Rice roots form microniches in paddy soils that control arsenic (im)mobilization

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Rice paddy soils are highly heterogenous environments with dynamic changes in structural and biogeochemical soil properties (such as redox state, iron mineralogy and pH). In particular the rhizosphere of these mostly water-logged soils is characterized by low redox potentials, a high content of dissolved organic carbon (DOC) and the availability of dissolved ferrous iron ($Fe(II)_{aq}$). Under these conditions, rice plants have evolved a strategy to counteract iron toxification by releasing oxygen (O_2) from their roots through radial oxygen loss (ROL) forming ferric iron (Fe(III)) plaque minerals on root surfaces. This iron plaque impacts the fate and mobility of nutrients and (heavy) metals, such as arsenic. The release of O_2 from the roots, bioavailability of DOC and the presence of Fe(II)/(III) in the rhizosphere not only form a geochemical potpourri, but create unique micro-environments for microorganisms that either couple i) the oxidation of Fe(II) to O_2 reduction: microaerophilic Fe(II)-oxidizers (microFeOx), or ii) the oxidation of DOC to Fe(III) mineral reduction: Fe(III)-reducing bacteria.

In the current study, we demonstrate that microFeOx can be microbial key players in Fe(II) turnover and that these microorganisms can find a suitable habitat in the highly dynamic rice plant rhizosphere where they can actively thrive and contribute by up to 40% to Fe(III) mineral formation. Further, we could prove that Fe(III)-reducing bacteria (isolated from a rice paddy) were able to reduce ferric iron plaque by 80% which lead to 30% remobilization of $Fe(II)_{aq}$. Arsenic, co-precipitated with iron plaque, was first remobilized and subsequently showed higher sorption affinity to secondary Fe(II)/(III) minerals (such as siderite, vivianite & Fe-S phases) formed during reductive dissolution. With our lab-based experimental setup we were able to non-invasively follow rice root growth and to spatio-temporally identify dynamic biogeochemical hotspots (O_2, pH, CO_2, $Fe(II)_{aq}$ and Fe(III)) that favour either microbial Fe(II) oxidation or Fe(III) reduction over the vegetative phase of a rice plant. Our findings demonstrate that rice roots and ROL can form highly dynamic rhizospheral microhabitats for microaerophilic Fe(II)-oxidizing and anaerobic Fe(III)-reducing bacteria and create a network of interconnected microenvironments which can significantly impact the (im)mobilization of arsenic in paddy soils.