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Summary

Samples were collected in a forest ecosystem close to the Nuclear Power Plant at Forsmark, Sweden. The soil was fractioned in bulk soil, rhizosphere, soil-root interface and fungal mycelium. At the same sampling sites, fruitbodies of fungi were also collected. The concentration (mg kg^{-1} dw of soil) of K, Rb, Cs, P, Ca, Cr, Mn, Co, Ni, Cu, Zn, As, Sr, Cd, I, Hg, Pb, Ra, Th and U, were analysed in the various fractions using masspectrometry.

The concentration of the stable potassium, rubidium and caesium in forest soil as well as in fungal compartment (fungal mycelium and fruitbodies) is discussed first and than the other 17 elements is discussed.

Potassium concentrations (median values) were 605 mg kg^{-1} dw in bulk soil; 806 mg kg^{-1} in rhizosphere; 3,280 mg kg^{-1} in soil-root interface; 2,750 mg kg^{-1} in mycelium and 39,500 mg kg^{-1} in fruitbodies of fungi. The concentrations of Rb were 2.5 mg kg^{-1} in bulk soil; 4.3 mg kg^{-1} in rhizosphere and 6.5 mg kg^{-1} in soil-root interface; 12.8 mg kg^{-1} in mycelium and 191 mg kg^{-1} in fruitbodies of fungi. The concentrations of Cs were 0.21 mg kg^{-1} in bulk soil; 0.32 mg kg^{-1} in rhizosphere; 0.2 mg kg^{-1} in soil-root interface; 0.51 mg kg^{-1} in mycelium and 3.9 mg kg^{-1} in fruitbodies of fungi.

Compared to bulk soil, rhizosphere was enriched with K, Rb and Cs by a factor 1.3, 1.7 and 1.5, and soil-root interface by factor 5.4 2.6 and 1.0. Paired T-test showed that only potassium concentration in bulk soil compared to concentration in rhizosphere and in soil-root interface differs significantly ($P < 0.05$). Rubidium and caesium concentrations in bulk soil, rhizosphere and soil-root interface were not significantly different.

Concentration of K, Rb and Cs was much higher in mycelium compared to bulk soil, indicating accumulation of these elements within fungi. The concentration ratios (CR) defined as mg kg^{-1} d.w in mycelium divided by mg kg^{-1} d.w in soil were found to be 4.5, 5.1 and 2.4 for K, Rb and Cs respectively. For fruitbodies of fungi, these ratios were about one order of magnitude higher than that for mycelium: 65, 3. 75.8 and 18.6 for K, Rb and Cs, respectively.

In mycelium, only weak correlations were found between K and Rb uptake ($r = 0.33$) and between K and Cs uptake ($r = 0.48$). The concentration of Rb and Cs in mycelium correlated rather well ($r = 0.79$, $P < 0.05$). In fruitbodies K and Rb concentration showed rather good correlation ($r = 0.51$, $P < 0.05$). Only weak correlation was observed between concentration of K and Cs in fruitbodies ($r = 0.26$). Rubidium and Cs concentrations in fruitbodies of fungi seemed to be better correlated ($r = 0.91$, $P < 0.01$).

The concentrations of the elements in fruit bodies of fungi were species-dependent. Highest ability to accumulate K was shown by *Cortinarius* sp. (89,600 mg kg^{-1}); *Suillus variegatus* (78,200 mg kg^{-1}); *Tricholoma equestre* (65,700 mg kg^{-1}); *Cortinarius armeniacus* (61,800 mg kg^{-1}) and *Sarcodon imbricatus* (53,700 mg kg^{-1}). The lowest concentration was found in *Lactarius deterrimus* (22,300 mg kg^{-1}).

Highest ability to accumulate Rb was shown by *Sarcodon imbricatus* (1,000 mg kg^{-1}); *Suillus variegatus* (469 mg kg^{-1}); *Cortinarius armeniacus* (421 mg kg^{-1}); *Cortinarius* sp. (371 mg kg^{-1}) and *Suillus variegatus* (337 mg kg^{-1}). Generally, fungi seemed to take up Rb more efficiently than K.

Highest Cs concentrations were found in fruitbodies of *Sarcodon imbricatus* (25.1 mg kg^{-1}); *Cortinarius armeniacus* (12.7 mg kg^{-1}); *Lactarius trivialis* (9.71 mg kg^{-1}) and *Suillus variegatus* (9.58 and 9.39 mg kg^{-1}).

Sarcodon imbricatus was found to accumulate K, Cs and especially Rb to greatest extent, followed by *Cortinarius* sp., and *Suillus variegatus*. Litter decomposing fungi *Hypholoma capnoides* and *Collybia peronata* showed relatively weak ability to accumulate K, Rb as well as Cs, compared to the mycorrhizal species.

No correlation was found between concentration of K, Rb and Cs in fruitbodies of fungi and soil pH as well as between CR and pH.

Seventeen elements, including P, Ca, Cr, Mn, Co, Ni, Cu, Zn, As, Sr, Cd, I, Hg, Pb, Ra, Th and U were divided into four groups, based on the concentration in bulk soil: very high concentration (> 100 mg kg^{-1} dw, high concentration (10–100 mg kg^{-1}); moderate concentration (1–10 mg kg^{-1}) and low concentration (< 1 mg kg^{-1}).

Fungal mycelium accumulated the following elements, listed in decreasing order: P, Cd, Cu, Ca, Zn, Sr, Co, As and Hg. Fruitbodies of fungi accumulate: P, Cd, Cu, Zn, As and Hg. Concentrations of these elements in fungi were found to be higher compared to concentration in bulk soil.

Phosphorus was accumulated by fungal mycelium very efficiently. Concentration ratio for mycelium (mg kg^{-1} dw in mycelium divided by mg kg^{-1} dw in soil) was found to be 7.4. Even higher accumulation was observed for fruitbodies of fungi, giving CR 8.5. Fungi did not accumulate Ca and this element seemed to be excluded from fungi particularly from the fruitbodies rather efficiently. Concentration ratio for Ca in mycelium was found to be 1.8. In fruitbodies of the studied species CR was about 0.03. Chromium was also excluded from fungi as indicated by low CRs – 0.5 for mycelium and 0.02 for fruitbodies. Manganese might also be excluded from fungi, particularly from the fruitbodies. Concentration ratio for Mn in mycelium was 0.9 and in fruitbodies 0.17. Cobalt was only moderately accumulated by fungal mycelium (CR = 1.4) and efficiently excluded from fruitbodies, giving CR 0.06. Our data did not show any accumulation of Ni by fungi. Concentration ratios for mycelium and fruitbodies were 0.9 and 0.4 respectively. Concentration ratios of Cu for mycelium were found to be 3.0, and for fruitbodies 5.9, indicating that copper concentration increase in the order soil-mycelium-fruitbodies. Fungi also accumulated zinc. Concentration ratios for zinc were found to be 1.6 in mycelium and 2.3 in fruitbodies. Arsenic was only moderately accumulated by mycelium (CR =1.4) as well as by fruitbodies (CR = 1.3). Sr seemed to behave similar as Ca. Concentration ratios of Sr were found to be 1.4 in mycelium and 0.04 in fruitbodies. Cadmium was an element, which was taken up very efficiently by fungi. Concentration ratios for Cd were calculated to be 3.0 in mycelium and 5.8 in fruit bodies. *Cortinarius armeniacus* showed extremely high concentration ratio for Cd – 33.3. Fungi did not accumulate iodine. Concentration ratios for iodine in mycelium were found to be 0.6, and 0.02 in fruitbodies of fungi. Mercury was accumulated by some fungal species. Concentration ratios for Hg in mycelium were about 1.1, and in fruitbodies 1.5. High Hg accumulations were observed for litter decomposing fungus *Collybia peronata* (CR = 11.7) and *Sarcodon imbricatus* (CR = 9.2). We found no accumulation of Pb in fungal mycelium or in fruitbodies. Concentration ratios for Pb in mycelium were found to be 0.6, in fruitbodies – 0.1, which indicates rather efficient exclusion of Pb from fungi. Exceptionally low thorium concentration was found in fungi indicating effective exclusion of Th from fruitbodies. Concentration ratios for the studied fungal species varied between 0.001 and 0.16. In fruitbodies of fungi uranium was found only as trace amounts – 0.006 mg kg^{-1}, indicating rather low uptake rate and very efficient exclusion of U from fungi. Higher U concentration was observed in fruitbody of *Cortinarius odorifer* – 0.216 mg kg^{-1}.

Phosphorus, Cd, Cu, Zn, Hg and As were accumulated mainly in fruitbodies of fungi. Concentrations of these elements were found to be higher in fruitbodies of fungi compared to that in mycelium, giving fruitbodies to mycelium concentration ratios 4.1, 2.2, 1.7, 1.4, 1.4 and 1.3 correspondingly. Highest preferences for accumulation of P within fruitbodies were shown by *Lactarius scrobiculatus* (CR = 20.7), for Cd by *Cortinarius armeniacus* (CR = 33.2), for Cu and Hg by litter decomposing fungus *Collybia peronata* (CR = 7.2 and 11.7), for Zn by *Sarcodon imbricatus* (CR = 8.4), for As by *Collybia peronata* and *Cortinarius* sp. (CR = 7.1).

Calcium, U, Th, Pb, Cr, Sr, Co, I, Ni and Mn showed higher concentrations in fungal mycelium, compared to concentrations in fruitbodies.

Contents

1 Introduction

Investigations related to management for long-term storage of nuclear waste are carried out by the Swedish Nuclear Fuel and Waste Management Co (SKB). In this study the accumulation of various elements and their concentration ratios in forest soil and fungal compartment of forest ecosystems in the Forsmark area have been investigated. The studies were made by the Department of Forest Mycology and Pathology and the Department of Soil Sciences, the Swedish University of Agricultural Sciences in Uppsala.

Information on the biological accumulation of various elements in forest ecosystems, including important radionuclides is necessary in order to model possible transport of leaching radionuclides, ending up in biosphere. Together with higher plants, fungi are important component in such transport chain. Being one of the most important components of forest ecosystems, fungi determine to a large extent the behaviour and transport of many elements in forest. Fungi play a key role in the mobilization, uptake and translocation of nutrients and are likely to contribute substantially to the long-term retention of radiocaesium in organic horizons of forest soil. Fungi are thought to be major contributors to accumulation and cycling of many elements in forest ecosystems.

The general approach in this work was to determine the concentrations of various elements in soil and fungi and their concentration ratios in fungal mycelium as well as in fruitbodies of many common species of fungi, including mycorrhizal species as well as saprophytes. Observed correlations between elements taken up by fungi are reported. The importance of rhizosphere and soil-root interface in accumulation of various elements and radionuclides was evaluated.

Results obtained in this study are discussed in two parts. In the first part concentration of potassium, rubidium and caesium in soil and fungi and their concentration ratios are discussed. In the second part of this report the concentration of P, Ca, Cr, Mn, Co, Ni, Cu, Zn, As, Sr, Cd, I, Hg, Pb, Ra, Th and U are discussed.

1.1 Potassium, rubidium and caesium

The elements belonging to the first group of the periodic table are called the alkali metals. They are Lithium (Li), Sodium (Na), Potassium (K), Rubidium (Rb), Caesium (Cs) and Francium (Fr). The first five can be found in the environment but Fr is not since there are only two isotopes of Fr both radioactive with short half-life (about 20 minutes). Two elements, Na and K are essential elements in biological systems. The others are found in living material but are not essential elements but analogues of Na or K. They are all very typical metals and react very vigorously with water under production of one-charged ions.

Potassium is a very abundant element, ranking seventh amongst all the elements in the Earth's crust, 2.59% of which is potassium (Table 1-1). Plant tissues contain between 1 and 2% of potassium. Potassium is a soft, silvery metal that is lighter than water. It is extremely reactive; it corrodes immediately on contact with air and reacts so vigorously with water that the hydrogen it liberates catches fire spontaneously. Potassium does not occur in nature at the zero level because of its great chemical reactivity. As a biogenic element K is essential constituent for plant growth and is found in rather high concentrations in most

soils and plays major roles in biological processes. It is also a vital element in the human diet; it makes up 0.35% of the human body. It exists in three naturally occurring isotopes. ^{40}K is one of the most common progenial radionuclides in our environment with a half-life of 1.26×10^{10} years, which accounts for c 0.012% of all potassium. Two potassium isotopes, ^{39}K and ^{41}K, are stable and occur in all living tissues. The artificially produced potassium isotope ^{42}K, which emits beta particles and has a half-life of 12.4 hours, is one of the radionuclides, which could be used in biochemical researches.

Rubidium is a light, low-melting, very reactive alkali metal. Rb is fairly abundant element in Earth's crust (Table 1-1) and in terms of abundance, rubidium ranks 34th amongst the elements in the earth's crust. Rubidium like caesium is tied up in complex minerals; it is not available in nature as simple salts as potassium. There are two naturally occurring isotopes of Rb; the stable ^{85}Rb and radioactive ^{87}Rb (β-decay with $T_{1/2} = 5 \times 10^5$ years). There are many other known radioactive isotopes of Rb; ^{81}Rb through ^{84}Rb, ^{86}Rb and ^{88}Rb through ^{90}Rb, all with comparatively short half-lives, measured in terms of minutes, hours and days.

Caesium is another chemical element in the alkali metal group, which is rather similar to potassium in its properties. It is the heaviest, softest, lowest melting, rarest, and most reactive of the stable alkali metals. It has only one naturally occurring stable isotope: ^{133}Cs. There are at least 15 radioactive isotopes of Cs from ^{125}Cs to ^{139}Cs. Among the caesium isotopes ^{135}Cs has very long half-life of 10^6 years. After the Chernobyl accident, ^{134}Cs with 2 years half-life and ^{137}Cs with 30 years half-life have been more investigated. The properties of potassium, rubidium and caesium are listed in Table 1-1.

Of the alkali metal lithium differs most from the rest of the group, and tends to resemble the alkali–earth metals in many ways. Lithium is a reactive metal, which is a solid only about half as dense as water. Lithium ion tends to bind preferentially with silicates rather than sulphides and is readily absorbed by clay minerals during weathering. Lithium has two naturally occurring stable isotopes, i.e. ^{7}Li and ^{6}Li and at least three radioactive with very short life time

Sodium is a very reactive silvery white to pink metal. Sodium is a major element in the Earth, especially in crustal rocks. Sodium is a volatile lithophilic element and is monovalent under natural conditions. There is only one stable sodium isotope ^{23}Na and several radioactive sodium isotopes with ^{24}Na having a longest half-life – 2.6 years.

Table 1-1. Some properties of potassium, rubidium and caesium /Enghag, 2000/.

