Application of Synchrotron Radiation-based Methods for Environmental Biogeochemistry: Introduction to the Special Section

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Abstract

To understand the biogeochemistry of nutrients and contaminants in environmental media, their speciation and behavior under different conditions and at multiple scales must be determined. Synchrotron radiation-based X-ray techniques allow scientists to elucidate the underlying mechanisms responsible for nutrient and contaminant mobility, bioavailability, and behavior. The continuous improvement of synchrotron light sources and X-ray beamlines around the world has led to a profound transformation in the field of environmental biogeochemistry and, subsequently, to significant scientific breakthroughs. Following this introductory paper, this special collection includes 10 papers that either present targeted reviews of recent advancements in spectroscopic methods that are applicable to environmental biogeochemistry or describe original research studies conducted on complex environmental samples that have been significantly enhanced by incorporating synchrotron radiation-based X-ray technique(s). We believe that the current focus on improving the speciation of ultra-dilute elements in environmental media through the ongoing optimization of synchrotron technologies (e.g., brighter light sources, improved monochromators, more efficient detectors) will help to significantly push back the frontiers of environmental biogeochemistry research. As many of the relevant techniques produce extremely large datasets, we also identify ongoing improvements in data processing and analysis (e.g., software improvements and harmonization of analytical methods) as a significant requirement for environmental biogeochemists to maximize the information that can be gained using these powerful tools.

Core Ideas

- SR-based techniques have revolutionized the field of environmental biogeochemistry.
- Improvements to light sources will provide SR with extreme brightness and coherence.
- This should be met with similar advances to synchrotron-related hardware and software.
- Environmental biogeochemists can drive the new advances in the synchrotron science.
- Advances in SR will enable future breakthroughs in environmental biogeochemistry.

ENVIRONMENTAL biogeochemistry is an extremely diverse and wide-ranging scientific field with cross-cutting research themes emphasizing the interplay between inorganic and organic compounds within soils and sediments, waters, air, and biota. It is an interdisciplinary subfield of the earth sciences, life sciences, and chemistry that brings together microbiologists, biologists, chemists, geochemists, soil scientists, oceanographers, ecologists, and environmental engineers interested in the biogeochemistry of terrestrial, aquatic and atmospheric environments (Berthelin, 1991). Studies in environmental biogeochemistry are conducted at different scales, from the mechanisms or kinetics of reactions at molecular (or cellular) level to the mass transfer or energy flow at ecosystem, regional, or global levels. The biggest challenge for environmental biogeochemistry is extrapolation of molecular-level knowledge to system or global levels. Models are frequently used to help understand the global cycling of nutrients and contaminants, and they need to be based on an accurate understanding of the fundamental mechanisms driving these cycles at the molecular or cellular level (Lombi et al., 2011b). Advanced spectroscopic techniques play an essential role in advancing our fundamental understanding of these reaction processes. However, due to the diversity, complexity, and interactions of these processes, these studies often require the integration of complementary research techniques.

A synchrotron is a large building-sized machine that accelerates charged particles such as electrons (most commonly) and positrons, to extremely high energies. The electrons are accelerated to almost the speed of light (relativistic electrons), and when they are forced to move along curved trajectories by applied magnetic fields, they emit extremely intense electromagnetic radiation called synchrotron radiation (SR, also known as synchrotron light). This very bright light is emitted tangentially to the direction of the circulating electrons' motion. Synchrotron radiation was first observed in 1947 at the General Electric laboratories in the United States (Robinson, 2009), and its usefulness for condensed matter research was first recognized in the late 1960s. Since that time, there has been explosive growth in

