PAST AND ONGOING RESEARCH

My research focuses on microbial community-soil-plant interactions, with an emphasis on pressures exerted by future climate scenarios. The goal of this work is to understand the fundamental interplay of microbial and geochemical processes, modified by plant-interactions that control metal(loid) dynamics within the rhizosphere and the resulting feedbacks on microbial communities and plant physiology. The translational research objective is to increase plant productivity and quality by optimizing microbially modified soil geochemistry, plant-microbe communication and rhizosphere conditions. Distinguishable changes in the rhizosphere affecting plant functioning are caused by shifts in microbial abundance, community diversity and function, changes in root physiology and plant activity, and alterations in soil aqueous chemistry. Therefore, my research is devoted to (1) identifying and (2) optimizing soil microbial communities, plant-microbe interactions, microbial metal-mobilizing and sequestration activities, plant traits, and agricultural practices for cropping and phytoremediation. In my diploma thesis, I systematically investigated how iron(II)-oxidizing bacteria and rice plants benefit when precipitating iron minerals sequester arsenic. I further determined how arsenate affects the transcription of all fourteen root and shoot phosphate transporters in rice plants. In my doctoral thesis, I explored whether and to what extent rhizosphere microbial communities affect the accumulation of cadmium in *Arabidopsis halleri*, a plant used in phytoremediation. Illustrating how microbial iron reduction affects the mobility of cadmium and arsenic provided the fundamental underpinning of this research. My postdoctoral work examines microbial functional diversity within the rhizosphere of arsenic contaminated rice paddies and alterations induced by future climate scenarios. The translational goal of this work is to provide an accurate estimation of rice productivity and grain quality under projected future climates in combination with the presence of toxic arsenic in paddy soils.

MICROBIALLY-ASSISTED PHYTOREMEDIATION

A major challenge of the 21st century is sustaining and increasing food production. Microbial communities, and the interface with plants and soil materials, have a central, but often overlooked, role in meeting this challenge. A growing stress on crop productivity and thus food security are increasing concentration of metal contaminants. Agricultural soils continuously become contaminated with heavy metals through fertilizers, pesticides, herbicides, and irrigation water. The rate of agricultural soil contamination is often low but still sufficient to compromise plant productivity and quality over long-term use. Phytoremediation and phytoextraction are sustainable and cheap alternatives for the restoration of lightly contaminated soils, as they do not negatively alter the soils physically or chemically, but would even restore soil fertility. An often overlooked key to phytoremediation is the microbial community and functional traits within the rhizosphere. Accordingly, within my Ph.D., I investigated how soil microbial communities affect metal uptake and accumulation by phytoremediating plants. Phytoextracting plants are able to grow on highly contaminated soils, take up the contaminant from the soil in large amounts, and accumulate it in the aboveground tissue. For example, the metal-hyperaccumulating plant *Arabidopsis halleri* is a model plant for studying phytoextraction, as it is able to store well more than 100 µg of cadmium per gram dry biomass in the aboveground tissue.

In studying the soil microbial community associated with *A. halleri* either grown on soil with its natural microbial community or on γ-irradiated soil with a perturbed but regrowing microbial community, we found that a well-developed, functioning soil microbial community is essential for the efficient uptake of cadmium (Figure 1a). The microbial taxa within the rhizosphere were identified using 16S rRNA gene amplicons and compared against the community of the bulk soil (Figure 1b). Interestingly, microbes involved in promoting plant growth, plant pathogenicity, microbe-on-microbe pathogenicity, and metal/ nutrient mobilization differed in the rhizospheres of *A. halleri* grown in presence of the natural soil microbial community or the γ-irradiated microbial community. Furthermore, the first isolation of a cadmium-tolerant iron(III)-reducing *Geobacter* sp. allowed us to