Symbol	K	Rb	Cs
Atomic number	19	37	55
Atomic weight	39.1	85.5	132.9
Density	0.87 g cm^{-3}	1.53 g cm^{-3}	1.87 g cm^{-3}
Valence	1	1	1
Melting point	62.3°C	39°C	28°C
Boiling point	760°C	688°C	678°C
Mean concentration:			
earth crust	21,000 mg kg^{-1}*	90 mg kg^{-1} **	3 mg kg^{-1}

* /Sittig,1998a/; ** /Sittig,1998a/

Francium is the heaviest of the alkali metal elements. Francium is extremely rare and is found only as very small traces in some uranium minerals and occurs as a result of a disintegration of actinium. Francium is unique amongst the alkali elements in that it has no stable or long-lived radioactive isotopes and exists only in radioactive form. It is the most unstable of the first 101 elements. The longest lived radioactive isotope, ^{223}Fr, a daughter of ^{227}Ac, has a half-life of 22 minutes. This is the only isotope of francium occurring in nature, but at most there is only 20–30 g of the element present in the earth's crust at any one time. There are about 20 known radioactive francium isotopes.

1.2 Potassium, rubidium and caesium in soil

The alkali metals K, Rb and Cs are considered together since they have similar chemical characteristics and similar behaviours in soil and in plants.

Potassium. Most mineral soils, except those of a sandy nature show comparatively high in concentration of potassium – about 1.5% by weight. The major part of this element is held rigidly as part of the primary minerals or is fixed in form that is at best only moderately available to plants. Competition by microorganisms for this element contributes also at least temporarily, to its unavailability to higher plants. The greatest part (between 90 to 95%) of all soil potassium in a mineral soil is in relatively unavailable forms /Brady, 1974/. The readily plant available potassium constitutes only about 1 to 2% of the total amount of this element in average mineral soil and exists in soils in two forms: (a) potassium in soil solution, and (b) exchangeable potassium adsorbed on the soil colloidal surfaces. Although most of this available potassium is in exchangeable form (c 90%), soil solution potassium is somewhat more readily absorbed by plants /Brady, 1974/. In the presence of vermiculite, illite and other clay minerals, the potassium becomes adsorbed and may be fixed by the soil colloids. As such, this element is not readily available for plants but is slowly available when released to the exchangeable form.

Rubidium. The alkali metal ion Rb^+ has similarities to K^+; both ions may enter onto cavities between oxygen atoms in clay minerals. The hydrated ion radius is almost identical (the ionic radii of K and Rb are 1.33 and 1.48Å, respectively). They are thought to compete for the same "carrier" during uptake by plants /Albertsson, 1994; Baligar, 1995/. Rubidium is firmly bound to acidic igneous rocks and sedimentary aluminosilicates /Kabata-Pendias and Pendias, 1992/ and bindings of Rb to silicates appear to be stronger than those for K. Average concentrations of Rb have been reported to be c 50 $\mu g\ g^{-1}$ d.w in soils and 10 $\mu g\ g^{-1}$ d.w in plants, giving an average plant:soil concentration ratio (CR) of about 0.2 /Coughtrey and Thorne, 1983/. This relatively low value relates not to the inability of plant roots to accumulate rubidium, but more to the slow rate of supply of the element from soil in relation to root activity. The plant accumulation of Rb from soil cannot be represented on the basis of K uptake from soil. Data concerning the mobility and chemistry of Rb in soil are limited, however much of Rb in soil is bound on exchange sites of clay minerals /Coughtrey and Thorne, 1983/.

Caesium. Cs ion has a low tendency to hydrate and has an ionic radius of 1.69Å, which fits well with the size of the hexagonal openings formed by oxygen atoms at the clay unit layer surface. Potassium ion has similar characteristics, but because of it smaller radius is not quite so strongly bound as Cs. Geochemical characteristics of Cs are similar to those of Rb, but Cs appears to have a greater affinity to be bound to aluminosilicates /Gaso et al. 2000/. The caesium content of soils, is to a large extent associated with the mineral content, and appears to be c 5 $\mu g\ g^{-1}$ /Szabo, 1979/. The variation in concentration of Cs in plants is rather large, i.e. between 8.8×10^{-5} $\mu g\ g^{-1}$ up to 89 $\mu g\ g^{-1}$ d.w /Coughtrey and Thorne, 1983/.

An average soil to plant transfer ratio for either ^{137}Cs or ^{134}Cs is about 0.25. The binding of Cs in soil is dominated by ion exchange sites. Strong binding of Cs occurs on a small number of sites located in weathered mica on frayed edge sites (FES), which are accessible only to poorly hydrated ions and show high selectivity for Cs^+ over K^+ and NH_4^+ /Cremers et al. 1988; De Preter, 1990/. Some studies /e.g. Comans and Hockley, 1992/ reported slow and almost irreversible sorption process of radiocaesium to clay minerals. Among the alkali elements Cs is most strongly bound to clay minerals. /Brouwer et al. 1983/ reported that the absorption of monovalent cations by clay minerals increases in the order K < Rb < Cs. Consequently, plant-soil (CR) for Cs was found to be smaller than (CR) for Rb, which in turn is smaller than (CR) for K /Wyttenbach et al. 1995/.

As reported by /Yoshida et al. 2004/ concentrations of stable caesium in contaminated forest ecosystems in Belarus were almost constant in the soil profile 0–20 cm. This indicates that the main source of stable caesium in soil is the mineral itself and the atmospheric deposition does not affect the vertical profile of this element in the soil. However, in the upper Of+Oh layers stable Cs concentrations were consistently higher suggesting possible bioaccumulation of this element. In the soil profile, ^{137}Cs is distributed mainly in the upper 10 cm in forest soils in the humic-rich layers and shows very little vertical migration /Fawaris and Johanson, 1994/. As reported by /Nikolova et al. 2000/ the ^{137}Cs activity found in the soil-root interface fraction was in some way bound to or associated with the living material such as small roots, mycorrhizae and mycelium.

In this connection, the role of rhizosphere, a zone surrounding the roots of plants in which complex relations exist among the plant, the soil microorganisms and the soil itself seems to be important. The rhizosphere is the absorbing root-soil interface and the impact of the rhizosphere on radiocaesium seems to be complex /Ehlken and Kirchner, 2002/. It is the zone, about one millimetre in width, surrounding the epidermis of living root hairs and the boundary cells of mycorrhizae as well as hyphae growing out from some mycorrhizae. The plant roots and the biofilm associated with them can profoundly, influence the chemistry of the soil including pH and nitrogen transformations. The differential uptake of cations and anions can affect the pH of the rhizosphere. The absorption of ammonium ions, for example, promotes the efflux of H^+ ions and reduces the pH of the rhizosphere, while the absorption of NO_3^- ion promotes the efflux of OH- and raises the rhizosphere pH. This change in pH is localized to the region adjacent to the root and does not affect the bulk soil pH. It has been reported /Thiry, 1997; Delvaux et al. 2000/ that root-induced degradation of vermiculites remobilizes fixed Cs and also increases Cs sorption on the minerals /Guirvarch et al. 1999/. It is assumed, that non-exchangeable Cs as well as K are released from interlayer positions of clay minerals as a result of plant-induced depletion of available K and Cs and the excretion of H^+ /Hinsinger and Jaillard, 1993/.

1.3 Potassium, rubidium and caesium uptake by plants

Mineral nutrients are taken up from soil and transported in the tree xylem in ionic form. At present, several principal theories of ion transport across the plasma membranes of cortical and xylem parenchyma cells are recognized: the carrier theory /Tanner and Caspary, 1996/, the ion pump theory /Cowan et al. 1993/ and ion channels theory /White, 1997/. Potassium is a macronutrient for plants /Marschner, 1995/ and as a biogenic element involved in many fundamental cellular processes. Potassium cations in higher plants are crucial for plant nutrition, growth, tropism, enzyme homeostasis osmoregulation, nerve impulses and membrane potential. K^+ uptake from soils into roots is largely mediated by high-affinity K^+ uptake (Km approximately 10–40 μM) /Epstein, et al. 1963; Newman et al. 1987/ where Km is the Michaelis-Menten constant, equal to the substrate ion concentration

giving half the maximum rate of uptake. However, the biophysical transport mechanism of the high-affinity K^+ pathway is not fully understood /Schachtman and Schroeder, 1994/. Soil-plant uptake of K is affected by both soil and plant factors. The plant roots absorb potassium from the soil by an active transport mechanism, which carries it through the membrane structure. Uptake of potassium into the cells occurs to a large extent and also more or less directly into the outer cells of the root tissue and is then easily transported in the tissue. It mostly occurs as a free cation and is important for the maintenance of the membrane potentials of plant cells and thus of ion fluxes across membranes /Greger, 2004/. Potassium differs from many of the other essential constituents of plant cells, K^+ is not build into the cell as a part of an organic compound, but it is rather an ion. Rb and Cs follow the uptake route of K; the radius of hydrated Rb^+ is rather similar to that of hydrated K^+, thus the binding site at the plasma membrane of root cells does not appear to distinguish between these two cations /Erdei and Trivedi, 1991/.

The rate of nutrient uptake by roots depends on the nutrient supply to the root surface, active absorption by roots, and plant demand for nutrients. It is generally accepted, that mycorrhizal infection often enhances plant growth by increasing nutrient acquisition /Marschner and Dell, 1994/, however, this response is not universal, since mycorrhiza and rhizosphere microorganisms may reduce uptake of some nutrients /Kothari et al. 1990/. Therefore the impact of mycorrhizae on the plant root absorption of heavy metals and radioactive trace substances cannot be generalised /Ehlken and Kirchner, 2002/.

Information on the relation between K, Rb and Cs in forest ecosystems is still limited, although some studies such as /Brunner et al. 1996; Muramatsu et al. 1991; Wyttenbach et al. 1995; Yoshida and Muramatsu, 1994, 1997, 1998/ are available. Forest plants apparently discriminate between K^+ and Rb^+ in soils and a shortage of K^+ favours the uptake of closely related Rb^+. Rubidium uptake by plants is affected by chemical conditions and K status of the soil. The Rb^+ concentration variability in tissues of vascular plants in deciduous forest of southern Sweden proved to be a close inverse function of the K^+ saturation and the pH of rhizosphere soils /Tyler, 1997; Folkeson et al. 1990/. Low K^+ status in the soil is resulting in increased uptake of Rb^+ by vascular plants /Nyholm and Tyler, 2000/. Studies of /Drobner and Tyler, 1998/ did not confirm any direct influence of the acidity of soils or solutions on Rb^+ uptake by the common acid-woodland sedge *Carex pilulifera*, whereas increasing K^+ availability of the system decreased Rb^+ uptake. Leaching losses of K^+ due to soil acidification resulted in greater uptake rate of Rb^+ from such soils /Falkengren-Grerup et al. 1987/. In experiment with soybean plants /Shinonaga et al. 1999/, Rb absorbed in plant was found to be as highly mobile as many other radionuclides and trace elements as ^{46}Sc, ^{54}Mn, ^{58}Co, ^{74}As, ^{75}Se, ^{85}Sr, ^{88}Y, ^{149}Eu, ^{146}Gd, ^{169}Yb, ^{175}Hf, ^{183}Re and ^{192}Ir. In studies with halotolerant bacterium *Oceanomonas baumannii* /Brown and Cummings, 2001/, Rb but not Cs could substitute for K in alleviating growth inhibition due to K limitation. The transfer factor of Rb is rather low (about 0.3), which relates to the slow rate of supply from soil in relation to root activity /Greger, 2004/. Therefore, available Rb in the immediate vicinity of active plant roots is rapidly depleted and further uptake appears to be diffusion controlled.

Knowledge and understanding of the processes driving the uptake of Cs by vascular plants is also limited, since the requirement for Cs via root uptake and its subsequent function in plants is not well understood. Ability of minerals to adsorb minerals and ability of plant to accumulate Cs generally determine the availability of Cs for plant uptake. In view of the different absorption strength for Cs, Rb and K it is to be expected that the effect is largest for Cs and smallest for K /Wyttenbach et al. 1995/. According to /Andersen, 1967/ the content of clay in soil is one of the main variables affecting plant uptake of Cs, where an increase in clay content decreases the plant uptake. Clay strongly binds Cs and thus depresses the root uptake, but organic matter content may increase the uptake of Cs by plants /Cornell, 1993; Valke and Cremers, 1994/.

/Broadley and Willey, 1997/ investigated difference in root uptake of radiocaesium by 30 plant taxa and found that the lowest Cs concentrations occurred in slow growing *Gramineae* and the highest in fast growing *Chenopodiaceae*. For stable Cs the data are highly variable compared to its radioactive isotopes, within particular vegetation type grown on different soils. It has been suggested that a plant:soil concentration ratio for ^{137}Cs and ^{134}Cs of 0.25 would probably represent the majority of soils and vegetation type /Coughtrey and Thorne, 1983/.

It is assumed that the uptake of Cs is driven by the requirements for K /Ronneau et al. 1987/, which suggests a possible competition between the two ions for binding sites on plant root. According to /Cline and Hungate, 1960/ the uptake of Cs is related to K and these elements are interrelated in a complex, concentration-dependent, manner rather than by simple competition. The difference between K and Cs are thought to be in the selectivity of the xylem loading process /Buysse et al. 1995/.

A negative correlation between ^{40}K and ^{137}Cs activities in grass plants was reported by /Ciuffo et al. 2000/ with highly variable transfer factors values for ^{137}Cs and low variability for ^{40}K. A weak relationship between Rb and Cs and K and Cs concentrations across 30 taxa studied was found by /Broadley and Willey, 1997/. However, a strong relationship between the above-mentioned elements was found within the Gramineae and Chenopodiaceae. Taxa in the Chenopodiaceae discriminated approximately nine times less between Rb and Cs during uptake than did those in the Gramineae. Studies by /Sombré et al. 1994/ on the cycles of stable K and Cs in needles of spruce and oak forest indicated that radiocaesium movements in tree are closely related to the K cycle and to the tree physiological status. However, it is not clear to what extent the plant uptake of Cs is correlated to K, since some plant species have selectivity for Cs /Zach et al. 1989/.

