Exposure and Health
https://doi.org/10.1007/s12403-023-00593-6

ORIGINAL PAPER

The Effects of Soil Microbial Disturbance and Plants on Arsenic Concentrations and Speciation in Soil Water and Soils

Hang Guan[1] · Veronica Caggìa[2] · Andrea Gómez-Chamorro[3] · Daniela Fischer[1] · Miquel Coll-Crespí[1] · Xiaowen Liu[1,4] · Teresa Chávez-Capilla[1] · Klaus Schlaeppi[2,5] · Alban Ramette[3] · Adrien Mestrot[1] · Moritz Bigalke[1,6]

Received: 19 April 2023 / Revised: 25 July 2023 / Accepted: 3 August 2023

Abstract

Arsenic (As) in soils harms soil organisms and plants, and it can enter the human food chain via the dietary consumption of crops. The mobility, bioavailability and toxicity of As are determined by its concentration and speciation. A greenhouse pot experiment was conducted to study the effects of soil microbial disturbance and maize plants on arsenic concentration and speciation in soil (pore) water and soils. Three soil treatments with varying microbial disturbance were designed for this experiment: native soil, sterilized soil and sterilized soil reconditioned with soil indigenous microbes. The three soil treatments were intersected with three levels of As in soils (0, 100 and 200 mg kg^{-1} spiked As). Ten pots of each treatment were planted with maize, while three pots were filled with soil without maize. The difference between native and reconditioned soil indicated the abiotic sterilization effect (artifact of the sterilization process), while the difference between sterilized and reconditioned soil showed the microbial disturbance effect. Both effects increased As release into soil water. The microbial disturbance effect was more pronounced for organic As species, showing the influence of soil microbes involved in As methylation. The abiotic sterilization effect was more evident in unplanted pots than planted pots and the microbial disturbance effect was observed only in unplanted pots, suggesting that both effects were mitigated by the presence of maize.

Keywords Metalloids · Soil sterilization · Soil-plant system · Arsenic in soil · Plant-microbe interactions

Introduction

Arsenic (As) is a toxic metalloid that can cause health problems to humans due to long-term exposures through drinking water and food (Shankar et al. 2014; Mandal 2017; Parascandola 2017). Natural As concentrations in the crust usually range from 1.5 to 5 mg kg^{-1} (Rahaman et al. 2021). In soils, typical background levels of As do not exceed 100 mg kg^{-1} (Rimondi et al. 2022). Anthropogenic As sources such as industrial and mining activities can increase As concentrations in soils up to 20,000 mg kg^{-1} (Smith et al. 1998). When crops are grown in As-contaminated soils, As can enter the human food chain. The transfer of As from soils to crops is determined by As concentration and speciation in soil water (Rosas et al. 1999; Prabpai et al. 2009). However, total As concentration has only limited relevance, because As speciation controls the mobility, bioavailability, distribution and toxicity of As in the food chain (Garcia-Manyes et al. 2002).

✉ Moritz Bigalke
moritz.bigalke@tu-darmstadt.de

1 Institute of Geography, University of Bern, Hallerstrasse 12, 3012 Bern, Switzerland

2 Institute of Plant Sciences, University of Bern, Altenbergrain 21, 3013 Bern, Switzerland

3 Institute for Infectious Diseases, University of Bern, Friedbühlstrasse 51, 3001 Bern, Switzerland

4 Center of Deep Sea Research, Center for Ocean Mega-Science, Institute of Oceanology, Chinese Academy of Sciences, Qingdao 266071, China

5 Department of Environmental Sciences, University of Basel, 4056 Basel, Switzerland

6 Institute of Applied Geoscience, Technical University Darmstadt, Schnittspahnstrasse 9, 64287 Darmstadt, Germany

Published online: 10 September 2023

The solubility of As to soil water is determined by the chemical speciation of As in soils and by the physicochemical properties of soils. The different As species have different sorption properties to different soil parameters at different pH. The study of As speciation in soils as well as in soil water allows to directly measure the solubility of As. To know the amount of As in soil water is important, because it comprises the fraction of As that is available to plants and other soil organisms and that is crucial for the risk assessment of As in soils (Huang et al. 2011). The two dominant inorganic As species (inAs) in soils are arsenate (As^{V}) and arsenite (As^{III}) (Huang et al. 2011). Arsenate represents the vast majority (70–99%) of inAs in oxic environments and is approximately 2–10 times less-toxic than As^{III} (Hong et al. 2014). In oxic soils, inAs can be converted by microbes to less-toxic organic As species (orgAs), such as methylarsonic acid (MMA^{V}), dimethylarsinic acid (DMA^{V}) and trimethylarsine oxide (TMAO) (Thomas 2021). These orgAs can be transformed to volatile arsine mainly under anaerobic conditions (Huang et al. 2011, 2012; Viacava et al. 2020; Kabiraj et al. 2022). Although MMA^{V} and DMA^{V} are the most abundant orgAs in oxic soil environment (Huang et al. 2011), they occur only in small quantities compared to inAs (Pongratz 1998; Garcia-Manyes 2002; Tlustoš et al. 2002; Dobran and Zagury 2006; Sadee et al. 2016). TMAO is detected only in a few cases with minor concentrations in soil water (Geiszinger et al. 2002). Arsenic speciation in soil water is essential to determine its toxicity and bioavailability to plants and humans.

Higher plants lack the ability to methylate As (Jia et al. 2013b; Zheng et al. 2013), and can instead take up inAs and orgAs from soil water, while orgAs in soil water is produced by soil microbes (Lomax et al. 2012). Thus, soil microbes play a key role in As bioavailability for plants (Turpeinen 2002; Zhao et al. 2013; Kuivenhoven and Mason 2019). Soil microbes can remediate metal(loid) toxicity in the rhizosphere, as they can facilitate the crystallization and precipitation of metal(loid)s (Diels et al. 2003; Ahemad 2019). Many microbes have the potential to conduct microbial methylation, i.e., convert inAs to less-toxic organic forms and eventually to volatile As species, allowing them to be removed from soils (Jia et al. 2013a; Upadhyay et al. 2018). The potential of microbes for As volitalization depends on soil chemistry, As level and organic matter concentrations (Mestrot et al. 2011). It can be significant under anaerobic conditions but the overall contribution of volatilization to the total As loss from soils is relatively low compared to other processes, such as leaching and erosion. Arbuscular mycorrhizal fungi, rhizospheric bacteria, fungi and algae can mitigate As stress in soils through bioaccumulation and biotransformation (Rahimzadeh and Pirzad 2017; Upadhyay et al. 2018). Microalgae can not only adsorb As on their surface, but also extract toxic As species from soil water, convert them to less-toxic species such as arsenosugars, and store them in their cells (Wang et al. 2015; Danouche et al. 2021).

Arsenic concentration and speciation in the rhizosphere are affected not only by soil microbes but also by plants. When encountering As stresses, plants can interact with soil microbes to mitigate As toxicity. The interactions between plants and soil microbes determine their responses to As contamination (Del Molina et al. 2020). Some plants can convert As^{V} to As^{III} in roots, which is the first step in the major detoxification pathway of As, followed by As methylation by soil microbes (Pickering et al. 2000). The As^{V} can bind to ferric sulfate precipitates on root epidermis and be immobilized in root vacuoles as arsenite-trivalent complexes (As^{III}–$(SR)_3$), effectively limiting As absorption into the aerial tissues of mesquite plants (Hammond et al. 2018). Arsenic can also be adsorbed and sequestered in the Fe(III)-containing plaques of wetland plants and rice, reducing As mobility to groundwater, soil water and wetland soils as well as As amount in root interiors and the As bioavailability to plants (Emerson et al. 1999; Blute et al. 2004; Hu et al. 2015). When plants encounter environmental stresses, such as exposure to toxic metal(loid)s, they can excrete chemicals like root exudates (sugars, amino acids, enzymes, etc.) to reduce metal toxicity. These responses include changes in soil pH and redox potential, increase in root surface area, and the release of anions. The response mechanism can enhance nutrient acquisition by roots and promote microbial activity (Rengel and Marschner 2005; Prasad et al. 2006; Colombo et al. 2014; Seshadri et al. 2015). The carbon sources obtained by photosynthesis can be deposited in the rhizosphere and fed by the plants to their soil microbes (Sasse et al. 2018; Zhalnina et al. 2018). The release of such root exudates can consequently apply a selective pressure to soil microbes (Pantigoso et al. 2022). Under As stress, plants may select As-resistant microbes that are efficiently involved in the oxidation of As^{III} to As^{V} and in the As detoxification/methylation process, thereby functionally reducing As concentrations in soil water and As availability to plants (Kowalczyk and Latowski 2018; Raturi et al. 2023). Such interactions between plants and microbes strongly influence As speciation and thus its toxicity to soils and plants, since various As species differ in their toxicities.

To study the microbe-based effects in soils, sterilization of soils is a common technique. The primary consequence of soil sterilization is the elimination of soil indigenous microbes (Blankinship et al. 2014). After soil sterilization, microbes were shown to rapidly acclimate and recolonize the rhizosphere, resulting in a new microbial community with lower diversity (Marschner and Rumberger 2004; Hinsinger et al. 2009; Mahmood et al. 2014; Li et al. 2019). Consequently, sterilized soil has a rather disturbed microbial composition and is referred to as disturbed soil in this study. Soil

sterilization also changes abiotic factors such as accelerating the decomposition of soil organic matter, thereby increasing dissolved organic carbon (DOC) content in soil water (Berns et al. 2008). Dissolved organic carbon can compete with As for adsorption sites on soils (Jackson et al. 2006; Fisher et al. 2015) as well as bind with As to form As-DOC complexes (Buschmann et al. 2006; Williams et al. 2011), leading to As mobilization into soil water. A decrease in soil pH is also an abiotic sterilization effect that results from the dissolution of organic acids (Razavi 2007), which can affect the speciation, mobility and toxicity of As (Masscheleyn et al. 1991). By distinguishing between abiotic sterilization and microbe-based effects, the role of soil indigenous microbes in As concentration and speciation in the soil environment can be better elucidated.

