2008; De Deckere et al., 2011). Hence, sediments nowadays play an important role in contaminant transfer and water quality, systematically causing partitioning of compounds back into the water column (Bilotta and Brazier, 2008). Thus, the sediment now acts as a contaminant source, affecting the benthic as well as the pelagic community (Taylor and Owens, 2009).

It has been shown that sediment-dwelling organisms promote the release of contaminants across the benthic-pelagic ecosystem boundary, thereby affecting the exposure to and uptake of sediment associated contaminants at the sediment-water interface by themselves and other organisms (Pang et al., 2012). This way, bioturbation activity may subsequently contribute to species specific sensitivities to sediment associated compounds (Milani et al., 2003; De Lange et al., 2005; Wang, 2013). It is these frequently observed species specific responses in sediment toxicity tests that indeed raise the question what actually determines the observed sensitivity of benthic organisms in terms of EC_x values. Here we hypothesize that ecological functional traits, especially bioturbation activity, contribute to species specific sensitivities to sediment contamination. Clear indications for the importance of sediment reworking on sediment toxicity were already reported by Chandler et al. (2014), who showed that contrasting sediment reworking intensity of two infaunal benthic invertebrates, equally sensitive in water only tests, caused a significantly different sensitivity in sediment tests through increased nickel mobilization to the pore water. Based on these results, the aim of the present desk study was to assess if benthic invertebrate bioturbation activity determines species specific sensitivities to sediment contamination. To this purpose we screened available literature for sediment toxicity data, attempting to obtain sufficient data to construct Species Sensitivity Distributions (SSD). Next, it was evaluated if the position of the species in the SSD could be linked to their ecological functional traits.

MATERIALS AND METHODS

We screened the available literature for freshwater sediment toxicity data. Since this study focused on sediment associated toxicants and bioturbation, only sediment toxicity data for organisms at the sediment-water interface were selected, excluding species which mainly occur in submerged vegetation. To assess the relationship between bioturbation and species-specific sensitivity, we aimed to construct a SSD for common sediment associated contaminants and benthic invertebrates with different levels of bioturbation activity. A SSD for benthic invertebrates was already constructed for nickel by Vangheluwe et al. (2013), however this study did not relate the position of species in the distribution to their bioturbation traits. The present study selected research reporting on toxicity of other sediment associated compounds to benthic invertebrates. The only substance with enough data points to construct a robust SSD was copper, with four studies reporting on the effect of sediment associated copper on the survival of eight benthic invertebrate species (**Table 1** and references therein). The Cu LC_{50} values from these papers were combined to construct a SSD using a SSD generator (US EPA, 2016). In case a species LC_{50} was reported in multiple studies, the LC_{50} value with the longest exposure duration was used. If two articles had the same exposure period, an average of the two reported LC_{50} values was taken. Next it was evaluated if the position of the species in the SSD could be linked to their ecological functional traits. To this purpose the invertebrates were divided into three groups based on their species-specific bioturbation activity: high, intermediate and low. To do so, literature relevant to the bioturbation activity of the species was consulted and summarized to attribute a bioturbation activity classification (**Table 1**).

RESULTS AND DISCUSSION

Kwok et al. (2014), reporting on a workshop held in 2011, stated that the paucity of sediment toxicity data posed the largest obstacle to improving current, and deriving new sediment quality guidelines (SQGs). Now, in 2017, the situation has scarcely improved. Only for two metals, Ni and Cu, sufficient sediment toxicity data were available to construct a SSD. The Ni SSD was previously reported by Vangheluwe et al. (2013), however, the link between the reported SSD and the bioturbation rate of the examined species was not described. **Figure 1** shows the presently constructed SSD for Cu, based on the literature derived experimental data presented in **Table 1**. The position of the species in the present SSD could indeed be linked to their bioturbation rate. The most active bioturbators, *Hexagenia* sp., and *A. aquaticus*, appeared to be most sensitive to sediment associated copper, followed by *G. pulex*, exhibiting intermediate bioturbation activity. The species least sensitive to sediment associated copper, *C. tentans*, *C. riparius*, *T. tubifex*, *H. azteca,* and *L. variegatus*, were categorized as the least active bioturbators.

