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Effect of organic matter amendment, arsenic amendment and water management regime on rice grain arsenic species

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ABSTRACT

Arsenic accumulation in rice grain has been identified as a major problem in some regions of Asia. A study was conducted to investigate the effect of increased organic matter in the soil on the release of arsenic into soil pore water and accumulation of arsenic species within rice grain. It was observed that high concentrations of soil arsenic and organic matter caused a reduction in plant growth and delayed flowering time. Total grain arsenic accumulation was higher in the plants grown in high soil arsenic in combination with high organic matter, with an increase in the percentage of organic arsenic species observed. The results indicate that the application of organic matter should be done with caution in paddy soils which have high soil arsenic, as this may lead to an increase in accumulation of arsenic within rice grains. Results also confirm that flooding conditions substantially increase grain arsenic.

1. Introduction

It has been established that rice accumulates high concentrations of arsenic in its grain compared to other cereal crops (Williams et al., 2007). The arsenic in rice grains is present primarily as inorganic arsenic (arsenite and arsenate) and dimethylarsinic acid (DMA) (Williams et al., 2005; Meharg et al., 2008; Norton et al., 2009a,b). Traces of monomethylarsinic acid (MMA) and tetramethylarsonium have also been identified (Williams et al., 2005; Hansen et al., 2011). The accumulation of inorganic arsenic is of concern as it is a non-threshold, class 1 carcinogen (NRC, 2001). It has been proposed that rice accumulates higher concentrations of arsenic due to its cultivation in anaerobic conditions, where arsenic is more available (Xu et al., 2008). Not only is the accumulation of arsenic in rice grains a major concern, but rice growing in arsenic contaminated environments can have reduced yields (Panaullah et al., 2009). The mechanism for arsenate uptake, the dominant inorganic arsenic species under aerobic conditions, is through phosphate transporters, as arsenate is an analogue of phosphate (Ullrich-Eberius et al., 1989; Meharg et al., 1994). The uptake mechanism of arsenite, which is the dominant species in reducing environments (Xu et al., 2008), is thought to be via aquaporin channels; more specifically the nodulin26-like intrinsic proteins (NIPs) type aquaporins (Ma et al., 2008). It has also been demonstrated that undissociated methylated arsenic is also taken up via NIPs in rice (Li et al., 2009a). Recent evidence suggests that plants do not methylate arsenic (Lomax et al., 2012), therefore all methylated arsenic species within plants are probably obtained from the environment, most likely from soil micro-flora (Arao et al., 2011; Lomax et al., 2012).

Unloading of arsenic into the grain differs for inorganic arsenic and DMA, with DMA accumulating in the caryopsis before flowering and inorganic arsenic being mainly transported into the caryopsis during grain filling (Zheng et al., 2011). The uptake of DMA by roots is not very efficient (Raab et al., 2007a; Abbas and Meharg, 2008), however, it can accumulate to high concentrations in rice grain (Williams et al., 2005; Norton et al., 2009a,b, 2012). The observed efficient above-ground translocation of DMA may be due to its poor –SH coordination, in contrast to inorganic arsenite (Raab et al., 2007b). In arsenic fed excised panicles the rate of shoot to grain translocation of arsenic is considerably different for inorganic arsenic and DMA, with DMA being translocated at an order of magnitude greater than inorganic arsenic (Carey et al., 2010). The inorganic arsenic is predominantly translocated via the phloem, while DMA is translocated via both phloem and xylem (Carey et al., 2010).

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The addition of organic matter to soil has many important roles. For example it can improve the soil structure as well as being a nutrient supply of key elements such as nitrogen, phosphorus and sulphur (Batey, 1988). Organic matter has a major role in the mobilisation of arsenic from paddy fields (Sharma et al., 2011; Williams et al., 2011). This is because microbes utilising the organic matter consume oxygen that leads to a decrease in redox potential, which in turn leads to arsenic dissolution from FeOOH (Nickson et al., 1998, 2000; McArthur et al., 2001; Ravenscroft et al., 2001; Harvey et al., 2002; Smedley and Kinniburgh, 2002; van Geen et al., 2004; Rowland et al., 2009). Organic matter may also have two other roles in arsenic availability in soils: by desorbing arsenic species from soil surface exchange sites (Grafe et al., 2001; Weng et al., 2009), and dissolved organic matter (DOM) complexing arsenic species (Liu et al., 2011; Sharma et al., 2011; Williams et al., 2011).

