Ecological effects of lithium on aquatic biodiversity: a systematic literature review

*Andrea Paparini MSc, MSc, PhD [1,2,3,4]**

[1]*Faculty of Science, The University of Western Australia, Crawley WA 6009, Australia*
[2]*Econumerics Pty Ltd Consultants, Hilton, WA 6163, Australia*
[3]*College of Science, Health, Engineering and Education, Murdoch University, Murdoch, WA 6150, Australia*
[4]*School of Pharmacy and Biomedical Sciences, Faculty of Health Sciences, Curtin University of Technology, Bentley, WA 6102, Australia*

**Corresponding author.*

E-mail address: info@econumerics.com.au (A. Paparini)

Highlights

- The effects of lithium on aquatic “ecosystems as a whole” are still understudied
- Studies focusing on the effects of lithium on biodiversity indexes are scarce
- Several studies address lithium toxicity in individual aquatic model-species
- Paucity of numerical models and standardized methods that allow study-comparisons
- Shortage of studies from some major global lithium-producing countries

Abstract

Billions of electronic devices utilized daily worldwide depend on the energy supplied by high-performing lithium-ion batteries. As Li use grows rapidly and steadily, the risk of pollution, of terrestrial and aquatic ecosystems, is also likely to spread. To this end, understanding the broader effects on the composition of aquatic communities, of Li production or improper battery disposal is paramount. Here, a quantitative systematic search of peer-reviewed literature was conducted to determine the research *status quo*, around four topics: "contamination", "lithium", "water", and "biodiversity".

Of all studies on lithium, only about one tenth focuses specifically on pollution of water bodies. Of these, less than one third seems to delve into the effects of this metal on biodiversity. The analysis identified that there was a shortage of dedicated numerical models of trophic interactions, bioaccumulation, food-webs, population dynamics and ecosystem functioning, that concentrate on lithium pollution specifically. While several studies address toxicity in individual aquatic model-species, the lack of standardized methods thwarts study-comparisons. Like authors' affiliations, field studies conducted in some of the major global producers are scarce. About one third of the studies found by the present systematic search, utilized mesocosms or in vitro assays to test the effects on one species at the time only.

Ultimately, we speculate that the biggest gap found by the present literature review is the paucity of holistic studies, aimed at inferring the effects of lithium on the "ecosystem as a whole", and, more specifically, on the quantifiable parameters of biodiversity.

Keywords

1. lithium
2. water quality
3. aquatic ecology
4. biodiversity
5. aquatic ecosystem
6. metal contamination

1. Introduction

In the context of supply exhaustion and environmental decline, the use of fossil fuels is under increasing global pressure. This is pushing the technology towards cleaner and more sustainable energy sources, as well as towards technologies capable of exploiting such cleaner energy. Billions of electronic devices utilized daily worldwide (e.g., laptops, phones and mobile cameras), depend on the energy supplied by high-performing Lithium-ion batteries. The increasingly popular electric vehicles are also powered by the same batteries, containing up to 20 kg of Lithium (Li). To this end, Martin et al. (2017) showed how the global production of Li rose steadily from 1995 to 2008, from about 40,000 to 140,000 t; after a transitory and short decline associated with the 2009 global financial crisis, the production volume increased by 70% (Martin et al., 2017).

As Li use rapidly grows, the risk of pollution of terrestrial and aquatic ecosystems is likely to spread, due to increased production or improper disposal of batteries. Despite being considered a non-essential element for living organisms, lithium is also a widely used and effective treatment for mood disorders in humans (McKnight et al., 2012). While the latter 2012 systematic review and meta-analysis comprehensively summarizes the known effects in human subjects, the environmental effects of this this emerging contaminant may have been largely overlooked (Robinson et al., 2018). To address this question, a quantitative systematic search of peer-reviewed literature was conducted to determine the research *status quo*, around four topics: “contamination”, “lithium”, “water”, and “biodiversity”.

2. Material and Methods

2.1 Preliminary search

A quantitative systematic search of peer-reviewed literature was conducted in August 2019, using Scopus (https://www.scopus.com) and Web of Science (WoS) (https://www.webofknowledge.com). For each repository, four preliminary advanced-searches were performed around the four topics: “contamination”, “lithium”, “water”, and “biodiversity” (Table 1). For WoS, the following core collections were initially selected: Science Citation Index Expanded (SCI-EXPANDED), Conference Proceedings Citation Index- Science (CPCI-S), Conference Proceedings Citation Index- Social Science & Humanities (CPCI-SSH), Book Citation Index– Science (BKCI-S), Book Citation Index– Social Sciences & Humanities (BKCI-SSH), Emerging Sources Citation Index (ESCI). Subsequently, the search was narrowed to items published in English language, between 2004 and 2020, or between 2004 and 2019 (for Scopus, and WoS, respectively). Additional search limits were based on type of document (article or review only) and subject area (Table 1).

A. Paparini, 2020 (unpublished).

Table 1

Topic	Query	Database
Contamination	KEY (toxic* OR contaminant OR contamination OR tailings OR waste OR pollutant OR pollution OR ecotoxic* OR hazard* OR poison*) AND SUBJAREA (envi)	Scopus
	(TS = toxic* OR TI = toxic* OR TS = contaminant OR TI = contaminant OR TS = contamination OR TI = contamination OR TS = tailings OR TI = tailings OR TS = waste OR TI = waste OR TS = pollutant OR TI = pollutant OR TS = pollution OR TI = pollution OR TS = ecotoxic* OR TI = ecotoxic* OR TS = hazard* OR TI = hazard* OR TS = poison* OR TI = poison*) AND (SU = "Environmental Sciences & Ecology" OR SU = "Marine & Freshwater Biology" OR SU = "Public, Environmental & Occupational Health" OR SU = "Rehabilitation" OR SU = "Toxicology" OR SU = "Zoology" OR SU = "Biodiversity & Conservation" OR SU = "Fisheries" OR SU = "microbiology")	WoS
Lithium	KEY (lithium) AND SUBJAREA (envi)	Scopus
	(TS = lithium OR TI = lithium) AND (SU = "Environmental Sciences & Ecology" OR SU = "Marine & Freshwater Biology" OR SU = "Public, Environmental & Occupational Health" OR SU = "Rehabilitation" OR SU = "Toxicology" OR SU = "Zoology" OR SU = "Biodiversity & Conservation" OR SU = "Fisheries" OR SU = "microbiology")	WoS
Water	KEY (*littoral OR *pelagic OR *water OR abyssal OR aquatic OR bathyal OR benth* OR brackish OR coast* OR creek OR estuar* OR freshwater OR groundwater OR hadal OR lake OR limn* OR marine OR marsh OR ocean OR pond OR reservoir OR riparian OR river OR saline OR saltwater OR sea OR stream OR submerged OR swamp OR wetland) AND SUBJAREA (envi)	Scopus
	(TS = freshwater OR TI = freshwater OR TI = saltwater OR TS = saltwater OR TS = lake OR TI = lake OR TS = marine OR TI = marine OR TS = benth* OR TI = benth* OR TS = *littoral OR TI = *littoral OR TI = *pelagic OR TS = *pelagic OR TI = Bathyal OR TS = Bathyal OR TI = Abyssal OR TS = Abyssal OR TI = hadal OR TS = hadal OR TS = submerged OR TI = submerged OR TS = estuar* OR TI = estuar* OR TS = reservoir OR TI = reservoir OR TI = pond OR TS = pond OR TI = ocean OR TS = ocean OR TI = sea OR TS = sea OR TS = coast* OR TI = coast* OR TS = limn* OR TI = limn* OR TI = river OR TS = river OR TI = riparian OR TS = riparian OR TI = stream OR TS = stream OR TI = creek OR TS = creek OR TI = wetland OR TS = wetland OR TI = swamp OR TS = swamp OR TI = marsh OR TS = marsh OR TI = groundwater OR TS = groundwater OR TI = brackish OR TS = brackish OR TI = saline OR TS = saline OR TI = *water OR TS = *water OR TI = aquatic OR TS = aquatic) AND (SU = "Environmental Sciences & Ecology" OR SU = "Marine & Freshwater Biology" OR SU = "Public, Environmental & Occupational Health" OR SU = "Rehabilitation" OR SU = "Toxicology" OR SU = "Zoology" OR SU = "Biodiversity & Conservation" OR SU = "Fisheries" OR SU = "microbiology")	WoS