1.4 Potassium, rubidium and caesium uptake by fungi

It is generally accepted that fungi take up nutrients from aqueous solution in soil /Griffin, 1981/. However studies by /Lindahl et al. 2002/ showed that during the decomposition of plant litter, nutrients are transferred between two major organic pools, from plant matter to the fungal mycelia. Only a small fraction is likely to be released as inorganic ions to the soil solution. This means that the bulk soil solution is not the medium that nutrients pass through on their way to the plant, as was assumed earlier. Most substances are thought to move into hyphae via specific carrier molecules. Uptake of nutrient requires energy and is selective. Potassium being the most abundant mineral element in fungi /Manzi et al. 1999/ is accumulated to high concentrations in the sporophores of most fungi, whereas Ca normally seems to be excluded /Tyler, 1980; Vogt and Edmonds, 1980; Vogt et al. 1981/. Potassium level in many fungal species is usually higher than those in plants and varies between 1.5 and 117 g of K per kg dry matter /Seeger, 1978/ with the constant level of radioactive ^{40}K in the mixture of K isotopes as 1.17×10^{-2}%. The CR (fruitbody:soil) ranged from 20 to 40. As reviewed by /Kalač, 2001/ the natural isotope ^{40}K usually causes activities of 0.8–1.5 kBq kg^{-1} dry weight in wild growing mushrooms. In studies conducted in Japan /Yoshida and Muramatsu, 1998/ the highest median concentration in mushrooms was found for potassium, followed by rubidium and caesium. Concentration ratios of higher than one were observed for K, Rb and ^{137}Cs, in mushrooms and for Ca in plants. The concentration ratios for K, Rb and ^{137}Cs in mushrooms were at least one order of magnitude higher than those for plants growing in the same forest. The CR for ^{40}K varies between 1.5 to 22.7 with values exceeding 10 for *Xerocomus badius* and *Amanita rubescens* /Eckl et al. 1986/. The ^{40}K content was found to be lower for mycorrhizal species

/Gaso et al. 1996/. However, as reported by /Gaso et al. 2000/ in all species of fungi studied from Mexico the ^{40}K activity concentration was higher than ^{137}Cs, which is probably due to the low deposition level of ^{137}Cs in this country. This behaviour agrees with reported values in the basidiomycetes from a humic soil with a high mineral component /Dighton and Horrill, 1988/. It is probable, that the selection of Cs or K uptake is dependent upon soil factors, mobility and relative availability of the elements. /Baeza et al. 2004/ suggest that the incorporation of stable K, and therefore of ^{40}K is self-regulated by the fungus's own nutritional requirements. The incorporation of ^{137}Cs is not self-regulated by the fungus and activity concentrations of these two radionuclides in fruitbodies might show no correlation.

Unexpectedly high concentrations of Rb have been observed in several species of fungi /Allen and Steinnes, 1978; Tyler, 1980; Yoshida and Muramatsu, 1998; Gaso et al. 2000/. Concentration of Rb in mushroom was one order of magnitude higher than those in plants growing in the same forest /Yoshida and Muramatsu, 1998/. Fungi uptake of Rb correlates well with uptake of Cs /Gaso et al. 2000; Yoshida and Muramatsu, 1998/. The correlation between ^{137}Cs and ^{133}Cs (stable Cs) in mushrooms were found to be 0.96–0.99. Plants seem to take up Cs slightly differently, since radioactive Cs in the soil was found more available to plant than total stable Cs /Varskog et al. 1994/. However, Cs uptake by mushrooms was not correlated with K uptake /Eckl et al. 1986; Ismail, 1994; Yoshida and Muramatsu 1998/, suggesting that the mechanism of Cs uptake is different from that of K. Uptake of Rb might be at least partly use the same mechanism as Cs /Yoshida and Muramatsu, 1998/. Fungal species differ in their ability to accumulate potassium. In studies of elemental composition of ectomycorrhizal mycelia /Wallander et al. 2003/ *Suillus granulatus* was found to be a great accumulator of K. Mycelium of this fungus contained 3–15 times more potassium (3 mg g^{-1}) that the other species of fungi.

High concentrations of ^{137}Cs in mushrooms have been reported in many studies /Grueter, 1971; Haselwandter, 1978/ and many data concerning the amount of ^{137}Cs and ^{134}Cs in mushroom have been published after the Chernobyl accident. *Paxillus involutus, Xerocomus badius, Cortinarius armillatus* have shown highest radiocaesium concentration /Vinichuk and Johanson 2003/. Some mushrooms contain far less ^{137}Cs per gram K than humus, whereas other mushrooms e.g. *Boletaceae* spp contain 2–3 times as much ^{137}Cs per gram K than found in the humus layer /Ypelaar, 1980/. As reviewed by /Oolbekkink and Kuyper, 1989/ fungi growing on decaying wood seem to have a low activity concentration of radiocaesium and ectomycorrhizal species contain more radiocaesium than litter and humus-inhabiting fungi with extremely high variation between species. /Gillett and Crout, 2000/ reviewed ^{137}Cs transfer to fungi and found that transfer factors for species collected within Europe and former Soviet Union varying between < 0.001 and > 19 m^2 kg^{-1} (Bq kg^{-1} dw/Bq m^{-2}) across species and over three orders of magnitude for individual species (e.g. *Boletus badius*). Non-radioactive Cs accumulates in mushrooms to an average level of 7 mg kg^{-1} dry weight with highest value in *Cortinariaceae* – 308 mg kg^{-1} dry weight, collected near Uppsala in Sweden /Seeger and Schweinshaut, 1981/.

Since the biomass of fruitbodies constitutes only a small percentage of the total fungal biomass /Danielsson and Pruden, 1989; Olsen, 1994/, radiocaesium is expected to be stored predominantly within fungal biomass below ground in the fungal mycelium, which acts as a sink for ^{137}Cs /Olsen et al. 1990/. A data survey shows that about 10–40% of total ^{137}Cs activity in forest soil is accumulated or associated in the fungal mycelium. The following data are available in the literature: /Witkamp and Barzansky, 1968/ – 7%, /Olsen et al. 1990/ – 32% (range 10–50), /Dighton et al. 1991/ more then 40%, /Brückmann and Wolters, 1994/ – 13% (range 1–56), /Guillitte et al. 1994/ up to 40%, /Fawaris and Johanson, 1995/ – 22%, /Nikolova et al. 2000/ > 10%, /Vinichuk and Johanson, 2003/ – 11% (range 1–50).

Some studies /Brückmann and Wolters, 1994; Dighton et al. 1991/ estimated that the fungal compartment of the soil could immobilise the total ^{137}Cs fallout received in upland grasslands following the Chernobyl accident. Some papers /e.g. Guillitte et al. 1994/ deal with the total microbial biomass in forest soils. However, in acid forest soils microbial biomass is generally dominated by fungi /Parkinson et al. 1978/. These observations clearly explain the low vertical migration rate of ^{137}Cs. When ^{137}Cs is continuously pumped into the fungal mycelium, it balances the downward migration with an upward migration /Brückmann and Wolters, 1994; Wirth et al. 1994; Rafferty et al. 1997/.

1.5 The role of fungal compartment in the turn over of radionuclides in forest

Fungi are important components of forest ecosystems, since they determine to a large extent the fate and transport processes of elements in forest. They play a key role in the mobilization, uptake and translocation of nutrients and are likely to contribute substantially to the long-term retention of radiocaesium in organic horizons of forest soil /Steiner et al. 2002/. The biomass of fruitbodies constitutes relatively small (only around 5%) part of the total fungal biomass /Olsen, 1994/. The fungal mycelium seems to be very important for ^{137}Cs uptake and retention /Vinichuk and Johanson, 2003/. However, it is known very little about Cs, K and Rb uptake by fungal mycelium. Recent studies /Nikolova et al. 2000/ showed that a substantial fraction of the ^{137}Cs in soil in some way is associated with the biological part of the forest soil, probably with the fungal compartment. Grass plants inoculated with arbuscular mycorrhizae had greater ^{137}Cs uptake than those that did not receive mycorrhizal inoculation /Entry et al. 1999/. Studies with root-organ culture /Declerck et al. 2003/ demonstrated that extraradical mycelium of arbuscular mycorrhizal fungus can take up, possibly accumulate and unambiguously translocate radiocaesium from Cs-labelled synthetic root-free compartment to a root compartment and within the roots. However, studies of /Riesen and Brunner, 1996/ on ^{134}Cs uptake into seedlings of Norway spruce in a pouch test system showed that ectomycorrhizae reduced the ^{134}Cs uptake. It is assumed that the translocation of radiocaesium is coupled with the intensity of water fluxes through the xylem.

The rhizosphere effects on the plant available fraction of radionuclides might be significant /Nikolova et al. 2000/ and as reviewed by /Ehlken and Kirchner, 2002/ the importance of these effects still seems to be inadequate to enable quantification. The combined effects of roots and rhizosphere organisms in a small volume of soil create bioavailabilities, which may be completely different to those of bulk soil.

Under the nutrient-poor forest situation, potassium and therefore also caesium, availability may not be controlled by diffusion and transport process in the soil. Availability of caesium is determined more by surface absorption-desorption on organic matter, decomposition rates on small roots and mycorrhizae and enhanced dissolution and precipitation of minerals. It is mainly due to root exudates in the close vicinity of the small roots, colonized by fungi. As suggested by /Nikolova et al. 2000/ the transfer of nutrients from soil to fruit bodies of fungi and green plants are a two-step processes with a common first step. The first step is an accumulation of more than 10% of the soil inventory of ^{137}Cs mainly in the fungal compartment. In the second step radioceasium is transferred or distribution from the fungal pool of ^{137}Cs to the host plant across a symbiotic interface or translocated to the fruitbody of fungus within the fungal system. Our studies /Vinichuk, 2003/ indicate that usually, the ^{137}Cs activity concentrations in mycelium were still higher than those found in soil, and ^{137}Cs activity concentrations in the fruitbodies of fungi were still higher than those

in the mycelium. The rhizospheric communities ‘continually pull themselves up by their own bootstraps’ /Perry et al. 1989/ so that the nutrient cycling and bioavailability in the rhizosphere and soil-root interface is higher than in the bulk soil.

However very little is known about the mechanisms involved in the uptake and retention of radionuclides by fungi /Steiner et al. 2002/. In comparison with green plants, the concentration of ^{137}Cs, Cs, Rb and K in fungal fruitbodies is much higher than that found in plants (at least one order of magnitude) /Yoshida and Muramatsu, 1998. Clint et al. 1991, Dighton et al. 1991/ investigated the uptake of radiocaesium by fungi and their capacity to retain radiocaesium within the mycelium after uptake. They suggest that the ability of fungi to “accumulate” radiocaesium attributed to high influx and low efflux rates. The rate of radiocaesium influx varied by a factor of 4 between 24 studied species and the loss of radiocaesium following loading proceeds at a much slower rate than the original uptake.

1.6 P, Ca, Cr, Mn, Co, Ni, Cu, Zn, As, Sr, Cd, I, Hg, Pb, Ra, Th and U

The global budget of toxic trace elements has increased dramatically due to a number of industrial activities /Nriagu, 1979/. In Sweden, for example, with the increasing industrial activity, Pb, Cd and Hg contents in the upper soil organic layers have increased by 50% /EEA, 1998/. The upper organic-rich forest soil layers, particularly those in coniferous forests is often effective at retaining heavy metals /Van Hook et al. 1977; Heinrichs and Mayer, 1980; Jones et al. 1988, Tyler, 1978; Bergkvist, 1987/.

Metal contaminants in the soil undergo complex interactions depending on many factors, such as mineral composition, organic matter content and are mediated by physico-chemical processes /Krosshavn et al. 1993; Zhu and Alva, 1993/. Retention of many metals in organic soils is due to formation of complexes or adsorption to organic matter of soil /Tyler, 1972/. However, recent studies /Berthelsen and Steinnes, 1995/ revealed that a significant amount of Zn, Cd and Cu can be associated with soil fungal biomass. Studies with a multi-compartment experimental system /Ledin et al. 1999/ indicated that microorganisms may accumulated a considerable part (up to 38%) of the zinc, cadmium and mercury, despite the fact that the microorganisms constituted only a minor fraction (0.4 or 1.7%) of the total soil mass.

While trace amounts of some metals are essential for fungal growth and metabolism, e.g. manganese, iron and zinc, other nonessential metals such as cadmium (Cd^{2+}), lead (Pb^{2+}) and mercury (Hg^{0}) can also interact with fungal cells and be accumulated. The non-essential and toxic metal compounds may also be solubilized and became available to fungi and other soil organisms /Morley et al. 1996/.

Fungi being predominant in acid forest soil comprising the largest pool of biomass /Parkinson et al. 1978/ and are able to solubilize essential as well as non essential metals and metalloids from insoluble mineral compounds /Burgstaller and Schinner, 1993/. In acidic soil, metals can readily be speciated into soluble and therefore more mobile forms /Hughes and Poole, 1991/.

Accumulation of heavy metals by mushrooms has been known for a few decades and a number of works describing metal content in fruitbodies have been published /Jorhem and Sundström, 1995; Gabriel et al. 1997; Garcia et al. 1998; Gast et al. 1988; Sesli and Tüzen, 1999/.

Most studies on heavy metals and fungi have been concerned with heavy metal accumulation in fruitbodies. Considerable variability in the contents of the trace elements and heavy metals has been found both between species of fungi and also within individual species /Ismail, 1994; Zimmermannova et al. 2001; Alonso et al. 2003; Demirbaş, 2001, 2002, 2003; Falandysz et al. 2003, Malinowska et al. 2004/. Most of the examined metals in the fruitbodies showed significant correlation with concentration in soil. /Kalač and Svoboda, 2000/ reviewed trace element concentrations in edible mushrooms and found that some species, mainly from genera *Agaricus, Macrolepiota, Lepista* and *Calocybe* accumulate high levels of cadmium and mercury even in unpolluted and mildly polluted areas.

/Deborah et al. 1998/ explored the differences in metal uptake in sporocarps of ectomycorrhiza forming fungi and found that elevated levels in the mushrooms included four metals of environmental interest (Ag, Cd, Ba, and Pb) and three lanthanides (La, Ce, and Nd). More than 1 mg kg^{-1} of lanthanides (rare earth elements), such as cerium, lanthanum and neodymium were found in wild-growing fungi by /Stijve et al. 2002/.

Studies by /Galli et al. 1994/ indicate that fungal ecotypes from heavy metals contaminated sites seem to be more tolerant to heavy metals than reference strains from non-contaminated sites. The abundance of the extrametrical mycelium was shown to be important for heavy metals binding by the fungus.

The strong accumulation of cadmium, lead and mercury in some edible mushrooms is of great interest when considering human health. In the case of edible fungi, toxic metals may be incorporated into food chains. /Rácz and Oldal, 2000/ outlined several reasons for the analytical examination of trace elements from the viewpoint of nutrition and environmental science: (i) the quantity of trace elements indispensable for normal vital functions might either increase or decrease to a considerable extent during the course of certain stages of the food chain; (ii) certain toxic elements, even radioactive ones, show a high likelihood of getting into human organisms if contained in the food consumed.

1.7 Phosphorus

Phosphorus is never found as a free element but is widely distributed in many minerals. Phosphate rock, (apatite, impure calcium phosphate), is an important source of the element. The average total content phosphorus content of the earth's crust is 0.05% and most of the phosphorus present in soil is currently unavailable to plants. Organic phosphorus represents 20 to 60% of the total phosphorus in many soils. Mineral phosphorus is mainly found in combinations with aluminium, iron, calcium and magnesium. Phosphorus is a plant nutrient and is taken up in an ionic form along with hydrogen ions, $2H^+ + PO_4^{2-}$ /Marschner, 1995; Greger, 2004/.

1.8 Calcium

Calcium is a nutrient element in plants /Marschner, 1995/ and is most common in nature within the alkaline earth metals. Calcium make up 3.6% of the Earth' crust. Plant roots take up Ca as divalent ions, the uptake is passive by a facilitated diffusion via a specific Ca channel. Calcium is restricted to the apoplast and an efflux mechanism is important, since Ca easily forms complexes with phosphate, which may affect the energy mechanism /Greger, 2004/.