Arsenic uptake in crops and its transfer to the human food chain is a significant problem worldwide, because of its potential toxicity. The problem occurs mostly on soils with high As concentrations, causing high As in crops. This is especially relevant for crops like maize (*Zea mays* L.), which is the most widely grown cereal in the world (with an annual production of more than one billion tons (Rosas-Castor et al. 2014)). However, plant–microbe interactions are known to mitigate As toxicity (Anand et al. 2022; Raturi et al. 2023), but the relative contributions of plant and microbial mechanisms in the As speciation and release to soil water and soil remain largely unknown. Based on these considerations we conducted an experiment growing maize on a soil with three different As concentration levels (0, 100 and 200 mg kg^{-1} As added) and three different levels of microbial disturbance (natural, sterilized but reconditioned with the indigenous microbiome, sterilized). Rather than analyzing the effects of individual microbes, we aim to examine the global disturbance effects of soil microbes and their interactions with maize plants and answer the following questions: (1) What are the abiotic sterilization effects on As concentration and speciation in soil water and soils? (2) What are the microbial disturbance effects on As concentration and speciation in soil water and soils? (3) What are the effects of the different soil As levels on As speciation? (4) How do maize plants influence As concentration and speciation in soil water and soils? (5) How do the interactions between maize plants and soil microbes affect As concentration and speciation?

Materials and Methods

Greenhouse Pot Experiment

The soil for this experiment (silty loam) was taken from the uppermost 20 cm of an agricultural site in Frauenkappelen, Switzerland. The soil was then stored outside the greenhouse in the Institute of Plant Sciences at the University of Bern (Ostermundigen, Switzerland). Prior to the experiment, a six-month preliminary experiment was conducted to test the effect of the three As levels on plants. We targeted As concentrations that would show a significant effect on plant health but not kill the plants. Based on similar experiments from the literature, 0, 100 and 250 mg As kg^{-1} soil were selected for our preliminary experiment. Thus, the soils were spiked with 0, 100 and 250 mg As kg^{-1} soil, incubated for 2 months and the soil water was sampled regularly. The soil As concentrations stabilized after 2 months. After stabilization of the As concentration maize was grown. The maize plants grown at 100 mg kg^{-1} soils grew well, showing only minor effects. However, the health of maize grown at 250 mg kg^{-1} was strongly affected. Some of the plants died and the plant heights were generally very low. As a result, we decided to apply 200 mg kg^{-1} as the third As group for our main experiment.

For the greenhouse pot experiment, around 800 kg of soil were sampled and sieved to 1 cm. This experiment included a total of 18 different groups: three soil treatments (native soil (NS), reconditioned soil (RS) and disturbed soil (DS)) × three soil As levels (As_0, As_{100} and As_{200}, namely addition of 0, 100 and 200 mg As kg^{-1} soil) × two crop scenarios (with no plant (No-plant) and with plant (Plant)). Three replicates in unplanted pots and ten replicates in planted pots were established (Fig. 1). Soils in the As_0 group were not spiked with As and had a natural concentration of 2.91 ± 0.54 mg kg^{-1}. For As_{100} and As_{200} groups, around 510 kg of soils were spiked with sodium arsenate ($Na_2HAsO_4 \cdot 7H_2O, \geq 98.0\%$; Sigma-Aldrich®, CH) to enrich an additional 100 and 200 mg kg^{-1} of As in soils. The soils were incubated at room temperature for two months at 50% water holding capacity (WHC), simulating soil aging and allowing for As equilibration between soil water and soil phases (Song et al. 2006).

Afterwards, soils in the three As treatments were further subdivided into three subgroups for the three soil treatments. The first subgroup was kept untreated and named native soil (NS). The second and third segments were sterilized by X-ray (25 kGy minimum to 60 kGy maximum at Synergy Health Däniken AG, Switzerland). Due to these concomitant abiotic and microbial changes of soil sterilization, a treatment with reconditioned soil (RS) was performed to disentangle microbial effects on As speciation. A soil microbial extract was applied on the sterilized soils, making the soils independent of abiotic changes caused by soil sterilization. The third part (without microbial reconditioning) was referred to as disturbed soil (DS). Due to the presence of microbes in the greenhouse and potential microbial recolonization, DS was not assumed to be free of microbes, but rather to have a disturbed microbial composition.

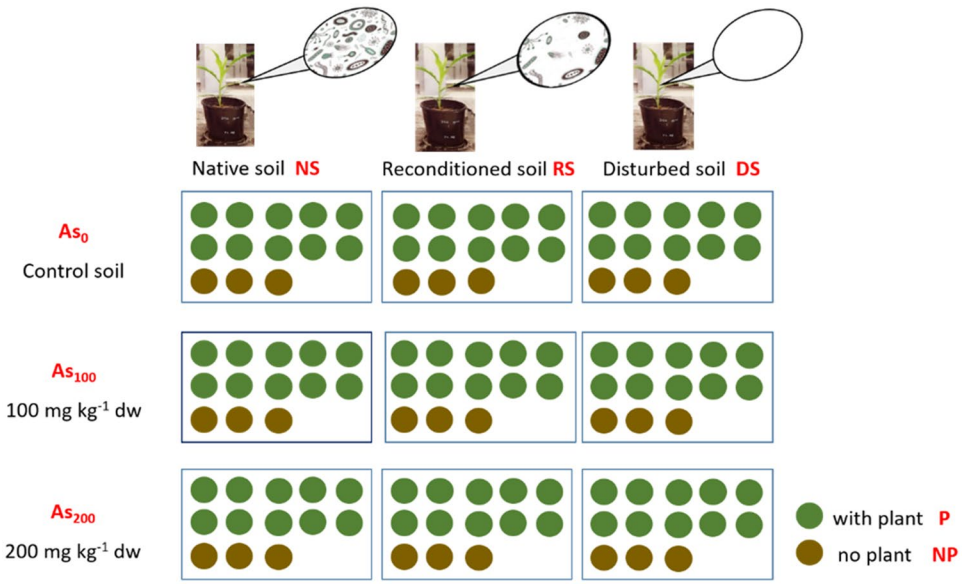

Fig. 1 Overview of the experimental design

The microbial extracts for the RS treatment were obtained by mixing 70 kg of native soils entirely with 70 L of Milli-Q water (> 18.2 MΩ cm at 25 °C) in a pre-sterilized concrete mixer (pre-sterilized with ethanol and a gas burner) (Fig. S1). The solutions were left to stand for 2 h and filtered through a 250 µm stainless sieve and 25 µm filter papers (Whatman®, CH). Lastly, 800 mL of the microbial extracts were added sequentially to RS. This method was adopted from the literature (Hu et al. 2018), allowing us to achieve an approximate microbial structure in RS as in NS. The microbial extracts still contained nematodes, arbuscular mycorrhizal spores and suspended microbes after filtration (Hu et al. 2018). The detailed characterizations of NS and DS can be found in Table S1.

The abiotic sterilization effect was the same between RS and DS, while the microbial disturbance by soil sterilization was partly eliminated in the RS treatment due to the reconditioning with microbial extracts. Therefore, it was assumed that the difference between RS and DS showed the microbial disturbance effect, and the difference between NS and RS reflected the abiotic sterilization effect. All soils were adequately homogenized. Each pot (7 L) was filled with 6.5 kg of soils and reached the same height to ensure a uniform bulk density of soils. In the end, 90 pots with maize plants and 27 pots without maize were cultivated from April to September 2019.

Maize Cultivation

Maize seeds (*Zea mays* L., W22 genotype) were soaked for 6 min in a commercial bleach containing 5% active hypochlorite (Potz Javel-Wasser Natur, Migros, Switzerland) followed by six washes and an 8 h soak in autoclaved MilliQ-water (> 18.2 MΩ cm at 25 °C). Before sowing, one week after soil sterilization, seeds were placed overnight in plastic Petri plates (Petri dish 94 × 16 mm, without vents, sterile, Greiner Bio-One, Switzerland) with moist filter papers (Rundfilter Sorte 1 Whatman, 90 mm, Huberlab, Switzerland). Each pot was initially sown with three pre-sterilized maize kernels and only the best performing seedling was kept per pot for further growth. To minimize the difference in growth conditions among treatments, all pots were initially randomly placed in the greenhouse. In the beginning, maize plants were watered weekly by weighing pots and adjusting the WHC to 50%. From the third month of growth, maize was watered more frequently as they needed more water for growth. The weekly fertilization in both No-plant and Plant pots started with 100 mL of 2 g L^{-1} complex fertilizer (Plantaktiv Starter 151, Hauert®) plus a 0.25 g of low iron ingredient (Sequestrene Rapid, Maag®), increasing to 200 mL complex fertilizer with a 0.5 g of high iron ingredient after one month. The complex fertilizer mainly contained 52% phosphate (P_2O_5), 10% total nitrogen (8.4% NH_3-N and 1.4% NO_3-N) and 10% potassium oxide (K_2O).

Additionally, a side experiment was conducted to estimate the fresh biomass of maize during growth, while maintaining the same WHC in the soil (50%) by controlling the weight of all pots. In this experiment, 60 maize plants were grown for five months and three of them were harvested weekly to determine their fresh biomass. Maize images were simultaneously recorded to derive the green pixels area of leaves. Therefore, a linear model could be built between the calculated biomass and the leaf area to estimate the maize's actual fresh biomass (Fig. S2) (Neumann et al. 2015; Valasek and Thomasson 2016). The estimated fresh biomass was then

applied to calculate the amount of irrigation water to correct pot weight to retain 50% of WHC.

Sample Preparations and As Analysis

The soil pore water sampler (0.15 µm pore size, Rhizosphere Research Products) was installed in a hole located 2 cm above the level of the pot saucer (details see Fig. S3). The tip of the sampler reached the center of the pot close to the rhizosphere. 30 mL syringes were connected to the samplers and fixed with a wooden stick to suck the soil water overnight at a low pressure. The soil water was sampled biweekly and divided into four sets of aliquots. In the first set of aliquots, pH was immediately measured using a WTW SenTix® Mic pH micro combination electrode (pH electrode; Xylem™, Rye Brook, NY). In the second set of aliquots, major cations and anions were analyzed by the Dionex™ Aquion™ Ion Chromatography System (IC; Thermo Fisher Scientific, Waltham, MA), including Na^+, NH_4^+, K^+, Mg^{2+}, Ca^{2+}, F^-, Cl^-, NO_2^-, NO_3^-, PO_4^{3-} and SO_4^{2-}. The third set was analyzed for DOC concentrations by the vario TOC cube (TOC analyzer; Elementar, Langenselbold, DE).

