Ecological Effects of Coal Combustion Products (CCPs): A Literature Review of Observed Effects and Considerations for Managing Risks

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ABSTRACT

An extensive amount of research has been conducted to evaluate the potential adverse effects of coal combustion products (CCPs) on the health of ecosystems. This presentation provides an overview of the documented ecological effects of CCPs and the primary CCP-related factors that have the potential to pose the most substantial risk to ecological receptors. To meet this objective, we conducted a comprehensive review of the peer-reviewed chemical and toxicological literature on the ecosystem effects associated with exposure to CCPs. Our research demonstrates that the ecological effects associated with exposure to CCPs vary widely among sites and ecological receptors. Selenium (for aquatic organisms) and boron (for terrestrial plants) have been studied frequently and have been suggested as contributing factors to observed effects in several studies. Mortality of invertebrate and fish species has been reported to occur following releases of CCP-related wastes or effluents. Additional reported ecological effects include reduced growth, reduced reproductive capacity, altered development, reduced metabolic activity, and behavioral changes. In some cases, organism-level effects have also manifested at the population level. In most cases, however, clear and consistent correlations between exposure to CCPs, organism-level effects, and population-level effects could not be demonstrated. Future investigations of CCP impacted sites should evaluate multiple ecological health endpoints via an integrative approach that will allow site managers to focus on the most critical site-specific stressors and implement the most effective strategies for reducing potential ecological impacts.

1 Introduction

Coal combustion products (CCPs) constitute a number of solid materials that are generated from coal-fired electric utility plants and include fly ash, bottom ash, boiler slag, flue gas desulfurization (FGD) residues, and fluidized bed combustion wastes. Trace metals and other constituents in CCPs have the potential to cause adverse environmental effects if released into aquatic and terrestrial environments. Over the past several years, the United States Environmental Protection Agency (US EPA) has devoted significant resources to evaluate the human health and ecological effects from CCPs. A US EPA risk assessment, first released in 2007 and updated in 2010,[1] determined that the disposal of CCPs was associated with elevated ecological risks from certain metals (including arsenic, boron, cadmium, lead, and selenium).

An extensive amount of research has been conducted to evaluate the potential adverse effects of CCPs on various ecological receptors (see reviews by Rowe et al.,[2] Carlson and Adriano,[3] Dellantonio et al.[4]). However, available research findings are not necessarily synthesized in a manner that facilitates informed risk management decisions. An informed risk management decision, for example, would need to consider the most current and best available information on the relationships between CCPs and ecological health, while taking into account the associated uncertainties. Identifying uncertainties and data gaps also allows for the development of targeted research programs that can inform future risk management decisions.

Therefore, the objectives of this project were: 1) to evaluate the ecological effects of CCPs, 2) to understand the CCP-related factors that pose the most substantial ecological risk, and 3) to identify knowledge gaps that limit current understanding of these issues. To meet these objectives, we conducted a comprehensive review of the chemical and toxicological literature on adverse ecological effects associated with exposure to CCPs, mainly from the peer-reviewed literature. This information was synthesized in a manner that could be used to support future ecological assessments.[5]

2 Framework for Evaluating Ecological Effects

Ecological assessments typically follow a structured process that defines the exposure pathways of concern, ecological receptors of concern, stressors of concern, stressor-related effects, and ecological risks associated with potential stressor exposures (including a qualitative or quantitative evaluation of uncertainties). Ecological investigations involving CCP exposures have included a wide variety of ecological receptors and biological endpoints as well as various environmental factors that influence the toxicity of CCPs (e.g., bioavailability and bioaccumulation). These elements were used as a basis to organize and evaluate the various facets of CCPs-associated environmental effects. These important aspects of ecological investigation are presented below.