In agreement with the present study, Vangheluwe et al. (2013) reported that *G. pseudolimneus* and *Hexagenia* sp. were relatively sensitive to sediment bound Ni, with EC_{10} values all below 236 mg/kg. *L. variegatus, C. riparius, C. dilitus, L. siliquoidea,* and *T. tubifex* were less sensitive: the EC_{10} for *L. variegatus* was 554 mg/kg, while for the other species the NOEC was at least 762 mg/kg (Vangheluwe et al., 2013). Thus, the sensitive species were active bioturbating epifaunal biodiffusors, whereas the less sensitive species were infaunal conveyor belt transporters or gallery diffusors. *L. siliquoidea* is a sedentary bivalve and therefore not an active bioturbator. Only for *H. azteca* this agreement was not observed, with the amphipod exhibiting a

TABLE 1 | Benthic invertebrate bioturbation activity and sediment associated Cu LC_{50} values derived from literature.

Species	Bioturbation activity	Rationale	Reference	LC_{50} Cu (mg/kg)	References
Chironomus tentans	Low	- Bio irrigation with long intervals - Low redox potential in sediment	Walshe, 1951 Hunting et al., 2012	1,026	Suedel et al., 1996
Tubifex tubifex	Low	- O_2 collection by protruding appendages above sediment - Decreased O_2 concentration in sediment	Kaster and Wolff, 1982 Mermillod-Blondin et al., 2002	426	Milani et al., 2003 Roman et al., 2007
Chironomus riparius	Low	- Bio irrigation with long intervals - Low redox potential in sediment	Walshe, 1951 Hunting et al., 2012	320	Roman et al., 2007
Hyalella azteca	Low	- Avoids contaminated sediment - Mostly swimming, little interaction with sediment	Call et al., 2001 Bryan, 1971	222	Milani et al., 2003 Roman et al., 2007
Lumbriculus variegatus	Low	- O_2 collection by protruding appendages above sediment - Increased AVS in sediment - Low redox potential in sediment	Gerhardt, 2007 Penttinen et al., 1996 Vandegehuchte et al., 2013 Hunting et al., 2012	211	Roman et al., 2007
Gammarus pulex	Intermediate	- Decreased AVS in sediment - Minor increase of redox potential in sediment	Vandegehuchte et al., 2013 Hunting et al., 2012	151	Roman et al., 2007
Asellus aquaticus	High	- Increased redox potential in sediment, increased O_2 concentration up to 5 cm - Homogenization of sediment up to 3 cm	Hunting et al., 2012 Mermillod-Blondin et al., 2002	106	Hunting et al., 2013
Hexagenia sp.	High	- Continuous irrigation of burrow, creating new burrows constantly	Gallon et al., 2008	93	Milani et al., 2003

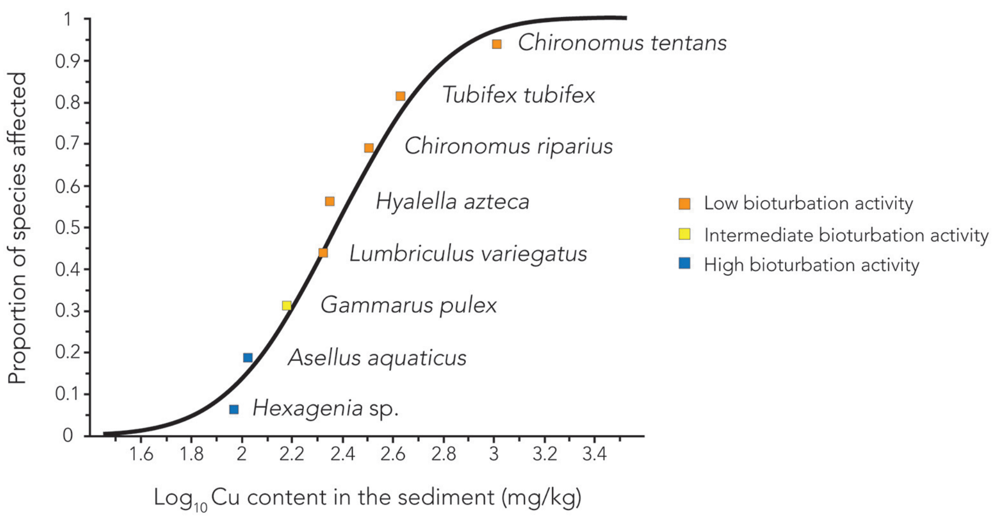

FIGURE 1 | Species sensitivity distribution for sediment associated copper: Benthic invertebrates are categorized according to their bioturbation activity.