The last set of aliquots was spiked with 1% (v/v) of 14.65 M nitric acid (HNO_3; VWR®, Switzerland) and stored at 4 °C prior to the multielement analysis by inductively coupled plasma mass spectrometry (ICP-MS; 7700 × Agilent Technologies, Santa Clara, CA). The multielement analysis with ICP-MS concluded totAs, B, Al, V, Cr, Mn, Co, Ni, Cu, Zn, Ga, Se, Rb, Ag, Cd, Cs, Ba, Ti, Pb and U. In the As speciation analysis, 250 µL soil water was spiked with 50 µL H_2O_2 and 200 µL 1% (v/v) of 14.65 M HNO_3 (VWR®, Switzerland), and stored at 4 °C maximum for 1 week before the analysis by high-performance liquid chromatography (HPLC; 1200 Infinity, Agilent Technologies, Santa Clara, CA) coupled to ICP-MS. Due to the addition of H_2O_2 and HNO_3, all trivalent As species were oxidized and all determined As species were pentavalent. Arsenic species were separated into inorganic As species (inAs or As^V) and organic As species (orgAs, including MMA^V, DMA^V, TMAO and unknown species) using a Hamilton PRP-X100 anion-exchange column (4.1 × 50 mm, 5 µm). An example chromatogram for soil water is given in Fig. S4. The operating parameters for HPLC are listed in Table S2 and adapted from the literature (Jackson 2015).

Bulk soils (3.6 g) were taken monthly from pot edges with a small auger to measure their As speciation. The soils were air-dried at room temperature, sieved to 2 mm, and ground into powders by a Retsch MM400 Mixer Mill (Retsch GmbH, Haan, D). Afterwards, 0.2 g of ground soil powder was mixed with 4.8 mL of 1% (w/w) subboiled HNO_3 and 0.2 mL of 30% (w/w) peroxide (Suprapur H_2O_2; Sigma-Aldrich®, CH), left for at least 30 min at room temperature before conducting an open-vessel microwave digestion (95 °C for 30 min) (Microwave Digestion System MARS™ 6; CEM GmbH, Kamp-Lintfort, DE) (Norton et al. 2013). After extraction, the solutions were centrifuged at 2500 RPM for 5 min, filtered with a 0.22 µm hydrophilic Polytetrafluoroethylene Filter (13 mm syringe filter, BGB®, CH), diluted if needed, and stored at 4 °C for less than one week before the analysis with HPLC-ICP-MS. The column recovery for bulk soils was 91 ± 15% (n = 28). Triplicates of certified reference materials (CRMs) and blanks were extracted and measured together with the soil samples. The CRM ERM®- BC211 Rice was utilized and the percentage recoveries of acid extraction for inAs and DMA^V in CRMs were 70 ± 8% (n = 12) and 100 ± 3% (n = 12), respectively.

Statistical Analysis

All the statistical analysis was performed in R software (version 1.2.5033) including the following packages: car, multcomp, emmeans and vegan. The concentrations of total As (totAs) and As species in soil water (Table S3) and in soils (Table S6) were Log10-transformed to improve normality and analyzed using linear mixed effects models. The experimental factors were soil sterilization (three levels: NS, DS and RS), As treatments (three levels: As_0, As_{100} and As_{200}), crop scenarios (two levels: No-plant and Plant) and time as well as their interactions. The interactions stand for the combined effects of the experimental factors on the response variables, e.g., totAs concentrations in soil water. The estimated marginal means (in the *emmeans* package) were calculated for the post-hoc analysis. The emmeans, formerly known as least-squares means in the context of traditional regression models, are derived to make predictions using a model. These predictions are typically averaged with equal weights across one or more predictors. Such marginally averaged predictions are helpful in describing the results of fitting a model, particularly when presenting factor effects. The compact letter display (CLD; in the multcomp package) was used to visually report the pairwise comparisons. Groups with the same CLD letters did not differ significantly, whereas groups that significantly differed had different CLD letters. For multiple As species (multiple-dependent variables), the multivariate analysis of variance (MANOVA) was applied to the comparison of multivariate sample means in soil water and in soils, studying interaction effects and single effects of the four experimental factors on single As species (Table S5). The original data emmeans are listed in the supplementary document (Tables S4 and S7).

Results

Total As and Inorganic As Species in Soil Water

Significant interactions among the three experimental factors (microbial disturbance, soil As levels and plant scenarios) were observed in six out of our eight cases (details see Tables S3, S5 and S6). The interactions among the three experimental factors significantly affected total As (totAs) concentrations in soil water ($F_{4, 587} = 6.506$, $p < 0.001$) (Table S3). Regarding the effects of single experimental factors, the abiotic sterilization effect could be observed by the difference between NS and RS, resulting in higher totAs concentrations in the soil water of RS than of NS in the As_0 group and in No-plant pots of the As_{100} group. The microbial disturbance effect increased totAs concentrations in soil water ($F_{2, 587} = 105.286$, $p < 0.001$). As the microbial disturbance increased, totAs concentrations in soil water increased following the pattern NS < RS ≤ DS (Fig. S5 and Table S4). In uncontaminated soils (As_0 group), totAs concentrations in the soil water was lower in No-plant than in Plant pots. Conversely, in contaminated soils (As_{100} and As_{200} group), totAs concentrations were consistently higher in No-plant than in Plant pots, i.e., Plants decreased totAs concentrations in soil water ($F_{1, 587} = 3.97$, $p = 0.047$). The totAs levels were higher in the soil water of DS than of RS in No-plant pots of the As_0 group (Fig. 2a). The totAs and inAs concentrations in the soil water of RS and DS decreased in the first 2 months in all three As groups ($F_{11, 587} = 67.4$, $p < 0.001$) (Fig. S5 and S6). In contrast, totAs concentrations in the soil water of NS were temporarily stable in the absence of microbial disturbance.

The inAs levels in soil water changed over time ($F_{11, 545} = 8.170$, $p < 0.001$). Microbial disturbance increased inAs concentrations in the soil water of contaminated RS and DS. Their concentrations increased in the first two months of the experiment and then decreased, while inAs levels in the soil water of NS remained stable over time (Fig. S6). In uncontaminated soils, No-plant and Plant pots had a similar range of inAs concentrations in soil water, whereas inAs levels in contaminated soils were sometimes lower in the presence of plants.

Organic As Species in Soil Water

The abiotic sterilization effect resulted in higher orgAs concentrations in the soil water of RS than of NS, and still affected orgAs but not inAs at the high soil As level (200 mg kg^{-1}). The microbial disturbance increased orgAs concentrations (sum of MMA^V, DMA^V, TMAO and three unknown species) in soil water ($F_{2, 545} = 87.929$, $p < 0.001$). Due to the microbial disturbance effect, orgAs concentrations were higher in the soil water of RS than of DS in No-plant pots (Fig. 3a). While NS had the lowest orgAs concentrations in the soil water of both No-plant and Plant pots. The orgAs concentrations decreased over time in contaminated soil water, while it remained stable in uncontaminated soil water (Fig. S7). In both the uncontaminated and contaminated soils, the presence of plants decreased orgAs concentrations in soil water (Plant ≤ No-plant) ($F_{1, 545} = 7.432$, $p = 0.007$). Moreover, the microbial disturbance effect increased orgAs% in soil water ($F_{2, 545} = 47.777$, $p < 0.001$), leading to higher orgAs% in the soil water of RS than DS in No-plant pots of the As_{200} group (Fig. 3b). In contaminated soils, RS soil water had higher orgAs% than that of NS. Moreover, orgAs% in soil water decreased with the increasing As levels in soils. It ranged from 26.8 to 91.7% in the As_0 group and was lower in the As_{100} group (0.12–31.3%) and lowest in the As_{200} group (0.10–8.67%).

In addition, all effects were examined on the three single orgAs (MMA^V, DMA^V and TMAO) in soil water. The interactions between microbial disturbance and As levels or between As levels and plant scenarios significantly affected the concentrations of inAs, DMA^V and TMAO ($p < 0.001$), but not of MMA^V (Table S3). Only MMA^V concentrations were affected by the interactions between microbial disturbance and plant scenarios ($p < 0.001$). Organic As species showed a concentration trend of $MMA^V < DMA^V <$ TMAO in soil water, increasing from NS to RS to DS (Fig. S8). The abiotic sterilization effect was significant in both No-plant and Plant pots for TMAO as well as in No-plant pots of MMA^V and DMA^V, whereas the microbial disturbance effect was not observed in Plant pots for single orgAs.

Arsenic Speciation in Soils

As in the soil water, the same three orgAs i.e., MMA^V, DMA^V and TMAO were found in soils. The three-way interactions among the microbial disturbance, soil As levels and plant scenarios were insignificant for all As species in soils (Fig. 4a and Table S5). Only MMA^V concentrations were affected by the interactions between microbial disturbance and As levels ($F_{4, 294} = 2.945$, $p = 0.021$) (Table S6), showing higher concentrations in RS than in NS ($F_{2, 294} = 3.935$, $p = 0.021$) (Fig. S9). The orgAs% in soils decreased with the increasing As levels in soils (Fig. 4b).

The orgAs% in soil water and soils varied only slightly between No-plant and Plant pots (Figs. 3b and 4b) and is thus not discussed separately here. OrgAs were the dominant form of As in uncontaminated soil water, with unknown species being the main composition and the three organic species i.e., MMA^V, DMA^V and TMAO accounting