Here two experiments were conducted to investigate the effect of watering regime and the application of organic matter to soil on total grain arsenic accumulation and arsenic speciation. A third experiment was performed to investigate the unloading of DMA into filling grain. The results were interpreted in the light of field management practice with respect to paddy rice cultivation.

2. Material and methods

2.1. Plant growth conditions for organic amendment experiment

Rice cultivars used in this experiment were Dawn and Nortai. Dawn has been identified as an arsenic sensitive, while Nortai has been identified as being an arsenic tolerant cultivar (Dasgupta et al., 2004). Dawn has also been identified as straighthead sensitive while Nortai is straighthead tolerant cultivar (Wells and Gilmour, 1977). The rice seeds were sown into seed trays and grown for 20 days before seedlings of equal size and vigour were transplanted into the experimental pots. Commercial topsoil was purchased from Rolawn (arsenic concentration 9.1 mg kg^{-1}) and commercial farm yard manure (FYM, Homebase; arsenic concentration 1.9 mg kg^{-1}), soil properties are given in Supplementary Table 1. Both the soil and FYM were dried and sieved. Soil was amended with 0, 2.9 or 10% FYM (on a dry weight basis). Soils were then amended with arsenic (in the form of arsenate) to give an additional final dry weight concentration of 0, 10 or 50 mg kg^{-1} arsenic. The weight of the soil or soil and FYM for each pot was 1.4 kg. The experiment had a fully factorial design with two genotypes, three arsenate treatments, three FYM treatments and three replicates (total of 54 pots) arrange fully randomly. Prior to transplanting the plants the pots were flooded to a depth of 3 cm, and in half the pots (pots that would have the rice cultivar Nortai transplanted into them) 5 cm Rhizon samplers were placed in the soil. The pots were then covered to keep out the light, and the rice plants were transplanted into the soil 7 days later. Flowering occurred between days 104 and 154 after transplanting. After harvesting plant material was dried; shoot biomass, tiller number, and grain yield were determined. The grain was then analysed for total arsenic and arsenic speciation.

2.2. Pore water sampling for organic amendment experiment

Pore water was sampled on day 1, 15, 36, 57, 78, 97, 121, 140, and 160 after transplanting. 10 mL of pore water was extracted from the soil into a tube containing 0.5 mL of 10 mM EDTA to stabilise the inorganic arsenic species. Pore water was then analysed for total arsenic and arsenic speciation.

2.3. Plant growth conditions for water management experiment

The rice cultivar used in this experiment was Italica Carolina; this cultivar has previously been used to study the uptake of arsenic (Carey et al., 2010, 2011). Seeds were first sown in a potting tray filled with multipurpose compost and were transplanted after 14 days into 18-cm pots containing 1400 g of commercial topsoil (Rolawn). Three watering treatments were setup with three replicates of each treatment. The treatments were flooded until grain harvest, flooded until the start of flowering, and non-flooded. For the flooded treatment the water was kept at 3 cm above the soil surface. The grain and flag leaf were harvested six weeks after anthesis; grain was dehusked. Arsenic was determined in the husk, grain, and flag leaf.

2.4. Plant growth conditions for DMA feeding experiment

The rice cultivar used in this experiment was Italica Carolina. Seeds were first sown in a potting tray filled with multipurpose compost and were transplanted after 14 days into 18-cm pots containing 1400 g of commercial topsoil (Rolawn); plants were kept flooded during the course of the experiment. Four replicates of each of the following three treatments were performed. For the first treatment 18.4 mg of DMA was applied to the soil (to give an arsenic concentration of 10 mg kg^{-1}) before flowering (approximately 4 days after onset of panicle formation), and for the second treatment DMA was applied at the same concentration as the first treatment but 14 days after anthesis. The third treatment was a control without the addition of DMA. The grain and flag leaf were harvested six weeks after anthesis; grain was dehusked. Total arsenic and arsenic speciation was determined in the husk, grain, and flag leaf.