relatively high Cu LC_{50} value and being classified as having a low bioturbation rate in the present study, while being relatively sensitive to sediment associated Ni in the study by Vangheluwe et al. (2013). This might be explained by the ability of *H. azteca* to avoid contaminated sediment by their swimming capabilities (**Table 1**). Hence, *H. azteca* is a facultative bioturbator, and in a test setup where it is able to avoid exposure by obtaining its food away from the sediment, as was the case in the Ni test (Besser et al., 2011), low bioturbation and thus low exposure to sediment associated compounds may occur. Contrastingly, in a test setup where *H. azteca* is compelled to obtain its food from within the sediment, active bioturbation and thus high exposure may ensue. This can in turn result in differences in observed sensitivity, caused by differential bioturbation activity within the same species, causing a shift in the position of that species in a SSD.

Besser et al. (2013) argued that the relatively high sensitivity of *G. pseudolimneus* and *Hexagenia* sp. was due to their specific sediment mixing and/or bioirrigation rates. These high rates of bioturbation and bioirrigation lead to an increase in oxygen content of the sediment and therewith to a reduction in acid volatile sulfides (AVS) concentration. This reduction in AVS concentration in turn increases the bioavailability of metals in the sediment, and promotes release of contaminants from the sediment to the pore water and the pelagic zone (De Jonge et al., 2012; Simpson et al., 2012). Although other infaunal invertebrates, like chironomids and oligochaetes, also bioirrigate their burrows, their bioirrigation rate is lower than that of the mayfly larvae. While mayfly larvae need to pump oxygen into their burrows almost continuously (Gallon et al., 2008), oligochaetes collect their oxygen by protruding their appendages above the sediment, and chironomids irrigate their burrows with long intervals, as they contain hemoglobin that allows them to withstand low oxygen concentrations (Walshe, 1951). This results in low oxygen concentrations in the sediment around oligochaetes and chironomids relative to mayfly larvae. Chironomids can, nevertheless, increase oxygen penetration depth or sediment oxygen consumption (De Haas et al., 2005), but the redox values in the sediment remain generally reducing. Hunting et al. (2012) also observed low oxygen concentrations and reducing conditions around chironomids and oligochaetes, thus potentially increasing AVS concentration. In contrast, the epifaunal biodiffusor *A. aquaticus* increased the sediment oxygen concentration by its bioturbation activities (Hunting et al., 2012), which may lead to a decrease in AVS concentration. In agreement, Vandegehuchte et al. (2013) demonstrated that the presence of *G. pulex* decreased the AVS concentration in the sediment, while the mayfly *E. virgo* had little effect on the AVS concentration and the presence of the oligochaete *L. variegatus* resulted in an increase in AVS concentration in the sediment.

CONCLUSION

The studies cited above all support the here presented cascade of high bioturbation activity leading to oxygenation of the sediment and therewith to low AVS concentration, in turn causing a higher metal bioavailability and leading to higher exposure and thus higher sensitivity of the test species. It is therefore concluded that active bioturbators enhance their own exposure to toxicants, therewith increasing the observed sensitivity in terms of EC_x. Moreover, active bioturbators can hence promote release of sediment-associated contaminants across the benthic-pelagic ecosystem boundary, thereby stimulating delivery of contaminants from what is often the most polluted environmental compartment in freshwater ecosystems (Burton, 2013; Roig et al., 2015). Although research linking traits to toxicant sensitivity is still relatively rare, trait based ecotoxicology offers a possibly potent tool for predicting sensitivity of benthic invertebrates and the benthic community to sediment-associated contaminants (Baird et al., 2008; Archaimbault et al., 2010). It is alarming though, that the paucity of sediment toxicity data still poses the largest obstacle to deriving reliable SQGs. We therefore stress that future reliable sediment toxicity data derivation should incorporate trait based ecotoxicological assessment.

AUTHOR CONTRIBUTIONS

Conception or design of the work: TvdM and MK. Data collection: TvdM. Data analysis and interpretation: TvdM, MdB, PV and MK. Drafting the article: TvdM, MdB, PV and MK. Critical revision of the article: MdB, PV and MK. Final approval of the version to be published: TvdM, MdB, PV and MK.

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