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Mycorrhizal association of maritime pine, *Pinus pinaster*, with *Rhizopogon roseolus* has contrasting effects on the uptake from soil and root-to-shoot transfer of ^{137}Cs, ^{85}Sr and ^{95m}Tc

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Abstract

The beneficial role of mycorrhizal association on plant nutrition and water supply is well-known, however, very little information exists with respect to the availability of radionuclides. We have measured the effect of controlled mycorrhizal association on the root uptake from soil and accumulation in leaves of three radionuclides. The radionuclides have contrasting chemical and biological properties: Cs is strongly adsorbed on soil, has no biological role and is a close analogue of potassium; Sr is less strongly adsorbed on soil and behaves very similarly to calcium; and Tc is very mobile in soil as pertechnetate, but immobilised when reduced to Tc(IV), it is also considered to be easily assimilated by biological systems. We found that mycorrhizal association had no effect on root-to-needle transfer of Cs, but increased root uptake and that this increase could not be explained by improved potassium nutrition. In contrast, the symbiotic relation decreased Tc soil-to-needle transfer, but this resulted from complex dynamics of root uptake and rapid immobilisation of Tc in soil. No effect of mycorrhizal association on Sr, like its stable analogue Ca, was observed. The addition of a phytotoxic metal, Cu, inhibited mycorrhizal association, thus eliminating the effects observed for non-contaminated plant–fungus couples, but had no additional effect on radionuclide dynamics.

Keywords: Radiocaesium; Radiostrontium; Technetium; Copper; Ectomycorrhiza; Root uptake; Soil-to-plant transfer factor; Maritime pine; *Rhizopogon roseolus*

1. Introduction

Mycorrhizal association is widespread and almost ubiquitous in nature and plays important roles in the nutrition of higher plants. Water uptake is improved due to increased exploration of soil by external hyphae. Nutrient uptake, notably of phosphorus and nitrogen, is enhanced by these symbiotic relationships, because of both the increased exploration of soil and the exudation of enzymes and more simple chemical compounds that enhance the solubilisation of nutrients from insoluble organic and inorganic soil components. The storage capacity of mycorrhizal fungi has been reported to protect plants against potentially toxic concentrations of metals, including Cd, Cu

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and Zn (Tonin et al., 2001; Christie et al., 2004 and references therein). However, very little is known on its effect on the soil-to-plant transfer of radionuclides. Since the concentrations of radionuclides found in the environment are not phytotoxic, there is no selection pressure for plants or symbiotic partners to develop strategies to limit uptake. Very few studies have attempted to study the effect of mycorrhizal association on the fate of radionuclides in soil, and the findings are often contradictory, for example, Riesen and Brunner (1996) report that ectomycorrhizal association led to an increase in ^{134}Cs and ^{85}Sr uptake by *Picea abies* seedlings from solution, whereas Entry et al. (1999) found larger concentrations of ^{137}Cs and ^{90}Sr when grasses were inoculated with *Glomus* fungi. More recently, Declerck et al. (2003) have demonstrated that arbuscular mycorrhizal fungi take up and accumulate radiocaesium and can also transfer it to their host plants (Dupré de Boulois et al., 2005, 2006). In contrast, the accumulation of radionuclides in the fruiting bodies of edible fungi has attracted much attention because of the large contribution that soil-to-fungi transfer can make to the contamination of the food chain (Howard and Howard, 1996; Skuterud et al., 1997; Gillet and Crout, 2000). In addition, sampling of edible fungi is simpler than the quantification of symbiotic fungi.

We chose to investigate three radionuclides that contrast in their chemistry in soil and their physiological properties. All are γ-emitters for experimental simplicity. The most mobile and most easily taken up by biological systems is technetium. We studied ^{95m}Tc with a half-life of 60 days, but the isotope most likely to be of concern in the environment is the long-lived ^{99}Tc ($\tau_{1/2} = 2.1 \times 10^5$ years) that is a component of radioactive waste. In well-aerated soil the dominant chemical form of Tc is the pertechnetate anion, TcO_4^-, that is not strongly adsorbed by soil components and so is very mobile. Values of the distribution coefficient, or K_d, are reported to be close to zero (Sheppard et al., 1990; Bird and Schwartz, 1997). Under reduced conditions, it may be reduced to sparingly soluble forms of Tc(IV) (Sheppard et al., 1990; Tagami and Uchida, 1999; Abdelouas et al., 2005; Burke et al., 2005). It is also immobilised by chemical reactions with soil organic matter, particularly humic substances (Rössler et al., 2000; Geraedts et al., 2002; Maes et al., 2003). Pertechnetate is readily taken up by plant roots and translocated within plants and Tc is found in a range of organic compounds in plants, particularly proteins (Murphy and Johnson, 1993; Echevarria et al., 1997; Krijger et al., 1999). Chemical toxicity probably arises when Tc is substituted for S in thio-containing ligands. The fate of Tc in the environment has been reviewed by Coughtrey et al. (1983) and Bennett and Willey (2003), but we know of no studies of its accumulation by edible or mycorrhizal fungi. In contrast to Tc, Cs is strongly adsorbed by many soils and so is generally considered to be immobile and not easily bioavailable. We studied ^{137}Cs that has been introduced into the environment as a result of atmospheric nuclear weapons testing, the accident near Chernobyl in 1986 and more locally as a result of other accidents and waste storage. It has a radioactive half-life of 30 years, but another longer lived isotope, ^{135}Cs ($\tau_{1/2} = 2.9 \times 10^6$ years), is found in long-lived nuclear waste. A vast amount of data exists on the fate of Cs in the soil–plant system and reviews have been published by Coughtrey and Thorne (1983) and Staunton et al. (2007). Cesium is strongly, and to some extent irreversibly, adsorbed onto the clay minerals of soil (Cornell, 1993; Cremers et al., 1988; Staunton, 1994; Poinssot et al., 1999). Adsorption on organic matter is not as strong and the presence of organic matter decreases the affinity of clay minerals for Cs (Staunton et al., 2002). Cesium has no known biological role and is thought to act very much like the chemically similar nutrient, potassium (Broadley and Willey, 1997; Zhu and Smolders, 2000). The third isotope studied was ^{85}Sr. Like Cs, Sr has been introduced into the environment as ^{90}Sr ($\tau_{1/2} = 28.5$ years) by the deposition following the Chernobyl accident and soil contamination of the two elements are often reported together. None of the isotopes of Sr are important components of radioactive waste. Strontium has a very simple chemistry in soil, behaving much like calcium. It is not strongly adsorbed by soil components and this adsorption is easily reversible (Rigol et al., 1999; Wang and Staunton, 2005). There is little biological discrimination between the two cations (Nisbet and Woodman, 2000; Morgan et al., 2001).

Our aim was to measure uptake and translocation of each of the three contrasting radioisotopes from soil-to-seedlings of maritime pine, *Pinus pinaster*. The experimental set-up allowed contamination in various plant parts to be analysed separately and so we could distinguish between uptake by roots and hyphae and redistribution throughout the plants. We attempted to relate the uptake of each isotope to the degree of mycorrhizal association. The presence of potentially toxic metals is known to interfere with the degree of mycorrhizal association (Gildon and Tinker, 1983; Jones and Hutchinson, 1986; Hartley et al., 1999), especially by reducing the mycorrhizal development. Copper has been extensively used in agricultural practices and could be present in soil at high concentrations. Therefore, we also investigated the effects of a copper contamination on ectomycorrhizal development and the resulting change in radionuclide uptake and transfer as might occur in a mixed pollution scenario.