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the use of SR for research applications. Due to the usefulness of SR, many accelerators today are not dedicated to accelerator physics but exist solely to generate light for SR-based scientific experiments. Synchrotron radiation covers a very broad and continuous spectral range from the infrared up to the hard X-ray region. Its significant properties include high intensity, naturally narrow angular collimation, high degree of polarization, pulsed time structure, and high beam stability, and all of these properties can be quantitatively evaluated (Balerina and Mobilio, 2015). The high brightness of SR is due to the small cross-section of the electron beam and the high degree of collimation. Although the application of SR-based imaging and analysis techniques in environmental biogeochemistry only began about half a century ago, the special properties of SR have meant that SR-based imaging and analysis techniques have revolutionized research in environmental biogeochemistry. For example, combining advanced imaging and analytical techniques with other novel sample preparation techniques, we have been able to advance our understanding of the fundamental processes involved in carbon cycling in soil (Lehmann and Solomon, 2010; Solomon et al., 2012). Lehmann et al. (2008) were the first to couple near-edge X-ray fine structure (NEXAFS)-scanning transmission X-ray microscopy (STXM) with an innovative soil preparation method that preserves the spatial assemblage of the soil aggregates. They used this approach to demonstrate the spatial complexity of soil organic matter at the nanometer scale. Peth et al. (2014) combined novel staining techniques with microscale-computed tomography (CT) to visualize the presence of soil organic matter in three-dimensional soil space. The combination of micrometer-scale X-ray fluorescence (XRF) imaging and X-ray absorption spectroscopy techniques (such as X-ray absorption near-edge spectroscopy [XANES] or extended X-ray absorption fine-structure spectroscopy [EXAFS]) is an extremely useful and increasingly popular, nondestructive approach for studying trace element distribution, associations, and speciation in environmental samples. It has been used in numerous studies to investigate selected points of interest in soils (Manceau et al., 2004; Nachtegaal et al., 2005; Arai et al., 2006), wastes (Hettiarachchi et al., 2006; Al-Abed et al., 2008; Legros et al., 2010), and plants (Seyfferth et al., 2010; Castillo-Michel et al., 2011; Moore et al., 2014). Until recently, scanning fluorescence-XANES imaging has not been applied to investigate large sample areas, as scanning through a focused pencil beam to measure a XANES spectrum at each point is very time consuming. However, recent advances in XRF detection have made this approach feasible at some beamlines. For example, Etschmann et al. (2014) used megapixel fluorescence-XANES imaging to explore the heterogeneity of Cu speciation in a complex environmental matrix at the micrometer scale to identify the spatial distribution of minor species that cannot be assessed by conventional methods. Another exciting possibility is combining in situ phylogenetic analysis (such as fluorescence in situ hybridization [FISH]) with SR-based techniques (such as μ-XAFS [X-ray absorption fine structure]) to observe the biological inferences that affect speciation and distribution of elements in geomaterials. Here, Mitsunobu et al. (2012), who coupled XAFS and molecular biology to observe in situ the biogenic oxidation and reduction reactions in soils, can be considered as an example.

Continuous advancement and improvements to synchrotron rings and beamlines continue to improve the information available to environmental biogeochemists. In fact, synchrotron facilities now play a vital and irreplaceable role in many areas of environmental biogeochemistry because they enable scientists to investigate the distribution and speciation of contaminants and nutrients under in situ conditions in complex environmental materials at environmentally relevant concentrations. Figure 1, updated from Lombi et al. (2011b), shows results from a search of three leading journals in the field of environmental science (*Journal of Environmental Quality*, *Environmental Pollution*, and *Environmental Science & Technology*) for publications including the words "EXAFS" and "XANES." It is clear that the number of publications including these two techniques continues to rise, and this indicates a significant reliance on synchrotron techniques for advanced environmental studies (Fig. 1). The use of advanced analytical techniques such as SR-based X-ray techniques in environmental biogeochemistry research is slowly but steadily increasing, and their applications are broadening (Table 1). Some new advancements in SR-based techniques and beamlines of particular relevance for environmental biogeochemistry are presented in this special section (Proux et al., 2017; Sutton et al., 2017); however, it is not our intention to provide a thorough review of all SR-based techniques, so for more comprehensive information, please refer to de Jonge et al. (2014), Lombi and Susini (2009), or Thieme et al. (2007).

