Science of the Total Environment 485–486 (2014) 490–496

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Review

Bioaccumulation and effects of metals and trace elements from aquatic disposal of coal combustion residues: Recent advances and recommendations for further study

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HIGHLIGHTS

• Exposure to coal combustion residues elicits a variety of effects on aquatic biota.

ARTICLE INFO

Article history:
Received 4 December 2013
Received in revised form 19 March 2014
Accepted 23 March 2014
Available online 16 April 2014

Editor: Simon Pollard

Keywords:
Biological vector
Coal ash
Maternal transfer
Mercury
Population models
Selenium

ABSTRACT

Advances have been made recently in assessing accumulation and effects of coal combustion residues (CCR). I provide a brief review of recent advancements, provide a tabulated summary of results of recent work, and put forth recommendations for future studies. One advancement is that mercury accumulation has begun to receive (limited) attention, whereas it had rarely been considered in the past. Additionally, some constituents of CCR have been shown to be accumulated by adults and transferred to offspring, sometimes compromising offspring health. Studies have demonstrated that amphibians, possessing complex life cycles, may accumulate and transfer some contaminants to terrestrial systems. Some study has been given to molecular and cellular effects of CCR exposure, although these studies have been limited to invertebrates. Population models have also been applied to CCR affected systems and have shown that CCR may affect animal populations under some conditions. In light of these advancements, there are several topics that require further assessment. First, more attention to Hg and its dynamics in CCR affected systems is warranted. Hg can be highly accumulative and toxic under some conditions and may interact with other components of CCR (notably Se), perhaps altering accumulation and effects of the contaminant mixtures. Second, further investigation of maternal transfer and effects of CCR contaminants need to be conducted. These studies could benefit from incorporation of quantitative models to project impacts on populations. Finally, more attention to the organic constituents of CCR (PAHs) is required, as a focus on inorganic compounds only may restrict our knowledge of contaminant dynamics and effects as a whole. While further studies will shed light on some chemical and biological nuances of exposure and effect, information available to date from numerous study sites implicates CCR as a bulk effluent that presents risks of bioaccumulation and effects on organisms in aquatic systems.

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http://dx.doi.org/10.1016/j.scitotenv.2014.03.119
0048-9697/

1. Introduction

The United States produces approximately 130 million tons of solid coal combustion residues (hereafter "CCR") annually, consisting largely of metal- and trace element-rich fly and bottom ash (ACAA, 2011). About half of the residues are disposed of in landfills or aquatic surface impoundments. The latter, due to hydrological connections with local water bodies, may lead to contamination of surface waters with numerous potentially toxic metals and trace elements (see Rowe et al., 2002; Ruhl et al., 2012). While contamination of surface waters and potential impacts on biota have long been associated with disposal of CCR in surface impoundments/disposal basins (see Carlson and Adriano, 1993; Rowe et al., 2002; Lemly and Skorupa, 2012), renewed attention to potential impacts of CCR on wildlife resulted from a large-scale release of CCR following a structural failure of an impoundment in Kingston, TN in 2008 (see Ruhl et al., 2010).

A comprehensive review of ecotoxicological impacts of CCR disposal in aquatic systems was published over a decade ago by Rowe et al. (2002). Investigations since the publication of that review have continued to implicate the practice of CCR disposal in aquatic surface impoundments in contamination of and toxicological effects on wildlife that interact with these systems. Here I provide a compendium of studies conducted over the past decade that have demonstrated bioaccumulation of metals/trace elements by animals exposed naturally or experimentally to CCR and ecotoxicological impacts on exposed organisms. These recent studies have confirmed that release of CCR into aquatic systems, intentionally or unintentionally, is deleterious to aquatic and semi-aquatic biota. While providing a tabulated summary of work that has been recently completed on ecotoxicology of CCR in aquatic systems (which I largely restrict to the peer reviewed literature; Tables 1 and S1), I intend to highlight recent progress in examining accumulation of potentially toxic elements that previously received little or no consideration (such as Hg). Furthermore, recent work has evolved to consider more complex routes of exposure and effect, namely maternal transfer of CCR derived contaminants to offspring and resultant effects on reproduction. Based upon historical and recent research, as well as changes to operation of U.S. coal fired power plants to protect air quality (see http://www.epa.gov/airquality/powerplanttoxics/pdfs/20111221MATSsummaryfs.pdf and http://www.gpo.gov/fdsys/pkg/FR-2012-02-16/pdf/2012-806.pdf) which ultimately will change the composition of CCR itself (see Dellantonio et al., 2010), I provide recommendations for future studies of CCR in aquatic systems. While options for regulation of CCR disposal in surface impoundments are currently being considered by the U.S. E.P.A. (U.S.E.P.A., 2010), this pending legislation and its ecological and economic impacts have been recently addressed by Lemly and Skorupa (2012) and will not be addressed here.