Biodiversity	KEY ("biological assemblage" OR "biological composition" OR "biological dynamics" OR "biological structure" OR "community assemblage" OR "community composition" OR "community dynamics" OR "community structure" OR "ecological assemblage" OR "ecological composition" OR "ecological dynamics" OR "ecological structure" OR "ecosystem assemblage" OR "ecosystem composition" OR "ecosystem dynamics" OR "ecosystem dynamics" OR "ecosystem structure" OR "ecosystem structure" OR "population assemblage" OR "population composition" OR "population dynamics" OR "population structure" OR "species assemblage" OR "species composition" OR "species dynamics" OR "species structure" OR "taxonomic assemblage" OR "taxonomic composition" OR assemblage OR biodiversity OR composition OR dynamics OR structure) AND SUBJAREA (envi)	Scopus
	(TS = biodiversity OR TI = biodiversity OR TS = structure OR TI = structure OR TS = dynamics OR TI = dynamics OR TS = composition OR TI = composition OR TS = assemblage OR TI = assemblage OR TS = "community structure" OR TI = "community structure" OR TS = "community dynamics" OR TI = "community dynamics" OR TS = "community composition" OR TI = "community composition" OR TS = "community assemblage" OR TI = "community assemblage" OR TS = "ecosystem structure" OR TI = "ecosystem structure" OR TS = "ecosystem dynamics" OR TI = "ecosystem dynamics" OR TS = "ecosystem composition" OR TI = "ecosystem composition" OR TS = "ecosystem assemblage" OR TI = "ecosystem assemblage" OR TS = "ecological structure" OR TI = "ecological structure" OR TS = "ecological dynamics" OR TI = "ecological dynamics" OR TS = "ecological composition" OR TI = "ecological composition" OR TS = "ecological assemblage" OR TI = "ecological assemblage" OR TS = "species structure" OR TI = "species structure" OR TS = "species dynamics" OR TI = "species dynamics" OR TS = "species composition" OR TI = "species composition" OR TS = "species assemblage" OR TI = "species assemblage" OR TS = " taxonomic structure" OR TI = "ecosystem structure" OR TS = " taxonomic dynamics" OR TI = "ecosystem dynamics" OR TS = "taxonomic composition" OR TI = "taxonomic composition" OR TS = "taxonomic assemblage" OR TI = "taxonomic assemblage" OR TS = "population structure" OR TI = "population structure" OR TS = "population dynamics" OR TI = "population dynamics" OR TS = "population composition" OR TI = "population composition" OR TS = "population assemblage" OR TI = "population assemblage" OR TS = "biological structure" OR TI = "biological structure" OR TS = "biological dynamics" OR TI = "biological dynamics" OR TS = "biological composition" OR TI = "biological composition" OR TS = "biological assemblage" OR TI = "biological assemblage") AND (SU = "Environmental Sciences & Ecology" OR SU = "Marine & Freshwater Biology" OR SU = "Public, Environmental & Occupational Health" OR SU = "Rehabilitation" OR SU = "Toxicology" OR SU = "Zoology" OR SU = "Biodiversity & Conservation" OR SU = "Fisheries" OR SU = "microbiology")	WoS

Details of the advanced Boolean preliminary search, used for the quantitative systematic retrieval of peer-reviewed literature, from the two databases Scopus, and Web of Science (WoS). As detailed in Material and Methods (section 2), this preliminary search was also restricted to documents (articles or reviews) published in English language, between 2004 and 2020, or between 2004 and 2019 (for Scopus, and WoS, respectively). According to each database's rules,

the abbreviations used were: KEY: Keywords; SUBJAREA(ENVI): Subject Area “Environmental Science”; TS: Topic; TI: Title; SU: Research Area. Asterisks represent wild cards. Query expressions do not include limits.

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2.2 Combined search and final selection

Combined Boolean searches (one for each database) were performed based on the initial set of items, retrieved during the preliminary search. The documents found for each of the four topics were combined using the "AND" operator, and by all possible combinations; the results were then used to produce two Venn diagrams, to broadly illustrate the breadth of literature available in each database across the topics (Figure 1).

For each database, the final selection of papers forming the bulk bibliography of the present review was based on the "combined dataset". This was formed by the intersection of all four topics (e.g., "contamination" AND "lithium" AND "water" AND "biodiversity"). For Scopus only, the combined dataset was further constrained by the inclusion of the expression "AND ALL(species)", which retrieves only items containing the term "species" (in any field).

The final selection was produced after a careful assessment of the content, quality and relevance of the combined datasets. Additional publications found in the literature cited in the final selection (but not obtained through the preliminary search, due to some of the imposed limits), were also chosen for the present review. Duplicates items obtained across Scopus and WoS were removed.