1.9 Chromium

Concentration of chromium in soil is about 50 µg g^{-1} dry weight /Coughtrey and Thorne, 1983/ and this element can be considered to be relatively unavailable as very insoluble oxides /Lisk, 1972/, and relatively immobile, even under extreme conditions for example low pH /Tyler, 1978/. Chromium is taken up by plants at a low rate and typical concentration of Cr in most plants is about 1.0 µg g^{-1} dry weight /Coughtrey and Thorne, 1983/. The most available form is CrO_4^{2-}, but this is the most unstable and toxic one /Greger, 2004/.

1.10 Manganese

An average concentration of manganese in soil is about 850 µg g^{-1} dry weight /Bowen, 1966/ and about 5 to 10% of this total content may be available for plant uptake via soil solution. 90% of manganese in soil is associated with, or occluded in, the mineral lattice, and hence unavailable. The remaining 10% can be assumed to be distributed as 8% associated with organic matter and 2% in soil solution. Due to the relatively high content of manganese in parent materials and its high degree of complexing, the concentration of manganese in anaerobic, acidic and leached soils can be expected to be closer to 200 to 300 µg g^{-1} /Coughtrey and Thorne, 1983/. Manganese is a plant micronutrient, which is taken up as Mn^{2+} and is an activator of many plant enzymes. Mn plays a role in photosynthesis. Uptake of Mn seems to be metabolitically controlled but at high external concentrations and the uptake is passive /Greger, 2004/.

1.11 Cobalt

Cobalt concentration in soils and their parent materials ranging between 3 to 15 mg g^{-1} dry weight and between 6 to 7% might be available /Coughtrey and Thorne, 1983/. Cobalt concentration in plants can be between 0.1 to 1.0 µg g^{-1} dw. Requirement of cobalt in higher plants has not been proved, however in legumes it is essential for nitrogen fixation. /Epstein, 1972/. Uptake of cobalt into the roots is generally considered to be a passive process /Ernst, 1976/. For cobalt radionuclides transfer factor is very low and was determined in the range of 0.001–0.01 /Lux et al. 1995/, indicating that plants obviously do not accumulate cobalt.

1.12 Nickel

As recently discovered nickel is a nutrient element /Greger, 2004 and references therein). Nickel concentrations in soils is rather low – about 30 µg g^{-1} dry weight /Coughtrey and Thorne, 1983/ and between 1 to 4% is generally available /Berrow and Burridge, 1980/. Nickel is taken up as divalent cation (Ni^{2+}) and uptake appears to be limited by the availability of Ni in soil. The concentration ratio for the absorption of nickel by plants form soils is 0.1 in most species.

1.13 Copper

Copper is a nutrient element in plants. Copper forms stable complexes and is taken up by plants as Cu^{2+}, and possibly also as Cu^{+} /Greger, 2004/. The uptake of copper into cells at low concentrations may include an active component, whereas it is passive at higher concentrations.

1.14 Zinc

Zinc is a micronutrient for plants, and is taken up as Zn^{2+} and hydrated Zn. Zn uptake in cells is metabolically controlled but it can also be a non-metabolic process, probably both /Greger, 2004/. Normal Zn concentrations in soils are about 60 µg g^{-1} /Coughtrey and Thorne, 1983). Zinc appears to accumulate in surface organic matter as a result of redistribution from growing plants. As a result Zn concentration in litter horizons are in the order of 120 µg g^{-1}. The availability of Zn is greater in acid and anaerobic soils where the predominant ion is Zn^{2+}.

1.15 Arsenic

Arsenic is naturally occurring element in the earth's crust and is found normally in a number of minerals. As is taken up passively by the water flow due to the linear relationships between uptake and the soil concentration, but As is taken up across cell membranes in a similar way to phosphate since phosphate and arsenate (AsO_4^{3-}) are similar /Marschner, 1995/.

1.16 Strontium

The crust of the Earth contains 0.042% of strontium. Recorded concentrations of stable strontium in various soils are variable, a mean value of 300 µg g^{-1} dry weight appears to be representative of total contents in soils /Coughtrey and Thorne, 1983/. Uptake of Sr appears to occur equally by either metabolic or passive processes. Sr is considered to be approximate chemical and physiological analogues of Ca and Sr is often associated with Ca. The ratio between Sr and Ca is relatively stable in the biosphere.

1.17 Cadmium

Cadmium is widely known to be a very hazardous heavy metal pollutant, toxic to various ecosystems /Nriagu, 1980/ and one of the most mobile metallic elements in soil /Mc Bride, 1989/. Depending on soil parameters, a greater or lesser amount of Cd is absorbed by the soil. However, this Cd can, to some extent, be subsequently solubilized, e.g. by local variation in soil pH due to microbial activity /Chanmugathas and Bollag, 1988/. As a result, in acidic soils, anoxic soils and poorly drained-soils, the mobility and availability of cadmium can be expected to be considerable /Coughtrey and Thorne, 1983/. This mobility will probably be modified by the degree of microbiological activity in these soils. Cadmium is readily absorbed by plant roots and via the leaf cuticle /Greger, 1999/.

It is taken up as Cd^{2+} and the uptake is affected by soil factors, such as pH. Accordingly to /Smeyers-Verbeke et al. 1978/ root cells passively adsorb Cd, however, a metabolitic mechanism may be involved at low levels of Cd.

1.18 Iodine

Iodine is never found in nature as the free element. Iodine minerals are very rare. Concentration of iodine in soil is suggested to be 5 μg g^{-1} dry weight, however it seems likely that this concentration is more applicable to organic fractions of soils than to mineral fraction /Zyrin and Zborishchuk, 1975/. Most iodine in soils is water-soluble /Bollard and Butler, 1966/ and only relatively small fraction is available for root uptake /Fuge and Johnson, 1986/. However, soluble forms of iodine are easily available to plants /Greger, 2004/.

1.19 Mercury

Mercury and its compounds are very toxic. In its compounds, mercury is found in the 2+, 1+, and lower oxidation states. Same mercury (II) salts, for example, $Hg(NO_3)_2$ or $Hg(ClO_4)_2$, are quite soluble in water. Plants take up mercury via roots in both inorganic form and as organic methyl mercury /Kabata-Pendias and Pendias, 1992/.

1.20 Lead

Lead is a trace element, showing chalcophilic properties in the terrestrial environment, /Greger, 2004/. Most of Pb in soil is not available to plants; this element is taken up passively by plant roots and is accumulated in the cell walls. ^{210}Pb is an important radionuclide (physical half-life 22.3 years), naturally occurring from uranium decay chain. Following the decay of 3.8 days ^{222}Rn in the atmosphere, ^{210}Pb is produced rapidly, but its long half-life allows very little to decay in the atmosphere before it precipitates to the earth surface, mainly in rain or snow. ^{210}Pb in mushrooms mainly originates from direct uptake of ^{210}Pb present in the soil /Kirchner and Daillant, 1998/. Activity concentrations of ^{210}Pb were found in the range 1.8–36.5 Bq kg^{-1} dw

1.21 Thorium

Thorium-232 is naturally occurring isotope with half-life 1.41×10^{10} years. The Th content of various rocks indicates a range of 8.1 to 33 ppm for igneous rocks, with a mean value of 12 ppm /Faul, 1954/. In most geologic environment thorium exists in the 4+ and 6+ oxidation states.

1.22 Uranium

The uranium normally found in nature consists of four isotopes having mass number ^{230}U, ^{234}U, ^{235}U and ^{238}U. ^{238}U is present in the amount of 99.28% and is usually in equilibrium with ^{234}U, which is present in the amount of 0.0058%. ^{235}U, the parent isotope of actinium series, is present in the amount of 0.71%. ^{230}U, which is also s member of the ^{238}U series, has a short half-life (20.8 days). Typical concentrations of uranium in the acid igneous rock is in the order of 3 ppm /Eisenbud, 1987/.

1.23 Radium

Radium occurs in the environment as radioactive nuclide ^{224}Ra, ^{226}Ra and ^{228}Ra. ^{226}Ra and ^{228}Ra are naturally occurring decay products from ^{238}U and ^{232}Th decay chain with physical half-life 1,599 and 5.8 years respectively. Therefore ^{226}Ra is more stable and more abundant in environment. The concentration of Ra in vegetation ranges from 0.03 to 1.6 pg g^{-1} dry weight of matter /Kabata-Pendias and Pendias, 1992/ with wide variations of transfer factors. Radium has been detected in fungi /Baeza et al. 2004/, however, the mechanism of ^{226}Ra incorporation to the fruitbodies is independent of the nutritional mechanism and differs from that of ^{137}Cs and ^{40}K.

2 Material and methods

2.1 Sampling area

The study area was located in a forest ecosystem close the Nuclear Power Plant at Forsmark, Sweden. The Forsmark area is located on the Southwest Bothnian Sea coastline in the central east part of Sweden (approximately N 60°22′ and E 18°13′). The main soil parent material at the sampling sites was sandy or clayey till, the humus form was mainly mull, site hydrology was fresh with mesic mosses as prevailing ground-layer vegetation. Organic matter content in the soil profiles varied from 36 to 98% for the 0–5 cm layers and from 21 to 97% for the 5–10 cm layer (Table 3-1). pH was found to be between 3.8–6.9 for layer 0–5 cm and between 3.6–7.1 for layer 5–10 cm (Table 3-1). The prevailing field layer vegetation was low herbs without shrubs /Lundin et al. 2004/. In the field layer we observed many plant species, which are listed in Appendix VII. The forest types were typically spruce forest or mixed forest. The dominating trees were on site 1 to 7 Norway spruce (*Picea abies*) and in site 8–10 Scots pine (*Pinus sylvestris*). The stand was approximately 70–100 years old. In the field layer, the most common plants were bilberry *Vaccinium myrtillus*), eagle-like bracke (*Pteridium aqualinum*), coltsfoot (*Tussilago farfara*), horsetail (*Equisetum silvaticum*), stone bramble (*Rubus saxatilus*).

2.2 Sampling of soil and fruitbodies

The samples of soil and fruitbodies of fungi were collected simultaneously during the period from September to November 2003. We started by collecting fruitbodies of certain fungi species and then the corresponding soil samples were collected to a depth of 10 cm from 4 spots within an area of about 10 m^2 around and directly underneath the fruitbodies. For soil sampling, a cylindrical steel bore with a diameter of 5.7 cm was used. The soil cores were sectioned horizontally directly in the forest in layers of 0–5 and 5–10 cm thickness. Soil and fungal fruitbodies samples were collected from 10 sites. Before sampling of soil, fresh leaves and litter were removed. In the laboratory the species of the fungi were identified and ^{137}Cs activity concentration was measured. Afterwards the fruitbodies were dried at 35°C to constant weight for determination of the elements. For masspectrometric analyses soil samples taken from the depth 0–5 cm were used.

2.3 Preparation of fungal mycelium and fractionation of soil

An aliquot of the soil (30–50 g) was used for preparation of fungal mycelium. The mycelium from each layer of the soil profile 0–5 and 5–10 cm was prepared under microscopic examination (magnification 64 times) using pincers and adding distilled water to the soil. The prepared fraction of mycelium contained aseptate and septate hyphae, strands and rhizomorphs, sclerotia and also some small mycorrhizal rootlets. The method for mycelium preparation is described in /Vinichuk and Johanson, 2003/. After preparation of mycelium, the mycelium samples were dried at 35°C to constant weight for determination of the elements. The amount of mycelium obtained from each soil sample varied between 30 to 60 mg dw (dry weight) per sample.

The soil samples were also fractioned using the method described by /Gorban and Clegg, 1996/. Samples of the fresh soil were dissected out and big roots, stones and pieces of wood were removed. Then the soil was gently sieved through 2 mm mesh forming the bulk soil. The rest of the soil was squeezed with the fingers resulting in a separation of more soil from the roots giving the rhizosphere fraction. The residue was the third fraction, called soil-root interface fraction. The method is fully described in /Nikolova et al. 2000/.

2.4 Analyses

An aliquot of the soil samples was ignited at 550°C for determination of organic matter content (OM, %). pH was measured in soil samples, by using pH meter PHM 93.

2.5 Radiometry

In the laboratory, the ^{137}Cs activity concentrations in the bulk soil samples and fruitbodies samples were determined using well-calibrated HP Ge detectors. The ^{137}Cs activity concentration was expressed as Bq kg^{-1} dw.

2.6 Masspectrometry

A part of the samples were digested by 5 ml HNO_3 + 0.5 ml 30% hydrogenperoxide. The mixture was heated in microwave oven and thereafter diluted by MQ water and analyzed using ICP-AES or ICP-SFMS. The masspectrometric analysis were performed by Analytica, Luleå, Sweden.

2.7 Carbon and nitrogen analyses

Dried samples were milled and further dried at 50 to 55°C over night. About 2 mg of the samples were transferred to a tin capsule; the weight was determined and then transferred to the sampling carousal in a LECO elementary analyzer. The samples were burned and an IR detector was used to analyse the carbon content and a heat conductor detector was used for analyzing of nitrogen. The results were given as percentage of C and N in various fractions (dw) of the soil and fungi.

2.8 Statistical analyses

Statistical analysis (Pearson correlation and Paired T-Test) was performed by using Minitab program.

3 Results

3.1 Soil chemistry

Soils samples of the Forsmark area were sampled on ten sites and pH and organic matter content (OMC) were determined. Apart of this the total carbon and nitrogen content were determined in bulk soil, rhizosphere, soil-root interface, mycelium and fruitbodies of fungi.

Soil pH values of the investigated sites were rather high (Table 3-1). In the upper 0–5 cm soil layers pH value was on average 5.2 (range 3.8–6.9) and in 5–10 cm layer – 5.1 (range 3.6–7.1). These values were higher, compared with pH of between 4 and 5 for most forest soils in Sweden /Lundin et al. 2004/. Organic matter content values of investigated sites were also found to be rather high. In the upper 0–5 cm soil layer OMC value was on average 66.2 (range 36.4–97.7), in 5–10 cm layer – 52.9 (range 21.2–96.6). Content of C and N in analysed samples are shown in Appendices III and IV.

Table 3-1. Soil pH and organic matter content (OMC), %.

