Using Good Science to Communicate Toxicity, Exposure, and Risk

by Lisa J.N. Bradley

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The safe management, disposal, and reuse of industrial materials are the basis for many environmental regulations. Misinformation and misconceptions about industrial materials or waste management practices, however, can result in public concerns about human health. Often, these misconceptions result from a lack of understanding about toxicology, about how industrial materials or chemical constituents may or may not move in the environment, and lack of knowledge of what constituents are present in our natural environment. These issues are considered here in the context of the current national debate about the potential regulation of coal ash, with an emphasis on beneficial uses of coal ash.

What Is Toxicity?

Toxicity is a measure of how harmful a given constituent may be to humans. Each constituent has a specific toxicity. Toxicology, simply put, is the study of poisons, or the types of toxic effects constituents may have on humans. Paracelsus, the father of modern toxicology, said it best in the 1500s:

"All substances are poisons; there is none which is not a poison. The right dose differentiates a poison from a remedy."

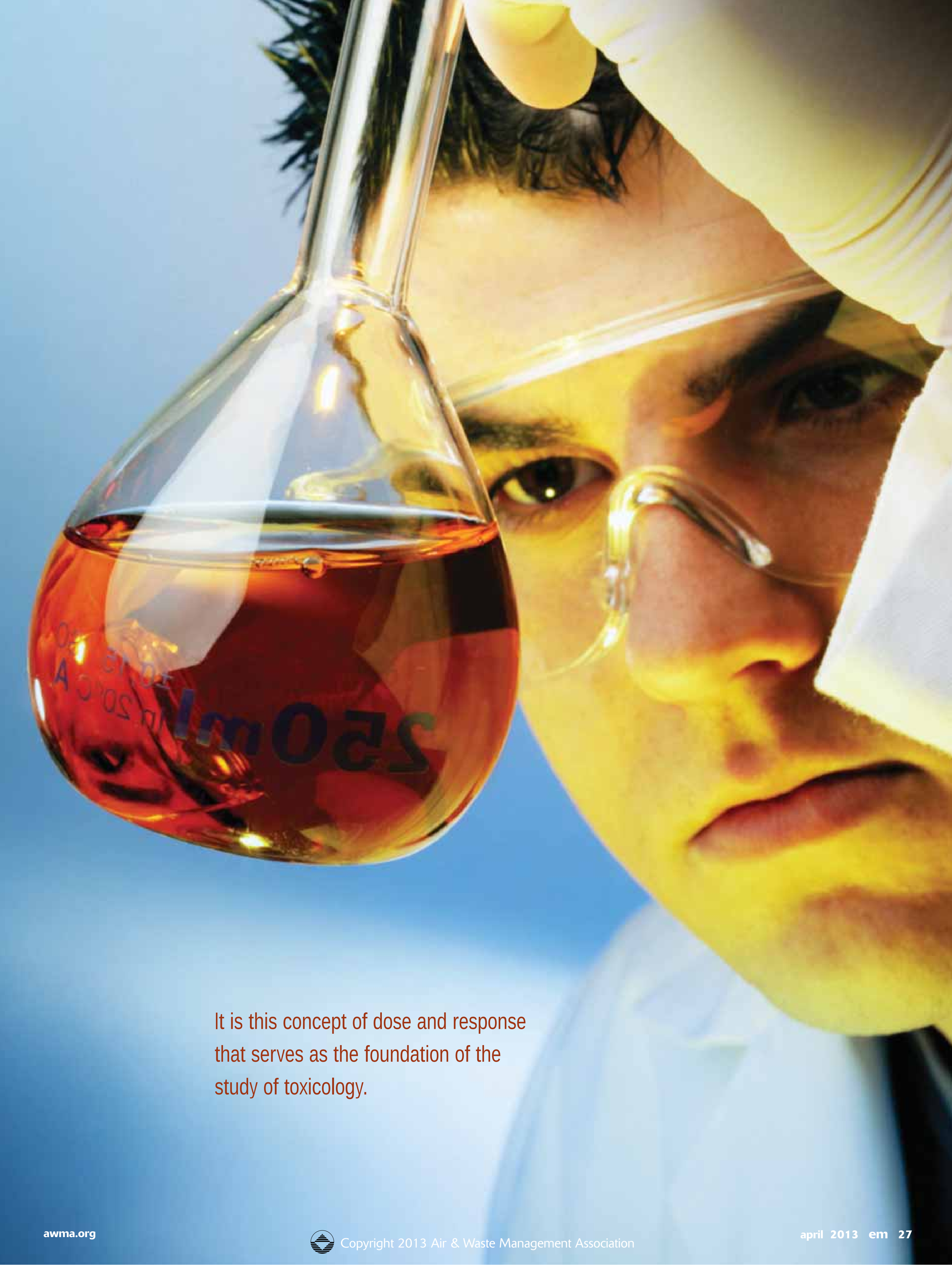
For example, aspirin is common in many home medicine cabinets. It can be taken safely and effectively, 2 tablets every 4 hours, for aches and pains or to control a fever. If taken for an extended period of time, this same dosage may cause stomach problems, or ringing in the ears. However, consuming an entire bottle of aspirin can be lethal. So, aspirin can be safe and effective at a low dose (2 tablets), and yet toxic at a very high dose (bottle).