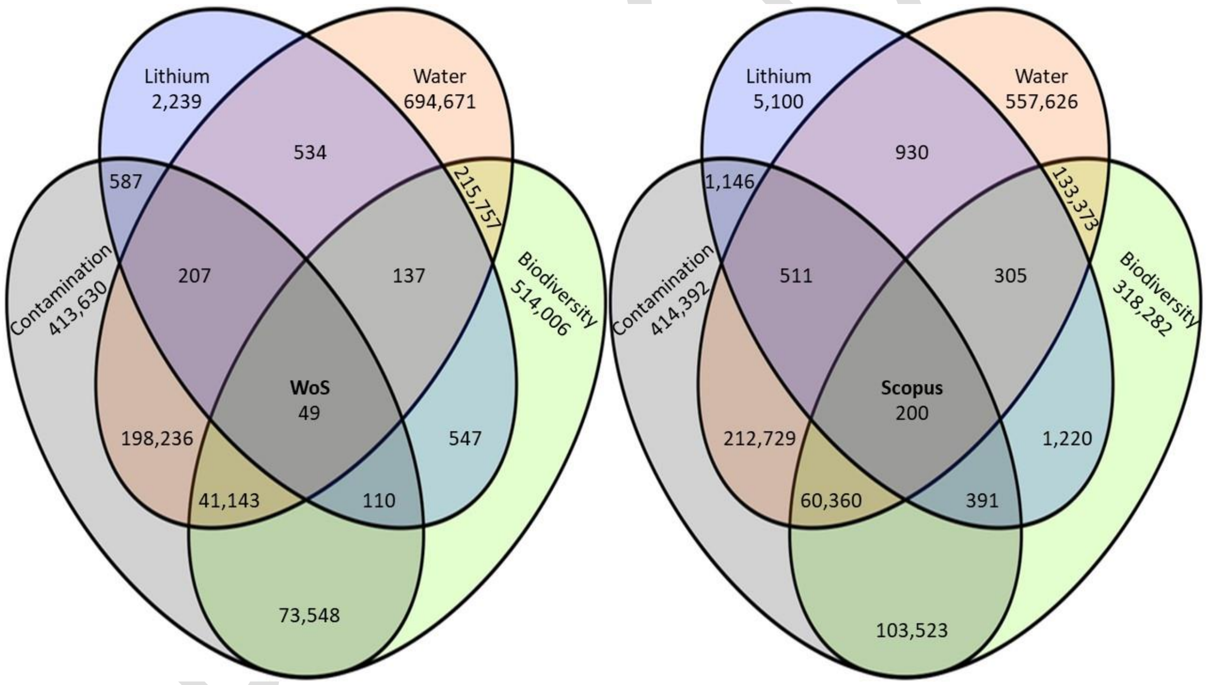

Figure 1. Venn diagrams showing the number of peer-reviewed publications retrieved, in August 2019, from the databases Web of Science (WoS) and Scopus. For each resource, four preliminary advanced-searches were performed around the four topics: "contamination", "lithium", "water", and "biodiversity", using systematic advanced-searches.

3. Results

3.1 Search results

Using the adopted systematic criteria, out of the four topics searched, water and lithium consistently yielded the highest and lowest number of papers, for both databases. Instead, an opposite trend was seen across the databases, for the topics contamination and biodiversity.

Except for lithium, all themes showed comparable importance, in terms of papers published. Lithium returned only 2,239 and 5,100 items in WoS and Scopus respectively, while 694,671 and 557,626 papers on water were found in WoS and Scopus respectively. The combined searches identified 49 and 200 publications (including inter-database duplicates) (Figure 1).A subjective screening of the two combined datasets, and the inclusion of an extra keyword ("species", for Scopus only), led to a list of 13/49 (26.53 %) and 45/200 (22.50 %) items, for WoS and Scopus respectively. This filter was necessary to remove irrelevant items that were found by the Boolean expressions adopted for the preliminary search. Overall, an excellent linear correlation (R^2>0.95) was observed between the databases, in terms of number of papers found for each topic and combination thereof (data not shown).

3.2 Literature review

Table 2 was compiled in August 2019 and compares a selection of primary-research publications from the last 15 years, that, to various extent, broadly covered the topics lithium contamination and aquatic biota (n = 27). The yearly number of papers published remained relatively constant; the last two years, however, seem to suggest an increasing interest in the topic, with five and three papers published in 2018 and 2019, respectively (2019 is partial data). Out of the 27 publications, 7 were published in the journal "*Science of the Total Environment*", with the remaining journals hosting 3 or fewer papers each. Among all countries, USA (n=6) and Canada (n=5) hosted most of the authors' affiliations, with all the remaining countries hosting 3 or fewer affiliations (Table 2).

While 9/27 studies (33 %) employed laboratory settings and/or mesocosms, the focus of the remaining investigations was roughly equally distributed between freshwater, marine and brackish/estuarine ecosystems (Table 2). Including genes, about 90 biochemical variables were studied, using a variety of techniques, primarily inductively coupled plasma mass spectrometry (ICP-MS), but also reverse-transcription real time PCR (RT-qPCR) (Bozich et al., 2017; Russo et al., 2018) or MariETT assays (Sawasdee and Heinz-R, 2010).

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Ref	Keywords	Aff	Study site	Eco	(Bio)chemical variables*	Target taxa#	Classification¥
Bozich J, et al. (2017); Environ Toxicol Chem	Nanotoxicology, Chronic, Daphnia, Gene expression	USA	Laboratory/mesocosm	n.a.	18S, actin, catalase, cobalt oxide (NMC), glutathione-s-transferase, heat shock protein, Li, lithium cobalt oxide (LCO), metallothionein, Mn, Ni, vitellogenin	Water flea (Daphnia *magna*)	Arthropoda; Branchiopoda; Daphniidae
Niemuth NJ, et al. (2019); Environ Sci Technol	n.a.	USA	Laboratory/mesocosm	n.a.	Lithium cobalt oxide (LCO), lithium nickel manganese cobalt oxide (NMC)	Harlequin fly (*Chironomus riparius*)	Arthropoda; Insecta; Chironomidae
Wu F, et al. (2013); Environ Sci Technol	n.a.	USA, Canada, China, Hong Kong	n.a.	n.a.	Ag, Al, As(III), Ba, Be, Ca, Cd, Co, Cr(III), Cr(VI), Cu, Fe(III), Hg, K, La, Li, Mg, Mn, Na, Ni, Pb, Sb, Sr, Tl, Zn	Midge (*Chironomus tentans*); rotifer (*Brachionus calyciflorus*); Asian common toad (*Bufo melanostictus*); amphipod (*Crangonyx pseudogracilis*); common carp (*Cyprinus carpio*); water flea (Daphnia *magna*); common duckweed (*Lemna minor*); radix (*Lymnaea acuminata*)	Arthropoda; Insecta; Chironomidae Rotifera; Monogononta; Brachionidae Chordata; Amphibia; Bufonidae Arthropoda; Malacostraca; Crangonyctidae Chordata; Actinopteri; Cyprinidae Arthropoda; Branchiopoda; Daphniidae Streptophyta; Spermatophyta; Lemnoideae Mollusca; Gastropoda; Lymnaeidae
García-Seoane E, et al. (2016); Mar Pollut Bull	Coastal lagoon, Fish assemblage, Ria de Aveiro, Trace metals	Portugal	Ria de Aveiro (Portugal)	Coastal lagoon	As, Ba, Cd, Co, Cr, Cu, Hg, Li, Mn, Ni, Zn	*Atherina* spp.; *Diplodus* spp.; *Liza* spp.; *Pomatoschistus* spp.	Chordata; Actinopteri; [Atherinidae, Sparidae, Mugilidae, Gobiidae]
Sofoulaki K, et al. (2018); Sci Total Environ	Metals, Greek coastal areas, Species-specific variations, Size-specific, Proximate composition	Greece	Thermaikos Gulf, Amvrakikos Gulf, Elefsina Gulf, Strymonian Gulf, Thracian Sea, Artemisium Straits (Greece)	Marine	As, Ba, Ca, Cd, Co, Cs, Cu, Fe, Ga, Hg, Li, Mg, Mn, Mo, Na, Ni, P, Pb, Pd, Rb, Se, Sr, Tl, U, V, Zn	Sardine (*Sardina pilchardus*); anchovy (*Engraulis encrasicolus*)	Chordata; Actinopteri; [Clupeidae, Engraulidae]
Cozzarelli IM, et al. (2017); Sci Total Environ	Unconventional oil and gas production, Wastewaters, Brine spills	USA	Blacktail Creek (USA)	Freshwater	Alkalinity, anions, C, Ca, cations, endocrine disruptors, extractable hydrocarbons, H, invertebrate bioassays, isotopes, LMWOA, low-level light hydrocarbons, N, NH_4, NVDOC, organic	Fathead minnow (*Pimephales promelas*); madtom catfish (*Noturus* sp.); amphipod (sp.?); midge (sp.?); mussel (sp.?)	Chordata; Actinopteri; [Cyprinidae, Ictaluridae] Arthropoda; Malacostraca; ? Arthropoda; Insecta; ? Mollusca; Bivalvia; ?

