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Using geochemical indicators to distinguish high biogeochemical activity in floodplain soils and sediments

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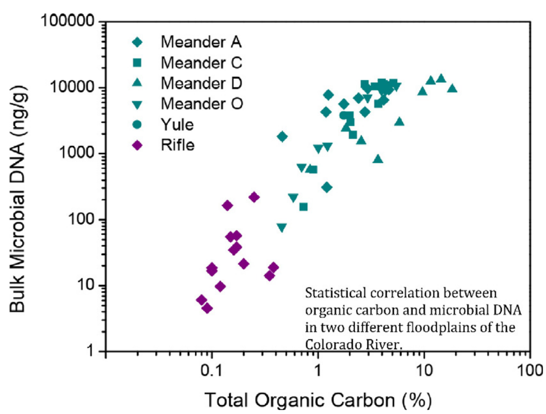
HIGHLIGHTS

- Biogeochemical characterization of alluvial floodplain soils and sediments was performed to investigate parameters that may indicate microbial hot spot formation.
- A correlation between geochemical parameters (total organic carbon and extractable metals) and bulk microbial DNA was found in two alluvial floodplain settings.
- Results of this study motivate additional work on understanding the influence of environment on microbial activity, and microbial activity on environment in natural systems.

GRAPHICAL ABSTRACT



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ABSTRACT

A better understanding of how microbial communities interact with their surroundings in physically and chemically heterogeneous subsurface environments will lead to improved quantification of biogeochemical reactions and associated nutrient cycling. This study develops a methodology to predict potential elevated rates of biogeochemical activity (microbial "hotspots") in subsurface environments by correlating microbial DNA and aspects of the community structure with the spatial distribution of geochemical indicators in subsurface sediments. Multiple linear regression models of simulated precipitation leachate, HCl and hydroxylamine extractable iron and manganese, total organic carbon (TOC), and microbial community structure were used to identify sample characteristics indicative of biogeochemical hotspots within fluvially-derived aquifer sediments and overlying soils. The method has been applied to (a) alluvial materials collected at a former uranium mill site near Rifle, Colorado and (b) relatively undisturbed floodplain deposits (soils and sediments) collected along the East River near Crested Butte, Colorado. At Rifle, 16 alluvial samples were taken from 8 sediment cores, and at the East River, 46 soil/sediment samples were collected across and perpendicular to 3 active meanders and an oxbow meander. Regression models using TOC and TOC combined with extractable iron and manganese results were determined to be

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the best fitting statistical models of microbial DNA (via 16S rRNA gene analysis). Fitting these models to observations in both contaminated and natural floodplain deposits, and their associated alluvial aquifers, demonstrates the broad applicability of the geochemical indicator based approach.

1. Introduction

Heterogeneous distributions of chemical and physical parameters in the subsurface exert control on important hydrologic, geochemical and microbial processes, but connectivity between these systems is poorly understood (Chen and MacQuarrie, 2004; Hedin et al., 1998; Boano et al., 2014). Variations in organic matter, nitrogen, iron and other metals can be found in natural systems at scales down to a centimeter and smaller (Schilling and Jacobson, 2012; Englert et al., 2009; Murphy et al., 1997; Boano et al., 2014). These variations contribute to microbial activity in the subsurface through availability of terminal electron acceptors and electron donors required for microbial metabolism (Sena et al., 2012; García-Balboa et al., 2011; Hakala et al., 2009). Thus, prediction of the distribution of microbial activity may be possible by defining geochemical indicators of biogeochemical activity. If such an approach is valid, simple geochemical tests can enhance our ability to identify important areas for detailed microbial characterization in natural systems. Of particular interest are operationally defined biogeochemical hotspots or small-scale heterogeneities where microbial activity is high relative to the bulk or average microbial activity of the larger system. Biogeochemical hotspot formation may be driven by high organic carbon and high bioavailable metal concentrations (Hakala et al., 2009).