It is this concept of dose and response that serves as the foundation of the study of toxicology. The U.S. Environmental Protection Agency (EPA) uses this type of dose/response information to derive numeric estimates of the toxicity of a wide range of constituents. These numeric estimates are used in risk assessments to evaluate exposures by humans to constituents in the environment. (These concepts also pertain to ecological receptors such as plants and animals, but this discussion will focus on human health.)

How Do We Know if Something in the Environment Will Be Toxic?

Risk can be defined as the likelihood (or probability) that a given chemical exposure or series of exposures may be toxic to exposed individuals (people). Some chemicals have or may present a risk of toxicity (e.g., household cleaning products). However, it is only through direct exposure to the chemicals in household cleaning products in certain quantities and over a certain duration that can result in toxic effects. Not all exposures result in toxicity. For example, common household cleaning products such as bleach are safe when used as directed; however, they can pose a risk if they are swallowed. Whether or not an adverse health effect will occur depends on how much is swallowed and whether it happens once or multiple times. Ultimately, the risk of a toxic effect depends on both exposure and toxicity.

Risk assessment is the tool used by regulatory agencies and environmental scientists to determine if exposure to something in the environment may result in toxic effects. Risk assessment is a step-wise process that makes a quantitative estimate of risk by combining information on exposure (i.e., how someone may be exposed to a material or constituent in the environment and at what level of exposure) with a quantitative estimate of the toxicity



It is this concept of dose and response that serves as the foundation of the study of toxicology.

Constituent	Units	Summary Statistics for Fly Ash (a) (b) FOD	Minimum Detect	Maximum Detect	Mean Detect	Median	10%ile	50%ile(Q2)	90%ile	USEPA Residential Soil RSLs (c)
Antimony	mg/kg	76:76	0.982	22.4	3.947	2.88	1.695	2.88	8.595	31
Arsenic	mg/kg	76:76	7.3	93.8	27.21	20.95	14.55	20.95	57.95	39
Barium	mg/kg	76:76	336	5730	2372	1745	389	1745	5050	15000
Beryllium	mg/kg	76:76	1.69	32.7	5.166	2.875	2.215	2.875	11.35	160
Cadmium	mg/kg	76:76	0.312	3.29	0.831	0.791	0.462	0.791	1.24	70
Chromium	mg/kg	76:76	33.7	984	180.5	100.6	36.1	100.6	360	109
Cobalt	mg/kg	76:76	14.5	264	32.1	28.65	15.35	28.65	41.25	23
Copper	mg/kg	76:76	55.1	692	134.2	139.5	64.6	139.5	186.5	3100
Lead	mg/kg	76:76	14.4	293	43.66	33.8	23.65	33.8	64.85	400
Lithium	mg/kg	76:76	13.2	560	63.47	30.15	21.75	30.15	110.5	160
Manganese	mg/kg	76:76	105	966	379.8	217.5	158.5	217.5	908	1800
Mercury	mg/kg	76:76	0.0127	1.15	0.276	0.128	0.0243	0.128	0.844	23
Molybdenum	mg/kg	76:76	4.95	90.5	15.67	8.705	5.755	8.705	35.25	390
Nickel	mg/kg	76:76	17.3	572	127.2	107	20	107	234.5	1500
Selenium	mg/kg	76:76	1.03	22.5	7.208	6.09	2.175	6.09	12.55	390
Strontium	mg/kg	76:76	319	2400	1093	700.5	375	700.5	2290	47000
Thallium	mg/kg	76:76	0.312	21	1.576	0.77	0.418	0.77	3.295	0.78
Uranium	mg/kg	76:76	0.682	34.1	7.422	7.37	0.848	7.37	12.7	230
Vanadium	mg/kg	76:76	106	1660	266.2	251	111.5	251	363.5	390
Zinc	mg/kg	76:76	33.1	848	121.8	106	51.55	106	184.5	23000