2. Bioaccumulation

Aquatic CCR disposal sites may act as "attractive nuisances" (e.g. Bryan et al., 2012) or "ecological traps" for wildlife such that animals may be attracted during breeding or feeding activities where they accumulate (and potentially are affected by) the suite of contaminants present. Thus such systems, if accumulation and effects are substantial enough, may serve as population sinks in the landscape (e.g. Pulliam, 1988; Rowe et al., 2001; note that formal metapopulation analysis is required to substantiate that CCR sites may play such a role in the landscape). Supplementary Table S1 is intended to serve as a compendium of recent data on bioaccumulation of contaminants from CCR to guide the reader in accessing the original publications discussing the data in detail. Numerous recent studies from 11 study sites have quantified bioaccumulation of potentially toxic metals and trace elements by organisms naturally or experimentally exposed to CCR (Table S1). What is at first apparent is that the greatest emphasis of recent studies has been on accumulation by fish and amphibians. This is likely due to these species' frequent occupation of impacted systems, as well as the emphasis of many previous studies on these groups (see Rowe et al., 2002). The large number of studies on amphibians also likely reflects recognition that these animals, due to their complex life cycles, can act as vectors of elements in CCR from the contaminated aquatic systems to nearby terrestrial systems (Snodgrass et al., 2003; Roe et al., 2005; Rowe et al., 2011). Second, while the specific elements quantified vary among studies, selenium was quantified in all studies likely due to its known toxic effects on fish in CCR-affected systems (see Lemly, 1985, 1999). Not only have animals been found to accumulate Se, in many instances whole body Se concentrations exceed those considered harmful. In fact, about 80% of observations in Table S1 for whole body Se concentrations in aquatic animals exceed the biological effects threshold for fish whole body concentrations (4 ug/g dw, Lemly, 1993). Thus, while several of the elements associated with CCR have no established tissue based criteria for biological effects, results for Se suggest that contamination by CCR can be expected to have adverse impacts on fish and perhaps other aquatic fauna.

Additionally, with respect to contaminant accumulation data presented in supplementary material (Table S1), recent work has shown an increased interest in quantifying a broader suite of inorganic compounds than was considered in the past, as was recommended by Rowe et al. (2002). Most notably, investigators have begun to quantify Hg in CCR affected systems, which was seldom accomplished in the past. In fact, in the 2002 review of CCR, Rowe et al. (2002) did not include Hg in their treatment of accumulation or effect due to the paucity of data for Hg in CCR affected systems. As will be discussed below, Hg may be particularly worthy of further study due to its projected increased presence in CCR due to measures to reduce airborne emissions (see Dellantonio et al., 2010) and due to its propensity to accumulate and potentially interact with another common constituent of CCR (Se) and subsequently vary in accumulation potential and toxicity.

Two other elements, Sr and V, which were little considered in prior studies of CCR have also been quantified in exposed organisms in recent studies. These additions to the data base for accumulation are important given recent studies showing that Sr is maternally transferred from female to offspring (Hopkins et al., 2006) and that V can have substantial physiological effects under some conditions (Rowe et al., 2009).

Examining bioaccumulation of CCR associated contaminants from an ecological perspective, several investigators have considered the ecological fate of contaminants in CCR disposal areas with respect to trophic transfer to nearby systems. A question that may be asked when examining CCR disposal (or other contaminated aquatic systems) is whether the contaminants are restricted to the directly impacted aquatic system, or whether the contaminated system may serve as a source of contaminants to nearby, terrestrial systems. Studies of amphibians in particular, due to their complex, biphasic life cycles, have shown that some CCR contaminants may be exported from the aquatic systems to terrestrial systems in amphibian tissues following metamorphosis, whereas other contaminants are depurated prior to metamorphosis from the contaminated aquatic system (Snodgrass et al., 2003; Roe et al., 2005; Rowe et al., 2011). In particular, Se does not appear to be depurated by amphibians during metamorphosis, and thus amphibians entering