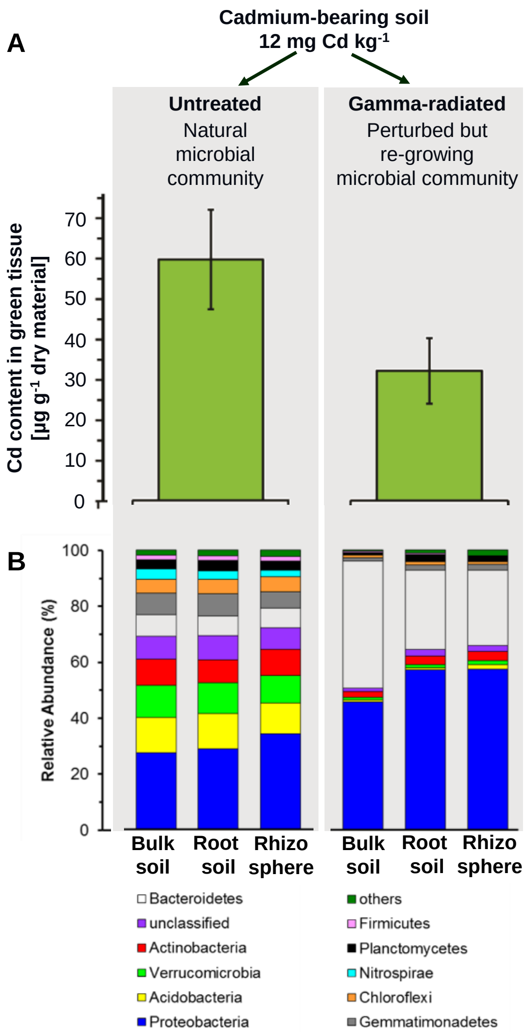

Fig. 1: (A) Accumulation of cadmium in A. halleri in presence of the natural or a γ-irradiated microbial community. (B) Shifts in microbial community composition from bulk soil to rhizosphere.

show a link between microbial iron(III) mineral dissolution and cadmium mobility changes.

Our approach provided the first indications of the microbial groups involved in the removal of Cd from soil by *A. halleri*. *My vision for this path of my future research is to (1) optimize the interplay of A. halleri with the soil microbial community to maximize the efficiency of phytoremediation, and (2) to test microbially facilitated phytoremediation in long term agricultural field trials.*

RICE PRODUCTION UNDER A CHANGING CLIMATE COUPLED WITH ELEVATED SOIL ARSENIC

With more than half of the world's population consuming rice daily, it is crucial to ensure future rice productivity and quality for a growing population. Here again, soil microbial communities play a critical role. The current assessment of climate change impacts on rice productivity points towards a decrease in grain production by up to 15%. Our greenhouse experiments, that let us fully control the climate, support these findings. These estimates, however, do not consider the increasing presence of toxic arsenic in paddy soils globally, and the linked loss in grain yield and quality. To solve this problem, we are preforming greenhouse experiments to understand the impact of climate change and elevated soil arsenic combined on rice growth, grain production and quality. In a future climate the mobility of arsenic in the soil will increase by 50%. The increased arsenic bioavailability to the plant results in a 35% loss of produced grain. Thus, we currently overestimate future rice productivity by approximately 22%. Additionally, a loss in grain quality is observed as 1.7 times more inorganic arsenic is accumulated in the grain.

One of the most important aspects of our project is the ability to differentiate between the effects of elevated temperature, elevated atmospheric CO_2, or elevated soil arsenic as we set-up individual incubation chambers for each and the combined climate conditions and have separate watering and soil containers for today's and future soil arsenic contents. An exciting and unexpected finding is that elevated atmospheric CO_2, and not just temperature, influences the mobility of arsenic in the soil. Furthermore, we are investigating changes in plant physiology and growth stages, alterations in soil geochemistry in the bulk and rhizosphere. We are presently examining shifts in microbial communities from root endophytes to bulk soil communities using shotgun metagenomics and transcriptomics and then focusing on specific functional guilds such as arsenic-oxidizers, reducers and methanogens. These sequencing datasets in combination with our knowledge of the shifts in soil geochemistry between today and future conditions will allow us to identify microbial taxa and functional groups involved in the loss of grain production and quality in the future. Furthermore, we are deciphering microbial communities involved in iron root plaque formation, as we believe that these iron precipitates around the roots are crucial for the mobility of arsenic in rice's rhizosphere and thus are heavily driven by iron-oxidizing and reducing microbial communities. We will use these enrichments to systematically investigate how plant-driven oxygen and carbon exudation is linked to microbial community composition, abundance and functioning and ultimately arsenic mobility.