Notes:
FOD - Frequency of Detection - Number of detected results: Total number of samples.
(a) - Statistics calculated using ProUCL version 4.1[7].
(b) - Data from USGS[4].
(c) - USEPA Regional Screening Level (RSL) – Residential Soil (May 2012)[1] http://www.epa.gov/region9/superfund//prg/index.html; see also notes to Figures 2 and 3.

Table 1. Summary statistics for constituents in fly ash.

of that material or constituent. The result is a quantitative estimate of risk.

For there to be a significant risk of an adverse effect, there must be both a direct exposure to a constituent and that exposure must be at a high enough level to result in an adverse effect. It is very important to understand: If there is no exposure to a chemical constituent or material, then there is no risk, and, if there is no toxicity, there is no risk.

Thus: Risk = Exposure x Toxicity.

Risk assessment is also used to develop screening levels for constituents, for example, in soil in a residential setting.[1] Screening levels for residential soil are those levels that a human child and adult could be exposed to daily without adverse effect. These levels are called screening levels because they are derived for a very generic and universal exposure setting and can be applied anywhere. If concentrations are below these levels, then it is accepted that there is no expectation of adverse effects. If concentrations are higher than these levels, it does not necessarily mean that there will be adverse effects; it means that the specific situation needs to be evaluated in more detail. Thus, constituent concentrations above screening levels can also be without adverse effect, depending on the specific situation.

These concepts of exposure, toxicity and risk are discussed below in the context of a risk-based evaluation of the beneficial uses of coal ash.

What Is Coal Ash?

Coal is a sedimentary rock that is a natural component of the earth's crust and it contains both organic material and inorganic minerals. It is the organic content of coal that produces energy upon combustion. In a modern coal-fired power plant, combustion of organic materials is nearly complete, leaving the inorganic minerals and elements in the ash (coal ash). The two most common types of coal ash are bottom ash, which settles out at the bottom of the boiler (similar to ashes in a fireplace), and fly ash, which is captured in the flue gas by air pollution control equipment (similar to the ash that goes up a fireplace chimney).

There are many beneficial uses of coal ash including uses in concrete, gypsum wallboard, blasting grit, roofing granules, and a variety of geotechnical and