Site	pH		OMC, %	
	0–5 cm	5–10 cm	0–5 cm	5–10 cm
1	6.8	7.1	45.2	31.6
2	6.9	6.2	36.4	21.2
3	5.4	4.7	46.0	42.8
4	4.2	4.0	69.5	47.8
5	6.7	7.2	88.4	79.6
6	4.5	4.8	76.7	49.4
7	4.4	3.9	60.4	57.5
8	3.9	4.2	90.9	80.9
9	3.8	3.6	97.7	96.6
10	4.5	4.7	50.9	22.0
Mean	5.2	5.1	66.2	52.9

3.2 Potassium, rubidium and caesium concentrations in soil and fungal compartment

The mean and median values were calculated. However, the median values seemed to be more representative than the mean values for K, Rb and Cs, because of the high variations of their concentrations. The median values allow quantitative comparison of data obtained among samples as well as elements. Concentrations of potassium, rubidium and caesium in bulk soil, rhizosphere and soil-root interface (median values and range) are shown in Table 3-2. Detailed analytical results of K, Rb and Cs concentrations in bulk soil, rhizosphere and in soil-root interface as well as in mycelium and fruitbodies are shown in Appendix I. The results presented in this report are calculated on a dry weight basis. Potassium concentration was between 370–986 mg per kg of bulk soil fraction; 647–1, 490 mg per kg of rhizosphere fraction; 1,840–4,200 mg per kg of soil-root interface fraction. Rb concentration varies between 1.48–10.1 mg kg^{-1} in bulk soil; 1.19–13.3 mg kg^{-1} in rhizosphere; 4.54–8.82 mg kg^{-1} in soil-root interface fraction.

Cs concentration varies between 0.08–0.68 mg kg^{-1} in bulk soil; 0.048–0.54 mg kg^{-1} in rhizosphere; 0.089–0.24 mg kg^{-1} in soil-root interface fraction.

Potassium concentration was found to be higher in rhizosphere and even still higher in soil-root interface compared to the concentration in bulk soil. The difference in concentration of potassium between bulk soil and rhizosphere was significant ($P < 0.05$) and between concentration in bulk soil and soil-root interface highly significant ($P < 0.001$). The same trend was observed for concentration of Rb however, the difference in concentration of those elements in bulk soil compared to rhizosphere was not statistically significant.

Table 3-2. Concentration of K, Rb and Cs, median values and range, mg per kg (dw) in bulk soil, rhizosphere and soil-root interface respectiovely.

Elements	Bulk soil	Rhizosphere	Soil-root interface
K	605 (370–986)	806 (647–1,490)*	3,280 (1,840–4,240)***
Rb	2.52 (1.48–10.1)	4.3 (1.19–13.3)	6.47 (4.54–18.88)
Cs	0.21 (0.080–0.683)	0.32 (0.048–0.539)	0.2 (0.089–0.239)

* $P < 0.05$, *** $P < 0.001$

The concentrations of K, Rb and Cs (median values and range) in bulk soil and mycelium and concentration ratio (CR) are shown in Table 3-3. It appears from the data that mycelium accumulates investigated elements in great extent. The increase in concentrations of potassium and rubidium in mycelium compared to concentration in bulk soil was pronounced and highly significant ($P < 0.001$). Even caesium seemed to be accumulated by the mycelium (CR = 2.4), however the difference in concentration of Cs in bulk soil and mycelium was not significant.

Table 3-3. Concentration of K, Rb and Cs (median values and range) in bulk soil and mycelium, mg kg^{-1} (dw) and concentration ratio, CR (mg per kg dw of mycelium divided by mg per kg of bulk soil dw).

Elements	Bulk soil	Mycelium	CR
K	605 (370–986)	2,750 (1,690–4,070)***	4.5
Rb	2.52 (1.48–10.1)	12.8 (5.7–23.3)***	5.1
Cs	0.21 (0.080–0.683)	0.51 (0.17–.2.82)	2.4

*** $P < 0.001$

Concentrations of K, Rb and Cs (median values and range) in bulk soil and fruitbodies and concentration ratio (CR) are shown in Table 3-4. Concentration ratios for each species of fungi are shown in Appendix V. The difference in concentration of K as well as Rb in bulk soil and fruitbodies of fungi was highly significant ($P < 0.001$). Caesium concentration in fruitbodies also increased significantly compared to concentration in bulk soil ($P < 0.01$). Concentration ratios were found to be 65.3, 75.8 and 18.6 for K, Rb and Cs respectively. Highest ability to accumulate K, Cs and especially Rb was shown by *Sarcodon imbricatus* (Appendix V).

Table 3-4. Concentration of K, Rb and Cs (median values and range) in bulk soil and fruitbodies, mg kg^{-1} dw, and concentration ratio, CR (mg per kg dw of fruitbodies divided by mg per kg dw of bulk soil)

Elements	Bulk soil	Fruitbodies	CR
K	605 (370–986)	39,500 (21,700–89,600)***	65.3
Rb	2.52 (1.48–10.1)	191 (17.5–1,000)***	75.8
Cs	0.21 (0.080–0.683)	3.9 (0.09–25.1)**	18.6

** P < 0.05, *** P < 0.001

The concentrations of K and Rb within the fruitbodies were much higher than found in the mycelium giving CRs 14.4 and 19.1, respectively. Even Cs concentration in fruitbodies was about 8 times higher compared to that in mycelium (Table 3-5). The difference in concentration of K and Rb in mycelium and fruitbodies of fungi was highly significant ($P < 0.001$). Caesium concentration in fruitbodies also differed significantly compared to that in mycelium ($P < 0.01$).

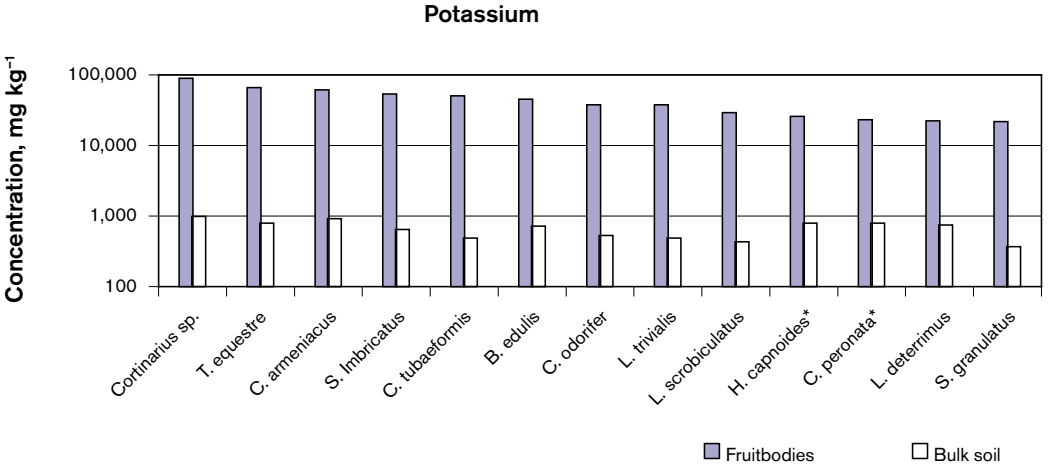
Table 3-5. Concentration of K, Rb and Cs (median values and range) in mycelium and fruitbodies, mg kg^{-1}dw, and concentration ratio, CR (mg per kg dw of fruitbodies divided by mg per kg dw of mycelium).

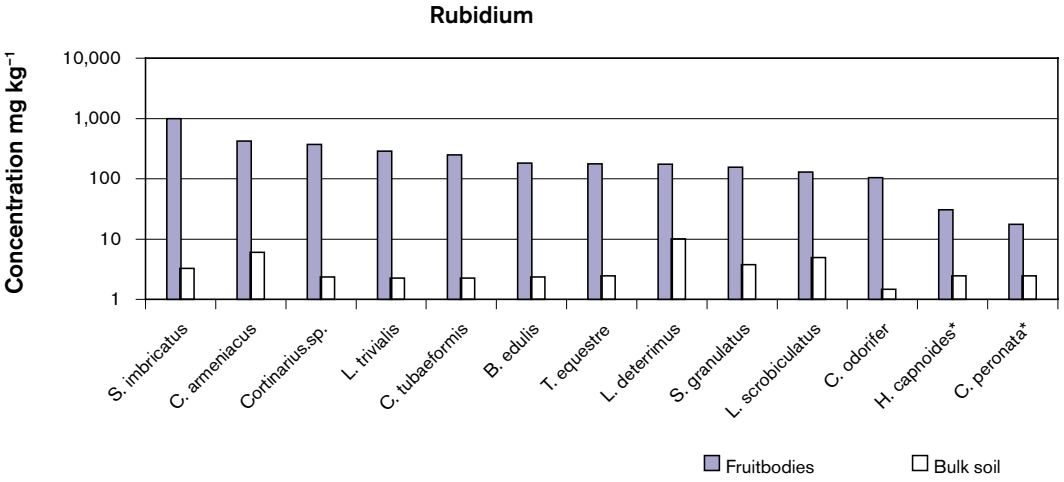
Elements	Mycelium	Fruitbodies	CR
K	2,750 (16,90–4,070)	39,500 (21,700–89,600)***	14.4
Rb	12.8 (5.7–23.3)	191 (17.5–1,000)***	19.1
Cs	0.51 (0.17–2.82)	3.9 (0.09–25.1)**	7.6

** P < 0.05, *** P < 0.001

Potassium was taken up by fruitbodies rather efficiently (Figure 3-1). *Cortinarius* sp. and *Tricholoma equestre* were species, which accumulated potassium to a great extent. *Lactarius* sp., *Suillus granulatus*, *Hypholoma capnoides* and *Collybia peronata* were relatively less effective in potassium accumulation. Two species, *Hypholoma capnoides* and *Collybia peronata* are saprophytes. Rubidium was taken up by fruitbodies most efficiently. Concentration of Rb in fruitbodies was almost two orders of magnitute higher compared to concentration of Rb in bulk soil (Figure 3-1). If concentration of Rb in bulk soil varied in the range between 1 and 10, concentration of Rb in fruitbodies of most analysed species of fruitbodies varied between 100 and 1,000. Two species, *Hypholoma capnoides* and *Collybia peronata* accumulated Rb to slightly less degree. Compared to potassium and rubidium, caesium was taken up less efficiently by fruitbodies. *Sarcodon imbricatus* showed great ability to accumulate Cs. Saprophytes fungi accumulated much less amount of Cs compared to mycorrhizal species.

Transfer factors (TF) defined as ^{137}Cs activity concentration in fruitbodies, Bq kg^{-1} divided by ^{137}Cs ground deposition, Bq m^2, are shown in Appendix VI. *Cortinarius armeniacus, C. odorifer* and *Lactarius trivialis* were species showing the highest TFs – 5.6, 2.9 and 2.0 respectively, whereas concentration ratios for stable Cs were highest in *Sarcodon imbricatus* (CR = 259), followed by *Lactarius trivialis* (CR = 52), *Boletus edulis* (CR = 37) *Cortinarius odorifer* (CR = 35) and *C. armeniacus* (CR = 19) (Appendix V).





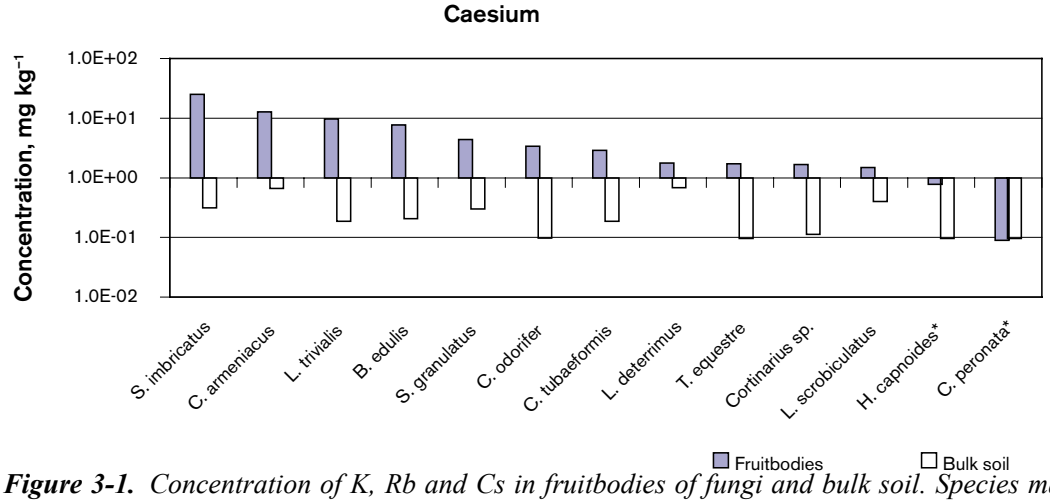


Figure 3-1. *Concentration of K, Rb and Cs in fruitbodies of fungi and bulk soil. Species marked with asterisk are saprophytes, others – mycorrhizal species. For details refer to Appendices I and II.*

3.3 Relationships between K, Rb and Cs in fungi

Relationships between the concentrations of K, Rb and Cs in mycelium and in fruitbodies of fungi were calculated and are shown in Table 3-6 and Figure 3-2 and 3-3. No correlations were found between K and Rb and between K and Cs concentrations in mycelium – r = 0.33 and 0.48 (Table 3-6). In fruitbodies no correlation was found between uptake of potassium and caesium (r = 0.26). Potassium and rubidium uptake showed a better correlation in fruitbodies (r = 0.51) and this correlation was found to be significant (P < 0.05). Rubidium and Cs uptake by mycelium and fruitbodies bodies of fungi showed good correlation, r = 0.79 for mycelium and r = 0.91 for fruitbodies bodies of fungi and both were significant (P < 0.05 and P < 0.01, respectively).

Table 3-6. Correlation coefficients between K, Rb and Cs concentration in mycelium and fruitbodies of fungi.

	Mycelium		Fruitbodies	
	K	**Rb**	**K**	**Rb**
K				
Rb	0.33		0.51*	
Cs	0.48	0.79*	0.26	0.91**

* P < 0.05, ** P < 0.01

Concentrations of potassium in bulk soil correlated well with that in fruitbodies (r = 0.74, P < 0.05, Table 3-7). Good and significant correlation was also found between concentration of Rb and Cs in bulk soil and concentration in mycelium (Figure 3-4). No correlation was found between rubidium and caesium concentrations in bulk soil and fruitbodies. Only weak correlation was found between potassium concentration in bulk soil and mycelium.

Table 3-7. Correlation coefficients among K, Rb and Cs concentration in mycelium and fruitbodies with concentration in bulk soil.