Overall this detailed analysis allows us to draw conclusions about which stressor affects which stage of the grain production process. *My vision is to use these findings to improve rice productivity and quality for a future climate through rhizosphere management. Specifically, I will examine how soil management (to alter soil chemical conditions) and plant traits can be optimized to maximize crop production*.

FUTURE RESEARCH

My fundamental science goals are to allow better prediction and optimization of future crop productivity and quality in the face of increasing soil contamination and climate change, leading to translational impacts of ensuring sustainable food production for a growing population. *Thus, my research program will focus on belowground processes, namely understanding microbial community–soil and microbial community root interactions in different cropping systems*. Part of this research will be to change individual components of these interactions to increase/maintain yields and quality in the future, however, a strong focus will be put on stimulating soil and rhizosphere microbial communities to improve soil health and to function as beneficial contributors to the productivity of plants.

My future research themes are:

(1) **Concept development: From description to optimization of soil microbial community functioning and plant cross talk.** How to analyze microbial community-plant-soil interplay in light of crop productivity optimization.

(2) **Optimization of anaerobic/microaerophilic microbial communities in the rhizospheres of rice to mitigate future yield and quality losses of rice when grown under climate and soil metal(loid) (arsenic, manganese, cadmium) stress.**

(3) **Understanding and optimizing microbial community-plant interactions of potato, corn, wheat, and cacao, for combined stresses of climate change and soil metal (cadmium, zinc) pollutants.**

(4) **Investigating rhizosphere microbial community differences and dynamics during phytormediation of soils simultaneous to crop production.**

THEME (1): FROM DESCRIPTION TO OPTIMIZATION OF MICROBIAL COMMUNITY FUNCTIONING AND PLANT CROSS TALK

The centrality of my future research themes will be on belowground dynamics arising from microbial-plant-soil interactions that can be represented as a ternary diagram (Figure 2). For each system described in the research themes above, the identified microbial community, and respective crop/phytoremediator and soil type/contaminant are placed at their respective vertices. By analyzing the acquired microbial, geochemical and plant physiological dataset, key features of the microbial community, plant roots and soil could be defined that develop during the growth cycle, or even just a certain growth stage (stated in blue in figure 2). By weighing the different features, I can ascertain how much each partner exerts power over the other two partners and define which of them determines most of what happens in the rhizosphere (yellow triangle in figure 2). As the overall goal is to improve microbial community-plant interaction (indicated by placing the purple star in figure 2), limiting and non-optimal features would be identified (stated in green in figure 2). The following questions can be used to devise strategies to improve microbial community-plant cross talk:

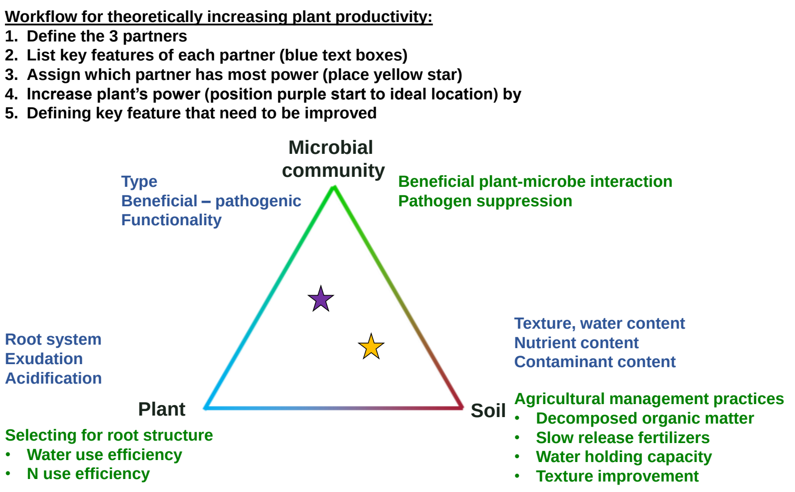

Fig. 2: Conceptual framework of interacting microbial communities, plants, and soil to identify features that need to be improved to increase microbial community functioning. The text boxes in blue list prominent features that develop for each partner during their interaction. Using these features, the partner that exerts most power over the other two during their interaction can be identified. This is indicated by placing the yellow star at a suitable position within the triangle. To increase microbial community functioning the microbial community's influence over soil and plant would need to be expanded, which is indicated by the position of the purple star. In order to move the system from the yellow to the purple star (maximizing the microbial community's control over the system), key features of microbial communities, plants, and agricultural management of the soil are defined that need improvement. These key features are given in the green text boxes and can represent the future translational impact goals.