Constituent	Units	Summary Statistics for Bottom Ash (a) (b)								USEPA Residential Soil RSLs (c)
		FOD	Minimum Detect	Maximum Detect	Mean Detect	Median	10%ile	50%ile(Q2)	90%ile	
Antimony	mg/kg	48:48	0.401	3.2	0.869	0.797	0.488	0.797	1.15	31
Arsenic	mg/kg	48:48	1.24	18.1	5.036	4.775	1.744	4.775	7.344	39
Barium	mg/kg	48:48	474	2990	1545	1435	486.8	1435	2840	15000
Beryllium	mg/kg	48:48	2.99	10.3	5.429	4.085	3.206	4.085	9.316	160
Cadmium	mg/kg	27:48	0.104	0.425	0.165	0.148	0.1132	0.148	0.2056	70
Chromium	mg/kg	48:48	17.5	461	150	72	19.47	72	397.5	109
Cobalt	mg/kg	48:48	7.29	55	28.92	36.05	7.818	36.05	49.46	23
Copper	mg/kg	48:48	40.4	148	76.03	59.8	41.81	59.8	135.6	3100
Lead	mg/kg	48:48	7.59	40	15.56	15.8	8.79	15.8	20.01	400
Lithium	mg/kg	48:48	29.5	120	76.78	90.15	33.64	90.15	106	160
Manganese	mg/kg	47:48	145	347	266.9	266	214.8	266	324	1800
Mercury	mg/kg	15:48	0.0123	0.155	0.047	0.0229	0.01474	0.0229	0.1122	23
Molybdenum	mg/kg	48:48	2.15	10.2	4.55	3.215	2.493	3.215	8.465	390
Nickel	mg/kg	48:48	28.8	255	106	74.45	31.29	74.45	214.6	1500
Selenium	mg/kg	37:48	0.121	1.28	0.382	0.253	0.136	0.253	0.8814	390
Strontium	mg/kg	48:48	270	2680	1105	588.5	291.7	588.5	2563	47000
Thallium	mg/kg	41:48	0.102	1.96	0.459	0.446	0.128	0.446	0.747	0.78
Uranium	mg/kg	48:48	5.27	11	8.229	9.045	5.597	9.045	9.96	230
Vanadium	mg/kg	48:48	69.4	591	223	206.5	72.65	206.5	512.1	390
Zinc	mg/kg	48:48	26.5	152	57.8	57.85	28.19	57.85	91.44	23000

Notes:
FOD - Frequency of Detection - Number of detected results: Total number of samples.
(a) - Statistics calculated using ProUCL version 4.1[7].
(b) - Data from USGS[4].
(c) - USEPA Regional Screening Level (RSL) – Residential Soil (May 2012)[1] http://www.epa.gov/region9/superfund//prg/index.html; see also notes to Figures 2 and 3.

Table 2. Summary statistics for constituents in bottom ash.

agricultural applications. Approximately 43.5% of the coal ash produced in the United States in 2011 was put into beneficial use;[2] this is material going into recycling rather than disposal and avoids the use of virgin materials that require mining and processing before delivery to the marketplace.

What Constituents Are Present in Coal Ash?
The makeup of coal ash is very similar to the makeup of naturally occurring soils and rock. Coal ash, soil, and rocks mainly consist of oxides of silica and aluminum and other minor elements.[3] Less than 1% of coal ash, soil, or rock is made up of

