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Assessing the impact of lanthanum on the bivalve *Corbicula fluminea* in the Rhine River

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HIGHLIGHTS

- Lanthanum incorporation into *C. fluminea* shells increased with increasing exposure dose.
- La affected the shell and somatic growth of *C. fluminea*.
- Energy reserves remained virtually unaffected by La.
- La interfered with the clam's energy budget by inflating metabolic demands.
- Clams showed improved tolerance under low-dose exposure scenario.

GRAPHICAL ABSTRACT

Sampling site	La_{shell}	Survival	Growth performance		Energy reserves		Physiological biomarkers			
			GR	CI	Gly	Prot	CR	SMR	ER	O:N
Kandel	↑	=	↓	↓	↓	=	↓	↑	↑	↓
Ibersheim	↑	=	↓	↓	=	=	=	↑	↑	=
Bingen	↑	=	↓	↓	=	=	=	↑	↑	=
Köln	↑	=	↓	↓	=	=	=	↑	↑	=

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ABSTRACT

Anthropogenic lanthanum predominantly derived from a point source has become an emerging contaminant in the Rhine River, but little is known about its ecotoxicological consequences on bivalve mollusks. A fundamental requirement of aquatic invertebrate adaptation and survival in stressful habitats is the maintenance of energy homeostasis. As such, the present study tested the impact of four dissolved La concentrations (0, 50, 100 and 200 μM) on the energy balance of the bivalve *Corbicula fluminea* in the Rhine River. Bivalves were collected at four sampling sites which were contaminated by La to different degrees, thereby allowing to understand the degree of their potential acclimation. With increasing exposure dose, shell and somatic growth (the most energetically expensive biological processes) decreased significantly in clams inhabited the control (uncontaminated) habitat; while less pronounced impacts were evident in all three contaminated sites. In particular, the latter showed virtually unaffected energy (glycogen and protein) reserves. An elucidation of shifts in the organismal energy budget may shed light on such improvement of growth performance. Irrespective of sampling sites, short-term exposure to La caused significant increases of oxygen consumption and ammonia excretion, indicating that the clams promoted their energy metabolism and thereby allocated more energy to essential physiological processes. Noteworthily, the clams originating from contaminated sites displayed virtually unaffected clearance rate, thereby being able to partially fulfill the increased energy demand and eventually alleviating the La-induced physiological interference. Taken together, findings of the present study demonstrate that whether, and to what extent, *C. fluminea* is able to sustain its energy homeostasis play a central role in the phenotypic plasticity and/or genetic adaptation in the face of anthropogenic La contamination in the Rhine River.

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1. Introduction

Lanthanides (or lanthanoids) comprise a total of 15 physically and chemically similar elements from lanthanum (La) to lutetium (Lu) (Holden and Coplen, 2004). Together with Scandium (Sc) and yttrium (Y), they are usually referred to as the rare earth elements (REEs). Because of their unique physicochemical properties (e.g., naturally coherent behavior, high luster and electrical conductivity; Topp, 1965), the REEs used to be taken as geochemical tracers of multiple natural processes (Smedley, 1991; Johannesson et al., 1997), and nowadays, are being more widely and intensively applied in numerous high-tech, medical and agricultural products and processes (US. EPA, 2012), consequently potentially releasing large amounts of anthropogenic REEs into the hydrosphere (Khan et al., 2017). The first case of the occurrence of anthropogenic REEs in natural waters emerged in the mid-1990s (Bau and Dulski, 1996). Anomalously high concentrations of gadolinium (Gd) – up to three orders of magnitude higher than background (geogenic) concentrations – were detected in the Havel River in Northeastern Germany (Bau and Dulski, 1996). Since then, significant Gd anomalies have been reported in numerous natural waters worldwide (Nozaki et al., 2000; Möller et al., 2002; Petelet-Giraud et al., 2009; Rabiet et al., 2009; Kulaksız and Bau, 2007, 2013). Apparently, these Gd anomalies are derived from anthropogenic origins rather than natural processes. In particular, discharges of waste waters from hospitals and radiological practices are the most likely primary sources given the indispensability of Gd-based contrast agents applied for magnetic resonance imaging (Kümmerer and Helmers, 2000; Telgmann et al., 2013).