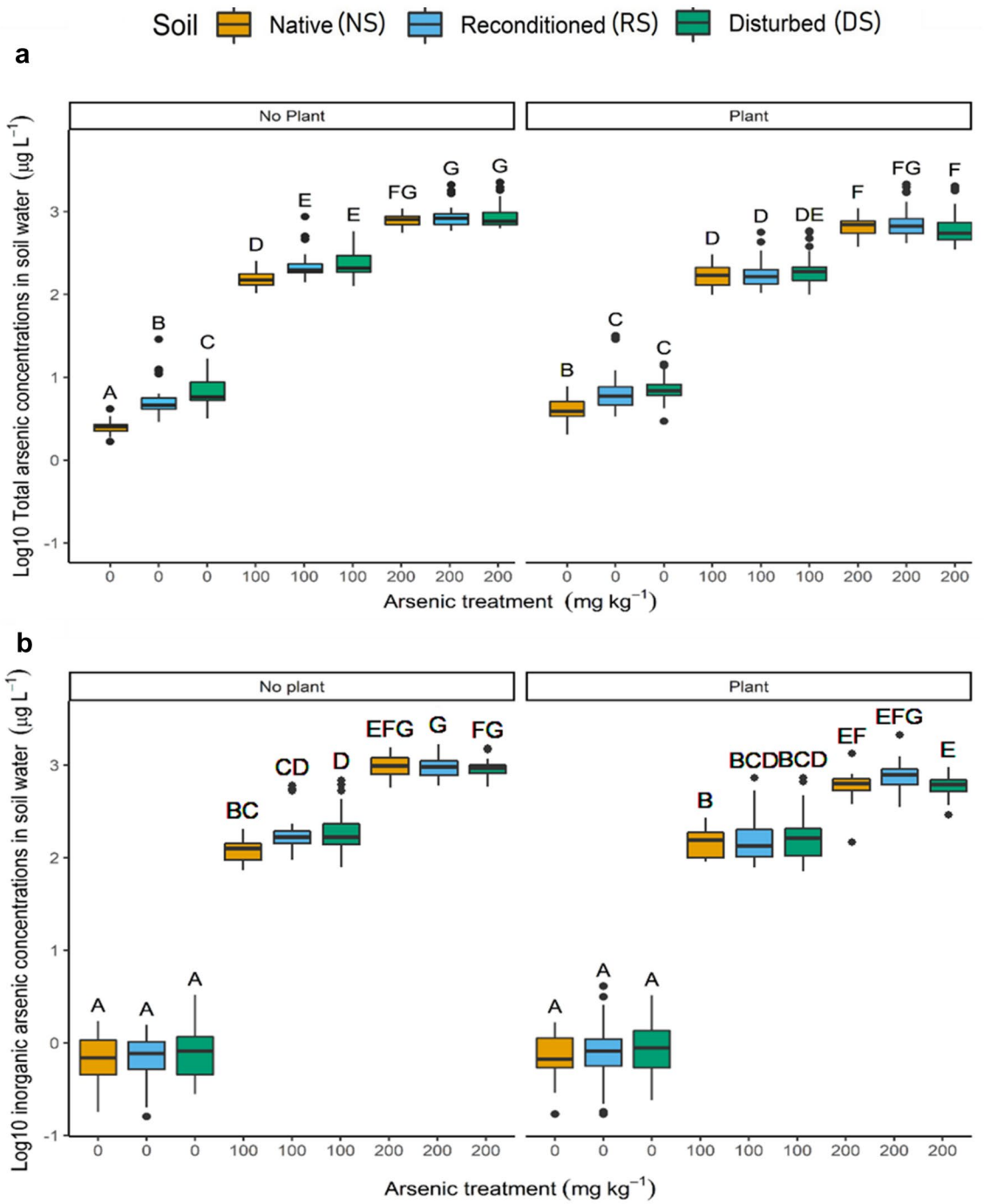

Fig. 2 The concentrations of **a** total As (totAs) and **b** inorganic As species (inAs) in soil water. Data were the estimated marginal means (emmeans) ± standard error. Pairwise comparisons were explored and reported using CLD letters. Different letters indicated a statistically significant difference between emmeans ($p < 0.05$)

for similar proportions (Fig. 5a). OrgAs decreased with rising As levels in both soil water and soils (Fig. 5b). In soils, inAs were the predominant species (> 96.8%) with DMA^V as the major orgAs (Fig. 5c and d).

Other Chemical Parameters in Soil Water

The redundancy analysis (RDA) was applied to explore the effects of experimental factors (microbial disturbance, soil As levels and plants scenarios) (Fig. 6a) on

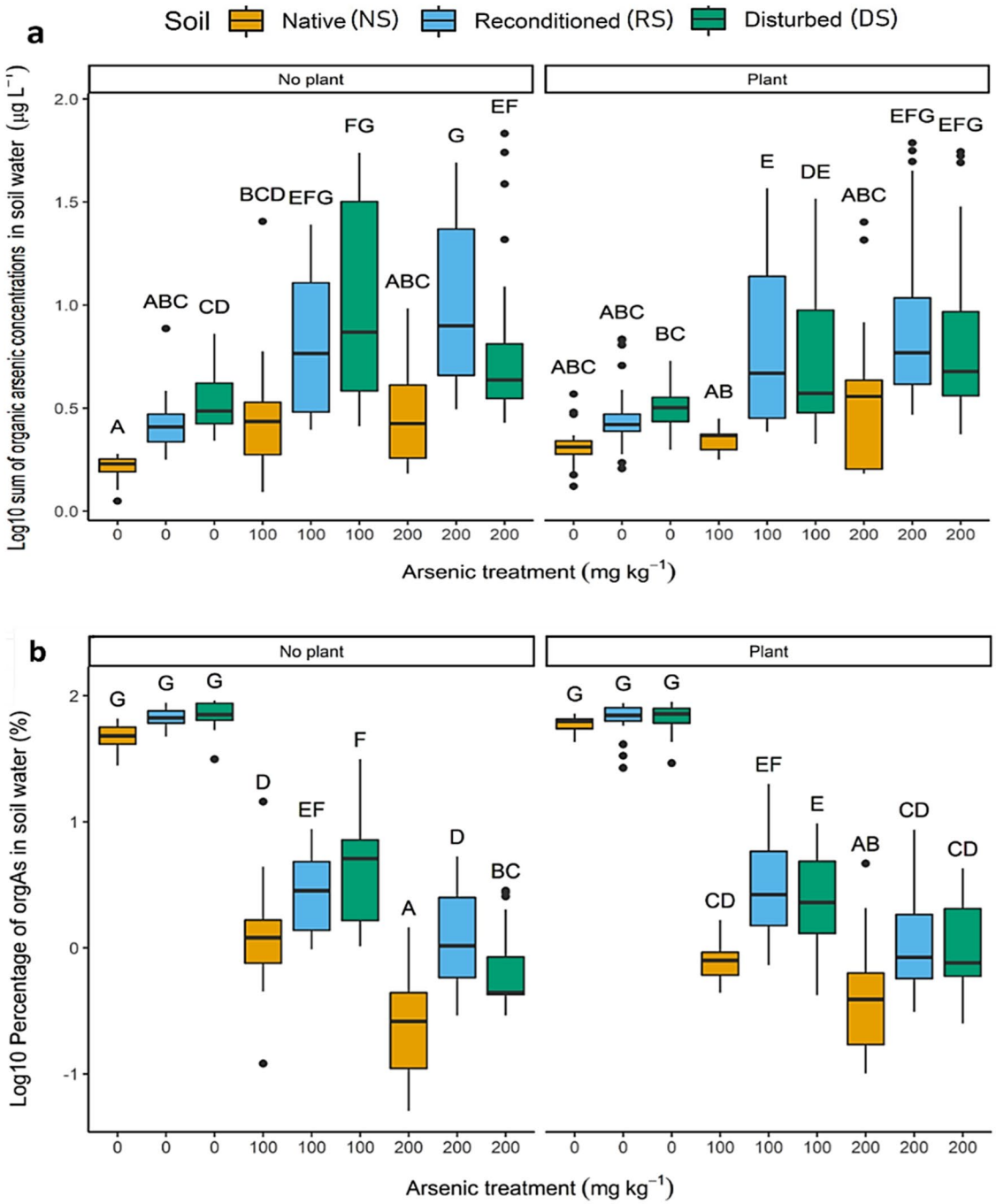

Fig. 3 The plot of **a** concentrations of the sum of organic As species and **b** percentage of orgAs (orgAs%) in soil water. Data were emmeans ± standard error. Pairwise comparisons were explored and reported using CLD letters. Different CLD letters indicated a statistically significant difference between emmeans ($p < 0.05$)

the corresponding changes in response variables. Response variables comprised soil water chemistry parameters, i.e., pH, DOC, major cations and anions as well as some major and trace elements (Fig. 6b). The RDA model explained 35% of the variations in soil water chemistry data, with RDA1 and RDA2 explaining 28% of the data. The three experimental factors, i.e., microbial disturbance, soil As levels and plants scenarios, all had a significant effect on the multiple response variables ($F_{10,\ 241} = 14.680$, $p < 0.001$) with adjusted R^2 values of 8.95%, 5.37% and 11.85%, respectively. Parameters with arrows pointing in the same direction in an RDA graph indicate positive

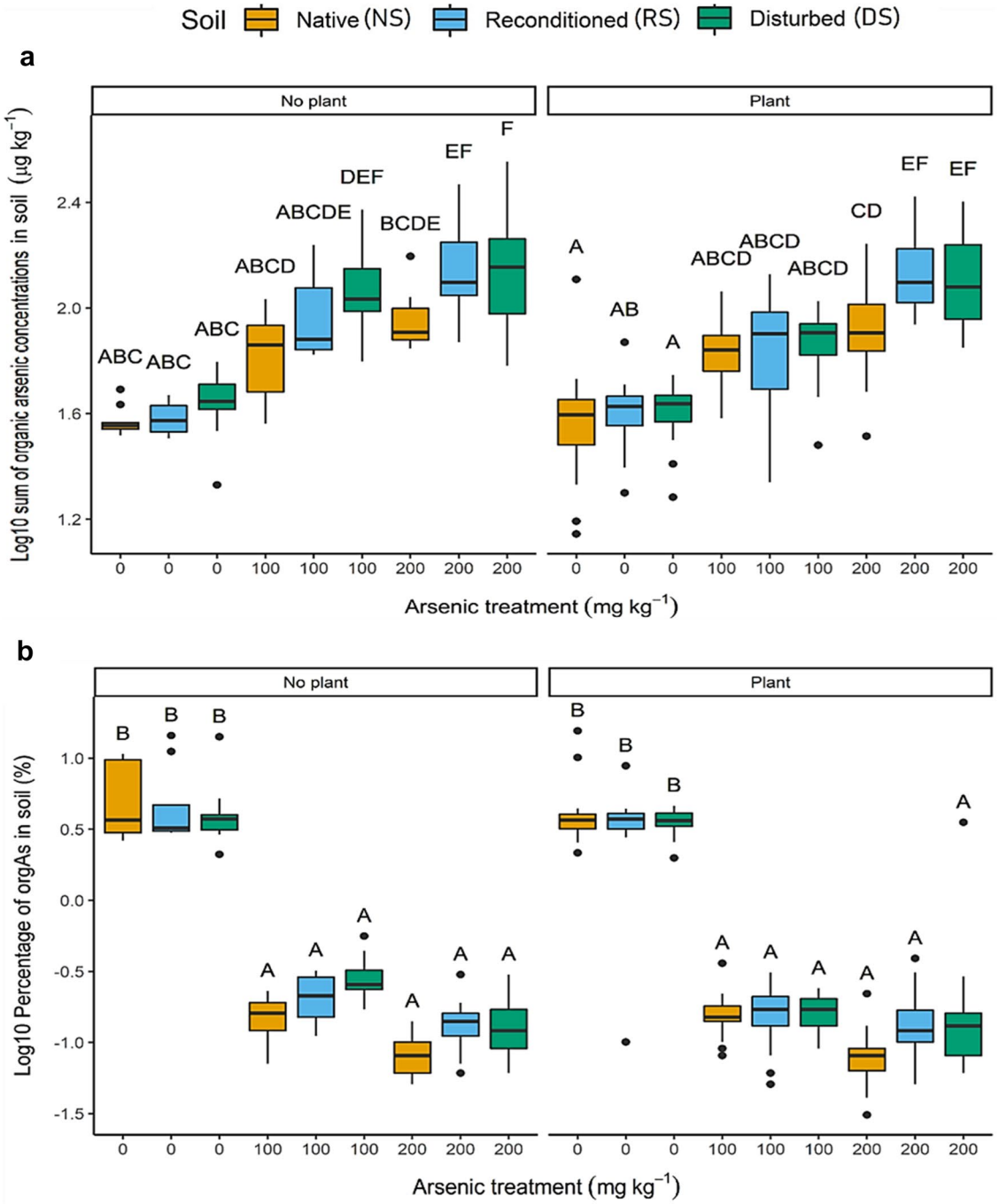

Fig. 4 The plot of **a** concentrations of the sum of organic As species and **b** percentage of orgAs (orgAs%) in soils. Data were emmeans ± standard error. Pairwise comparisons were explored and reported using CLD letters. Different CLD letters indicated a statistically significant difference between emmeans ($p < 0.05$)

associations, and arrows pointing in opposite directions indicate negative associations between them. The RS and DS and As_{100} and As_{200} groups pointed in the same direction as the concentrations of DOC, V, Ba, Na^+, NO_3^-, K^+ and Mg^{2+} on the RDA plot, which can be interpreted in a way that soil disturbance by sterilization or high As increased the concentrations of these parameters in soil water. In the opposite, RS and DS and As_{100} and As_{200} groups showed a negative association with the values of pH, Zn, Cr, Al, Cu, Ni, Ca^{2+}, Cl^-, SO_4^{2-} and U in soil water, indicating a decrease of these parameters in the soil solution as a result of disturbance. Meanwhile, the