The worldwide distribution of synchrotron light sources shows that they are currently spread across five continents (Fig. 2). Today, there are ~50 synchrotron light sources worldwide and their beamline capabilities continue to evolve (Lightsources, 2016). This evolution will facilitate scientific discoveries (Owen et al., 2016) in many fields. A famous quote by Sydney Brenner in 1980, cited by many times before (Robertson, 1980), states that "progress in science depends on new techniques, new discoveries, and new ideas, probably in that order." It is certainly well understood and accepted by environmental biogeochemists that there are significant challenges and limitations for any technique when diluted analytes are investigated in complex matrices, and that ongoing improvements in synchrotron techniques
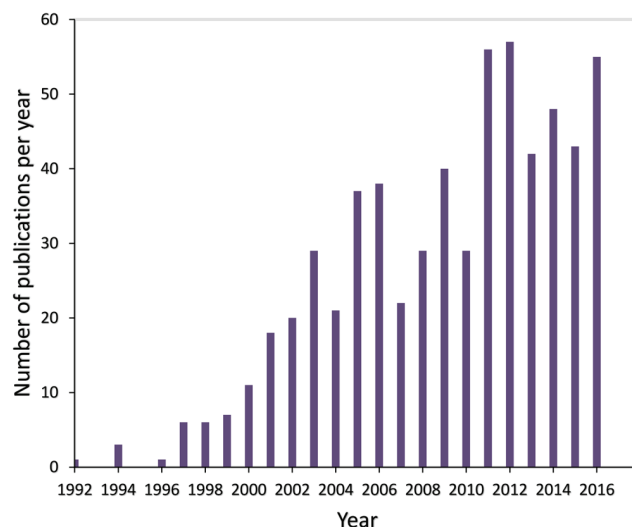

Fig. 1. Number of scientific articles (per year) published in three leading environmental journals including either the word "EXAFS" (extended X-ray absorption fine structure) or "XANES" (X-ray absorption near edge structure) in their text (updated from Lombi et al. 2011a).

Table 1. Synchrotron radiation-based analytical techniques commonly used in environmental biogeochemistry research and examples of their applications.

Analytical technique	Examples for applications	References
Bulk-X-ray absorption spectroscopy		
Bulk-extended X-ray fine structure spectroscopy (EXAFS)	Speciation of elements (contaminants, nutrients, etc.) in numerous environmental samples such as atmospheric aerosols, dust, plants, soils, sediments and various waste materials, etc.	Datta et al. (2012), Al-Abed et al. (2008), Burke et al. (2012), Cances et al. (2005), Blamey et al. (2015), Bodei et al. (2007)
Bulk-X-ray absorption near-edge structure spectroscopy (XANES)	Speciation of elements in numerous environmental samples such as atmospheric aerosols, plants, soils, sediments and various waste materials, etc., especially useful for studies focusing on the oxidation state of elements	Takahashi et al. (2006), Burke et al. (2012), Galkaduwa et al. (2017), Sarret et al. (2005)
Micro-X-ray absorption spectroscopy		
μ-XANES	Spatially resolved elemental speciation in numerous environmental samples such as atmospheric aerosols, plants, soils, sediments, and mine wastes, etc., especially useful for studies focusing on the oxidation state of elements	Castillo-Michel et al. (2011), Smith et al. (2009a), Bacquart et al. (2007), Arai et al. (2003, 2006), Karna et al. (2016)
Micro-extended XAFS (μ-EXAFS)	Spatially resolved elemental speciation in numerous environmental samples such as atmospheric aerosols, plants, soils, sediments, and mine wastes, etc.	Manceau et al. (2004), Mitsunobu et al. (2012), Baker et al. (2012), Strawn and Baker (2009)
Synchrotron radiation-based X-ray photoelectron spectroscopy (XPS)	Surface chemistry of minerals and solids and characterization of nanomaterials	Papaefthimiou et al. (2011)
Micro- and nanoscale X-ray fluorescence spectroscopy (XRF)	Elemental distribution and associations in soil, sediments, dust, plant tissues, roots, animal tissues, soil aggregates	Kyriacou et al. (2014), Moore et al. (2014), Seyfferth et al. (2010), Spielman-Sun et al. (2017)
Synchrotron radiation-based X-ray diffraction (SR-XRD)	Detection of crystalline trace precipitates in environmental mediums due to better collimation and lower spectral overlapping	Baker et al. (2012), Manceau et al. (2004)
High-energy resolution XAS (high-energy resolution fluorescence detected [HERFD] XANES; high-energy resolution auger detection [HERAD] XANES)	Precise determination of the local structure around the absorbing atom. Speciation of XAS nonsensitive elements such as Pb in soils, sediments, etc. Speciation of trace elements (diluted) in environmental mediums	Llorens et al. (2012), Manceau et al. (2016), Swarbrick et al. (2009)
X-ray μ-tomography	Aggregate microstructure, pore network geometry, and physical processes. If conducted in fluorescence mode, this method is also element specific and allows spatially resolved element maps to be generated.	Bhreasail et al. (2012), Wang et al. (2012), Peth et al. (2014), Smith et al. (2009b)
Scanning transmission X-ray microscopy (STXM)-near-edge X-ray fine structure (NEXAFS) spectroscopy	Characterizing organic matter, microaggregates, microorganisms, speciation of C, N, P, and S at the K- absorption edges and Al, Ca, and Fe speciation using L-edge NEXAFS	Wan et al. (2007), Lehmann et al. (2008), Behrens et al. (2012), Solomon et al. (2012), Chen et al. (2014), Peth et al. (2014)
STXM-low-energy XRF detection	Imaging of nanoscale biomineral formation, microbial-elemental interactions. Speciation and quantitation of diluted elements (such as As) in bacteria	Hitchcock et al. (2010, 2012)