					additives, Ra, S; Ba, semi-volatile hydrocarbons, Sr, trace inorganics		
Djikanović V, et al. (2018); Environ Pollut	Freshwater fish, Metal pollution, Fish tissue, Aquatic plant, Sediment, BSAF	Serbia	Medjuvrsje reservoir (Serbia)	Freshwater	Ag, Al, As, B, Ba, Cd, Co, Cr, Cu, Fe, Li, Mn, Ni, Pb, Sr, Zn	Freshwater bream (*Abramis brama*); common nase (*Chondrostoma nasus*); Prussian carp (*Carassius gibelio*); chub (*Squalius cephalus*); wels catfish (*Silurus glanis*); water chestnut (*Trapa natans*); hornwort (*Ceratophyllum demersum*); pondweed (*Potamogeton fluitans*); pondweed (*Potamogeton pectinatus*); common reed (Phragmites communis)	Chordata; Actinopteri; [Cyprinidae, Siluridae] Streptophyta; Spermatophyta; [Lythraceae, Ceratophyllaceae, Potamogetonaceae, Poaceae]
Tkatcheva V, et al. (2004); Ecotoxicol Environ Saf	Mining industry, Fish, Gill histology, Heavy metals, Lithium, Potassium, Na^+K^+ATPase, Phospholipids	Russia, Finland	Lake Poppalijarvi, Lake Koivas, Lake Kento, Lake Kamennoe, Lake Upper Kuito (Russia)	Freshwater	Cd, Cr, Fe, Hg, Zn	Perch (*Perca fluviatilis*); roach (*Rutilus rutilus*)	Chordata; Actinopteri; [Percidae, Cyprinidae]
Dubé MG, et al. (2005); Sci Total Environ	Artificial streams, Mesocosm, Metal mining discharge, Atlantic salmon, Slimy sculpin, Fish condition	Canada	Laboratory/mesocosm	n.a.	Ba, Cd, Cu, Li, Mn, Se, Sr, Tl, V, Zn	Atlantic salmon (*Salmo salar*); slimy sculpin (*Cottus cognatus*)	Chordata; Actinopteri; [Salmonidae, Cottidae]
Le Croizier G, et al. (2016); Sci Total Environ	Trace elements, Biochemical tracers, Diet, Contamination, Senegal, Tropical fish	France, Senegal	Dakar offshore station, Casamance offshore station (Senegal)	Marine	As, Cd, Co, Cr, Cu, fatty acids, Fe, Li, Mn, Ni, Pb, Sn, stable isotope, U, Zn	Bogue (*Boops boops*); false scad (*Caranx rhonchus*); Senegal seabream (*Diplodus bellottii*); West African goatfish (*Pseudupeneus prayensis*); chub mackerel (*Scomber japonicus*); Cunene horse mackerel (*Trachurus trecae*); bigeye grunt (*Brachydeuterus auritus*); Atlantic bumper (*Chloroscombrus chrysurus*); Lesser African Threadfin (*Galeoides decadactylus*); African	Chordata; Actinopteri; [Sparidae, Carangidae, Mullidae, Scombridae, Haemulidae, Polynemidae, Sphyraenidae]

						moonfish (*Selene dorsalis*); Guachanche barracuda (*Sphyraena guachancho*)	
Kalyoncu L, et al. (2012); Environ Monit Assess	Heavy metal, Fish, Muscle, Isıklı Dam Lake, Karacaören Dam Lake	Turkey	Karacaören Dam, Işıklı Dam (Turkey)	Freshwater	Bi, Ca, Cd, Co, Cr, Cu, Fe, K, Li, Mg, Mn, Na, Ni, Pb, Sr, Zn	Common carp (*Cyprinus carpio*); common rudd (*Scardinius erythrophthalmus*); tench (*Tinca tinca*); goldfish (*Carassius carassius*)	Chordata; Actinopteri; Cyprinidae
Hirata SH, et al. (2011); Environ Pollut	Isaza, Mass mortality, Arsenic, Manganese, Global warming	Japan	Lake Biwa (Japan)	Freshwater	Ag, Ba, Bi, Cd, Co, Cr, Cs, Cu, In, Li, Mg, Mn, Mo, Ni, Pb, Rb, Sb, Se, Sn, Sr, Tl, Tot-As, V, Zn	Isaza (*Gymnogobius isaza*); lake prawn (*Palaemon paucidens*)	Chordata; Actinopteri; Gobidae Arthropoda; Malacostraca; Palaemonidae
Sinnatamby RN, et al. (2019); Sci Total Environ	Laser ablation ICP-MS, Solution based ICP-MS, Otolith microchemistry, Trace elements, Bitumen, Athabasca River	Canada	Athabasca River, Clearwater River (Canada)	River	Ag, Al, As, Ba, Be, Bi, Cd, Co, Cr, Cu, Fe, Ga, Li, Mg, Mn, Mo, Na, Ni, Pb, Rb, Re, Sb, Sc, Se, Sn, Sr, Th, Tl, U, V, W, Y, Zn	Trout-perch (*Percopsis omiscomaycus*)	Chordata; Actinopteri; Percopsidae
Shotyk W, et al. (2019); Sci Total Environ	Thallium, Trout-perch, Otoliths, Athabasca River, Bituminous sands	Canada	Athabasca River, Clearwater River (Canada)	River	Al, Ba, Co, Cr, Cu, Fe, Li, Mn, Mo, Ni, Ni, Pb, Rb, Sr, Th, Tl, V, Y, Zn	Trout-perch (*Percopsis omiscomaycus*)	Chordata; Actinopteri; Percopsidae
Tkatcheva V, et al. (2007); Ecotoxicol Environ Saf	Fish gill, Chloride cells, Mitochondria, Lithium, Potassium, Lipids, Enzyme activity	Finland	Laboratory/mesocosm	n.a.	Ca, K, Li, Mg, Na, NH_4-N, Tot-N	Rainbow trout (*Oncorhynchus mykiss*)	Chordata; Actinopteri; Salmonidae
Tkatcheva V, et al. (2007); Arch Environ Contam Toxicol	Lithium, Fish gill, Plasma ions, Apolipoprotein AI, Lipids, Enzyme activity	Finland, Canada	Laboratory/mesocosm	n.a.	apoAI, cholesterol, Cl, enzyme activities, free fatty acid, K, Na, osmolality	Rainbow trout (*Oncorhynchus mykiss*)	Chordata; Actinopteri; Salmonidae
Stavros HCW, et al. (2011); Chemosphere	Trace metals, Marine mammals, Bottlenose dolphins, Tursiops truncatus, Mercury	USA	South Carolina coast, Indian River Lagoon (USA)	Marine, brackish lagoon	Al, As, Ba, Be, Cd, Co, Cu, Fe, Li, Mn, Ni, Pb, Sb, Se, Sn, Tot-Hg, V, Zn	Bottlenose dolphin (*Tursiops truncatus*)	Chordata; Mammalia; Delphinidae
Horai S, et al. (2014); Chemosphere	Contamination status, American alligator, NASA activity, Trace elements, Iron toxicity	USA, Japan	Lake Apopka, Lake Woodruff National Wildlife Refuge, Merritt Island National Wildlife Refuge (USA)	Freshwater, saltwater, brackish	Ag, Al, As, Bi, Cd, Co, Cr, Cs, Cu, Fe, Ga, Hg, In, Li, Mg, Mn, Mo, Ni, Pb, Rb, Sb, Se, Sn, Sr, Tl, V, Zn	American alligator (*Alligator mississippiensis*)	Chordata; Reptilia; Alligatoridae
Cortés-Gómez AA, et al. (2018); Mar Pollut Bull	Asymmetry, Marine turtles, Inorganic elements, Developmental instability, Cadmium	Spain, France	La Escobilla beach (Mexico)	Marine	Al, As, B, Bi, Cd, Co, Cr, Cu, Li, Ni, Pb, Sb, Se, Sr, Ti, Tl	Olive Ridley marine turtle (*Lepidochelys olivacea*)	Chordata; Reptilia; Cheloniidae
Russo R, et al. (2018); Mar Environ Res	Stress response, Proto-oncogene, Heavy metals, Metallothionein, Leucin zipper	Italy	Laboratory/mesocosm	n.a.	Li, Ni, Zn	Sea urchin (*Paracentrotus lividus*)	Echinodermata; Echinoidea; Echinidae
Protasowicki M, et al. (2008); Environ Monit Assess	Heavy metals, *Mytilus edulis*, Shell, Baltic sea	Poland, Turkey	Baltic Sea (Poland)	Marine	Al, Cd, Cr, Cu, Fe, Hg, Li, Mn, Ni, Pb, V, Zn	Blue mussel (*Mytilus edulis*)	Mollusca; Bivalvia; Mytilidae

