Evaluating Time Signatures of Nuclear Contamination Recorded in Plants and Microbial Biosensors

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Introduction and Motivation

Natural, in-situ biosensors that detect and record activities from various stages of the nuclear fuel cycle are critical for verifying nuclear nonproliferation and arms control.

It's been suggested that correlations between microbial gene sequence data and geochemical parameters can be used to characterize and predict contamination from past nuclear proliferation activities (Smith et al., 2015; Fig. 1, Fig. 2).

Similarly, comparison of radionuclide concentrations in soils and vegetation (Fig. 3) suggest some plants have potential to act as bio-monitors for radionuclide contamination (e.g. Wicker et al., 1990; Paller et al., 2008; Caldwell et al., 2011).

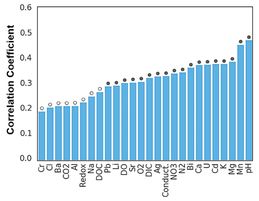

Fig. 1: Significant ($p < 0.0001$, sym: **O**) to highly significant ($p < 0.01$, sym: n) correlation observed between true and predicted (16S rRNA) values for 26 key geochemical parameters from a contaminated site (from Smith et al. 2015).

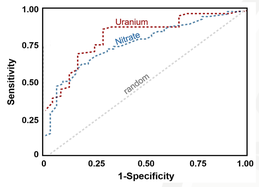

Fig. 2: Classification of uranium (A = 0.82) and nitrate (A = 0.76) from a contaminated site using 16S rRNA gene sequence data (from Smith et al. 2015).

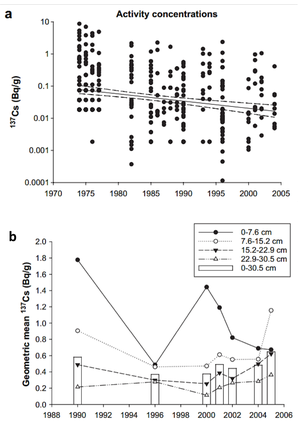

Fig. 3: (a) Changes in ^{137}Cs activity concentrations over time in vegetation at the SRS. Also shown are regression lines (solid) and 95% confidence intervals (dashed). **(b)** Geometric mean ^{137}Cs concentrations at different soil depths (from Paller et al., 2008).

Problem: Time signatures of contamination have not yet been evaluated for microbial biosensors and potential techniques for absolute dating of contamination events have not been investigated for microbial or plant biosensors.

Objectives: As part of Thrust Area 2: Signals and Source Terms for Nuclear Nonproliferation, part C In Situ Natural Monitoring (biota), we propose to measure how long microbiomes and associated plant biosensors retain signatures of radionuclide contamination, and establish a temporal framework for application of these potential biosensors.

Mission Relevance

This work aligns with the U.S Department of Energy's National Nuclear Security Administration (DOE/NNSA) mission by identifying natural biosensors that can be used to detect and monitor nuclear weapons proliferation activities. Technologies such as these are critical for developing an effective nonproliferation regime to prevent the spread of nuclear weapons while ensuring access to peaceful applications of nuclear energy worldwide.

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Technical Approach

Contamination pathways from well-characterized sites will be sampled for acquisition and analysis of new plant, microbiome, and geochemical data. Results will be integrated with historical records of contamination events, environmental radiation levels, seasonal weather conditions, remediation efforts, and prior biogeochemical analyses to identify time signatures and temporal constraints associated with potential biosensors. To achieve these goals, MTV project team members from the University of Tennessee Knoxville (UTK), Savannah River National Laboratory (SRNL), the University of Hawaii, Massachusetts Institute of Technology, University of California Berkeley, and Oak Ridge National Laboratory (ORNL) are collaborating on five major tasks as part of the In Situ Natural Monitoring (biota) effort:

Task 1 - Select Contaminated Areas
Task 2 - Generate Field Test Plan
Task 3 - Field Sample Collection
Task 4 - Molecular Microbial Analysis
Task 5 - In Lab Simulations

Work to-date includes selection of field sites as well as sample types, locations, and key parameters to be analyzed along contaminate pathways as part of tasks 1 and 2.

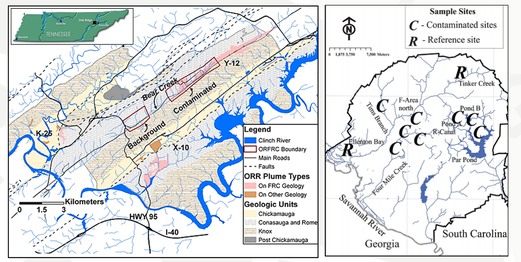

Fig. 4. Left - Map of the contaminated y-12 site at Oak Ridge Reservation (from Hazen et al., 2019). **Right -** Map of the Savannah River Site (Aiken, SC). Contaminated and reference sample sites are identified (from Caldwell et al., 2011).

Results

The Savannah River Site (SRS) and Y12 have been selected as contaminated sites of interest, with SRS contaminate pathways at the R and P canals/ponds and the northernmost arm of PAR pond identified for sample collection, as well as sample control sites at Tinker Creek (Fig. 4). Plants such as bur-reed and bladderwort have been identified for sampling and analysis (roots and shoots) along with their associated sediment and water microbiomes and geochemistry (Fig. 5).

Fig. 5: Photographs of American bur-reed (top, *Sparganium americanum*) and bladderwort (bottom, *Utricularia*) to be sampled at SRS.

Microbial community analysis will include 16s rRNA gene surveys for sediment, water, and plant samples coupled with metagenomics and metabolomics when possible. Potential contaminates of interest identified for analysis include: Ca, K, Al, Mg, Mn, Cs, Li, Pu, U, Am, Ac, Ag, Bi, Cd, Co, Pb, Th, Be, Zn, Ce, and other geochemical parameters such as dissolved (in)organic carbon, NO_3/N_2, and pH (Fig. 1).

Contamination time signatures for biosensors will be evaluated via ^{137}Cs, ^{210}Pb, and $^{230}Th/^{232}Th$ isotope systematics coupled with reactive transport models (e.g. Robbins and Edgington, 1975; Whicker et al., 1990; Mohler et al., 1997; San Miguel et al., 2001; Paller et al., 2008).

Expected Impact

Outcomes of this work will include the identification of natural microbial communities and plant biochemical signatures that can be used as biosensors to detect nuclear fuel cycle activities. University collaboration with SRNL and ORNL will provide students with an interdisciplinary framework for solving challenges related to nuclear proliferation and development of nonproliferation monitoring, technology and verification.

MTV Impact

Project activities are helping to develop technical expertise and research networks with national labs and universities to support DOE/NNSA's nuclear nonproliferation and arms control objectives. Sharing resources with ORNL and SRNL team members will provide access to field sites, samples, and analytical techniques that will be core components of graduate research. Technology transfer is being facilitated through collaboration and data sharing with team members at ORNL, SRNL, University of Hawaii, MIT, UC Berkley, and University of Michigan.

Conclusions

The Savannah River Site (SRS) and Y12 have been selected as sites of interest to investigate time signatures of radionuclide contamination in microbial communities and coexisting plant species.

Outcomes of this work will help to advance DOE/NNSA's mission by establishing a temporal framework for application of natural, in-situ biosensors that can be used to detect and monitor nuclear weapons proliferation activities.

Next Steps

Plans for ongoing work include collaboration with ORNL team members to determine contaminated areas of interest at Y12 (Task 1) and begin developing the sampling and analysis plan for the site (Task 2). UTK and SRNL will coordinate field and laboratory resources in preparation for Task 3 - Field Sample Collection at the SRS.

References

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