Heterogeneous distributions of microbial populations can result from variations of moisture content and geochemical conditions (Pinay et al., 2007; Schilling and Jacobson, 2012; Murphy et al., 1997), especially dissolved oxygen. Spatial separation of microbial communities, driven by available terminal electron acceptors can be very strong in lakes and aquifers (Sweerts et al., 1991; Chapelle and Lovley, 1992) but tends to be less distinct in fluvial systems due to substantial groundwater-surface water mixing that induces fluctuations in redox conditions (Morrice et al., 2000). In hyporheic zones, aerobic surface water mixes with groundwater (Boano et al., 2014) generating strong gradients in chemical conditions that stimulate microbial communities and drive much of the microbial activity in fluvial systems (Prommer et al., 2006; Hill et al., 2000; Hedin et al., 1998; McDowell et al., 1992).

Field observations of relationships between physical and chemical heterogeneity and microbial activity in subsurface materials are limited (Hedin et al., 1998; Pinay et al., 2000; Campbell et al., 2012), but are needed in order to parameterize and constrain conceptual and numerical models (Fleckenstein et al., 2010; Boano et al., 2014; Englert et al., 2009). This study evaluated the empirical relationships between geochemical properties of subsurface materials and bulk microbial DNA in soil and sediment samples from a stranded floodplain in Rifle, Colorado and an active floodplain on the East River, Colorado with linear statistical models. The objective of the study was to explore whether such models can provide a basis for (1) targeting areas for detailed analysis of microbial activity and structure and (2) simplification of numerical simulation of biogeochemical processes in this system. The two flood plains are sites of extensive and active research in subsurface microbial activity and represent different depositional processes and morphology so that statistical relationships across two sites can be compared.

Heterogeneous distributions of redox conditions and microbial populations are challenging aspects of subsurface modeling (Atchley et al., 2013; Li et al., 2011; Boano et al., 2014; Beisman et al., 2015). Co-dependence between distributions of geochemical properties of soils and development of microbial community structure would simplify model parameterization (Englert et al., 2009; Sena et al., 2012; Murphy et al., 1997; Prommer et al., 2006). If empirical relationships can be consistently identified between subsurface properties and microbial properties, microbial characteristics may be predictable based on only chemical and physical analyses.

1.1. Site descriptions

Two study sites that are the focus of extensive research on subsurface biogeochemical activity and microbial populations were chosen for this study.

1.2. Rifle, Colorado

The U.S. Department of Energy (DOE) field biogeochemistry study site in Rifle, Colorado is a stranded floodplain on the banks of the Colorado River (Fig. 1). The site consists of Wasatch Formation bedrock overlain by Quaternary alluvium sediment. Uranium contaminated alluvial sediments were removed in 1996 during reclamation efforts after closure of a uranium and vanadium mill (DOE, 1999), and the site was capped with ~1.5 m of silt-rich sediment. The Quaternary alluvium sediment consists of fluvial silts, sands and gravels and has a thickness of approximately 6–7.6 m. The Wasatch Formation bedrock is comprised of variegated claystone, siltstone and sandstone lenses that serve as a local aquitard (DOE, 1999). A majority of the water in the alluvial aquifer discharges into the Colorado River, which forms the southern boundary of the field site. More detailed reports on the geology, hydrologic conditions and geochemistry of the site are available (DOE, 1999, 2011; DOE(2), 2011.

1.3. East River, Gothic, Colorado

The East River floodplain is downstream of the Rocky Mountain Biological Laboratory (RMBL) in Gothic, CO (Fig. 1). This watershed exhibits characteristic fluvial progression and serves as a representative example of many headwater catchments within the upper Colorado River basin. The East River valley in the study area is comprised of Mancos Shale bedrock overlain by glacial moraine deposits. Four meanders from the study site with different characteristics were chosen for sampling to maximize the distribution of organic carbon concentrations (Fig. 1). Meander A has a narrow neck and short vegetation with no surface water channels. Meander C is a much longer meander with many potential hyporheic flowpaths and some inner channels and trees. Meander D is large, but contains dry areas with trees as well as regions that are seasonally saturated with wetlands and internal streams. Meander O is a cutoff oxbow meander whose riverbed is seasonally inundated with groundwater and does not contribute substantially to the main flow of the river.

2. Methods

2.1. Sample collection and preparation

2.1.1. Rifle

Samples of alluvial material from the Rifle site were collected from sediment cores extracted during the drilling of wells along the outer edge of the Rifle site in April 2013 (Fig. 2). A total of 16 samples from 8 wells were analyzed. Ten of these samples were collected during