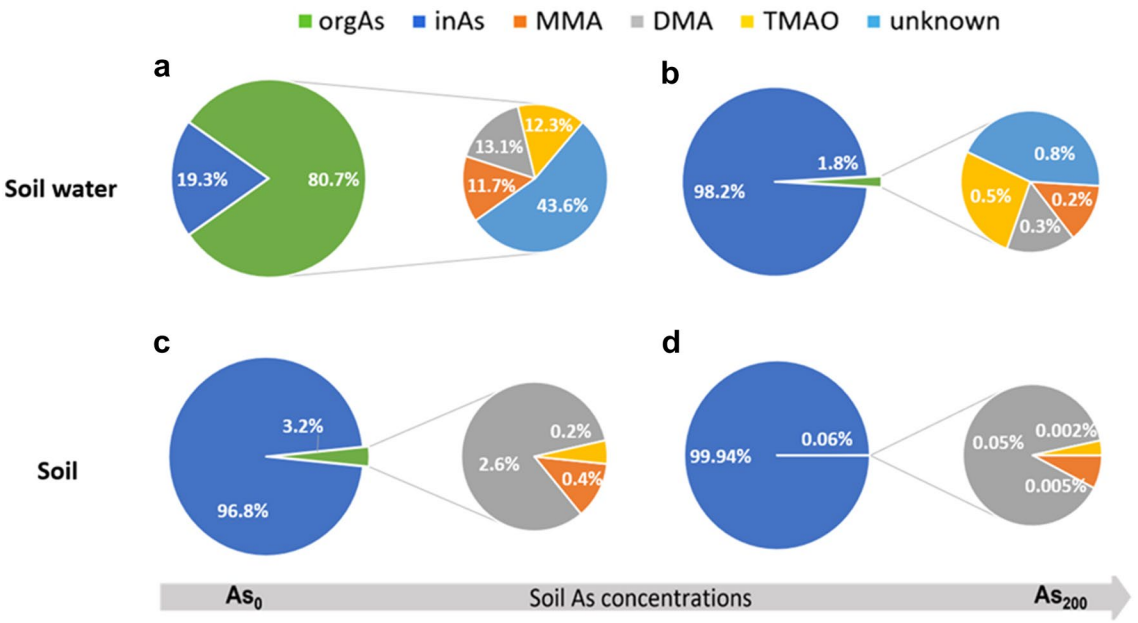

Fig. 5 The changes in As species in soil water and in soils of the Plant pots with the increasing As levels in soils, presenting the percentages of inorganic As species (inAs%) and orgAs (orgAs%, i.e., MMA^V, DMA^V, TMAO and unknown species) in **a** soil water of NS of the As_0 group; **b** soil water of NS of the As_{200} group; **c** NS of the As_0 group; and **d** NS of the As_{200} group

experimental factor plants (P_or_NP) pointed in the opposite direction than the microbial disturbance and As levels.

In all the three As groups, DOC levels in soil water from NS were lower than those from DS and RS (Fig. S10). Only in uncontaminated soil water, DOC levels correlated strongly with totAs ($R = 0.82$, $p < 0.001$) and orgAs ($R = 0.69$, $p < 0.001$) (Fig. S11). In uncontaminated soils, No-plant pots had a lower pH than Plant pots in NS and RS ($p < 0.05$). In contaminated soils, the pH difference between No-plant and Plant pots was less prominent and only significant in NS of the As_{100} group ($p = 0.003$).

Discussion

Abiotic Sterilization Effect on As Concentrations and Speciation in the Soil Environment

The abiotic effect of soil sterilization is a side effect of our experimental design, because it is impossible to sterilize soils without abiotic effects (McNamara et al. 2003). Thus, the observed sterilization effects need to be resolved to differentiate them from the microbial disturbance effect. In this study, totAs and As species in soil water showed higher concentrations in RS than in NS, suggesting that the abiotic sterilization effect promoted As release into soil water. This is because the immobilization of As by sorption on soils is reversible and the remobilization of adsorbed As may occur when the physicochemical conditions of soils are changed by sterilization (Wang and Mulligan 2006). Soil sterilization can also alter the sorption behavior of As due to changed soil pH (Dao et al. 1982; Razavi 2007) and ion competition e.g., with nutrients like phosphorus for sorption sites (Hongshao and Stanforth 2001; Tiberg et al. 2020). The DOC and other nutrients increased in our soil water, as microbes released their cellular compounds during soil sterilization. Increased DOC in soil water can compete with As for sorption sites on soils or complex As, leading to enhanced As mobilization (Schaller et al. 2011). Arsenic concentrations in the soil water declined in the first month of our experiment, which could be due to the re-equilibrium of As adsorption on soils after the initial sterilization.

The DOC concentrations have been observed to be positively correlated with orgAs concentrations in soil water up to 20 μg L^{-1} (Williams et al. 2011; Zhao et al. 2013), which is close to our orgAs levels in uncontaminated soils (< 10.10 μg L^{-1}). Indeed, in our uncontaminated soil water, DOC concentrations strongly correlated with orgAs concentrations. The positive correlation with DOC concentrations was consistent with reports that organic matter can stimulate As methylation and the volatilization of methylated As species, because DOC can serve as energy and carbon source for the growth of As-methylating microbes (Huang et al. 2012; Yan et al. 2020). In contrast, in our contaminated soil water, DOC levels correlated only slightly with orgAs concentrations. Given that DOC levels were similar between un- and contaminated soil water, DOC might have played a minor role in As availability in contaminated soil

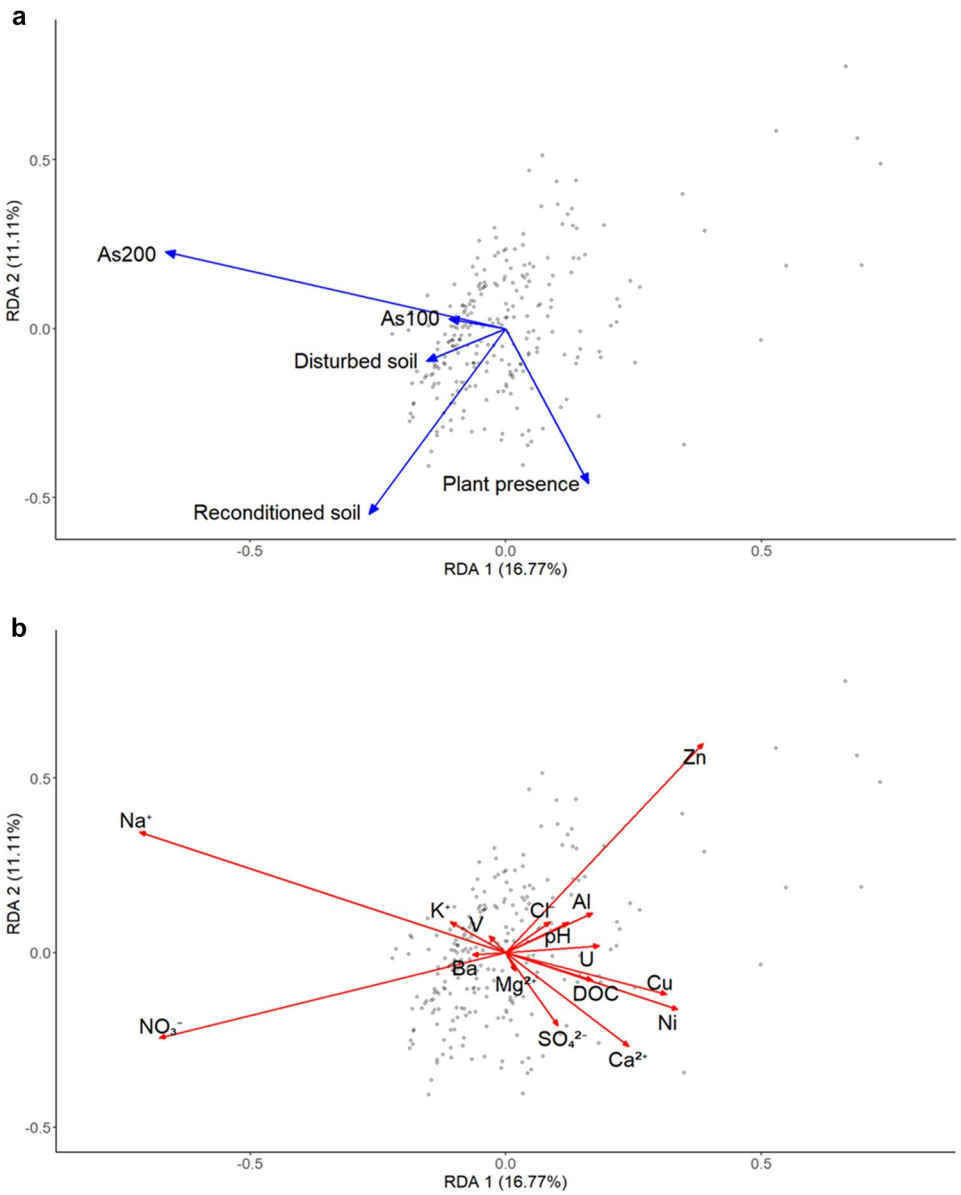

Fig. 6 Redundancy analysis (RDA) triplot showing samples as dots with **a** experimental factors (microbial disturbance, soil As levels and plants scenarios); **b** corresponding changes in response variables (soil water chemistry parameters) in the system. The percentages of explained variance were indicated on each axis

water probably due to the overprint effect of highly spiked As. The soil pH was negatively correlated with orgAs concentrations in contaminated soils, presenting an opposite pattern DS ≤ RS < NS. The same negative correlation has been found in a previous research because the activity of As methylation is higher in acidic soils (Zhao et al. 2013).