K	**Rb**	**Cs**
	Mycelium:Bulk soil	
0.45	0.86**	0.80**
	Fruitbodies:Bulk soil	
0.74*	0.02	0.22

* P < 0.05, ** P < 0.01

3.4 Potassium, rubidium and caesium concentrations in fruit bodies of fungi

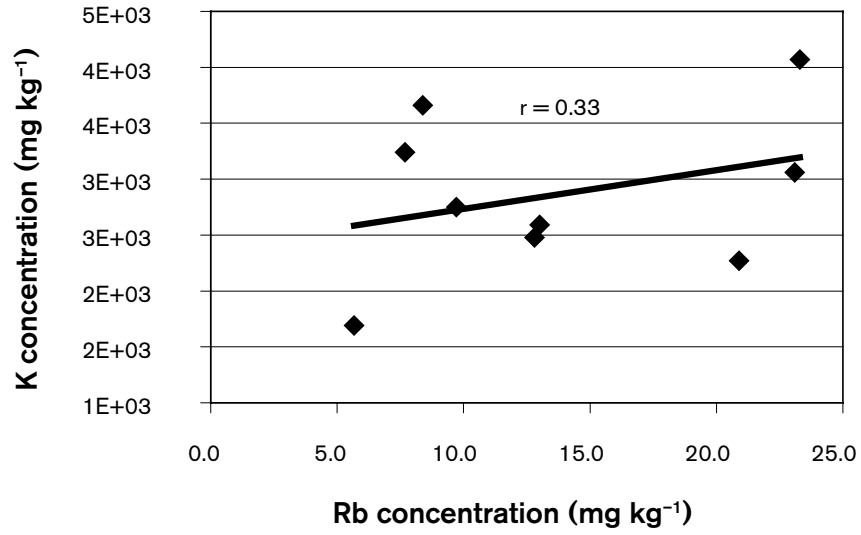
Concentrations of the elements in fruitbodies were generally species-dependent. We found significant differences in the ability to accumulate K, Rb and Cs in the fruitbodies of the investigated species (Appendix IV). Highest ability to accumulate K was shown by *Cortinarius* sp. (89,600 mg kg^{-1}); *Suillus variegatus* (78,200 mg kg^{-1}); *Tricholoma equestre* (65,700 mg kg^{-1}); *Cortinarius armeniacus* (61,800 mg kg^{-1}) and *Sarcodon imbricatus* (53,700 mg kg^{-1}). The concentration of K in fruitbodies of the above mentioned species varied between 8.9–5.3% of the dry weight. The lowest concentration was calculated for *Lactarius deterrimus* (22,300 mg kg^{-1}) or 2.2%.

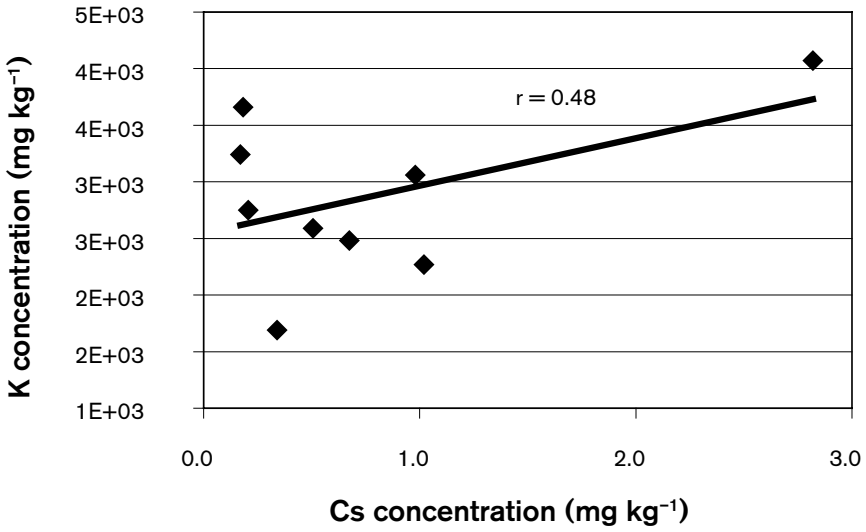
Rubidium concentrations decreased in the following order: *Sarcodon imbricatus* (1,000 mg kg^{-1}); *Suillus variagatus* (469 mg kg^{-1}); *Cortinarius armeniacus* (421 mg kg^{-1}); *Cortinarius phlemacium* (371 mg kg^{-1}) and *Suillus variegatus* (337 mg kg^{-1}). In spite of the fact that Rb concentration in fruitbodies bodies was much lower compared to K, CR for Rb was found to be higher than that for K. This indicates that Rb was accumulated even more efficiently than K. Seven fungal species of 16 analysed showed higher CR for Rb than for K. Extremely high concentration ratio for Rb was shown by *Sarcodon imbricatus, 676,* when median value was found to be 73.2. Even the CR for Cs was very high. A possible explanation of such phenomena might be the chemical similarities between K, Rb and Cs.

Highest Cs concentrations in fruitbodies were found in *Sarcodon imbricatus* (25.1 mg kg^{-1}); *Cortinarius armeniacus* (12.7 mg kg^{-1}); *Lactarius trivialis* (9.71 mg kg^{-1}) and *Suillus variegatus* (9.58 and 9.39 mg kg^{-1}).

Sarcodon imbricatus was found to accumulate K, Cs and especially Rb to greatest extent, followed by *Cortinarius* sp., and *Suillus variegatus*. *Sarcodon imbricatus* and *Suillus variegatus* are species, which are also known as accumulators of radioactive ^{137}Cs.

Generally, saprophytes showed lower concentrations of the alkali metals. As indicated by two saprophytes, *Hypholoma capnoides* and *Collybia peronata* they accumulated far less amounts of potassium, rubidium and caesium, compared to mycorrhizal species. No correlation was found between concentration of K, Rb and Cs in fruitbodies of fungi and soil pH as well as between CR and pH. Only weak correlation was found between concentration of K in fruitbodies bodies of fungi and organic matter content in upper 0–5 cm layers $r = 0.37$ and no correlation was found between concentration of Rb and Cs in fruitbodies bodies of fungi and organic matter content in upper 0–5 cm layers as well as between CR and organic matter content in soil.





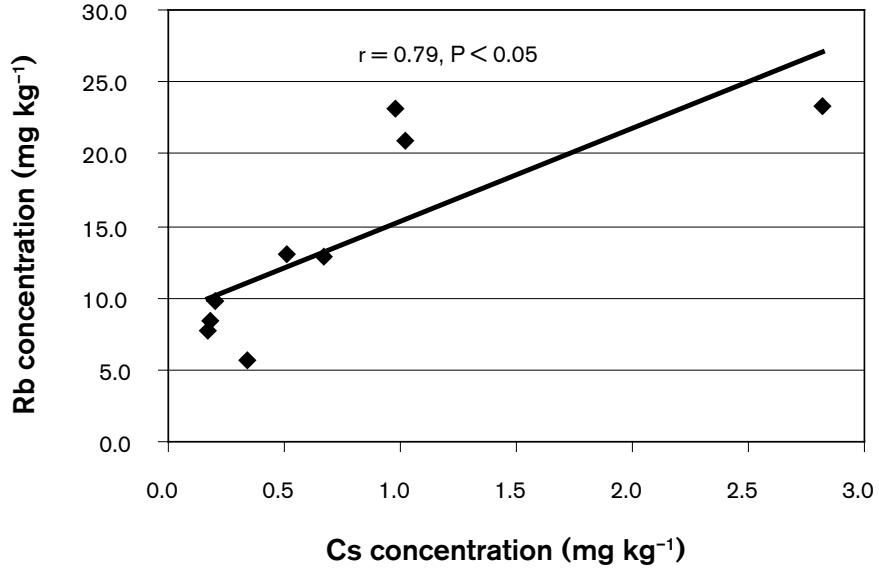
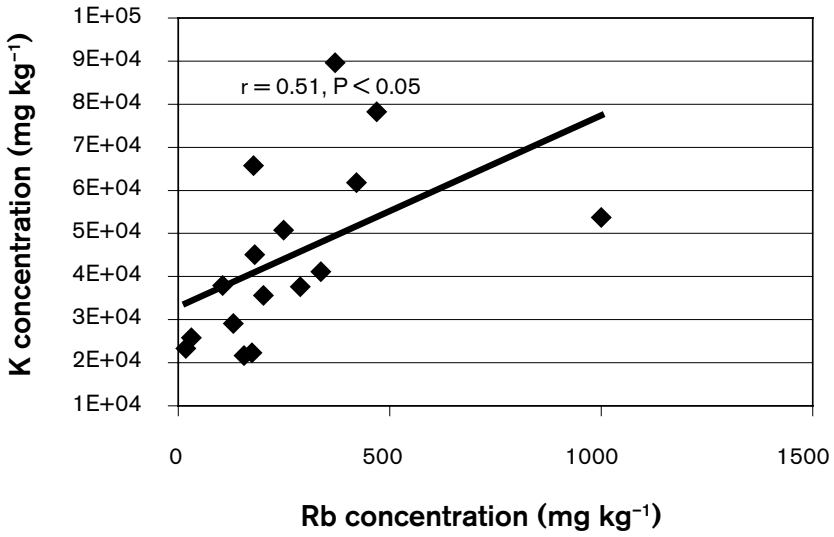
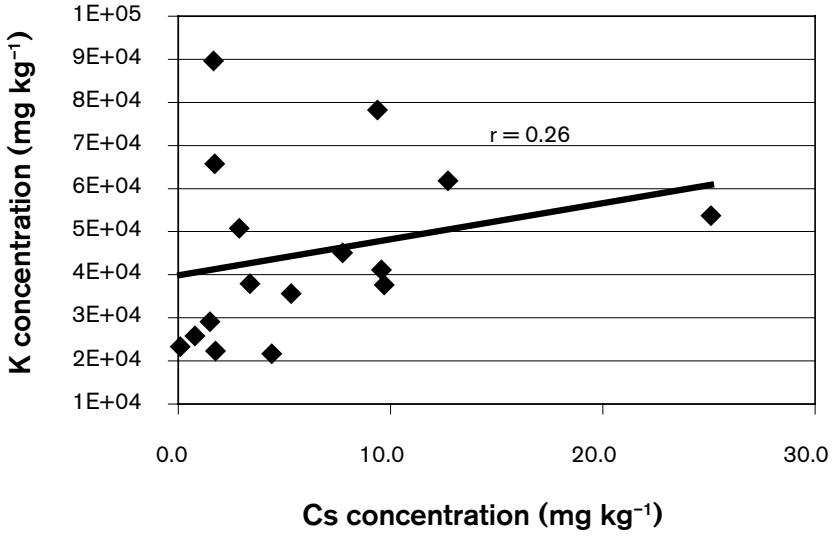


Figure 3-2. *Relationship between K, Rb and Cs concentration, mg per kg dw in fungal mycelium.*





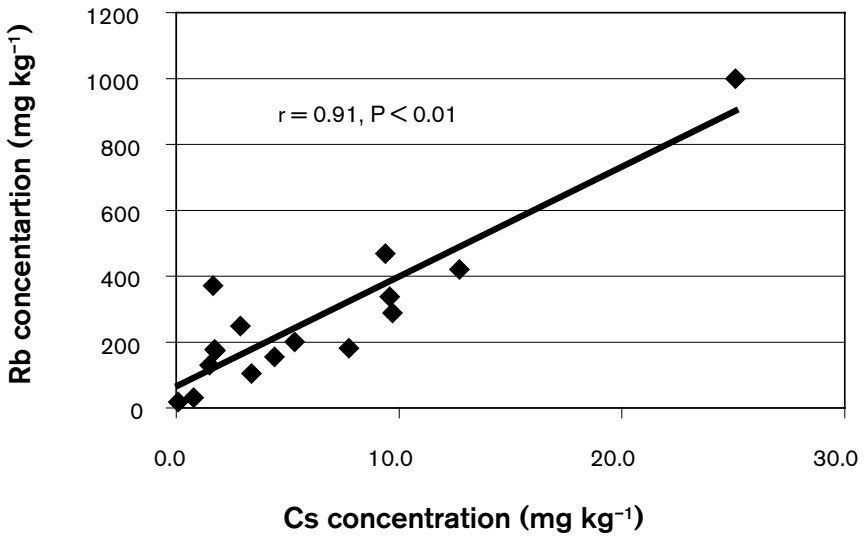


Figure 3-3. *Relationship between K, Rb and Cs concentration, mg per kg dw of fruitbodies bodies of fungi.*

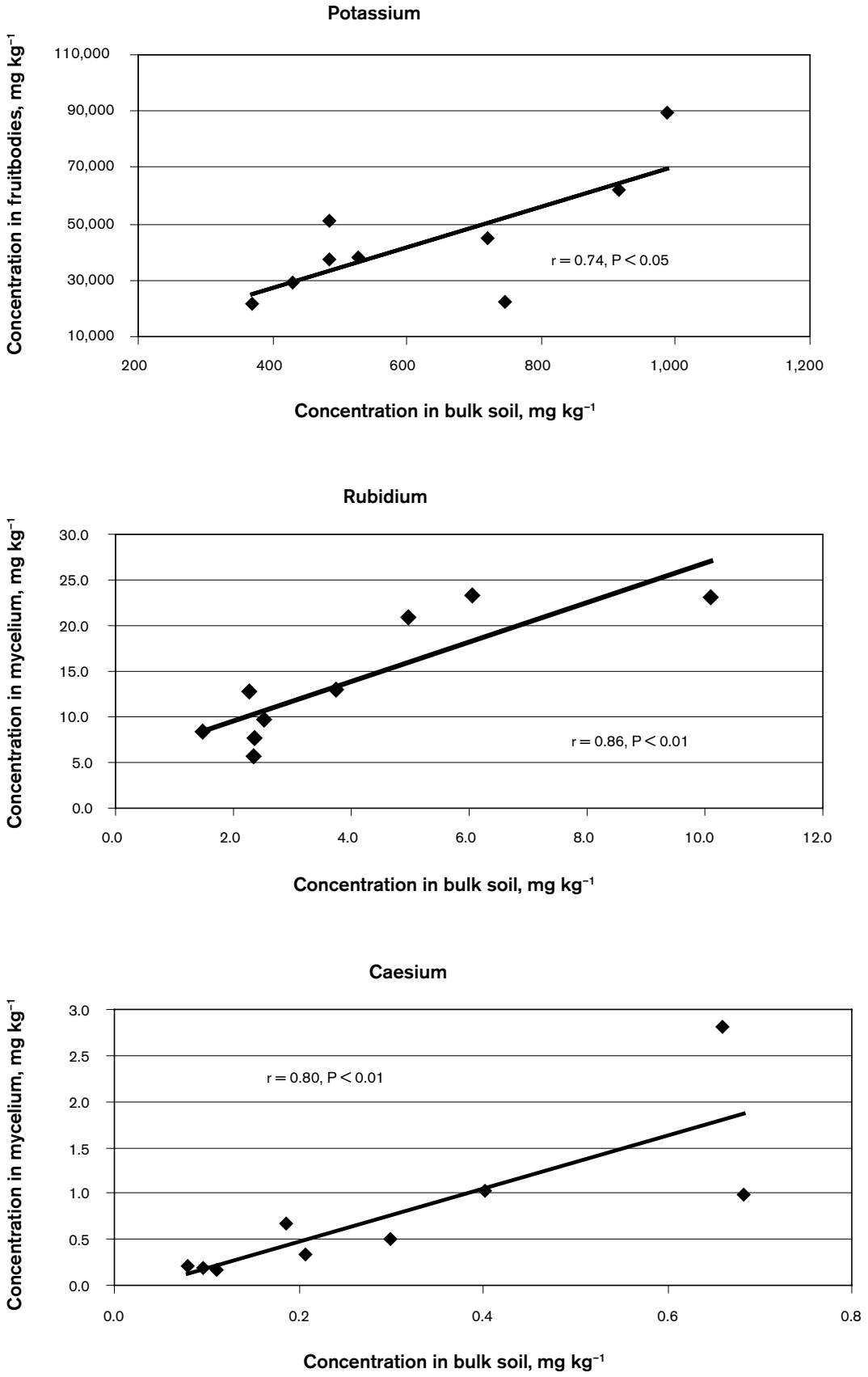


Figure 3-4. *Relationship between K, Rb and Cs concentration, mg per kg dw in bulk soil and fungal mycelium.*

3.5 Concentration of P, Ca, Cr, Mn, Co, Ni, Cu, Zn, As, Sr, Cd, I, Hg, Pb, Ra, Th and U in soil and fungi

In this study we analysed the concentration of 17 elements, including P, Ca, Cr, Mn, Co, Ni, Cu, Zn, As, Sr, Cd, I, Hg, Pb, Ra, Th and U in forest soil (bulk soil, rhizosphere, soil-root interface) as well as in fungal compartment (fungal mycelium and fruitbodies of fungi) (Table 3-8, 3-9 and 3-10, Appendix VII and VIII). The mean and median values were calculated as mg kg^{-1} but in the discussion we use the median values which seemed to be more representative. Data presented in this report were calculated on a dry weight basis. The list of analysed elements comprises essential macro-, and microelements such as Ca, P, Mn, I etc. as well as non-essential elements such as As, Cr, Cd etc. and the concentration of those elements differ considerably. The elements were divided into four groups, based on the concentration in bulk soil: very high concentration (> 100 mg kg^{-1} dw); high concentration (10–100 mg kg^{-1} dw); moderate concentration (1–10 mg kg^{-1} dw); low concentration (< 1 mg kg^{-1} dw).