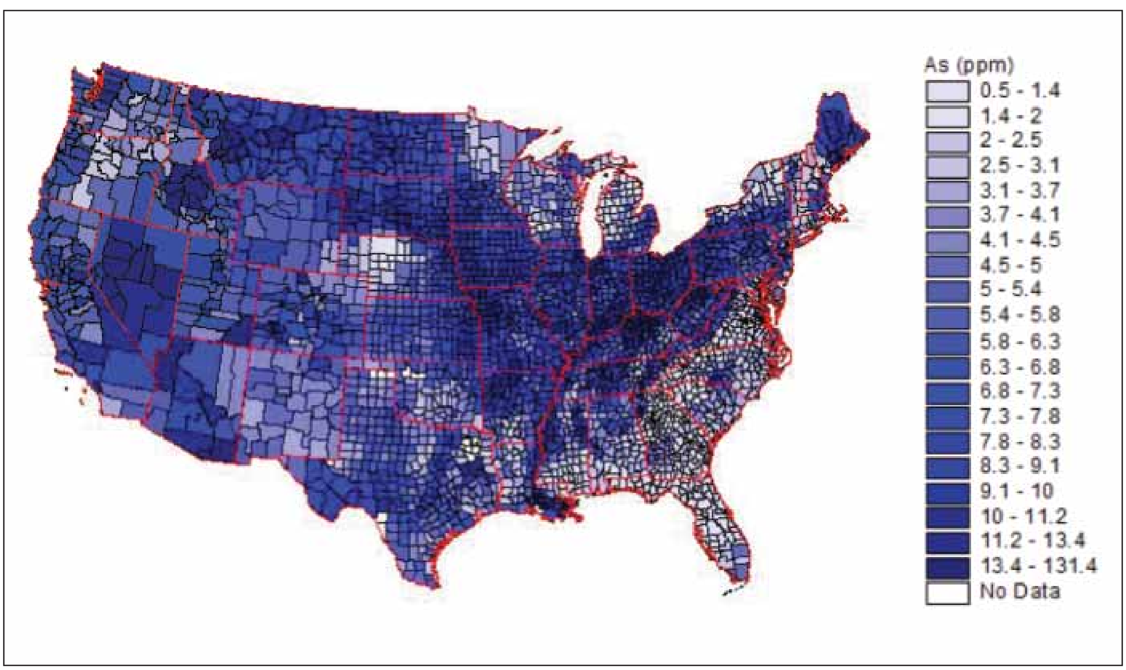


Figure 1. Background levels of arsenic in soil by U.S. county.

Source: USGS. National Geochemical Survey. http://mrdata.usgs.gov/geochem/doc/averages/countydata.htm.

Constituent	Units	Constituent Concentrations in US Soils (a)						USEPA Residential Soil RSLs (b)
		Number of Samples	Maximum	Percentile			Minimum	
				90th	50th	10th		
Arsenic	mg/kg	1258	97	12	5.8	2	<0.1	39
Antimony	mg/kg	355	8.78	1.3	<1	<1	<1	31
Barium	mg/kg	1320	5000	1000	500	200	10	15000
Beryllium	mg/kg	1304	15	2	<1	<1	<1	160
Cadmium	mg/kg	830	8.2	0.5	0.2	<0.1	<0.1	70
Chromium	mg/kg	1320	2000	100	50	15	<1	109
Cobalt	mg/kg	1324	70	15	7	<3	<3	23
Copper	mg/kg	1312	700	50	20	5	<1	3100
Lead	mg/kg	1320	700	30	15	<10	<10	400
Manganese	mg/kg	1318	7000	1000	300	100	<2	1800
Molybdenum	mg/kg	1299	15	<3	<3	<3	<3	390
Mercury	mg/kg	1268	4.6	0.19	0.05	0.02	<0.02	23
Nickel	mg/kg	1319	700	30	15	5	<3	1500
Selenium	mg/kg	1268	4.32	0.8	0.3	<0.1	<0.1	390
Thallium	mg/kg	830	1.8	0.7	0.5	0.2	<0.1	0.78
Vanadium	mg/kg	1320	500	150	70	20	<7	390
Zinc	mg/kg	1249	2890	99	50	22	<5	23000

Notes:
(a) - Data from EPRI[3]: Table 2-2: Statistical Summary of the Concentrations of Various Elements in Other Materials.
(b) - USEPA Regional Screening Level (RSL) – Residential Soil (May 2012)[1] http://www.epa.gov/region9/superfund//prg/index.html; see also notes to Figures 2 and 3.

Table 3. Summary statistics for constituents in U.S. soils.

what are called trace elements; it is these trace elements that are most commonly referenced by environmental groups as being of concern (e.g., arsenic, lead, mercury, cadmium, chromium, and selenium). These trace elements are present in all of these materials in concentrations of milligrams of constituent per kilogram of soil or other material (mg/kg). Note: 1 mg/kg is the same as 1 part per

