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Arbuscular mycorrhiza reduces phytoextraction of uranium, thorium and other elements from phosphate rock

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Abstract

Uptake of metals from uranium-rich phosphate rock was studied in *Medicago truncatula* plants grown in symbiosis with the arbuscular mycorrhizal fungus *Glomus intraradices* or in the absence of mycorrhizas. Shoot concentrations of uranium and thorium were lower in mycorrhizal than in non-mycorrhizal plants and root-to-shoot ratio of most metals was increased by mycorrhizas. This protective role of mycorrhizas was observed even at very high supplies of phosphate rock. In contrast, phosphorus uptake was similar at all levels of phosphate rock, suggesting that the P was unavailable to the plant–fungus uptake systems. The results support the role of arbuscular mycorrhiza as being an important component in phytostabilization of uranium. This is the first study to report on mycorrhizal effect and the uptake and root-to-shoot transfer of thorium from phosphate rock.

Keywords: Arbuscular mycorrhiza; Uranium; Thorium; Aluminium; Phosphate rock

1. Introduction

Phosphate rock is the raw material for production of most phosphate fertiliser products. The rock material may be of sedimentary or volcanic origin and the sedimentary phosphate rock of marine origin is of particular concern with respect to uranium (U) and its decay products. It has been known since the early 19th century that phosphate rocks contain relatively high concentrations of U and daughter products in secular equilibrium. Concentrations of U in phosphate rock are typically in the range of 320–4800 Bq kg^{-1} (UNSCEAR, 1982). The principal mechanism behind the incorporation of U in phosphorites is thought to be the replacement of calcium by U in the apatite component of the phosphorite (Burnett and Veeh, 1992).

For fertiliser purpose the phosphate rock is usually processed to produce phosphoric acid, which is an important step in the fertiliser manufacture. During this processing, U passes over to the phosphoric acid while radium is found in the gypsum precipitate. The addition of inorganic phosphate fertiliser may be performed by either using the raw phosphate rock material itself, or by using triple superphosphate or diammonium phosphate, but it is only in the case when applying the raw phosphate rock that the entire ^{238}U decay chain is added unaltered. Untreated ground

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phosphate rocks have been used as plant fertilisers in many parts of the world at rates ranging from 300 to 600 kg ha^{-1} (Makweba, 1993).

Since the phosphate rocks usually contain the ^{238}U decay products in more or less secular equilibrium with ^{238}U, concentrations of the dosimetric important radioisotopes ^{226}Ra, ^{210}Pb–^{210}Bi–^{210}Po are equally high. With respect to plant uptake from soils, usually radium is of major concern due to its higher mobility as an alkaline earth metal. Although the overall mobility of most elements in the phosphate rocks is extremely low the situation becomes different under exposure to the action of microorganisms and plants. The decrease of pH in the vicinity of plant roots as well as the excretion of chelating substances may significantly influence the mobility of otherwise almost immobile elements. During these conditions element fractionation may occur due to direct mobilisation of some elements by the root/microbial action or indirectly through plant uptake and later release during the breakdown of plant organic matter.

The ability of plants and microbes to change the mobility of elements (either causing them to become mobile or temporarily making them immobile through uptake) has initiated some discussions on their use in contaminated sites. Apart from the chemical and physical methods suggested for the management and restoration of U and other heavy metal-contaminated areas also biological methods have been proposed. The use of plants and associated microbiota would theoretically constitute an attractive way to clean up contaminated land (so-called phytoremediation) or to stabilise possible mobile species (phytostabilisation). Among soil microorganisms, mycorrhizal fungi are the only ones providing a direct link between soil and plant. Arbuscular mycorrhizal (AM) fungi form association through root symbiosis with 80–90% of all seed plant species (Harrison, 1997). The AM fungi are in particular recognized for their ability to channel phosphate from the soil into the roots (Smith et al., 2004). However, mycorrhizas can also lead to reduced metal uptake and increased plant growth in metal-contaminated soils (Leyval and Joner, 2001).

With concern to phosphate rock, the addition of such to metal-contaminated soils has been suggested as a method to 'fix' heavy metals into an insoluble form that cannot be readily dispersed (Basta et al., 2001; Hettiarachchi et al., 2001). The influence of a combined microbial/root action on phosphate rocks with respect to metal mobility has not been investigated before. The purpose of this study was therefore to test whether mycorrhizal fungi may influence metal uptake, and in particular U and thorium (Th), from phosphate rocks even when applied in high concentrations. Due to its dosimetric importance and the high concentrations of ^{226}Ra usually found in marine sedimentary phosphate rocks, this isotope is also of concern. Since the analytical possibilities to study barium with ICP–OES in this study were more favourable than using liquid scintillation counting for ^{226}Ra, we selected to use barium as an analogue for Ra. The ^{232}Th decay chain in phosphate rock usually is not present at levels significantly higher than in normal soils (2–5 mg kg^{-1}). In the Minjingu phosphate rock used in this study we, however, found rather high concentrations, around 220 mg kg^{-1}, which enabled us to analyse the behaviour of this isotope as well. From an activity point of view the ^{230}Th, in secular equilibrium with ^{238}U, still is the most abundant one but with respect to mass, ^{232}Th dominates. Since our analytical methods were based on using mass spectrometry on unseparated samples (to minimize blanks) we choose to study ^{232}Th instead of ^{230}Th. The ^{232}Th is probably not bound to the phosphate rock in the same close association as the ^{238}U decay product ^{230}Th but is more likely linked to some other minerals, not known to us.

2. Materials and methods

Medicago truncatula L. cv Jemalong was grown in 16 pots (ConeTainers®) with or without inoculation with the mycorrhizal fungus *Glomus intraradices* Schenck & Smith (BEG 87). The growth medium consisted of a partially sterilised (10 kGy, 10 MeV electron beam) 1:1 (w/w) sand:soil mixture with basal nutrients added (Pearson and Jakobsen, 1993) and an extractable P content of 5.8 mg kg^{-1} (Olsen et al., 1954). No additional P was added to the soil during the growth period and total P concentration in the pots was thus largely determined by the amount of phosphate rock added. Phosphate rock (Minjingu, Tanzania) with a uranium (^{238}U) and thorium (^{232}Th) concentration of about 4700 and 890 Bq kg^{-1}, respectively, was incorporated at different proportions from 0 to 27%. For each concentration of phosphate rock thus 1 set of samples (non-inoculated, respectively, inoculated) was grown. No replicates were used. Each pot was filled with 175 g of the soil/phosphate rock mixture, except that 25 g of the soil had been replaced by a similar amount of pot culture inoculum of *G. intraradices* in 8 of the pots. Nitrogen was added as 30 mg N kg^{-1} (NH_4NO_3) at the start of the experiment and 30 mg N was added to each pot after 26 days. The experiment was conducted in a growth room with a 16:8 h light:dark cycle with 21:16 °C temperatures, respectively. Plants were watered to weight daily to maintain 60% of the water-holding capacity. Plants were harvested 5 weeks after sowing. Shoot and root parts were separated and fresh and dry weights were recorded. Every visible sign of soil contamination was removed from the samples by washing with distilled water. Plant samples were dissolved by microwave digestion using a 3:1 mixture of distilled HNO_3 and HF. Along