Table 3-8. Concentration of elements, median values and range, mg per kg dw of bulk soil, rhizosphere and soil-root interface, respectively.

Elements	Bulk soil	Rhizosphere	Soil-root interface
	Very high > 100		
Ca	7,990 (3,870–38,400)	11,700 (6,350–26,400)	6,680 (3,320–19,100)
P	574 (217–801)	536 (490–699)	761 (644–901)*
Mn	102 (55–735)	114 (68–155)	89 (66–131)
	High 10–100		
Zn	38 (13–81)	33 (17–47)	45 (35–49)*
Pb	20.4 (6.7–31.0)	15.3 (9.3–25.2)	7.8 (4.0–11.4)*
Sr	14.3 (4.2–38.5)	24.9 (12.0–30.0)	21.3 (7.2–26.3)
	Moderate 1–10		
Cu	7.5 (6.2–30.7)	11.9 (6.2–19.6)	12.3 (5.9–18.0)
I	2.7 (1.6–6.8)	4.2 (0.2–2.9)	2.3 (0.05–0.6)
Ni	2.7 (1.6–8.3)	4.2 (3.2–7.3)	1.9 (0.8–3.3)*
Cr	2.1 0.9–6.9)	3.7 (0.8–9.8)	0.9 (0.2–2.4)**
U	1.9 (0.07–36.7)	5.3 (0.09–22.1)	2.9 (0.03–16.2)
	Low < 1		
Th	0.9 (0.1–2.9)	1.5 (0.2–2.9)	0.2 (0.05–0.6)**
Co	0.7 (0.3–1.4)	1.0 (0.2–1.8)	0.6 (0.1–0.9)*
As	0.7 (0.6–1.8)	1.0 (0.5–1.5)	0.6 (0.4–1.1)
Cd	0.3 (0.1–0.5)	0.3 (0.2–0.5)	0.6 (0.5–1.5)*
Hg	0.2 (0.05–0.3)	0.17 (0.09–0.2)	0.09 (0.06–0.13)

* P < 0.05, ** P < 0.01

Radium concentrations were below the detection limit (0.005 mg kg^{-1} dw) and were therefore not included in the table. Very high concentrations were found for Ca, P and Mn. Rhizoshere zone seemed to be enriched with Ca compare with bulk soil and soil-root interface, however due to large variation in concentration between sites, the difference was not statistically significant. Phosphorus concentration in soil-root interface was significantly higher compared to concentration in bulk soil ($P < 0.05$). Manganese concentration did not vary significantly in rhizosphere and soil-root interface compared to that in bulk soil.

Relatively high concentrations in analysed samples were observed for Zn, Pb and Sr. Compared to bulk soil, Sr concentration was found to be higher in the rhizosphere zone as in case with Ca and also in soil-root interface, however due to large variation the difference was not significant. Soil-root interface was also characterized by higher Zn concentration, compared to bulk soil ($P < 0.05$). Lead concentration decreased in order bulk soil, rhizosphere and soil-root interface ($P < 0.05$).

Table 3-9. Concentration of elements, median values and range, mg per kg dw of bulk soil, mycelium and concentration ratio, CR (mg per kg dw of mycelium divided by mg per kg dw of bulk soil).

Elements	Bulk soil	Mycelium	CR
	Very high > 100		
Ca	7,990 (3,870–38,400)	14,500 (4,420–31,100)	1.8
P	574 (217–801)	1,200 (789–1,670)**	7.4
Mn	102 (55–735)	96 (42–546)	0.9
	High 10–100		
Zn	38 (13–81)	62 (44–112)**	1.6
Pb	20.4 (6.7–31.0)	12.4 (7.4–19.4)	0.6
Sr	14.3 (4.2–38.5)	20.0 (6.0–25.9)	1.4
	Moderate 1–10		
Cu	7.5 (6.2–30.7)	15.7 (8.4–25.2)	2.1
I	2.7 (1.6–6.8)	1.5 (1.0–5.4)	0.6
Ni	2.7 (1.6–8.3)	2.5 (1.5–7.3)	0.9
Cr	2.1 0.9–6.9)	1.3 (0.4–8.9)	0.6
U	1.9 (0.07–36.7)	1.0 (0.04–10.3)	0.5
	Low < 1		
Th	0.9 (0.1–2.9)	0.3 (0.06–1.9)	0.3
Co	0.7 (0.3–1.4)	1.0 (0.2–2.2)	1.4
As	0.7 (0.6–1.8)	1.0 (0.6–1.5)	1.4
Cd	0.3 (0.1–0.5)	0.9 (0.5–5.6)*	3.0
Hg	0.2 (0.05–0.3)	0.22 (0.51–0.14)	1.1

* $P < 0.05$, ** $P < 0.01$

Moderate concentrations were found for Cu, I, Ni, Cr and U. Copper concentration was higher in rhizosphere zone as well as in soil-root interface compared to bulk soil but not significant. Iodine concentration was also higher in rhizosphere compared to that in bulk soil. Nickel and chromium concentrations were significantly lower ($P < 0.01$ and 0.05) in soil-root interface compared to concentration in bulk soil. Uranium was mainly found in the rhizosphere, however, concentration here did not differ significantly to that in bulk soil.

Low concentrations were found for Th, Co, As, Cd and Hg. Thorium and cobalt concentrations were found to be significantly lower ($P < 0.01$ and 0.05) in soil-root interface compared to concentration in bulk soil. Cadmium concentration was significantly higher ($P < 0.05$) in soil-root interface compared to that in bulk soil. Concentrations of As and Hg did nor vary significantly in bulk soil, rhizosphere and soil-root interface.

As indicate by CR value (Table 3-9) phosphorus was accumulated by fungal mycelium to large extent. Concentration ratio for this element was found to be 7.4. As indicated by paired T-test the concentration of P in mycelium was significantly higher compared to concentration in bulk soil ($P < 0.01$). Cadmium was also accumulated in fungal mycelium compared to concentration in bulk soil. Concentration ratio for Cd is 3.0 ($P < 0.05$). Copper concentration in mycelium was about two times higher than that in bulk soil but not significantly different. Concentration ratios above 1 were found for Ca (1.8), Zn (1.6), Sr (1.4), Co (1.4). The concentration of Zn in mycelium was higher compared to concentration in bulk soil ($P < 0.01$). Mn, Ni and Hg occurred in more or less equal amounts in bulk soil as well as in mycelium. Concentrations of Pb, I, Cr, U and Th showed a trend to be less in mycelium compared to bulk soil.

In fruitbodies of fungi (Table 3-10) the following concentrations of elements were detected.

Table 3-10. Concentration of elements, median values and range, mg per kg dw of bulk soil and fruitbodies and concentration ratio, CR (mg per kg dw of fruitbodies divided by mg per kg dw of bulk soil).

Elements	Bulk soil	Fruitbodies	CR
	Very high > 100		
Ca	7,990 (3,870–38,400)	215 (46–955)	0.03
P	574 (217–801)	4,890 (3,250–9,520)	8.52
Mn	102 (55–735)	17.3 (3–52)	0.17
	High 10–100		
Zn	38 (13–81)	85.6 (35.9–410)	2.25
Pb	20.4 (6.7–31.0)	0.2 (0.06–6.0)	0.10
Sr	14.3 (4.2–38.5)	0.54 (0.1–2.7)	0.04
	Moderate 1–10		
Cu	7.5 (6.2–30.7)	26 (6.3–64.1)	3.47
I	2.7 (1.6–6.8)	0.06 (0.03–0.8)	0.02
Ni	2.7 (1.6–8.3)	0.4 (0.06–1.2)	0.15
Cr	2.1 0.9–6.9)	0.04 (0.03–0.48)	0.02
U	1.9 (0.07–36.7)	0.01 (0.005–0.2)	0.01
	Low < 1		
Th	0.9 (0.1–2.9)	0.003 (0.001–0.013)	0.003
Co	0.7 (0.3–1.4)	0.04 (0.005–0.4)	0.06
As	0.7 (0.6–1.8)	0.9 (0.09–7.9)	1.29
Cd	0.3 (0.1–0.5)	1.76 (0.17–7.7)	5.90
Hg	0.2 (0.05–0.3)	0.3 (0.07–3.0)	1.50

Concentrations of P, Cd, Cu and Zn in fungal fruitbodies were much higher than that in bulk soil, indicating accumulation of those elements by fungi. Concentration ratios were calculated to be 8.5, 5.9, 3.5 and 2.3 correspondingly (Table 3-10). As and Hg concentrations in fruitbodies were only slightly higher compared to concentrations in bulk soil samples. Based on our data we conclude that these elements were moderately accumulated by fruitbodies of fungi. Concentrations of Ca, Mn, Pb, Sr, I, Ni, Cr, U, Th, and Co were much lower in fruitbodies compared to bulk soil, suggesting that no accumulation of those elements by fruitbodies take place.

Table 3-11. Concentration of elements, median values and range, mg per kg dw of mycelium and fruitbodies and concentration ratio, CR (mg per kg dw of fruitbodies divided by mg per kg dw of mycelium).

Elements	Mycelium	Fruitbodies	CR
	Very high > 100		
Ca	14,500 (4,420–31,100)	215 (46–955)	0.01
P	1,200 (789–1,670)	4,890 (3,250–9,520)	4.08
Mn	96 (42–546)	17.3 (3–52)	0.18
	High 10–100		
Zn	62 (44–112)	85.6 (35.9–410)	1.38
Pb	12.4 (7.4–19.4)	0.2 (0.06–6.0)	0.02
Sr	20.0 (6.0–25.9)	0.54 (0.1–2.7)	0.03
	Moderate 1–10		
Cu	15.7 (8.4–25.2)	26 (6.3–64.1)	1.66
I	1.5 (1.0–5.4)	0.06 (0.03–0.8)	0.04
Ni	2.5 (1.5–7.3)	0.4 (0.06–1.2)	0.16
Cr	1.3 (0.4–8.9)	0.04 (0.03–0.48)	0.03
U	1.0 (0.04–10.3)	0.01 (0.005–0.2)	0.01
	Low < 1		
Th	0.3 (0.06–1.9)	0.003 (0.001–0.013)	0.01
Co	1.0 (0.2–2.2)	0.04 (0.005–0.4)	0.04
As	1.0 (0.6–1.5)	0.9 (0.09–7.9)	0.9
Cd	0.9 (0.5–5.6)	1.95 (0.17–7.7)	2.17
Hg	0.22 (0.51–0.14)	0.3 (0.07–3.0)	1.36

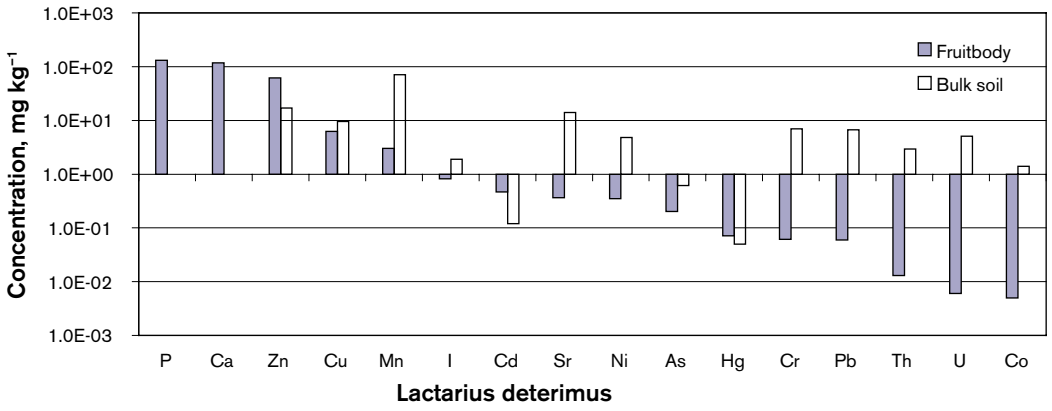
Comparison between concentrations of elements in fruitbodies of fungi and fungal mycelium (Table 3-11) indicates that fruitbodies accumulated P and Cd, giving CR 4.1 and 2.2 correspondingly. Only weak accumulation was observed for Cu, Zn and Hg. Concentration ratios were found to be 1.7, 1.4 and 1.4. Concentration of arsenic was more or less the same in mycelium and fruitbodies, indicating no accumulation of this element. Concentrations of Ca, Mn, Pb, Sr, I, Ni, Cr, U, Th and Co in mycelium samples were much higher compared to fruitbodies.

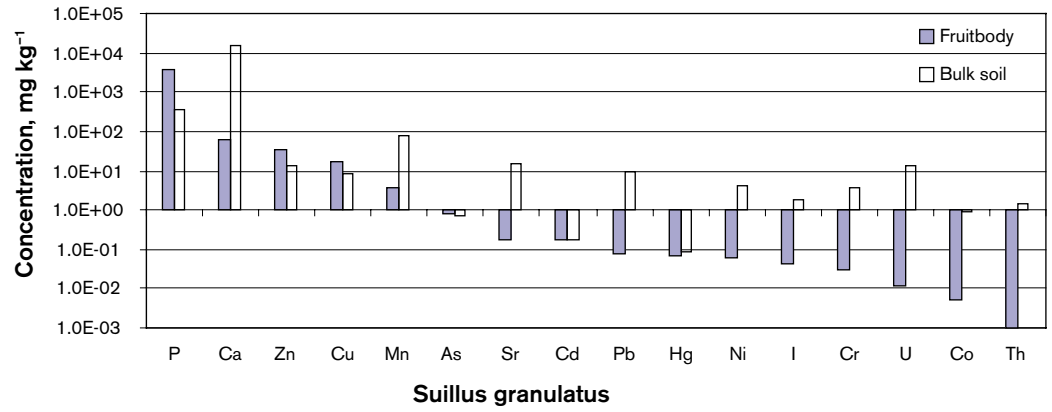
Results of the present investigation show species dependent differences of fungal fruitbodies to accumulate elements studied. Concentrations of some elements as P, Cu, Zn, As, Cd, Hg were found to be higher in fruitbodies of fungi compared to concentrations in bulk soil (Table 3-12 and Figure 3-5). Fruitbodies of Suillus variegatus were collected separately in Stalbo area. This sampling area has different forest type with low pH values and poor nutrient status of soils. Detailed data about concentrations of elements in fruitbodies are shown in Appendix VIII.