Microbial Disturbance Effect on As Concentrations and Speciation in the Soil Environment

In the present study, the microbial disturbance effect resulted in higher concentrations of totAs and orgAs in the soil water of DS than of RS (Fig. 2a). This is in line with a publication that reported the elimination of oxidizing bacteria by soil sterilization slows iron oxidation, leading to insufficient sorptive sites for As and higher As leaching in sterilized soils (Kumpiene et al. 2007). Soil sterilization causes damage to proteins by ionizing radiation, which disrupts enzyme activity and halts microbial exoenzyme production (Blankinship et al. 2014). The enzyme activities of both sterilized and reconditioned soils were lower than those of unsterilized soils (Xun et al. 2015; Gianfreda 2015). Microbial activity has been found to be negatively correlated with As mobility, demonstrating the importance of microbial activity in As immobilization in soils (Kumpiene et al. 2007). Soil sterilization might have halted enzyme and microbial activities in our experiment that are important for As immobilization in soils, which may explain higher As concentrations in soil water from the sterilization soil treatment (DS). Soil sterilization might also has disturbed or eliminated soil indigenous

microbes and inhibited their roles in the demethylation process of As, thereby increasing orgAs levels in our soil water.

Moreover, as orgAs concentrations increased in soil water and orgAs% increased in sterilized contaminated soils, together with an increase in DOC concentration because of the abiotic sterilization effect. The observed trends pointed to a higher available carbon supply for As-methylating microbes in sterilized soils (Huang et al. 2012; Yan et al. 2020). However, the microbial disturbance affected only orgAs in RS, implying that the recolonized soil microbes in RS promoted As methylation compared to the DS treatment. Other studies reported that DMA^V and TMAO are detected only in unsterilized soils but not in sterilized soils, because microbes were eliminated during soil sterilization (Ultra et al. 2007). However, in our experiment, the soils might have been recolonized fast by microbes after sterilization and the increased availability of DOC might have caused increased orgAs. Taken together, our results showed that the microbial disturbance effect led to lower totAs and orgAs concentrations in sterilized soil water.

As Level Effect on As Speciation

In this study, the orgAs% in both soil water and soils were observed to decrease with the increasing As levels in soils. This could be explained by dilution with the high amount of spiked inAs to the soils. The changes in As speciation with the increasing soil As levels were evident in soil water but not in soils. The three orgAs species (MMA^V, DMA^V and TMAO) had similar proportions in uncontaminated soil water. While in contaminated soil water, TMAO was higher than MMA^V and DMA^V, indicating that As was more methylated or that less demethylation occurred. Two unknown As species occurred in the soil water but were not detected in the soil. In both un- and contaminated soils, DMA^V was always the primary orgAs. While TMAO was predominant in the contaminated soil water, but not in soils. This might be because TMAO has three methyl groups, rendering it more mobile in soils than DMA^V. The additional methyl groups not only remove deprotonation sites from TMAO, making it less negatively charged and less electrostatic attracted, but also cause the TMAO molecule to become larger and occupy more space (Shimizu et al. 2011). Thus, As-binding in soil was weaker and more TMAO remained in soil water.

Maize Plant Effect on As Concentrations and Speciation

The maximum percentage of As uptake by plants from soils (totAs concentrations in plants/in soils) was highest in our As_0 group (1.34%), lower in the As_{100} group (0.66%), and lowest in the As_{200} group (0.28%). These low percentages were not surprising because extractable As has been known to account for only a minor proportion even in As-rich soils, as evidenced by the poor correlation ($r = 0.38$) between water extractable As (mean = 0.019 mg L^{-1}) and soil As (mean = 57.8 mg kg^{-1}) levels (Itabashi et al. 2019). In our uncontaminated soils, totAs concentrations in soil water were higher in the presence of plants (Fig. 2a), probably due to the higher pH in planted pots compared to unplanted pots (Fig. S12). Since totAs concentration has been found positively correlated with soil pH (Katsoyiannis and Katsoyiannis 2006; Podgorski et al. 2017). However, in our contaminated soils, lower concentrations of totAs were found in the soil water with plant cultivation. This could not be attributed to As uptake by plants alone, because such a low percentage of As uptake by plants could not explain the lower As levels in contaminated soil water with plant cultivation. Instead, the presence of maize plants limited the As mobilization into soil water through potential interactions with soil microbes. The details are described in the following chapter.

Plant-Microbe Interactions Reduce As Concentrations in the Soil Water

Both abiotic sterilization and microbial disturbance effects were more significant in the soil water of unplanted than of planted pots. The abiotic sterilization effects played a significant role in all groups of unplanted pots, but only in some groups of planted pots. The microbial disturbance effect was observed only in unplanted pots for totAs and orgAs concentrations. As a result, the concentration differences among the three soil treatments were generally smaller in planted than in unplanted pots, suggesting that both abiotic sterilization and microbial disturbance effects were less significant in planted than in unplanted pots. This might be explained by the mitigation effect of maize plants, which reduced As concentrations in the soil water of RS and DS, resulting in indifferent As levels among the three soils in planted pots.

Maize may help soil microbes to recover from soil sterilization (Zhalnina et al. 2018; Li et al. 2019), while reshaping their communities and favoring beneficial soil microbes (Broeckling et al. 2008). We hypothesize that maize plants can help microbes to recover from soil sterilization and recruit beneficial soil microbes via root exudations to fulfill their demands. This might have helped soil microbes to cope with As stress, leading to lower As concentrations in soil water with the presence of maize. After soil sterilization, plants can act as a filter for their own microbiome and reshape their rhizosphere microbes by helping them to recover from soil sterilization (Reinhold-Hurek et al. 2015). Depending on their structural and functional diversity in soils, plants can recruit beneficial rhizosphere communities through root exudations to adapt to environmental stress, such as aboveground pathogens (Yuan et al. 2018), plant herbivores (Hu et al. 2018) and As stress (Xiao et al. 2021). By

altering the chemical composition of the rhizosphere, plants can create diverse microhabitats and enhance their adaptability to environmental stressors (Zhalnina et al. 2018). For instance, root exudations of the As-hyperaccumulator *Pteris vittate* can mediate root microbes that play an important role in As requisition, which promotes the growth and fitness of the host plant and improve plant capability to adapt to As stress in the environment (Xiao et al. 2021). Comprehensively, the existing evidence supports our hypothesis that the presence of maize plants might have assisted soil microbes in recovering from soil sterilization, while recruiting beneficial microbes via root exudations. In return, maize plants may benefit from their recruited soil microbes in coping with As stress together. This can be considered as a survival mechanism for both maize plants and their associated soil microbes.

Conclusion

The concentrations of totAs and As species in the soil water showed that both abiotic sterilization and microbial disturbance effects enhanced the release of As from soils into soil water. Both effects had a greater impact on orgAs concentrations than inAs concentrations in soil water, which is consistent with the potential role of microbes involved in promoting As methylation. Maize plants reduced the impacts of both abiotic sterilization and microbial disturbance effects to offset rising As levels in the soil water of RS and DS. Maize grown in soils with natural As levels increased totAs concentrations in the soil water. However, when soil As levels were elevated, maize interacted with soil microbes to lower totAs concentrations in the soil water. To mitigate the impacts of microbial disturbance, maize plants likely reshaped their growing environment by assisting the recolonization of soil microbes after soil sterilization and by favoring or disfavoring soil microbes to mitigate the microbial disturbance effects. Overall, this study highlights the role of maize plants and their interactions with soil microbes in lowering As concentrations in the soil water and As bioavailability to themselves as a survival mechanism in response to As stress in the soil environment.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s12403-023-00593-6.

Acknowledgements We especially thank Patrick Neuhaus for his support in the laboratory as well as Pia Bergamaschi and Andrea Weber for their help with data collection. We would also like to thank Dr. Suyi Hu for his help with data organization and Nichole Wetter for her proofreading.

Author Contributions HG: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data curation, Writing—Original draft, Visualization, Project administration. VC: Investigation, Writing—Review and Editing. AGC: Formal analysis, Writing—Review and Editing. DF: Methodology. MCC and XL: Investigation. TCC: Methodology, Writing—Review and Editing. AR: Conceptualization, Formal analysis, Writing—Review and Editing. KS: Conceptualization, Resources, Writing—Review and Editing. AM: Methodology, Conceptualization, Supervision, Funding acquisition, Writing—Review and Editing. MB: Conceptualization, Methodology, Supervision, Writing—Review and Editing, Funding acquisition, Project administration.

Funding Open Access funding enabled and organized by Projekt DEAL. This research was financially supported by the University of Bern through the Interfaculty Research Cooperation One Health (https://www.onehealth.unibe.ch/).

Data Availability The data used in the manuscript will be made available from the corresponding author of the manuscript on request.

Declarations

Conflict of interest The authors declare that they have no conflicts of interest.