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Pourang N, et al. (2014); Environ Monit Assess	Trace elements, Environmental proxy, *Pinctada radiata*, Shell layers, Soft tissues, Sediments	Iran, United Kingdom	Persian Gulf (Iran)	Marine	Al, Ba, Cd, Cu, Cu, Fe, Li, Mg, Mn, Ni, Pb, Pb, Sr, V, Zn	Pearl oyster (*Pinctada radiata*)	Mollusca; Bivalvia; Pteriidae
Sawasdee B, et al. (2011); Chemosphere	Histopathology, Metal toxicity, Prosobranch snail, Copper, Lithium, *Marisa cornuarietis*	Germany	Laboratory/mesocosm	n.a.	Cu, Li	Ramshorn snail (*Marisa cornuarietis*)	Mollusca; Gastropoda; Ampullariidae
Sawasdee B, et al. (2010); Ecotoxicology	Development, Embryo toxicity test, Metals, *Marisa cornuarietis*	Germany	Laboratory/mesocosm	n.a.	Cu, Li, Pb, Pd	Ramshorn snail (*Marisa cornuarietis*)	Mollusca; Gastropoda; Ampullariidae
Brito GB, et al. (2012); Mar Pollut Bull	Macroalgae, Trace elements, Biomonitoring, Todos os Santos Bay	Brazil	Todos os Santos Bay (Brazil)	Marine	As, Ba, Cd, Co, Cr, Cu, Li, Mn, Ni, Pb, V, Zn	Red alga (*Acanthophora spicifera* Vahl Boergesen); red alga (*Bostrychia montagnei* Harvey); brown alga (*Dictyopteris jamaicensis* W.R. Taylor); peacock's tail (*Padina* spp.); *Sargassum* spp.; sea lettuce (*Ulva lactuca Linnaeus*); hen pen (*Bryopsis plumosa* Hudson C. Agardh); *Caulerpa racemosa* var. occidentalis J. Agardh Boergesen; *Caulerpa scalpelliformis* (R. Brown ex Turner) C. Agardh); *Penicillus capitatus* Lamarck	Rhodophyta; Florideophyceae; Rhodomelaceae Ochrophyta; Phaeophyceae; [Dictyotaceae, Sargassaceae] Chlorophyta; Ulvophyceae; [Ulvaceae, Bryopsidaceae, Caulerpaceae, Udoteaceae]
Mendes LF, et al. (2013); Environ Toxicol Chem	Daily growth rates, Generic function approximation (GFA), MINTEQA2, Free ions, Quantitative ion–character relationship (QICAR) models	Brazil	Laboratory/mesocosm	n.a.	Ca, Cd, Co, Cu, K, La, Li, Mg, Mn, Na, Ni, Pb, Sr, Zn	Red seaweed (*Gracilaria domingensis*)	Rhodophyta; Florideophyceae; Gracilariaceae
Ribeiro C, et al. (2018); Sci Total Environ	Trace elements, Douro river estuary, Estuarine sediments, Pollution indices, Contamination factor, Geo-accumulation index	Portugal	Douro River (Portugal)	Estuary	Ag, Al, Ba, Be, Cd, Co, Cr, Cu, Li, Mo, Ni, Pb, Sb, Se, Tl, U, V, Zn	Blue-scarlet pimpernel (*Anagallis arvensis* L.); European searocket (*Cakile maritima* Scop.); sea lettuce (*Enteromorpha* sp.); water-dropwort (*Oenanthe crocata* L.); spreading pellitory (*Parietaria judaica* L.); Buck's-horn plantain (*Plantago coronopus* L.); ribwort plantain	Streptophyta; ?; [Primulaceae, Brassiceae, Apiaceae, Urticaceae, Plantaginaceae, Caryophyllaceae] Chlorophyta; Ulvophyceae; Ulvaceae Rhodophyta; Bangiophyceae; Bangiaceae

						(*Plantago lanceolata* L.); purple laver (*Porphyra umbilicalis* Kütz); common catchfly (*Silene gallica* L.); hedge mustard (*Sisymbrium officinale* L. Scop.); water speedwell (*Veronica anagallis-aquatica* L.)	

Table 2. *Main (bio)chemical variables and genes studied in the original reference. Additional variables may have measured for ancillary tests.

#Some studies include a combination of terrestrial and aquatic species.

¥Based on NCBI taxonomy (https://www.ncbi.nlm.nih.gov).

Comparison of a selection of primary-research publications from the last 15 years, that, to various extent, broadly covered the topics lithium contamination and aquatic biota (n = 27), and that were retrieved from the two databases Scopus and Web of Science (WoS) in August 2019. Abbreviations: Ref: Reference; Aff: Authors' affiliations; Eco: Ecosystem; n.a.: not available or not applicable; Tot: total; apoAI: apolipoprotein AI; NVDOC: non-volatile dissolved organic carbon; LMWOA: low molecular weight organic acids; ?: class not available or unknown.