- Primary Release Pathways: A variety of CCP release pathways include regulated effluent releases, accidental releases due to basin failure and spills, unintended releases due to flooding, leaching, runoffs, and aerial and transported depositions.
- Exposure Media: Various environmental media receive and accumulate CCP-related contaminants which could have potential direct or indirect adverse effects on the incumbent organisms. Surface water, sediment, and biota (e.g., fish) constitute the primary CCPs related exposure media.
- Primary Stressors: Adverse ecological effects may be elicited by chemical, physical, or biological stressors. Often several stressors co-occur in CCP-impacted ecosystems due to the complex nature of these wastes. An example relevant physical stressor would be a change in water temperature due to the input of cooling water from power plants. Chemical stressors may include metal contaminants associated with CCPs or changes in pH. Biological stressors, such as limitation of food resources, due to habitat modification or reduced species abundance, can indirectly affect ecosystems.
- Ecological Receptors: The primary ecological receptor groups that may be exposed to CCPs include plants, invertebrates, fish, amphibians, reptiles, birds, and mammals.
- Stressor-Related Effects: Ecological investigations often include evaluations of health effects at the sub-organism (i.e., cells, tissues, organs, organ systems), individual, population, or community level. Sub-organism effect assessments can include changes in hematology, protein or hormone levels, organ function, or gross organ damage. Individual organism-level measures may include mortality (e.g., number or time to death after exposure), growth (e.g., body weights or lengths), and reproduction (e.g., number of offspring). These individual-level endpoints are typically used to extrapolate to population-level and community-level effects. Population or community level assessments are typically more difficult to conduct and interpret compared to sub-organism or organism-level assessments, but may provide a better measure of the overall ecological effect of environmental stressors. Population assessments can include measures of abundance (i.e., number of individuals of a species) and diversity (i.e., number of species or taxa). Community assessments can include measures of community

structure (i.e., number or type of trophic groups represented). For CCPs, there has been extensive investigation into individual and sub-organism level effects, but overall, documented community level effects have been limited.

3 Review of Case Studies

We evaluated the available scientific literature regarding ecological effects related to CCPs with a focus on the primary elements of ecological evaluations (as described above). The majority of the studies on CCPs-related effects have been conducted on a select number of sites in the United States (Table 1). Many of the studies we reviewed involved releases that took place in the 1960s-1980s. Waste and spill management practices are improving continuously, and the effects observed in studies reviewed here may not represent the future potential for ecological effects accurately under more current waste management practices. Some of the releases that we evaluated involved primary releases to man-made constructed reservoirs. For example, the effects observed at Belews Lake, Hyco Reservoir, and Martin Lake were the result of direct discharges from on-site settling basins to these man-made water bodies. These sites experienced some of the more pronounced effects on fish populations, but ash management practices at these sites have changed and the water bodies are now in a state of recovery. Releases at other sites affected natural water bodies and were mainly the result of runoff or leaching from CCP wastes (e.g., Savannah River, Rocky Run Creek). In these more long-term unintentional environmental releases, ash management practices were changed upon recognition of observed or potential ecological impacts. The most recent, and largest, unintended release of ash into the environment came in the form of a spill from the Kingston Plant in Tennessee. The potential ecological effects from this release are currently under investigation.