References

Ahemad M (2019) Remediation of metalliferous soils through the heavy metal resistant plant growth promoting bacteria: paradigms and prospects. Arab J Chem 12:1365–1377. https://doi.org/10.1016/j.arabjc.2014.11.020

Anand V, Kaur J, Srivastava S, Bist V, Singh P, Srivastava S (2022) Arsenotrophy: a pragmatic approach for arsenic bioremediation. J Environ Chem Eng 10:107528. https://doi.org/10.1016/j.jece.2022.107528

Berns PH, Narres HD, Burauel P, Vereecken H, Tappe W (2008) Effect of gamma-sterilization and autoclaving on soil organic matter structure as studied by solid state NMR, UV and fluorescence spectroscopy. Eur J Soil Sci 59:540–550. https://doi.org/10.1111/j.1365-2389.2008.01016.x

Blankinship JC, Becerra CA, Schaeffer SM, Schimel JP (2014) Separating cellular metabolism from exoenzyme activity in soil organic matter decomposition. Soil Biol Biochem 71:68–75. https://doi.org/10.1016/j.soilbio.2014.01.010

Blute NK, Brabander DJ, Hemond HF, Sutton SR, Newville MG, Rivers ML (2004) Arsenic sequestration by ferric iron plaque on cattail roots. Environ Sci Technol 38:6074–6077. https://doi.org/10.1021/es049448g

Broeckling CD, Broz AK, Bergelson J, Manter DK, Vivanco JM (2008) Root exudates regulate soil fungal community composition and

diversity. Appl Environ Microbiol 74:738–744. https://doi.org/10.1128/AEM.02188-07
Buschmann J, Kappeler A, Lindauer U, Kistler D, Berg M, Sigg L (2006) Arsenite and arsenate binding to dissolved humic acids: influence of pH, type of humic acid and aluminum. Environ Sci Technol 40:6015–6020. https://doi.org/10.1021/es061057
Colombo C, Palumbo G, He JZ, Pinton R, Cesco S (2014) Review on iron availability in soil: interaction of Fe minerals, plants and microbes. J Soils Sediments 14:538–548. https://doi.org/10.1007/s11368-013-0814-z
Danouche M, El Ghachtouli N, El Arroussi H (2021) Phycoremediation mechanisms of heavy metals using living green microalgae: physicochemical and molecular approaches for enhancing selectivity and removal capacity. Heliyon 7:e07609. https://doi.org/10.1016/j.heliyon.2021.e07609
Dao TH, Marx DB, Lavy TL, Dragun J (1982) Effect and statistical evaluation, of soil sterilization on aniline and diuron adsorption isotherms. Soil Sci Soc Am J 46:963–969. https://doi.org/10.2136/sssaj1982.03615995004600050016x
Del Molina MC, White JF, García-Salgado S, Quijano MÁ, González-Benítez N (2020) A gnotobiotic model to examine plant and microbiome contributions to survival under arsenic stress. Microorganisms. https://doi.org/10.3390/microorganisms9010045
Diels L, Spaans PH, van Roy S, Hooyberghs L, Ryngaert A, Wouters H, Walter E, Winters J, Macaskie L, Finlay J, Pernfuss B, Woebking H, Pümpel T, Tsezos M (2003) Heavy metals removal by sand filters inoculated with metal sorbing and precipitating bacteria. Hydrometallurgy 71:235–241. https://doi.org/10.1016/S0304-386X(03)00161-0
Dobran S, Zagury GJ (2006) Arsenic speciation and mobilization in CCA-contaminated soils: influence of organic matter content. Sci Total Environ 364:239–250. https://doi.org/10.1016/j.scitotenv.2005.06.006
Emerson D, Weiss JV, Megonigal JP (1999) Iron-oxidizing bacteria are associated with ferric hydroxide precipitates (Fe-plaque) on the roots of wetland plants. Appl Environ Microbiol 65:2758–2761. https://doi.org/10.1128/AEM.65.6.2758-2761.1999
Fisher DJ, Yonkos LT, Staver KW (2015) Environmental concerns of roxarsone in broiler poultry feed and litter in Maryland, USA. Environ Sci Technol 49:1999–2012. https://doi.org/10.1021/es504520w
Garcia-Manyes S (2002) Arsenic speciation in contaminated soils. Talanta 58:97–109. https://doi.org/10.1016/S0039-9140(02)00259-X
Garcia-Manyes S, Jiménez G, Padró A, Rubio R, Rauret G (2002) Arsenic speciation in contaminated soils. Talanta 58:97–109
Geiszinger A, Goessler W, Kosmus W (2002) Organoarsenic compounds in plants and soil on top of an ore vein. Appl Organometal Chem 16:245–249. https://doi.org/10.1002/aoc.294
Gianfreda L (2015) Enzymes of importance to rhizosphere processes. J Soil Sci Plant Nutr. https://doi.org/10.4067/S0718-95162015005000022
Hammond CM, Root RA, Maier RM, Chorover J (2018) Mechanisms of arsenic sequestration by *Prosopis juliflora* during the phytostabilization of metalliferous mine tailings. Environ Sci Technol 52:1156–1164. https://doi.org/10.1021/acs.est.7b04363
Hinsinger P, Bengough AG, Vetterlein D, Young IM (2009) Rhizosphere: biophysics, biogeochemistry and ecological relevance. Plant Soil 321:117–152. https://doi.org/10.1007/s11104-008-9885-9
Hong YS, Song KH, Chung JY (2014) Health effects of chronic arsenic exposure. J Prev Med Public Health 47:245–252. https://doi.org/10.3961/jpmph.14.035
Hongshao Z, Stanforth R (2001) Competitive adsorption of phosphate and arsenate on goethite. Environ Sci Technol 35:4753–4757. https://doi.org/10.1021/es010890y
Hu M, Li F, Liu C, Wu W (2015) The diversity and abundance of As(III) oxidizers on root iron plaque is critical for arsenic bioavailability to rice. Sci Rep 5:13611. https://doi.org/10.1038/srep13611
Hu L, Robert CAM, Cadot S, Zhang X, Ye M, Li B, Manzo D, Chervet N, Steinger T, van der Heijden MGA, Schlaeppi K, Erb M (2018) Root exudate metabolites drive plant-soil feedbacks on growth and defense by shaping the rhizosphere microbiota. Nat Commun 9:2738. https://doi.org/10.1038/s41467-018-05122-7
Huang JH, Hu KN, Decker B (2011) Organic arsenic in the soil environment: speciation, occurrence, transformation, and adsorption behavior. Water Air Soil Pollut 219:401–415. https://doi.org/10.1007/s11270-010-0716-2
Huang H, Jia Y, Sun GX, Zhu YG (2012) Arsenic speciation and volatilization from flooded paddy soils amended with different organic matters. Environ Sci Technol 46:2163–2168. https://doi.org/10.1021/es203635s
Itabashi T, Li J, Hashimoto Y, Ueshima M, Sakanakura H, Yasutaka T, Imoto Y, Hosomi M (2019) Speciation and fractionation of soil arsenic from natural and anthropogenic sources: chemical extraction, scanning electron microscopy, and micro-XRF/XAFS investigation. Environ Sci Technol 53:14186–14193. https://doi.org/10.1021/acs.est.9b03864
Jackson B (2015) Fast ion chromatography-ICP-QQQ for arsenic speciation. J Anal at Spectrom 30:1405–1407. https://doi.org/10.1039/C5JA00049A
Jackson BP, Seaman JC, Bertsch PM (2006) Fate of arsenic compounds in poultry litter upon land application. Chemosphere 65:2028–2034. https://doi.org/10.1016/j.chemosphere.2006.06.065
Jia Y, Sun GX, Huang H, Zhu YG (2013a) Biogas slurry application elevated arsenic accumulation in rice plant through increased arsenic release and methylation in paddy soil. Plant Soil 365:387–396. https://doi.org/10.1007/s11104-012-1391-4
Jia Y, Huang H, Zhong M, Wang FH, Zhang LM, Zhu YG (2013b) Microbial arsenic methylation in soil and rice rhizosphere. Environ Sci Technol 47:3141–3148. https://doi.org/10.1021/es303649v
Kabiraj A, Biswas R, Halder U, Bandopadhyay R (2022) Bacterial arsenic metabolism and its role in arsenic bioremediation. Curr Microbiol 79:131. https://doi.org/10.1007/s00284-022-02810-y
Katsoyiannis IA, Katsoyiannis AA (2006) Arsenic and other metal contamination of groundwaters in the industrial area of Thessaloniki, Northern Greece. Environ Monit Assess 123:393–406. https://doi.org/10.1007/s10661-006-9204-y
Kowalczyk A, Latowski D (2018) Role of plant-microorganism interactions in plant tolerance to arsenic. Mechanisms of arsenic toxicity and tolerance in plants. Springer, Singapore, pp 219–237
Kuivenhoven M, Mason K (2019) Arsenic toxicity. StatPearls Publishing, St. Petersburg
Kumpiene J, Castillo Montesinos I, Lagerkvist A, Maurice C (2007) Evaluation of the critical factors controlling stability of chromium, copper, arsenic and zinc in iron-treated soil. Chemosphere 67:410–417. https://doi.org/10.1016/j.chemosphere.2006.08.031
Li K, DiLegge MJ, Minas IS, Hamm A, Manter D, Vivanco JM (2019) Soil sterilization leads to re-colonization of a healthier rhizosphere microbiome. Rhizosphere 12:100176. https://doi.org/10.1016/j.rhisph.2019.100176
Lomax C, Liu WJ, Wu L, Xue K, Xiong J, Zhou J, McGrath SP, Meharg AA, Miller AJ, Zhao FJ (2012) Methylated arsenic species in plants originate from soil microorganisms. New Phytol 193:665–672. https://doi.org/10.1111/j.1469-8137.2011.03956.x
Mahmood T, Mehnaz S, Fleischmann F, Ali R, Hashmi ZH, Iqbal Z (2014) Soil sterilization effects on root growth and formation of rhizosheaths in wheat seedlings. Pedobiologia 57:123–130. https://doi.org/10.1016/j.pedobi.2013.12.005

Mandal P (2017) An insight of environmental contamination of arsenic on animal health. Emerg Contam 3:17–22. https://doi.org/10.1016/j.emcon.2017.01.004

Marschner P, Rumberger A (2004) Rapid changes in the rhizosphere bacterial community structure during re-colonization of sterilized soil. Biol Fertil Soils 40:1–6. https://doi.org/10.1007/s00374-004-0736-4

Masscheleyn PH, Delaune RD, Patrick WH (1991) Effect of redox potential and pH on arsenic speciation and solubility in a contaminated soil. Environ Sci Technol 25:1414–1419. https://doi.org/10.1021/es00020a008

McNamara NP, Black H, Beresford NA, Parekh NR (2003) Effects of acute gamma irradiation on chemical, physical and biological properties of soils. Appl Soil Ecol 24:117–132. https://doi.org/10.1016/S0929-1393(03)00073-8

Mestrot A, Feldmann J, Krupp EM, Hossain MS, Roman-Ross G, Meharg AA (2011) Field fluxes and speciation of arsines emanating from soils. Environ Sci Technol 45:1798–1804. https://doi.org/10.1021/es103463d

Neumann K, Klukas C, Friedel S, Rischbeck P, Chen D, Entzian A, Stein N, Graner A, Kilian B (2015) Dissecting spatiotemporal biomass accumulation in barley under different water regimes using high-throughput image analysis. Plant Cell Environ 38:1980–1996. https://doi.org/10.1111/pce.12516

Norton G, Deacon C, Mestrot A, Feldmann J, Jenkins P, Baskaran C, Meharg AA (2013) Arsenic speciation and localization in horticultural produce grown in a historically impacted mining region. Environ Sci Technol 47:6164–6172. https://doi.org/10.1021/es400720r

Pantigoso HA, Newberger D, Vivanco JM (2022) The rhizosphere microbiome: Plant-microbial interactions for resource acquisition. J Appl Microbiol 133:2864–2876. https://doi.org/10.1111/jam.15686