Out of the 27 publications, the total number of unique aquatic taxa studied (in mesocosm experiments or from field campaigns) was approximately 81. This number is difficult to establish with confidence due to known uncertainties, biases and errors in taxonomic classification and identifications (Conn et al., 2013). Moreover, at least one study included a combination of terrestrial and aquatic species (Ribeiro et al., 2018). Overall, however, the 27 publications from Table 2, focused on 9 phyla (Chordata, Streptophyta, Arthropoda, Mollusca, Chlorophyta, Rhodophyta, Ochrophyta, Rotifera, Echinodermata), and 16 known Classes (Actinopteri, n.a., Spermatophyta, Ulvophyceae, Insecta, Malacostraca, Gastropoda, Bivalvia, Florideophyceae, Phaeophyceae, Branchiopoda, Reptilia, Monogononta, Amphibia, Mammalia, Echinoidea, Bangiophyceae) (Figure 2).

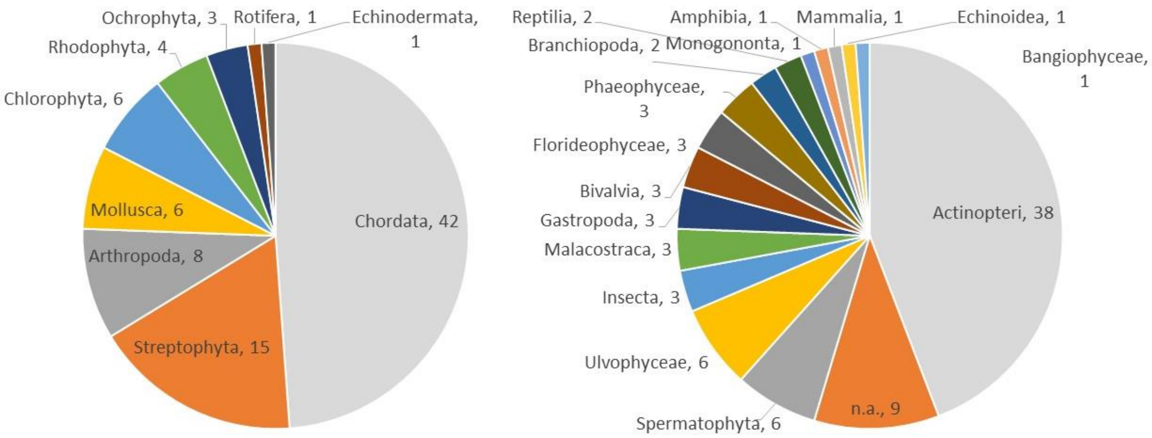

Figure 2. In August 2019, a selection of primary-research publications from the last 15 years, that to various extent, broadly covered the topics lithium contamination and aquatic biota (n = 27), were retrieved from the two databases Scopus and Web of Science. The pie chart summarizes the number of species belonging to each phylum (left) or class (right), that were studied in these publications. Abbreviations: n.a.: class not available or unknown. Note: some studies include a combination of terrestrial and aquatic species. Taxonomy is based on the NCBI taxonomy database (https://www.ncbi.nlm.nih.gov).

The three most represented phyla were Chordata (49%), Streptophyta (17%) and Arthropoda (9%), including respectively 42, 15, and 8 species each. The second phylum includes also some terrestrial plants that were co-investigated with water species (Table 2). Thirty-eight aquatic species studied (44%) belonged to the group of ray-finned bony fishes of the class Actinopteri. Among the selection of paper from Table 2, this was by far the most studied group, followed by the seed plants Spermatophyta (6 species/86, 7%), and the green algae Ulvophyceae (6 species/86, 7%). Other important classes (each with 3 species/86) were insects (Insecta); crabs, lobsters, crayfish, shrimp etc. (Malacostraca); snails and slugs (Gastropoda); clams, oysters, cockles, mussels etc. (Bivalvia), red algae (Florideophyceae), and brown algae (Phaeophyceae) Figure 2. The total number of known families studied was 54; most species belonged to the families Cyprinidae (11/86; 13%) and Carangidae (4/86; 5%) (data not shown). Respectively, these are freshwater fishes like carps, true minnows, barbs, and barbels, or oceanic fast-swimming predatory fishes like jacks, pompanos, jack mackerels, runners, and scads.

4. Discussion

The low toxicity of Li {Aral, 2008 #388} may have diverted current research efforts from this environmental contaminant. Global Li production, however, has tripled since 2000 (Martin et al., 2017), and the associated growing risks of exposure for humans, animals and plants, are likely understudied. To assess the research *status quo* on the topic, a quantitative systematic search of peer-reviewed literature was conducted, around four topics: “contamination”, “lithium”, “water”, and “biodiversity”.

The present analysis highlighted how, of all studies on lithium found (Figure 1), only about one tenth focuses specifically on pollution of water bodies. Of these, just approximately one third seems to delve into the effects of this metal on biodiversity (n=49 and 200, for WoS and Scopus, respectively). Even worse, however, a proportion of these latter subsets includes papers irrelevant to the scope of this review, due to the limitations of the search approach implemented.

It was also found that, while the authors of the selected papers (Table 2) were affiliated with a wide range of countries (n = 17), geographic biases and gaps were present. Huge lithium reserves (19.0 Mt, corresponding to 43.6 % of the global total) come from South American salt-lake brines, located in Argentina, Bolivia, and Chile (Grosjean et al., 2012). Australia is among the top five global countries for lithium mineral deposits (560 kt), and its mine of Greenbushes is currently one of the few places left in the world where spodumene (a lithium-rich ore) is extracted (Grosjean et al., 2012). Moreover, about 1.3 Mt the 43.6 Mt of global lithium reserves come from countries located in the South of the African continent. Despite this, all these countries were underrepresented in Table 2, both among authors’ affiliations and study sites.

Laboratory settings including mesocosms, in vitro assays, aquaria etc. were used in one third of the studies from Table 2 (n = 9/27). This represents a large proportion of studies were field conditions, animal behaviors and ecosystem dynamics were simulated under artificially controlled conditions, rather than being observed and measured in natural settings.

A well-known and common limitation in scientific research is the lack of standardized procedure, methods and experimental conditions, adopted across similar studies dealing with the analysis of the same phenomenon. The immaturity of the research on the effect of lithium on aquatic biodiversity is testified not only by the relatively few publications available, but also by the lack of experimental results that can be compared directly. While this is less true for mesocosms, results from field studies are particularly difficult to weigh against each other, especially if different (biological) species and combinations of dependent and independent variables are considered each time (e.g., spatial scales, time scales, chemical environmental load etc.). For instance, an interesting biomolecular study by Russo et al. (2018), addressed the *in vitro* response to metals of sea urchin embryos, by measuring the expression of genes (e.g., *Pl-Fra*, *Pl-jun*, *Pl-MT*), broadly implicated in heavy metals protection. While identifying metal-responsive genes may eventually lead to the development of new type of molecular biomarkers for the evaluation of metal injuries in marine organisms in either natural or polluted environment (Russo et al., 2018), using such inferences to understand the lithium effect on biodiversity is undoubtedly more challenging. An earlier study on the aquatic model species *Daphnia magna* (Bozich et al., 2017) reported a dose-dependent downregulation of genes important in metal detoxification, metabolism, and cell maintenance, and suggested altering the chemical composition of nanomaterial in batteries to mitigate environmental contamination. These emerging pollutants were also tested on the harlequin fly (*Chironomus riparius*) by a more recent study (Niemuth et al., 2019) which also highlighted difference in toxicity across these complex metal oxides. Hence, the great

majority of studies listed in Table 2 concentrates on the toxicity of dissolved elemental contaminants but overlooks the toxicity for the benthos, of settling next-generation lithium oxides from modern batteries (Niemuth et al., 2019).