A) Which microbial taxa and functionalities disturb plant-beneficial microbial community functioning?
B) Which root (growth) feature would optimize positive microbial community functioning (i.e. promote plant growth, repress plant and microbe pathogenicity, minimize climate and contaminant stress)?
C) What agricultural management practices support microbial community functioning and positive plant-microbe interaction?

Ultimately, the describe triangular relationship of figure 2 would be used as a tool in all of my research themes to transition from describing the microbial community of a crop system to defining strategies of improving this system by optimizing microbial community functioning and plant cross talk.

THEME (2): OPTIMIZATION OF MICROBIAL COMMUNITIES IN RICE UNDER CLIMATE AND POLLUTANT STRESS

To date, no successful strategy has been devised for rice plants to deal successfully with climate change and elevated soil arsenic—a condition common to most of the large rice growing regions. However, grain productivity is already falling behind population growth and we are under immense pressure to provide sufficient amounts of rice in the future. The dataset we are acquiring during my postdoctoral appointment at Stanford is vast and unique, as it will consist of detailed information about microbial community dynamics, plant physiological effects, and soil and pore water geochemistry. This dataset will be analyzed according to the concept developed in theme (1) and will then serve as a baseline for research theme (2) to identify optimization strategies for the interaction of microbial communities and rice roots. For example, iron plaque formation around rice roots has been shown to immobilize arsenic. The thriving of microorganisms involved in its formation can be promoted, while ones involved in its dissolution can be repressed. Furthermore, microbial functional guilds involved in reductive dissolution (iron reduction, arsenate reduction) are promoted by climate change, while ones involved in mineral precipitation are repressed by climate change. By optimizing plant carbon exudation (namely quantity and type) and agricultural management (e.g. timing and quantity of fertilization, aeration of soil) a repression of microbial communities involved in reductive dissolution and stimulation of ones involved in arsenic immobilization could be feasible. How these change in processes affect nutrient availability in the soil and uptake will also be considered. Work will start at pot scale in the greenhouse, and once successful be transferred to field trials. Microbial communities as a function of plant and agricultural management will be monitored using state of the art sequencing techniques.

THEME (3): MICROBIAL COMMUNITIES OF POTATO, CORN, AND WHEAT UNDER CLIMATE AND POLLUTANT STRESS

An expanding array of agricultural soils are being contaminated with metal pollutants such as cadmium and zinc due to their presence as impurities in fertilizers. Although presently unknown, but very likely possible, climate change will increase this problem as it increases the mobility of pollutants in soils. Simultaneously, the availability, and consequently uptake, of N, P and K, and micronutrients might change. I believe that the activity of microbial communities in agricultural soils are key to controlling the fate of pollutants and nutrients alike. In order to investigate this probability, I will first conduct greenhouse studies will be performed with potato, corn, wheat and cacao under projected future climates and with and without elevated soil cadmium and zinc contents. Productivity data will be paired with microbial community descriptions in transects from bulk soil to rhizosphere soil to rhizoplane. Once a good descriptive dataset is acquired, this dataset will be analyzed according to the concept developed in theme (1), which defines flaws in pure microbial community functioning and microbial community-crop communication. Strategies to optimize microbial community functioning, nutrient uptake, and minimize contaminant impacts on each crop will be tested in greenhouse studies followed by field trials. State of the art metagenomics and transcriptomics analysis of the different microbial communities will be paired with culture-dependent enrichments, which are then tested as model systems for specific functions in the laboratory.