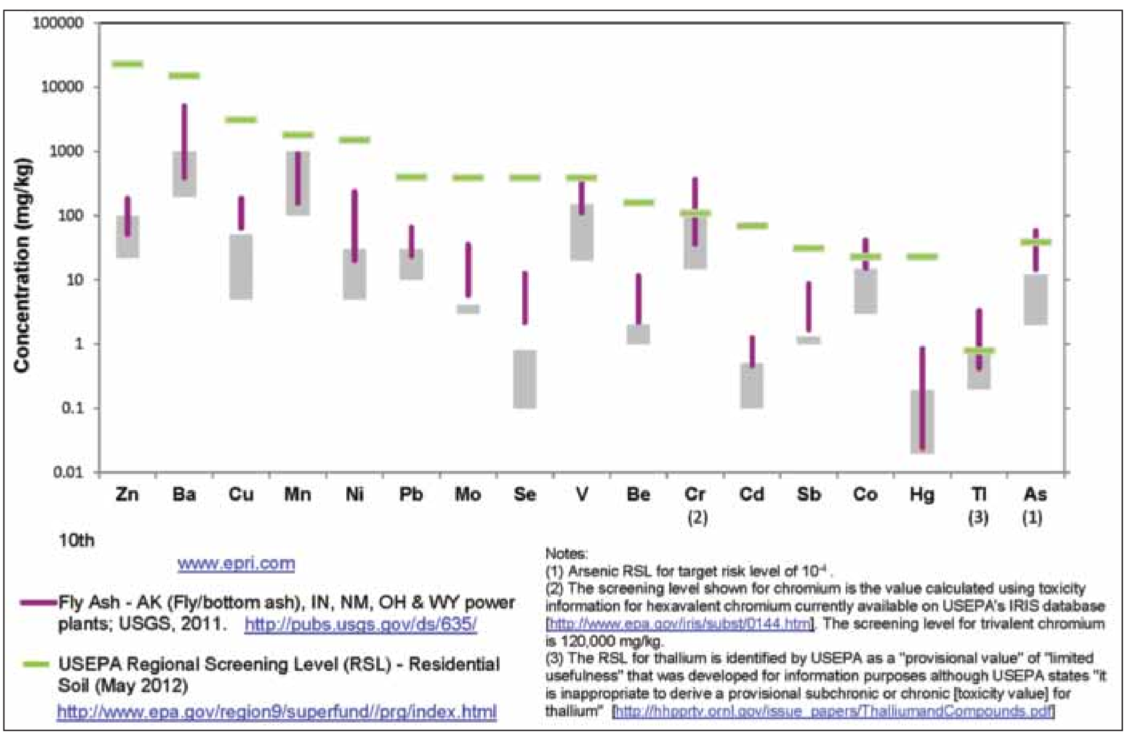


Figure 2. Comparison of 10th and 90th percentile USGS database constituent concentrations in fly ash and background levels in U.S. soils to EPA regional screening levels for residential soils.

million (ppm), or the same as 1 penny in a stack of $10,000 worth of pennies, 1 second in 11.5 days, or 1 inch in 15.8 miles.

Concentrations of constituents in coal ash have been published by the U.S. Geological Survey (USGS).[4] The report provides coal ash data from a range of U.S. power plants, each utilizing coal from different U.S. coal provinces. Tables 1 and 2 provide data summaries for the combined results for two types of coal ash from power plants: fly ash and bottom ash.

How Else Can One Be Exposed to These Constituents?

As stated above, it is important to note that all of the constituents in coal ash are also naturally present in the soils in our environment. USGS has also studied the background levels of these constituents in natural soils (thus providing a background data set), and a summary of that data is presented in Table 3. As an example, Figure 1 shows a map of naturally occurring arsenic concentrations in soils in the United States developed by the USGS.[5] Because these constituents are present naturally in soils, they are also commonly present in the food we eat. Thus, humans are naturally exposed to these constituents on a daily basis.

Are Constituent Levels in Coal Ash Harmful?

The range of concentrations of the constituents in coal ash has been compared to USGS background levels, and to EPA screening levels for residential soil.[1] These screening levels are considered by EPA to be protective for daily exposure by humans (including sensitive groups) over a lifetime. By making this comparison, it is assumed that coal ash could completely replace the soil in a residential yard. In the majority of beneficial use settings, exposure would be far less than that assumed for the residential scenario used here. Therefore, this assumption provides for a conservative evaluation of potential risk for coal ash beneficial uses.

Figure 2 shows the comparison to residential soil screening levels for fly ash, and Figure 3 shows the comparison for bottom ash (numerical comparisons are provided in Tables 1 through 3). Of the 17 constituents shown on the graphs, concentrations in coal ash (shown by vertical purple bars) of

The makeup of coal ash is very similar to the makeup of naturally occurring soils and rock.