The long-term effects of historical contaminations and seasonal patterns of metals' influence on fish density distribution were nicely captured in the Portuguese coastal lagoon Ria de Aveiro (Hg, Li and Zn) (García-Seoane et al., 2016). Persistent consequences on aquatic biota have also been described for spills of lithium-rich wastewaters from unconventional oil and gas (UOG) resources, generated by horizontal drilling and hydraulic fracturing technologies (Cozzarelli et al., 2017).

A quantitative structure activity relationship (QSAR) method was developed to predict metals' aquatic toxicity, based on their physical and chemical characteristics (Wu et al., 2013). Another similar study (Mendes et al., 2013) developed a model for predicting the toxicity of metal cations using the median inhibitory concentration (IC50; dependent variable) as a function of several physical-chemical properties (independent variables). However, none of the studies selected in Table 2 developed exhaustive numerical models to simulate the temporal and spatial dynamics within the trophic chain, mortality rates, changes in community composition, predation, behavior, hydrology etc. (Robson et al., 2017).

In the selected literature presented in Table 2, lithium was always measured but not always thoroughly discussed, or fully reviewed. Many papers presented a snapshot of various metals' concentrations in water and tissues (flora and fauna). Although this is useful, it does not account for lithium mass transfer balances across the various taxa in the food web. Nor it explains the sources of biocontamination for each species tested, or the important repercussions of such bioaccumulation on the whole community assemblage and structure.

Bioaccumulation is known to depend on a variety of factors including body biochemical composition (species) and size (Sofoulaki et al., 2018). Djikanović et al. (2018) also highlighted differences in the metals' bioaccumulation factor for the tissues of different freshwater macrophytes, and fish species (Djikanović et al., 2018). The physiological and biochemical effects of lithium and mixed mining effluents on the rainbow trout, perch and roach, were extensively studied both in laboratory mesocosms and during field campaigns (Tkatcheva et al., 2007a; Tkatcheva et al., 2007b; Tkatcheva et al., 2004). Three studies from two American and one Mexican sites, examined the toxicity of environmental levels of trace-metals on dolphins, alligators and marine turtles (Cortés-Gómez et al., 2018; Horai et al., 2014; Stavros et al., 2011).

Understanding bioaccumulation of heavy metals in the flesh of edible filter-feeding bivalves such as oysters and mussels, is particularly important for the aquaculture industry. This was addressed by two studies conducted off the Polish and Iranian coasts (Baltic Sea and the Persian Gulf, respectively) (Pourang et al., 2014; Protasowicki et al., 2008), which also highlighted how this screening effort can be used as an effective tool for monitoring water quality parameters. *In vitro* experiments were performed to identify possible histopathological effects of metals, on the juvenile stages and embryonic development of the ramshorn snail (*Marisa cornuarietis*), which is used as a biological control agent or aquarium pet (Sawasdee and Heinz-R, 2010; Sawasdee et al., 2011).

Three studies from Brazil and Portugal specifically addressed bioaccumulation of trace elements in aquatic plants, coastal flora, seaweeds and algae (red algae, and brown algae) (Brito et al., 2012; Mendes et al., 2013; Ribeiro et al., 2018). This is particularly relevant due to the position within the trophic chain of these plants. Although a high variability within and between species and sampling

sites was often found, taxa like *Padina* spp. accumulated Li levels higher than other species (Brito et al., 2012), and may thus represent potentially useful bioindicators. In one of these studies, Li (along several other elements) was found to be associated with strong anthropogenic contaminations of an estuary (Ribeiro et al., 2018).

Out of the many available, only two databases were interrogated, using an *ad hoc* combination of keywords and Boolean searches (Table 1). While the "contamination" topic may have been omitted to relax the stringency of the search (Table 1), the "biodiversity" topic search was essential for the scope of this study, but more challenging. Keywords like "structure", "dynamics", "composition", or "assemblage" are common in ecology but they are not exclusive to this field (e.g., "chemical structure"). Although combination of keywords like "phytoplankton assemblage", "zooplankton structure" or "eukaryotic composition" may reduce the number of irrelevant hits fetched, clearly the number of possible combinations can be overwhelming. This technical limitation explains the proportion of irrelevant hits fetched during the preliminary search, and warrants the inclusion of the expression "AND ALL(species)" in subsequent search refinements (cf. Section 2.2).

5. Conclusions

The quantitative systematic advanced-search approach developed here was successfully used to analyze published sources, on the effect of lithium on aquatic biota. The approach is reproducible and flexible and can be repeated to easily update literature repositories that have been previously created.

The analysis conducted highlighted several gaps in our understanding of the environmental impact of lithium contaminations in aquatic ecosystems and biodiversity. The term "*BioDiversity*", originally introduced in the mid 80's as a portmanteau of biological and diversity (1988), has neither a precise or commonly accepted definition, nor a measurement unit. For instance, biodiversity can be measured in terms of counts and identity, and expressed as genetic diversity (e.g., taxon-specific DNA sequences), taxonomic diversity of individuals etc. Several quantifiable parameters have been used to describe the functional properties of the ecosystems, including richness, evenness, dominance, diversity indexes (alpha, beta and gamma) etc. The present review, however, highlights how such parameters have often been overlooked, together with formal statistical analyses, and suggests that little is known on the impact of anthropogenic lithium pollution on biodiversity. After comparing the rapidly increasing use of lithium globally (Robinson et al., 2018), to the extent of peer-reviewed literature available, it seems that the broader effects of this emerging metal contaminant are still understudied.

While several advantages are associated with the use of model organisms in isolation, *in vitro* simulations, chemostats and mesocosms experiments, collating the results from uncoordinated investigations to infer the ecological effects of lithium at community level, and under variable environmental conditions, is virtually impossible. This is a significant limitation in our understanding of the topic, and thwarts previous research efforts. Ultimately, we speculate that the biggest gap found by the present literature review is the paucity of holistic studies, aimed at inferring the effects of lithium on the "ecosystem as a whole", and, more specifically, on the quantifiable parameters of biodiversity.

References

1988. Biodiversity. The National Academies Press, Washington, DC.

Bozich, J., Hang, M., Hamers, R., Klaper, R., 2017. Core chemistry influences the toxicity of multicomponent metal oxide nanomaterials, lithium nickel manganese cobalt oxide, and lithium cobalt oxide to *Daphnia magna*. Environ. Toxicol. Chem. 36, 2493-2502.

Brito, G.B., de Souza, T.L., Bressy, F.C., Moura, C.W.N., Korn, M.G.A., 2012. Levels and spatial distribution of trace elements in macroalgae species from the Todos os Santos Bay, Bahia, Brazil. Mar. Pollut. Bull. 64, 2238-2244.