achieved through the availability of brighter light sources, better monochromators, and more sensitive detectors will help unlock new research possibilities and discoveries. In this context, the advent of the new multibend achromat lattice design for synchrotrons, as recently pioneered at MAX IV in Sweden, will provide unprecedented brilliance and coherence and can be expected to provide a new step change in synchrotron biogeochemistry (e.g., de Jonge et al., 2014). On the other hand, this unprecedented brightness increases the risk of different types of radiation damage to samples, especially biological samples and organic compounds. Examples for radiation damages include structural changes, dehydration, oxidation, or sample heating (Lombi et al., 2011a; Wallander and Wallentin, 2017). Improvements to sample environments and shorter data acquisition time can help to circumvent this problem.

Access to synchrotron facilities for the general user community is granted on a merit basis, where users from any discipline anywhere in the world can submit a proposal and proposals are assessed on a competitive basis according to established criteria focusing on the scientific purpose and significance of the proposed experiment. Demand for access to SR-based techniques by highly active environmental biogeochemists continues to increase, and it is becoming increasingly difficult to obtain beamtime to conduct research using the newer and/or less common techniques and beamlines, such as STXM-NEXAFS, for environmental biogeochemistry research. An increase in the number of such beamlines and the amount of beamtime available for the user community is needed to permit more reliable access to these techniques.

Continent				
Asia	**Australia**	**Europe**	**North America**	**South America**
ASRC	AS (3rd)	ALBA (3rd)	ALS	LNLS
CANDLE		ANKA	APS (3rd)	
CAT		DAFNE	CAMD	
BSRF		DELSY	CHESS	
HISOR		DELTA	CLS	
ILSF		DIAMOND	NSLS-II (3rd)	
NSRL		ELETTRA	SSRL	
NSRRC		ELSA	SURF	
PF		ESRF		
PLS		HZB		
RitsSR		ISA		
SAGALS (3rd)		KSRS		
SESAME		MAX IV		
SLRI		MLS		
SPring-8		PETRA III		
SSLS		SLS (3rd)		
SSRC		SOLARIS (4th)		
SSRF (3rd)		SOLEIL (3rd)		
UVSOR		TNK		

Abbreviations:

ALS - Advanced Light Source
ANKA - Angstromquelle Karlsruhe
APS - Advanced Photon Source
ASRC - Aichi Synchrotron Radiation Center
AS - Australian Synchrotron
BSRF - Beijing Synchrotron Radiation Facility
CAMD - Center for Advanced Microstructures and Devices
CANDLE - Center for the Advancement of Natural Discoveries using Light Emission
CAT - Centre for Advanced Technology
CHESS - Cornell High Energy Synchrotron Source
CLS - Canadian Light Source
DELSY - Dubna Electron Synchrotron
DELTA - Dortmund Electron Storage Ring Facility
ELETTRA- Elettra Synchrotron Light Laboratory
ELSA - Electron Stretcher Accelerator
ESRF- European Synchrotron Radiation Facility
HISOR - Hiroshima Synchrotron Radiation Center
HZB - Helmholtz-Zentrum Berlin
ILSF - Iranian Light Source Facility
ISA - Institute for Storage Ring Facilities
KSRS - Kurchatov Synchrotron Radiation Source
LNLS - Laboratorio Nacional de Luz Sincrotron

MLS - Metrology Light Source
NSLS-II - National Synchrotron Light Source II
NSRL - National Synchrotron Radiation Laboratory
NSRRC - National Synchrotron Radiation Research Center
PETRA III - PETRA III at DESY
PF - Photon Factory
PLS - Pohang Light Source
RitsSR - Ritsumeikan University SR Center
SAGALS - Saga Light Source
SESAME - Synchrotron-light for Experimental Science and Applications in the Middle East
SLRI - Synchrotron Light Research Institute
SLS - Swiss Light Source
SOLARIS - National Synchrotron Radiation Centre SOLARIS
SPring-8 - Super Photon ring-8 GeV
SSLS - Singapore Synchrotron Light Source
SSRC - Siberian Synchrotron Research Centre
SSRF - Shanghai Synchrotron Radiation Facility
SSRL - Stanford Synchrotron Radiation Lightsource
SURF- Synchrotron Ultraviolet Radiation Facility
UVSOR - Ultraviolet Synchrotron Orbital Radiation Facility

Fig. 2. Worldwide distribution of synchrotron light sources (figure credit M.B. Galkaduwa, Kansas State University).

Summaries of Papers in This Special Section

Although this special collection of articles does not intend to cover the full spectrum of advanced in situ spectroscopic techniques, it represents a good cross-section of the most popular techniques used in environmental biogeochemistry and provides examples of their applications to study environmentally important nutrients and contaminants in natural samples.

Advancements in SR-Based Research Techniques

Determining the speciation of highly dilute trace elements in environmental media is one of the major challenges facing environmental biogeochemistry researchers, as the speciation of nutrients and contaminants largely determines their bioavailability, mobility, and fate. Due to the difficulties inherent in this challenge, studies reporting the speciation of trace elements in plants or organisms, at environmentally realistic concentrations, and in vivo or under natural conditions, are rare. Giving examples, Proux et al. (2017) discusses the use of an innovative synchrotron spectroscopy technique called high-energy resolution fluorescence detected X-ray absorption spectroscopy (HERFD-XAS). This technique uses a crystal analyzer spectrometer (CAS), which allows XAS signals to be measured in fluorescence mode with an energy resolution of ~1 eV; this can be compared with typical energy resolutions of ~150 to 300 eV for traditional solid-state detectors (SSD) or silicon drift detectors (SDD). This technique provides new opportunities, such as the possibility to study ultra-diluted elements by filtering background photons with great efficiency and improving the sensitivity of the measurements with acquisition of better-resolved XANES spectra, which could revolutionize our ability to accurately determine the speciation of dilute elements in biological and geological samples (Proux et al., 2017). It is exciting to see that there are beamlines (for example, the FAME-UHD, or the French absorption spectroscopy beamline in material and environmental sciences at ultra-high dilution at the European Synchrotron Research Facility, Grenoble, France; and the I20 beamline at the Diamond Light Source, Didcot, UK) devoted particularly to the study of highly dilute chemical elements, and these beamlines are continuously being modified to enhance their analytical capabilities (Burke et al., 2015; Net et al., 2015).