Table 1 Summary of Selected CCP Case Studies

Plant/Location	Primary Release Pathway(s)	Exposure Media	Primary Stressors	Ecological Receptors Investigated	Observed Stressor Related Effects and Findings
Kingston Fossil Fuel Plant, Tennessee Valley Authority (Harriman, TN)	Failure of a dredge cell containment wall	Sediment and Surface Water	Physical characteristics (smothering), arsenic, and selenium	Benthic Invertebrates, Fish, Amphibians, Reptiles, Birds	Sublethal effects observed in some studies while population level effects not apparent.[6,7]
Savannah River Project, D-Area within the Savannah River Site (Aiken, SC)	Long-term, continuous release of sluice water overflow from fly ash settling basins	Sediment, Surface Water, and Soil	Physical effects, habitat alteration, metals, and non-CCP-related VOCs and Tritium)	Benthic Invertebrates, Fish, Amphibians, Reptiles, Birds, and Mammals	Wide ranging sublethal effects have been reported, but no clear links have been established between individual-level sublethal effects and the purported population-level effects.[8,9,10,11,12,13,14,15]
Appalachian Power Company Plant, Clinch River (near Carbo, VA)	Failure of the dike surrounding the fly ash pond	Sediment and Surface Water	Alkaline water conditions (pH ~ 12), food availability	Benthic Invertebrates and Fish	Short-term population level effects (count, density, and diversity) with subsequent recovery.[16,17]
Belews Creek Steam Station, Duke Power Company (Belews Lake, NC)	Direct discharge of effluent from settling basin	Surface Water	Selenium	Fish	Population-level and community-level effects observed. One of the most commonly cited examples of selenium bioaccumulation and toxicity in fish populations.[18,19,20,21]
Columbia Generating Station (Rocky Run Creek, WI)	Direct discharge of water from sub-basins and flood related transport of CCPs	Sediment and Surface Water	Metals (barium, chromium, iron, selenium, and zinc)	Benthic Invertebrates	Effects observed on macro-invertebrate populations (abundance and diversity).[22,23]
CP&L Roxboro Steam Electric Plant, Hyco Reservoir (Roxboro, NC)	Direct discharge of effluent from settling basin	Surface Water	Selenium	Fish	Observed, selenium bioaccumulation, sub-lethal effects, and population declines.[2,24]

Plant/Location	Primary Release Pathway(s)	Exposure Media	Primary Stressors	Ecological Receptors Investigated	Observed Stressor Related Effects and Findings
Glen Lyn Power Plant (New River, VA)	Effluent, thermal and chlorinated water discharges	Sediment and Surface Water	Arsenic, cadmium, copper, selenium, and zinc	Benthic Invertebrates and Fish	Effects were observed in population count and diversity of benthic invertebrates, with subsequent recovery within 10 months.[25,26]
Texas Utilities Generating Co. Power Plant (Martin Creek Reservoir, TX)	Direct effluent discharged from settling ponds.	Surface Water	Selenium	Fish and Birds	Individual-level morphological changes in fish associated with selenium bioaccumulation. Recovery not complete after eight years. No effects on the reproductive health of birds.[27,28]
Department of Energy, Y-12 Plant (Oak Ridge, TN)	Direct discharge of overflowing coal ash slurry	Sediment and Surface Water	Arsenic, mercury, selenium, and thallium (primary source of mercury not CCPs)	Benthic Invertebrates and Fish	Reduced benthic invertebrate community structure, but the primary CCP stressor was not identified. Selenium concentrations in fish were elevated. An interaction between selenium and mercury suggested to mitigate adverse effects of mercury.[29,30,31]
American Electric Power Gavin Plant (Stingy Run, OH)	Discharge of treated fly ash effluent	Sediment and Surface Water	Metals (e.g., arsenic, cadmium, selenium, and zinc)	Fish	Observed sub-organism-level effects in fish did not affect populations. Selenium tissue concentrations were not a reliable measure of adverse effects.[32,33,34]

4 Key Findings and Uncertainties

Ecological effects have been investigated since the late 1960s at sites impacted by environmental releases of CCPs. Some of the impacted sites (such as the Savannah River D-Area site) have received far more attention than others. Studies at all the sites were almost exclusively focused on aquatic habitats. In the 1970s and 1980s, benthic invertebrates and fish species were widely used in ecological effects studies. More recently, additional groups, such as amphibians and reptiles, have received increasing attention. Ecosystem studies using plants (both aquatic and terrestrial) and terrestrial wildlife (e.g., higher mammals) have been rare, most likely since CCP releases of significance are much more common in aquatic habitats.