Conn, P.B., McClintock, B.T., Cameron, M.F., Johnson, D.S., Moreland, E.E., Boveng, P.L., 2013. Accommodating species identification errors in transect surveys. Ecology 94, 2607-2618.

Cortés-Gómez, A.A., Romero, D., Girondot, M., 2018. Carapace asymmetry: A possible biomarker for metal accumulation in adult olive Ridleys marine turtles? Mar. Pollut. Bull. 129, 92-101.

Cozzarelli, I.M., Skalak, K.J., Kent, D.B., Engle, M.A., Benthem, A., Mumford, A.C., Haase, K., Farag, A., Harper, D., Nagel, S.C., Iwanowicz, L.R., Orem, W.H., Akob, D.M., Jaeschke, J.B., Galloway, J., Kohler, M., Stoliker, D.L., Jolly, G.D., 2017. Environmental signatures and effects of an oil and gas wastewater spill in the Williston Basin, North Dakota. Sci. Total. Environ. 579, 1781-1793.

Djikanović, V., Skorić, S., Spasić, S., Naunovic, Z., Lenhardt, M., 2018. Ecological risk assessment for different macrophytes and fish species in reservoirs using biota-sediment accumulation factors as a useful tool. Environ. Pollut. 241, 1167-1174.

García-Seoane, E., Coelho, J.P., Mieiro, C., Dolbeth, M., Ereira, T., Rebelo, J.E., Pereira, E., 2016. Effect of historical contamination in the fish community structure of a recovering temperate coastal lagoon. Mar. Pollut. Bull. 111, 221-230.

Grosjean, C., Miranda, P.H., Perrin, M., Poggi, P., 2012. Assessment of world lithium resources and consequences of their geographic distribution on the expected development of the electric vehicle industry. Renew. Sustain. Energy Rev. 16, 1735-1744.

Horai, S., Itai, T., Noguchi, T., Yasuda, Y., Adachi, H., Hyobu, Y., Riyadi, A.S., Boggs, A.S.P., Lowers, R., Guillette, L.J., Tanabe, S., 2014. Concentrations of trace elements in American alligators (*Alligator mississippiensis*) from Florida, USA. Chemosphere 108, 159-167.

Martin, G., Rentsch, L., Höck, M., Bertau, M., 2017. Lithium market research – global supply, future demand and price development. Energy Storage Mater. 6, 171-179.

McKnight, R.F., Adida, M., Budge, K., Stockton, S., Goodwin, G.M., Geddes, J.R., 2012. Lithium toxicity profile: a systematic review and meta-analysis. Lancet (London, England) 379, 721-728.

Mendes, L.F., Zambotti-Villela, L., Yokoya, N.S., Bastos, E.L., Stevani, C.V., Colepicolo, P., 2013. Prediction of mono-, bi-, and trivalent metal cation relative toxicity to the seaweed *Gracilaria domingensis* (Gracilariales, Rhodophyta) in synthetic seawater. Environ. Toxicol. Chem. 32, 2571-2575.

Niemuth, N.J., Curtis, B.J., Hang, M.N., Gallagher, M.J., Fairbrother, D.H., Hamers, R.J., Klaper, R.D., 2019. Next-Generation complex metal oxide nanomaterials negatively impact growth and development in the benthic invertebrate *Chironomus riparius* upon settling. Environ. Sci. Technol. 53, 3860-3870.

Pourang, N., Richardson, C.A., Chenery, S.R.N., Nasrollahzedeh, H., 2014. Assessment of trace elements in the shell layers and soft tissues of the pearl oyster *Pinctada radiata* using multivariate analyses: A potential proxy for temporal and spatial variations of trace elements. Environ. Monit. Assess. 186, 2465-2485.

Protasowicki, M., Dural, M., Jaremek, J., 2008. Trace metals in the shells of blue mussels (*Mytilus edulis*) from the Poland coast of Baltic sea. Environ. Monit. Assess. 141, 329-337.

Reynolds, C.S., 2006. The Ecology of Phytoplankton. Cambridge University Press, Cambridge.

Ribeiro, C., Couto, C., Ribeiro, A.R., Maia, A.S., Santos, M., Tiritan, M.E., Pinto, E., Almeida, A.A., 2018. Distribution and environmental assessment of trace elements contamination of water, sediments and flora from Douro River estuary, Portugal. Sci. Total. Environ. 639, 1381-1393.

Robinson, B.H., Yalamanchali, R., Reiser, R., Dickinson, N.M., 2018. Lithium as an emerging environmental contaminant: mobility in the soil-plant system. Chemosphere 197, 1-6.

Robson, B.J., Lester, R.E., Baldwin, D.S., Bond, N.R., Drouart, R., Rolls, R.J., Ryder, D.S., Thompson, R.M., 2017. Modelling food-web mediated effects of hydrological variability and environmental flows. Water Res. 124, 108-128.

Russo, R., Bonaventura, R., Chiaramonte, M., Costa, C., Matranga, V., Zito, F., 2018. Response to metals treatment of Fra1, a member of the AP-1 transcription factor family, in P. lividus sea urchin embryos. Mar. Environ. Res. 139, 99-112.

Sawasdee, B., Heinz-R, K., 2010. Metal sensitivity of the embryonic development of the ramshorn snail *Marisa cornuarietis* (Prosobranchia). Ecotoxicology 19, 1487-1495.

Sawasdee, B., Koehler, H.-R., Triebskorn, R., 2011. Histopathological effects of copper and lithium in the ramshorn snail, *Marisa cornuarietis* (Gastropoda, Prosobranchia). Chemosphere 85, 1033-1039.

Sofoulaki, K., Kalantzi, I., Machias, A., Mastoraki, M., Chatzifotis, S., Mylona, K., Pergantis, S.A., Tsapakis, M., 2018. Metals and elements in sardine and anchovy: species specific differences and correlations with proximate composition and size. Sci. Total. Environ. 645, 329-338.

Stavros, H.C.W., Stolen, M., Durden, W.N., McFee, W., Bossart, G.D., Fair, P.A., 2011. Correlation and toxicological inference of trace elements in tissues from stranded and free-ranging bottlenose dolphins (*Tursiops truncatus*). Chemosphere 82, 1649-1661.

Tkatcheva, V., Franklin, N.M., McClelland, G.B., Smith, R.W., Holopainen, I.J., Wood, C.M., 2007a. Physiological and biochemical effects of lithium in rainbow trout. Arch. Environ. Contam. Toxicol. 53, 632-638.

Tkatcheva, V., Holopainen, I.J., Hyvarinen, H., Kukkonen, J.V.K., 2007b. The responses of rainbow trout gills to high lithium and potassium concentrations in water. Ecotoxicol. Environ. Saf. 68, 419-425.

Tkatcheva, V., Hyvarinen, H., Kukkonen, J., Ryzhkov, L.P., Holopainen, I.J., 2004. Toxic effects of mining effluents on fish gills in a subarctic lake system in NW Russia. Ecotoxicol. Environ. Saf. 57, 278-289.

Wu, F., Mu, Y., Chang, H., Zhao, X., Giesy, J.P., Wu, K.B., 2013. Predicting water quality criteria for protecting aquatic life from physicochemical properties of metals or metalloids. Environ. Sci. Technol. 47, 446-453.