Synchrotron radiation-based X-ray microprobes (XRM) are powerful tools for environmental biogeochemistry research. Since its first commissioning experiments (energy-dispersive diffraction) in September 1996, the GeoSoilEnviro Center for Advanced Radiation Sources (GSECARS) has provided environmental biogeochemists and other earth

scientists with access to high-brilliance, hard X-rays from the Advanced Photon Source's third-generation synchrotron light source to conduct pioneering research work. In their review paper, Sutton et al. (2017) discussed the XRM instrumentation, techniques, and applications, demonstrating their existing capabilities, as well as the prospects for further improvements associated with the proposed upgrade of the Advanced Photon Source. Among the major advancements at the GSECARS facility is the new 3.6-cm-period undulator used by the XRM, which allows access to lower-energy absorption edges than previously accessible. The new capabilities at GSECARS allows high-spatial-resolution XAFS spectra to be collected sequentially on absorption edges down to 2.3 keV (sulfur K edge) and high-energy edges up to 28 keV (cadmium K edge) on the same sample spot. Another advancement is the availability of high-speed digital flat-panel detectors that are optimized for X-ray diffraction. This allows real-time imaging of diffracted X-rays from a sample in combination with high-speed µ-XRF imaging.

Integrated Approaches

Soil is a highly heterogeneous and very complex medium composed of inorganic and organic solids, water, and air. Understanding the interactions between organic matter and inorganic components in soils is needed to understand soil carbon sequestration, as well as global cycling of carbon, nutrients, and metals. Imaging techniques allow us to gather spatial information on organo-mineral associations. Scanning electron microscopy (SEM) and transmission electron microscopy (TEM) are widely used to obtain information on the arrangement of organo-mineral associations. Although both of those two approaches are not species sensitive, when coupled to electron-dispersive X-ray microscopy or electron energy loss spectroscopy (EELS), these techniques can be used to identify mineral species and/or metal valance ratios, as discussed by Stuckey et al. (2017) in this issue. Scanning transmission X-ray microscopy is a powerful SR-based technique that uses soft, high-flux X-ray photons to map micrometer-sized environmental samples with nanometer spatial resolution (Jacobsen et al., 2000). When STXM is coupled with NEXAFS (STXM-NEXAFS spectromicroscopy), it can be used for spectral fingerprinting of fine structures. This approach has contributed to the greatest set of advancements in the understanding of soil organo-mineral interactions in recent years (Stuckey et al., 2017).

Integration of micro- or nanoscale XRF with XAS analyses allows the in situ analysis of metal(loid)s in soils and plants. Kopittke et al. (2017) presents a comprehensive overview on the use of these SR-based X-ray techniques to elucidate the speciation, distribution, uptake, acquisition, and compartmentalization of trace metal(loid)s in plants. These authors also point out that it is necessary to consider complementing synchrotron-based techniques with other experimental approaches, such as nanoscale secondary ion mass spectroscopy (NanoSIMS), laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS), proton-induced X-ray emission microscopy (micro-PIXE), or electron microscopy, to satisfactorily answer the full diversity of hypotheses arising in environmental biogeochemistry.

Integrating spectroscopic analyses at multiple scales, from the millimeter scale to the submicron scale, is useful for identifying nutrient or contaminant species diversity in highly heterogeneous environmental media, such as soils, with a high degree of specificity. This approach is important when developing in situ remediation technologies for contaminants (Nachtegaal et al., 2005; Arai et al., 2006) and for assessing and managing the potential environmental risks of excess nutrients (Hesterberg et al., 2017). Hesterberg et al. (2017) discusses how precise management of soil phosphorus to meet competing demands from agriculture and environmental protection can benefit from more comprehensive characterization of P speciation in soils by integrating both bulk or millimeter-scale and spatially resolved nanoscale XANES. They show that spatially resolved nanoscale XANES are more species sensitive and better able to show some missing species in comparison with millimeter-scale analysis, and they discuss how these species may be useful for connecting speciation to the chemical reactivity and mobility of P in soils.