As one of the largest rivers in Europe, the Rhine River (Fig. 1) is profoundly impacted by intensive human activities and consequently no exception to display significant Gd anomalies (Kulaksız and Bau, 2007). Aside from Gd, the river carries large amounts of anthropogenic La with an annual export of approximately 1.5 t to the North Sea (Kulaksız and Bau, 2011), which can be traced back to an industrial point source (waste discharges from the production of fluid catalytic cracking catalysts) in the Upper Rhine at river-kilometer 447.4 (Fig. 1) and through the middle and lower reaches of the river to the Netherlands (Verheul et al., 2011). In particular, extremely high concentrations of La (up to 47 mg L^{-1}) are measured in the vicinity of the effluent mouth (Kulaksız and Bau, 2011), well above the median lethal concentrations (LC50) estimated in crustacean *Hyalella azteca* (1.67 mg L^{-1}), oligochaete *Lumbriculus variegatus* (18.8 mg L^{-1}) and fish *Danio rerio* (23.0 mg L^{-1}) (summarized by Herrmann et al., 2016). Anthropogenic Gd and La can dominate approximately 97% of total dissolved REEs in the Rhine River (Kulaksiz, 2012), thereby severely disrupting the distribution and biogeochemical behavior of other REEs compounds. Therefore, it is reasonable to assume that anthropogenic-sourced Gd and La have already become emerging contaminants, potentially causing major environmental and public health issues in the Rhine River watershed. Likewise, anthropogenic La pollution has been reported in other European freshwater systems, for example in the Odiel River (Spain) and the Weser River (Germany) which showed high concentrations of dissolved La to 10.6 μg L^{-1} (Bonnail et al., 2017) and 10.5 μg L^{-1} (Merschel and Bau, 2015), respectively. Consequently, long-term monitoring surveys along with ecotoxicological studies on aquatic biota are becoming imperative for integratedly managing and/or precisely eliminating Gd and La contamination.

The Asian clam *Corbicula fluminea* (Müller, 1774), native to Southeast Asia, is becoming one of the most invasive species in American and European freshwater ecosystems, mainly due to its short life span, rapid growth, early sexual maturity and high fecundity (Sousa et al., 2009). In particular, the clams are tolerant to salinity up to 5 PSU (Morton and Tong, 1985) and have rapidly invaded many estuaries (McMahon, 1983). No exception to this are the Rhine River and some of its tributaries, where *C. fluminea* exhibits high population densities and plays various ecological roles (Weitere and Arndt, 2002; Weitere

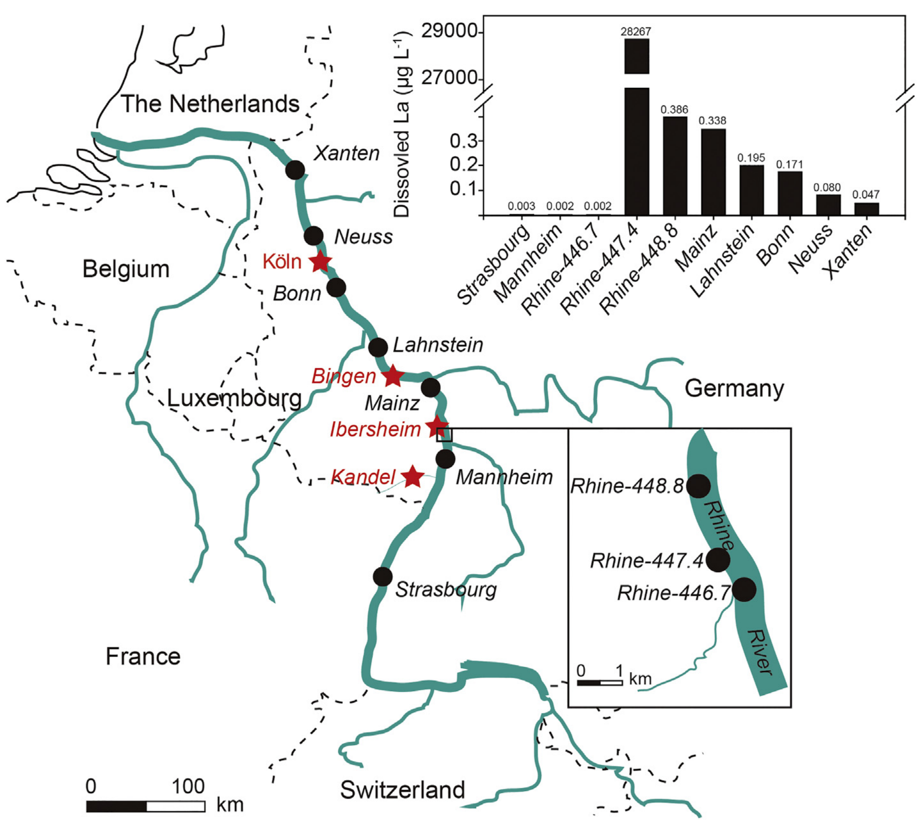

Fig. 1. Map of the Rhine River and its major tributaries. Red stars mark the sampling sites in the present study and black circles indicate the localities where concentrations of dissolved La in the water were measured by Kulaksız and Bau (2011). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)