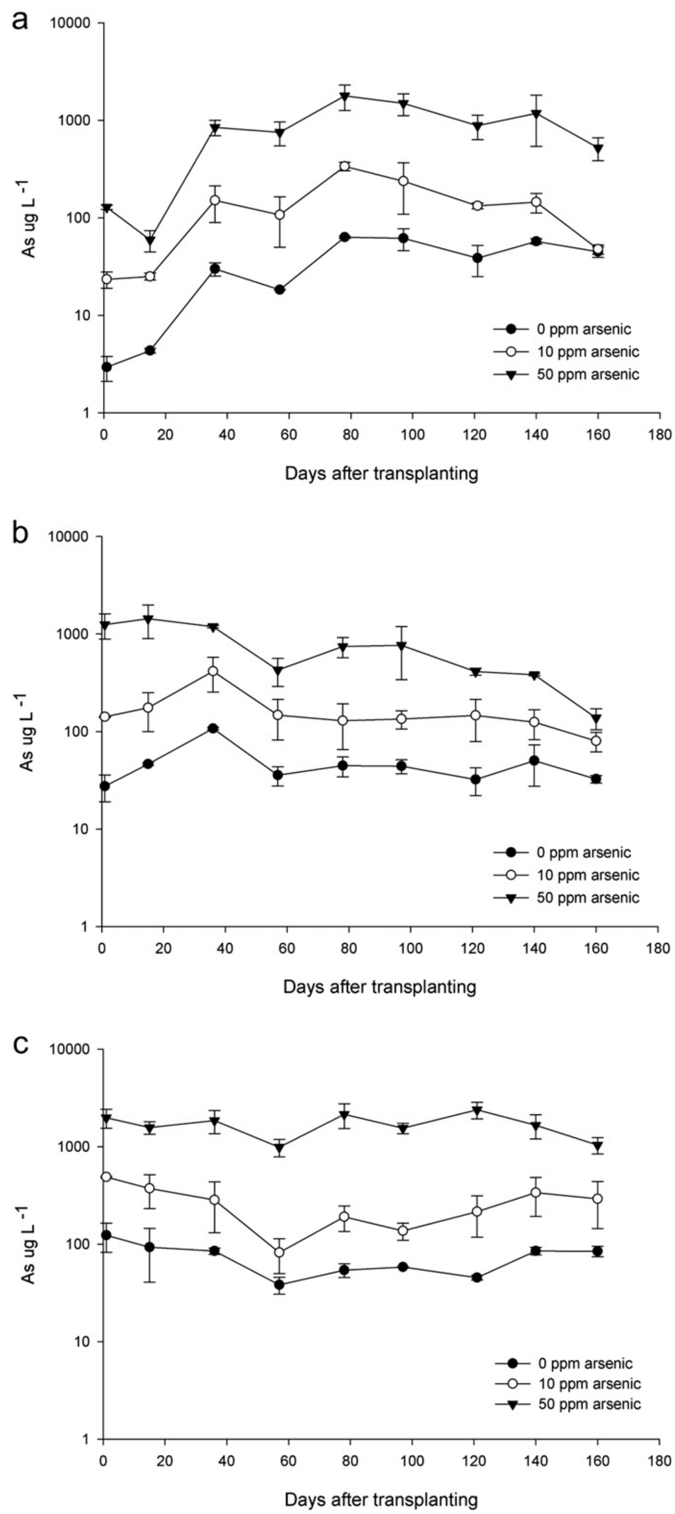

Fig. 1. Total arsenic in the pore water sampled from the pots not amended with FYM (a), pots amended with 2.9% FYM (b), and pots amended with 10% FYM (c) (mean ± s.e.m.).