Fate and Bioavailability of Contaminants in Soils

Bioavailability of soil contaminants largely depends on their speciation in soils. Some contaminant species are more soluble and bioavailable, whereas some species are more stable and less bioavailable. Regardless of the original source, contaminant elements can undergo different biochemical reactions in soil and be in association with different soil constituents, depending on the soil pH, redox potential, and availability of other associated elements. Using XAS, Sekine et al. (2017) investigated the short-term (<5 d) aging profile and the long-term (135 d) speciation of dissolved Cu, CuO, and CuS nanoparticles. Their work showed that although the short-term reactions of nanomaterials are dependent on the Cu form and soil chemistry (e.g., pH), in the long term, irrespective of their original form, all of the examined forms of Cu nanoparticles transformed into Cu bound to iron oxyhydroxide or natural organic matter.

Colzato et al. (2017) studied short-term temporal changes in Cd speciation and long-term changes in Cd extractability in relation to the properties of highly weathered Brazilian Oxisols and less weathered Mollisols and Entisols. Cadmium L-edge XANES showed that Cd was mainly sequestered as Cd bound to organic matter and to Fe and Al oxides (or montmorillonite in the smectite-rich soil sample). However, chemical fractionation showed that the attenuation of soil applied Cd was not progressing over times of up to 4 mo.

Community gardening initiatives in urban areas are thriving due to increasing societal interest in sustainable practices, and a growing demand for fresh, locally grown food. Effective in situ mitigation strategies to minimize the effect of soil contaminants in urban soils on human health are becoming increasingly important as more community gardens are established. Using XAS, Attanayake et al. (2017) studied how compost amendments affected soil Pb speciation in the field and examined the change in soil Pb speciation during an in vitro bioaccessibility extraction test. Although the short-term effects of compost addition on Pb speciation were not clear, they found that the fraction of Pb bound to organic matter increased as the soil-compost mixture aged in the field.

The importance of considering bioavailability for the risk assessment of soil contaminants has gained much attention over the past couple decades. Karna et al. (2017) provides an example of how a synchrotron-based XAS technique can be used to validate in vitro bioaccessibility test results. Their research focused on two of the most common soil contaminants, Pb and As, and

examined how speciation and bioaccessibility change as a function of soil particle size.

Natural attenuation of soil contaminants (the processes by which the mobility, bioavailability, and toxicity of the contaminants introduced to soils decline over time), or the aging effect, is a well-known phenomenon (Ma et al., 2006). Mariet et al. (2017) combined speciation and extractability to study Pb left in soils for several centuries after metallurgical activities. Using EXAFS, they found that Pb was mainly sorbed to Fe oxy(hydr)oxides and attributed weakly acid-soluble Pb fractions to the reversibility of Pb bound to oxy(hydr)oxides. This observation has important environmental consequences and considerations, and the authors attributed this lack of aging effect to the acidic pH of the soil.

Bright and Exciting Future

Synchrotron science is undergoing a new revolution with the advent of multiband acromat lattices to achieve diffraction-limited storage rings (Eriksson et al., 2014; Eriksson and van der Veen, 2014). This will deliver SR with unprecedented brightness and coherence. This progress in SR will need to be met by similar advances in optics, beamline, and detector technologies to realize its full potential. Also, there will be the need to develop sampling environments, especially cryosystems, to reduce beam damage due to the increased flux (unless we become much more efficient at collecting signal). All of this will result in a data deluge that will require new ways to store and analyze data to extract increasing amounts of information. It is important to continue to make progress in all aspects of synchrotron-related hardware and software, as the weakest component will likely limit the quality of the new science being delivered. Strong linkages between these components can be achieved through continued communication between environmental biogeochemists and experts in synchrotron techniques and data analysis. It seems that many advances have come about because of partnerships between the earth and environmental science and the synchrotron communities. We believe that the environmental biogeochemistry community can help to drive the synchrotron technology advances in the synchrotron science by developing creative new research ideas. We are optimistic and looking forward to the future breakthroughs in environmental biogeochemistry that synchrotron-based X-ray techniques such as high-resolution imaging microscopy and spectroscopy can be anticipated to deliver.

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