THEME (4): MICROBIAL COMMUNITIES IN COMBINED CROP-PHYTOREMEDIATION SYSTEMS

Many agricultural soils are burdened with increased concentrations of metal(loid) pollutants including cadmium, zinc, lead, and arsenic. Phytoremediation offers an opportunity to clean and rejuvenate agricultural soils simultaneously to large crop productions as phytoremediator plants are often small (*Noccaea caerulescens*, *Arabis paniculata*, *Arabidopsis halleri*) and could be used as cover crops with crops such as corn, wheat, and others. For theme (4) my research goal is to compare microbial community dynamics of only phytoremediator plants or crops or when phytoremediator plants are jointly grown with large crops. In a joint growth system, the geochemical gradients by the two different plants would be steep, potentially causing the microbial community to split more distinctly into metal-uptake supporting microbes on the phytoremediator side compared to metal-uptake suppressing microbes on the crop side. Thus, microbially assisted phytoremediation and clean crop production could be improved simultaneously. Metagenomics and transcriptomics would serve as tools to investigate microbial community dynamics in greenhouse and field studies. Microbial community enrichments in combination with sequencing would allow to gain further insight into the splitting of functionality between the two types of plants.

GROUP STRUCTURE AND LABORATORY PHILOSOPHY

Overall, I envision a research group of 1 to 2 postdocs, 4 to 6 graduate students, and a few master and bachelor students. Students and researchers from across disciplines, including environmental microbiology, soil science, and plant physiology, would be sought to work in the group and tackle the different research projects jointly to maximize success. Over the years of mentoring, I have found that students and interns of all ages and disciplines are usually excited and interested in learning about research tackling global challenges. The mix of field studies, greenhouse trials and laboratory experiments I envision for my future research allow ample of opportunity for students and interns to get involved in line with their own interests. Students in my lab would be encouraged to participate in lab exchanges and summer programs such as Stanford's Summer Research in Geosciences and Engineering Program for underrepresented groups. My research allows ample of opportunity for local collaborations and I would be very excited to work with groups involved in Environmental Soil Microbiology, Soil Ecology and Global Climate Change, Cropping Systems and Nutrient Cycling, Crop Production, Alternative Crop Development, Environmental Soil Quality and Soil Fertility, and Wheat research programs. I would seek funding for my research from NSF, DOE, and USDA, and I would pursue non-government sources through Gates and Mars foundations, for example. Further, I am well-versed on European government support for graduate students and post-docs to work abroad and would pursue researchers for my studies through these means. My experience in writing proposals to advance my previous research will help to acquire funding for my future research.

In conclusions, I believe that providing clean sustainable fields and agriculture under a changing climate to a growing population will be essential to produce sufficient amounts of good quality food in the future. Understanding and optimizing belowground microbial community, plant and geochemical processes will be key to achieving this goal. Besides having a high interest in this global challenge, I bring a unique skill and tool set to this field of research, making it possible to deal with this challenge from all the different angles. I am very excited about the soil microbiomes professorship position being opened at the Soil and Crop Science Department at Colorado State University, as this interdisciplinary department offers a perfect setting for the research I am interested in and the potential for many fruitful collaborations.

TEACHING PHILOSOPHY

For me, the responsibility of a teacher and mentor is to trigger and support any students' curiosity and thirst for knowledge. Thus, providing the broad societal significance and impact of a topic serves as a motivation for its study. Within a classroom setting, I like to start my lectures and talks with the context or bigger picture of how this topic influenced our society. This is followed by an outline of what the students will be able to accomplish after having taken the lecture or module. These goals are in conjunction with bloom's taxonomy on learning and are usually comprised of one or two lower levels of learning (remember, understand, apply) and one to two higher levels of learning (analyze, evaluate, create). Moreover, I strive to ensure an active learning environment where the students engage with lecture materials through discussion, small-group exercises, and outside investigative learning.