Parascandola J (2017) The king of poisons: a history of arsenic. Potomac Books Inc, Sterling

Pickering IJ, Prince RC, George MJ, Smith RD, George GN, Salt DE (2000) Reduction and coordination of arsenic in Indian mustard. Plant Physiol 122:1171–1177. https://doi.org/10.1104/pp.122.4.1171

Podgorski JE, Eqani SAMAS, Khanam T, Ullah R, Shen H, Berg M (2017) Extensive arsenic contamination in high-pH unconfined aquifers in the Indus Valley. Sci Adv 3:e1700935. https://doi.org/10.1126/sciadv.1700935

Pongratz R (1998) Arsenic speciation in environmental samples of contaminated soil. Sci Total Environ 224:133–141. https://doi.org/10.1016/S0048-9697(98)00321-0

Prabpai S, Charerntanyarak L, Siri B, Moore MR, Noller BN (2009) Effects of residues from municipal solid waste landfill on corn yield and heavy metal content. Waste Manag 29:2316–2320. https://doi.org/10.1016/j.wasman.2009.02.009

Prasad MNV, Sajwan KS, Naidu R (2006) Trace elements in the environment: biogeochemistry, biotechnology and bioremediation. CRC/Taylor and Francis, Boca Raton

Rahaman MS, Rahman MM, Mise N, Sikder MT, Ichihara G, Uddin MK, Kurasaki M, Ichihara S (2021) Environmental arsenic exposure and its contribution to human diseases, toxicity mechanism and management. Environ Pollut 289:117940. https://doi.org/10.1016/j.envpol.2021.117940

Rahimzadeh S, Pirzad A (2017) Arbuscular mycorrhizal fungi and Pseudomonas in reduce drought stress damage in flax (*Linum usitatissimum* L.): a field study. Mycorrhiza 27:537–552. https://doi.org/10.1007/s00572-017-0775-y

Raturi G, Chaudhary A, Rana V, Mandlik R, Sharma Y, Barvkar V, Salvi P, Tripathi DK, Kaur J, Deshmukh R, Dhar H (2023) Microbial remediation and plant-microbe interaction under arsenic pollution. Sci Total Environ 864:160972. https://doi.org/10.1016/j.scitotenv.2022.160972

Razavi L (2007) Evaluation of chemical and biological consequences of soil sterilization methods. Casp J Environ Sci 5(87):91

Reinhold-Hurek B, Bünger W, Burbano CS, Sabale M, Hurek T (2015) Roots shaping their microbiome: global hotspots for microbial activity. Annu Rev Phytopathol 53:403–424. https://doi.org/10.1146/annurev-phyto-082712-102342

Rengel Z, Marschner P (2005) Nutrient availability and management in the rhizosphere: exploiting genotypic differences. New Phytol 168:305–312. https://doi.org/10.1111/j.1469-8137.2005.01558.x

Rimondi V, Costagliola P, Lattanzi P, Catelani T, Fornasaro S, Medas D, Morelli G, Paolieri M (2022) Bioaccessible arsenic in soil of thermal areas of Viterbo, Central Italy: implications for human health risk. Environ Geochem Health 44:465–485. https://doi.org/10.1007/s10653-021-00914-1

Rosas I, Belmont R, Armienta A, Baez A (1999) Arsenic concentrations in water, soil, milk and forage in Comarca Lagunera, Mexico. Water Air Soil Pollut 112:133–149. https://doi.org/10.1023/A:1005095900193

Rosas-Castor JM, Guzmán-Mar JL, Hernández-Ramírez A, Garza-González MT, Hinojosa-Reyes L (2014) Arsenic accumulation in maize crop (*Zea mays*): a review. Sci Total Environ 488–489:176–187. https://doi.org/10.1016/j.scitotenv.2014.04.075

Sadee BA, Foulkes ME, Hill SJ (2016) A study of arsenic speciation in soil, irrigation water and plant tissue: a case study of the broad bean plant, *Vicia faba*. Food Chem 210:362–370. https://doi.org/10.1016/j.foodchem.2016.04.066

Sasse J, Martinoia E, Northen T (2018) Feed your friends: do plant exudates shape the root microbiome? Trends Plant Sci 23:25–41. https://doi.org/10.1016/j.tplants.2017.09.003

Schaller J, Weiske A, Dudel EG (2011) Effects of gamma-sterilization on DOC, uranium and arsenic remobilization from organic and microbial rich stream sediments. Sci Total Environ 409:3211–3214. https://doi.org/10.1016/j.scitotenv.2011.05.014

Seshadri B, Bolan NS, Naidu R (2015) Rhizosphere-induced heavy metal(loid) transformation in relation to bioavailability and remediation. J Soil Sci Plant Nutr 15:524–548

Shankar S, Shanker U, Shikha (2014) Arsenic contamination of groundwater: a review of sources, prevalence, health risks and strategies for mitigation. Sci World J 2014:304524. https://doi.org/10.1155/2014/304524

Shimizu M, Arai Y, Sparks DL (2011) Multiscale assessment of methylarsenic reactivity in soil. 2. Distribution and speciation in soil. Environ Sci Technol 45:4300–4306. https://doi.org/10.1021/es103577e

Smith E, Naidu R, Alston AM (1998) Advances in agronomy: arsenic in the soil environment: a review. Academic Press, San Diego

Song J, Zhao FJ, McGrath SP, Luo YM (2006) Influence of soil properties and aging on arsenic phytotoxicity. Environ Toxicol Chem 25:1663–1670. https://doi.org/10.1897/05-480r2.1

Thomas DJ (2021) Arsenic methylation—Lessons from three decades of research. Toxicology 457:152800. https://doi.org/10.1016/j.tox.2021.152800

Tiberg C, Sjöstedt C, Eriksson AK, Klysubun W, Gustafsson JP (2020) Phosphate competition with arsenate on poorly crystalline iron and aluminum (hydr)oxide mixtures. Chemosphere 255:126937. https://doi.org/10.1016/j.chemosphere.2020.126937

Tlustoš P, Goessler W, Száková J, Balík J (2002) Arsenic compounds in leaves and roots of radish grown in soil treated by arsenite, arsenate and dimethylarsinic acid. Appl Organometal Chem 16:216–220. https://doi.org/10.1002/aoc.282

Turpeinen (2002) Interactions between metals, microbes and plants: bioremediation of arsenic and lead contaminated soils. University of Helsinki, Helsinki

Ultra VUY, Tanaka S, Sakurai K, Iwasaki K (2007) Arbuscular mycorrhizal fungus (*Glomus aggregatum*) influences biotransformation of arsenic in the rhizosphere of sunflower (*Helianthus annuus* L.). Soil Sci Plant Nutr 53:499–508. https://doi.org/10.1111/j.1747-0765.2007.00143.x

Upadhyay MK, Yadav P, Shukla A, Srivastava S (2018) Utilizing the potential of microorganisms for managing arsenic contamination: a feasible and sustainable approach. Front Environ Sci. https://doi.org/10.3389/fenvs.2018.00024

Valasek J, Thomasson JA (eds) (2016) Autonomous air and ground sensing systems for agricultural optimization and phenotyping. SPIE Proceedings. SPIE

Viacava K, Meibom KL, Ortega D, Dyer S, Gelb A, Falquet L, Minton NP, Mestrot A, Bernier-Latmani R (2020) Variability in arsenic methylation efficiency across aerobic and anaerobic microorganisms. Environ Sci Technol 54:14343–14351. https://doi.org/10.1021/acs.est.0c03908

Wang S, Mulligan CN (2006) Natural attenuation processes for remediation of arsenic contaminated soils and groundwater. J Hazard Mater 138:459–470. https://doi.org/10.1016/j.jhazmat.2006.09.048

Xiao EZ, Cui JL, Sun WM, Jiang SM, Huang MY, Kong DG, Wu QH, Xiao TF, Sun TF, Sun XX, Ning ZP (2021) Root microbiome assembly of As-hyperaccumulator Pteris vittata and its efficacy in arsenic requisition. Environ Microbiol. 23:1959–1971. https://doi.org/10.1111/1462-2920.15299

Xun WB, Huang T, Zhao J, Ran W, Wang BR, Shen QR, Zhang RF (2015) Environmental conditions rather than microbial inoculum composition determine the bacterial composition, microbial biomass and enzymatic activity of reconstructed soil microbial communities. Soil Biol Biochem 90:10–18. https://doi.org/10.1016/j.soilbio.2015.07.018

Wang Y, Wang S, Xu P, Liu C, Liu M, Wang Y, Wang C, Zhang C, Ge Y (2015) Review of arsenic speciation, toxicity and metabolism in microalgae. Rev Environ Sci Biotechnol 14:427–451. https://doi.org/10.1007/s11157-015-9371-9

Williams PN, Zhang H, Davison W, Meharg AA, Hossain M, Norton GJ, Brammer H, Islam MR (2011) Organic matter-solid phase interactions are critical for predicting arsenic release and plant uptake in Bangladesh paddy soils. Environ Sci Technol 45:6080–6087. https://doi.org/10.1021/es2003765

Yan M, Zeng X, Wang J, Meharg AA, Meharg C, Tang X, Zhang L, Bai L, Zhang J, Su S (2020) Dissolved organic matter differentially influences arsenic methylation and volatilization in paddy soils. J Hazard Mater 388:121795. https://doi.org/10.1016/j.jhazmat.2019.121795

Yuan J, Zhao J, Wen T, Zhao M, Li R, Goossens P, Huang Q, Bai Y, Vivanco JM, Kowalchuk GA, Berendsen RL, Shen Q (2018) Root exudates drive the soil-borne legacy of aboveground pathogen infection. Microbiome 6:156. https://doi.org/10.1186/s40168-018-0537-x

Zhalnina K, Louie KB, Hao Z, Mansoori N, Da Rocha UN, Shi S, Cho H, Karaoz U, Loqué D, Bowen BP, Firestone MK, Northen TR, Brodie EL (2018) Dynamic root exudate chemistry and microbial substrate preferences drive patterns in rhizosphere microbial community assembly. Nat Microbiol 3:470–480. https://doi.org/10.1038/s41564-018-0129-3

Zhao FJ, Harris E, Yan J, Ma J, Wu L, Liu W, McGrath SP, Zhou J, Zhu YG (2013) Arsenic methylation in soils and its relationship with microbial arsM abundance and diversity and as speciation in rice. Environ Sci Technol 47:7147–7154. https://doi.org/10.1021/es304977m

Zheng R, Sun G, Zhu Y (2013) Effects of microbial processes on the fate of arsenic in paddy soil. Chin Sci Bull 58:186–193. https://doi.org/10.1007/s11434-012-5489-0