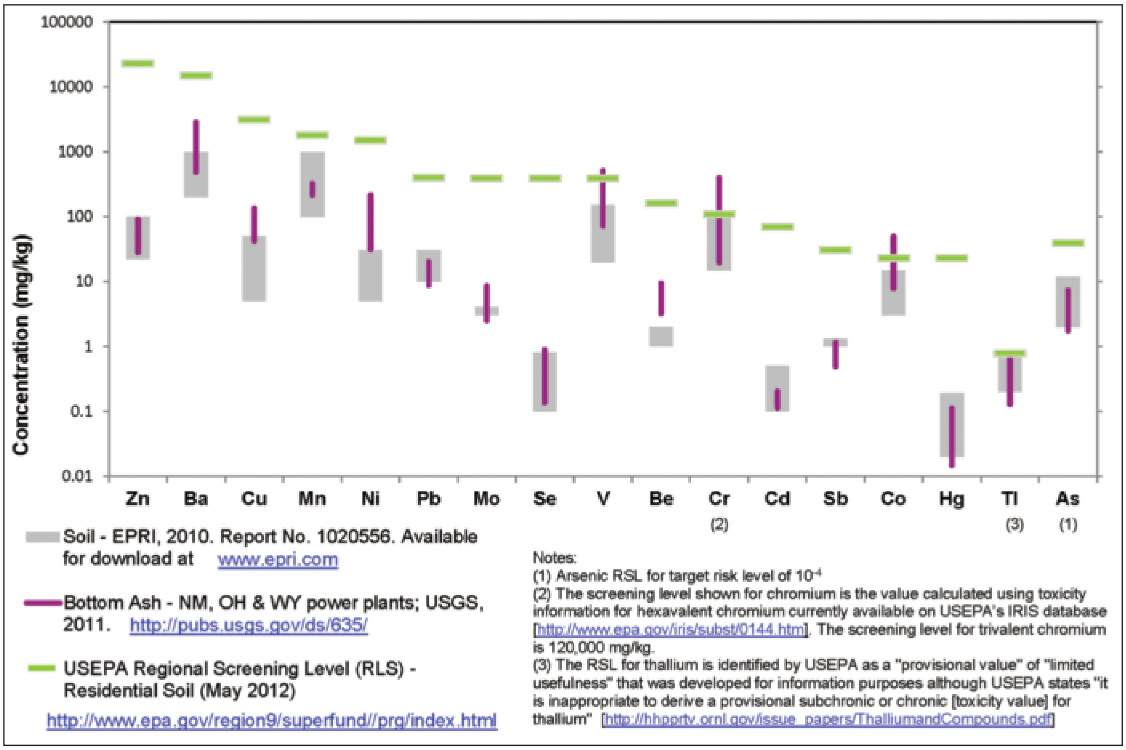


Figure 3. Comparison of 10th and 90th percentile USGS database constituent concentrations in bottom ash and background levels in U.S. soils to EPA regional screening levels for residential soils.

only five constituents range to above the residential soil screening level (shown by a horizontal green bar): arsenic, chromium, cobalt, thallium, and vanadium. Moreover, concentrations at the high end of the range are only slightly above the screening levels. Finally, these constituent concentrations in coal ash are similar to constituent concentrations in background soil (shown by vertical grey bars). More details can be found in the following report[6]: "Coal Ash Material Safety: A Health Risk-Based Evaluation of USGS Coal Ash Data from Five US Power Plants."

What Do These Results Mean?

This evaluation takes a worst-case approach by assuming that exposure to coal ash put into beneficial use could be at the same level and intensity as that of a resident child and adult's exposure to soils in a backyard setting. Therefore, this assumption provides for a conservative evaluation of potential risk for coal ash beneficial uses. The results indicate that with few exceptions constituent concentrations in coal ash are below of the screening levels for residential soils, and are similar in concentration to background levels in naturally occurring U.S. soils. In the majority of beneficial use settings, exposure would be far less than that assumed for the residential scenario used here, and the potential risks would be below levels of concern. **em**

References

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