I like to divide a lecture into smaller intervals to maximize the students' attention span, but also to be able to adapt to the students' needs on maximizing their learning of the material. As a student myself, I was most successful at learning when I was actively involved in the classroom and also in cutting-edge research questions. Thus, I emphasize active participation through in-class discussion and small group exercises. My teaching philosophy may best be communicated by example, and here I provide an exercise on rice rhizosphere processes I developed. Rice is the staple providing food to more than 50% of the global population. Its future production is crucial for a growing population, inspiring current research to focus on the rhizosphere and its optimization. In a 5 minute lecture, I engaged students on how severely climate change and/or soil arsenic decrease rice productivity. The students then divided into groups of three to four and were assigned to evaluate the rhizosphere of rice under climate stress, arsenic stress, or both. As a first task, each group came up with a hypothesis how their assigned stressor affects the rhizosphere and communicated these hypotheses to the class. Then, each group got two rice rhizosphere photos from my rhizotron experiments. The first photo showed the rhizosphere grown under todays' non-stress conditions, the second photo, depending on assigned stressor, showed the rhizosphere of rice grown under the respective stressor. For the second activity, each group listed the differences they observed between both rhizospheres. The findings were presented to the entire class, so that groups with the same assigned stressor complemented each other. The goal for the third activity required the students to think of ways to improve the rhizosphere of rice to minimize the effects of climate change and/or soil arsenic and hence, maximize rice productivity. Students were encouraged to think outside the box and combine changing plant growth with plant-microbe interactions and soil management strategies. Besides active learning, this kind of activity should stimulate critical thinking, observation and debating skills, and also include student-by-student teaching.

Outside the classroom, I seek to provide real-case scenarios to work on weekly and an out of class project for the entire term. To optimize presentations and exercises, I assess students' base-knowledge using approaches such as clicker questions. Further, by asking the same questions at the beginning and end of the lecture, I am able to assess the effectiveness of my teaching and adjust to fill gaps in essential knowledge.

TEACHING AND MENTORING EXPERIENCE

As a graduate student at Tübingen I was a teaching assistant twice for the Geomicrobiological field excursion to the Engadin, Switzerland, which was followed by a laboratory course. During this field trip I was responsible for coordinating and advising student project groups and teaching them to analyze their taken samples microscopically in the laboratory later on. This year I was fortunate to have the opportunity to teach two lectures in the department's Science of Soils class (EARTHSYS 155). Besides scientific teaching I have a lot of experience in teaching about the Environment of the Western Cape in South Africa to school kids from various townships and in Ultimate Frisbee from beginners to advance to competitive level. I enjoy these kinds of classes because they allow a more playful interaction between instructor and student and give room for self-exploration to the students.

During my research career at the University of Tübingen I supervised a total of three Master students, three Bachelor students, four Scientific Practice students, and one guest researcher. Two out of these Master students and one Bachelor student were able to publish their research findings in well-received peer-reviewed journals. The third master student and the guest researcher are in the process of publishing their work. Since being at Stanford I supervised 5 summer interns, ranging from high school to bachelor degree students, three of these coming from underrepresented minority groups. Two of them presented their data at last year's AGU meeting. One of the interns also stayed on in the Fendorf lab and just started her PhD this year. I believe that it is the job of a mentor to design projects for their students that demonstrate the complexity of research in terms of laboratory skills, failure and success, but also going from planning to executing to publishing. Overall, teaching a number of different students with very diverse backgrounds, education levels, and personal stories has taught me how different each student is and that individually adapted mentoring styles are needed for each of them.

TEACHING EXISTING AND NEW COURSES

In order to prepare better for teaching I am currently doing the Stanford Postdoc Teaching Certificate. This certificate is based on building and improving one's teaching skills, practicing new teaching techniques, and reflecting on one's experiences for further improvement. Two thirds of the certificate are dedicated to teaching preparation and training and the remainder to teaching itself. I have taken some very illuminating classes specific for teaching undergraduate and graduate students in STEM fields.

As a faculty member I look forward to continuing to learn new and innovative teaching techniques. There are numerous courses that I would enjoy teaching including Environmental Issues in Agriculture (SOCR 171), Microbiology for Sustainable Agriculture (SOCR 341), Soil & Global Change: Science and Impacts (SOCR 400), Greenhouse Gas Mitigation, Land Use and Management (SOCR 401), (Advanced) Soil Microbiology (SOCR 455/ SOCR 755), Global Challenges in Plant and Soil Sciences (SOCR 475), Soil-Plant Nutrient Relationships (SOCR 540). In addition, I am interested in developing upper level / graduate courses on soil microbiology, plant-microbe-soil interactions, crop productivity and food security, and crop production in metal-bearing soils or wetlands. Conducting undergraduate lab rotations and master's degree research in combination with environmental education in South Africa very strongly influenced my decision to pursue an academic career in environmental science. I enjoy motivating students to learn more about our environment and have them participate in the lab. My research offers opportunity for numerous projects, ranging from semester long research projects to theses.