Early field studies of abundance, diversity, and density of benthic invertebrates, as well as several fish species, documented significant adverse ecological effects related to direct CCP releases. The effects on benthic invertebrates appeared to be due primarily to the physical effects of smothering coal ash residues and/or severe pH excursions and habitat perturbations (e.g., Cherry et al.[8,9,35] and Cairns et al.[16]). Following mitigation of environmental releases of CCPs (either through cessation of the spill or through improved disposal processes), these effects were generally reversed and the affected benthic populations recovered, albeit the recoveries took place over the course of several years in some cases.

A variety of lethal and sublethal effects, at the organism- and population-levels, have been documented in several species of fish exposed to CCPs. Although re-colonization of the affected habitats and population recovery has been observed (even in dramatic cases such as at Belews Lake), long-term impacts of selenium through bioaccumulation appears to be a primary concern for fish in CCP-impacted aquatic systems. Environmental concentrations and tissue residues of selenium, however, were not a consistent predictor of adverse effects across all the case studies reviewed. Some of the factors potentially contributing to observed discrepancies in effects on fish are discussed further below.

Recent studies have employed more sophisticated and controlled experiments (e.g., laboratory experiments on isolated individuals, microcosms, mesocosms, and transplants) and focused on a wide array of sublethal effects (e.g., deformities, reduced growth, reproductive effects, and metabolic rates), particularly using amphibians and reptiles.[13] These sublethal effects are expected to compromise general fitness, survival, behavior, growth, and reproduction; eventually, these effects have the potential to affect populations, although this relationship has rarely been investigated at CCP sites. A wide array of these sublethal effects have been observed at CCP-impacted sites, although not always consistently.

For the CCP-impacted sites reviewed here, several associations were suggested between the observed ecological effects (e.g., fish mortality) and the CCP releases. However, studies demonstrating clear causal links between specific CCP constituents and ecological effects based on field studies are infrequent. Selenium is generally indicated to be the primary CCP constituent causing reproductive toxicity in fish. Arsenic, cadmium, mercury, and other trace elements have also been suggested as causative agents, but mostly in roles secondary to that of selenium. Belews Lake is one of the few sites where selenium was clearly demonstrated to have led to significant declines in several fish populations, which persisted for many years. In most cases, however, the observed ecological effects are complicated by the following key factors:

- Complexity of CCPs. CCPs are a complex mixture of many trace elements, and the relative concentration of individual trace elements and their bioavailabilities are unique to each site. As indicated above, an individual constituent (selenium) has been identified as the causative stressor only in few instances, and ecological effects should be interpreted as a response to the overall mixture of contaminants. In addition, interactive effects may exist with certain trace elements, and these may further confound interpretation of ecological effects. Some of these interactions may be antagonistic (*e.g.*, arsenic and selenium).
- Site and Species Specificity. Observed effects were not necessarily consistent for a particular species or group of species among the various sites. Site-specific characteristics, such as the chemistry of the abiotic media, greatly influence contaminant bioavailability and uptake by organisms. Furthermore, varying sensitivity of the species present at the site, as well as their tolerance, resilience, and adaptability, has lasting bearing on the overall ecological health.
- Organism- versus Population-Level Effects. Ecological implications of effects on growth and reproduction have been well established and are widely recognized as significant. However, other sublethal measures, such as increased metabolic rates and hormonal disturbances, are much less established in terms of their predictive power for population-level effects. Measures of exposure (such as bioaccumulation) and biomarkers indicate that an organism has been exposed, but do not necessarily predict the presence or severity of ecological impact. Thus, while examination of several measures of effect and exposure are informative, these are often unreliable for demonstrating population-level effects when examined individually.

5 Conclusions

An extensive amount of research has been conducted on the potential impacts of CCPs on various ecological receptors. Studies on CCPs releases have primarily focused on effluent or storage basin releases and their effects on aquatic organisms, primarily benthic invertebrates, fish, and amphibians. Other ecological receptor groups, such as aquatic and terrestrial plants, plankton, reptiles, birds, and mammals, have been studied at most sites reviewed herein. Reported ecological effects as a result of exposure to CCPs vary widely between sites and ecological receptors. Mortality of invertebrate and fish species has been reported to occur following direct releases of CCP-related wastes or effluents due to smothering or extreme pH conditions, as well as some of the chemical constituents in CCPs. For instance, selenium bioaccumulation has been associated with declines in fish populations at some sites and remains a key constituent that should be monitored at CCP affected sites. Additional reported effects include reduced growth and reproductive capacity, altered development, reduced metabolic activity, and behavioral changes.

Selenium (for aquatic organisms) and boron (for terrestrial plants) are studied frequently and have been suggested to be contributing factors to observed effects in several studies. The current literature contains many examples of potential ecological effects based on laboratory studies with exposures to highly concentrated CCP constituents; however, these effects are often not observed in the local wild populations. In some cases, organism-level effects also manifested at the population level (e.g., reduction or loss of species or populations). However, clear and consistent links between exposure to CCPs, organism-level effects, and population-level effects have not been demonstrated in most cases. Most recently, investigations of the Kingston ash spill found limited indications of population or community level effects based on numerous field studies.[7] These adverse effects were generally observed closest to the spill location and diminished with distance. Direct exposure to ash, arsenic and selenium were the primary factors associated with effects on benthic invertebrates.[7] Elevated tissue concentrations of selenium were also identified in other organisms (e.g., birds and reptiles), however field investigations have not identified population level effects resulting from increased selenium exposure. Several factors contribute to the difficulty in establishing such links, including variability in the composition of CCPs, differences in site habitat and hydrology, species variability and sensitivity, and chemical or physical interactions.

Based on this review,[5] several risk assessment/management-related issues were apparent and may be worth considering for future CCP-related ecological investigations:

- With the exception of selenium and boron, no individual CCP contaminant has been directly and repeatedly implicated as a contributing factor for observed ecological effects. This could be, in part, due to the design and focus of the ecological investigations and also due to the complexity and interaction of multiple variables at each site.

- In addition to metals, the primary stressors identified in the literature include extreme pH conditions (acidic or alkaline), elevated TSS (leading to smothering), and habitat alteration (leading to reduced food resources). The ecological effect concentrations or limits for each of these stressors varied among sites and were confounded by the lack of complete exposure information. Future risk assessments should carefully consider whether existing toxicological benchmarks are appropriate depending on site-specific conditions.
- A variety of ecological receptors and individual species have been examined in the literature. However, no one sentinel species can be identified as an indicator of ecological damage, due to site specificity. Ecological studies should be designed in a manner to evaluate multiple trophic levels and exposure pathways to ensure that key ecological characteristics are considered.
- The preponderance of the literature on ecological effects of CCPs is related to releases from surface impoundments rather than landfills or other land-based storage facilities. Further study of land-based storage facilities may be warranted to understand the potential risks to terrestrial ecosystems.
- In several historical case studies, adversely affected ecosystems experienced recovery following cessation of CCP releases. Management practices that limit the aforementioned stressors (e.g., metals, pH, TSS) appear to effectively mitigate and even reverse damages. However, since some contaminants are bioaccumulative (e.g., selenium and mercury), biological monitoring programs are typically recommended to evaluate and track recovery.

It is apparent that numerous variables need to be examined and considered in ecological assessments of CCP releases (including those listed above). To understand ecosystem health, a systematic study design coupled with an integrative approach is necessary to manage the complexity of CCP releases. The approach currently being undertaken at the TVA Kingston spill site includes an evaluation of multiple environmental matrices, exposure regimes, and receptor groups. This integrative approach includes an evaluation of multiple factors (e.g., bioavailability, toxicity, chemical interactions) such that any observed effects can be interpreted and associated with all available site-specific information. A weight-of-evidence analysis (i.e., synthesizing multiple studies from sub-organism to population-level observations) can then be used to identify those constituents or receptors that are most at risk. Using this approach remedial efforts can focus specifically on the most significant stressors.

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