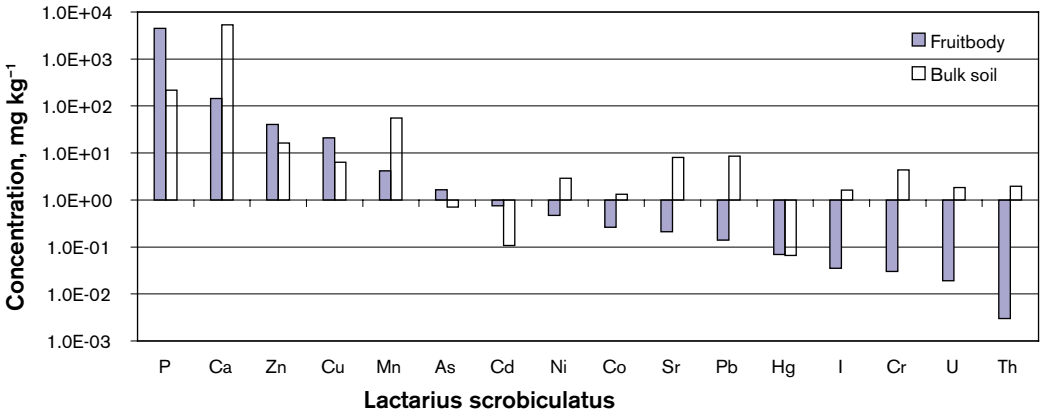
Table 3-12. Concentration ratios for some of the elements in fruitbodies of fungi. Only CRs > 1.0 are shown.

Sites	Species	Type of fungi*	P	Cu	Zn	As	Cd	Hg
1	Lactarius deterrimus	M	No data		3.6		3.9	1.4
2	Suillus granulatus	M	10.4	1.9	2.8	1.2		
3	Lactarius scrobiculatus	M	20.7	3.3	2.5	2.3	6.9	1.1
4	Boletus edulis	M	9.3	1.2	1.5	1.2	3.4	1.9
5	Cortinarius odorifer	M	5.9		3.8		7.2	
5–7	Sarcodon imbricatus	M	8.4	2.1	8.4		9.9	9.2
6	Cantharellus tubaeformis	M	5.9	4.4	2.2		1.1	
6	Lactarius trivialis	M	12.2	3.3	2.9		4.4	1.2
7	Cortinarius armeniacus	M	7.0	3.9	3.6	1.2	33.3	5.9
8	Cortinarius sp.	M	6.8	6.7	5.1	7.1	17.2	2.3
8–10	Hypholoma capnoides	S	9.4	3.0		1.3	2.3	
8–10	Tricholoma equestre	M	8.4	5.5	5.1		5.8	1.1
10	Collybia peronata	S	17.2	7.2		7.1	18.9	11.7

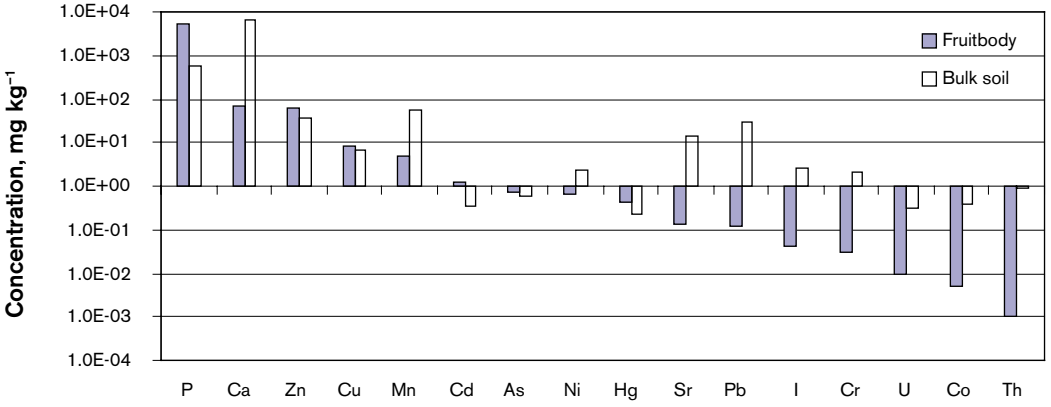
* M – mycorrhizal; S – saprophytes.



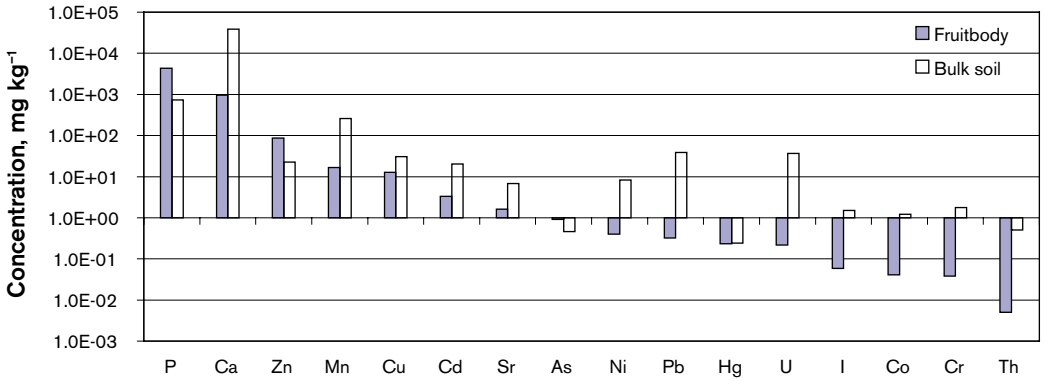




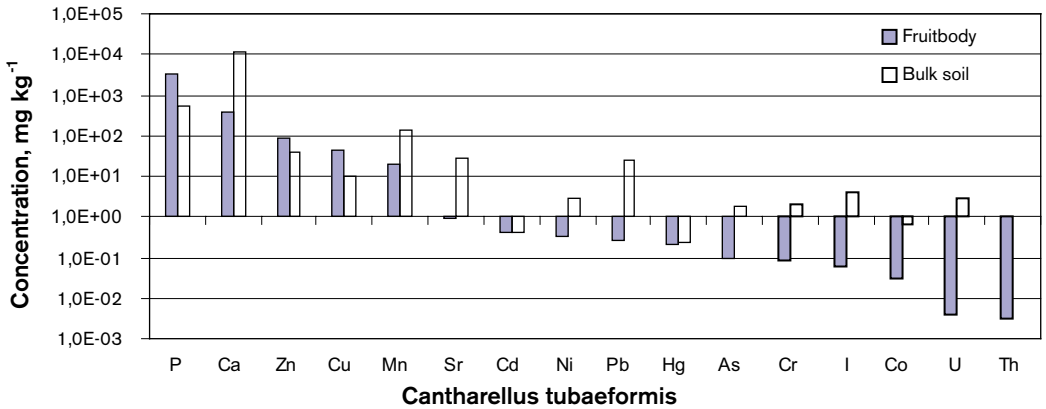
Lactarius scrobiculatus



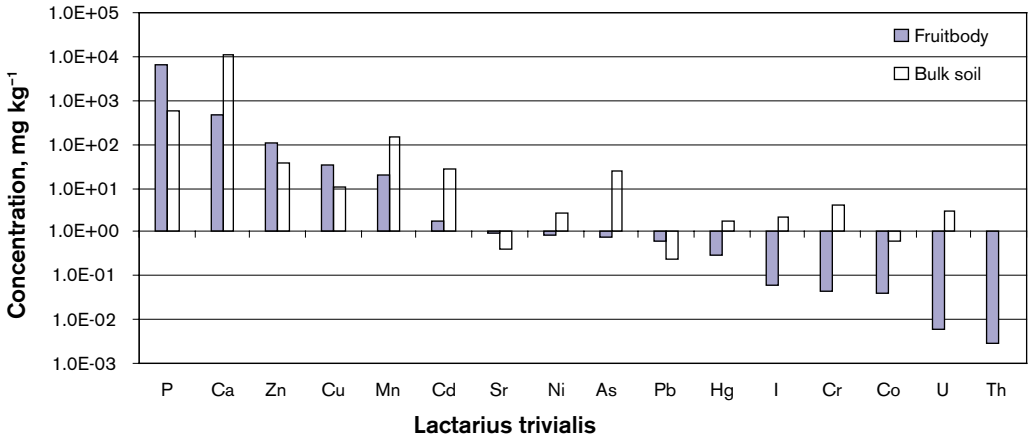
Boletus edulis



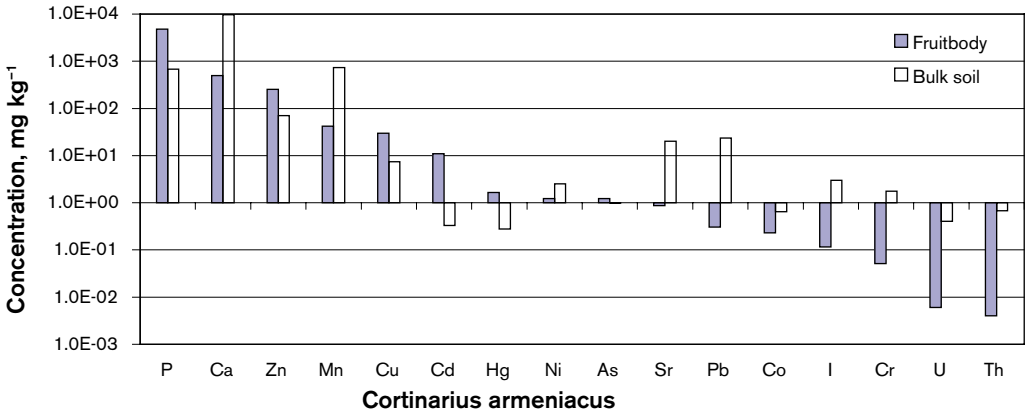
Cortinarius odorifer



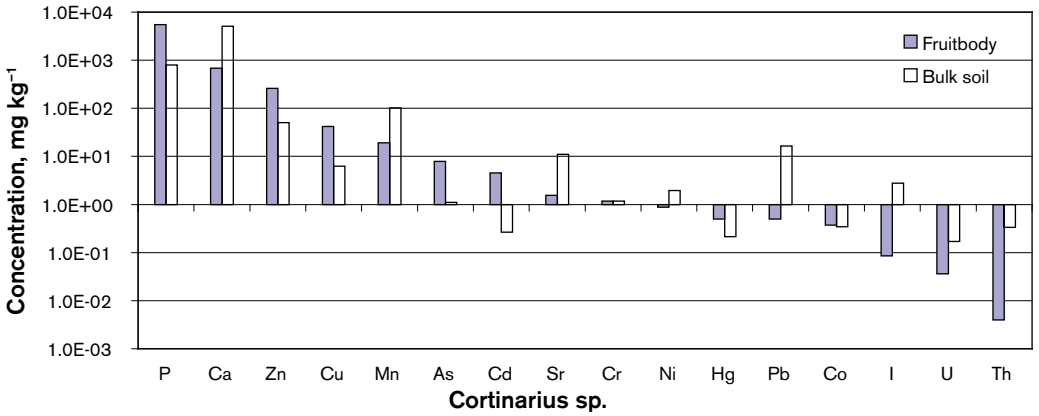
Cantharellus tubaeformis



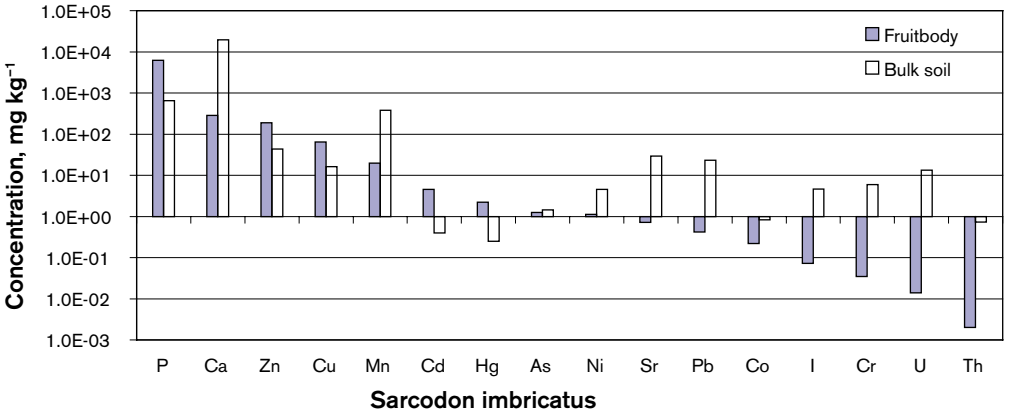
Lactarius trivialis



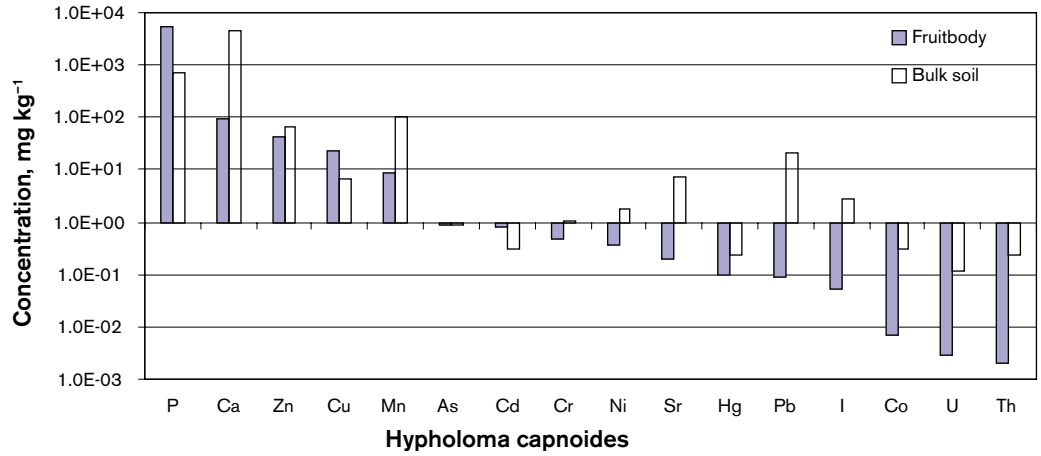
Cortinarius armeniacus

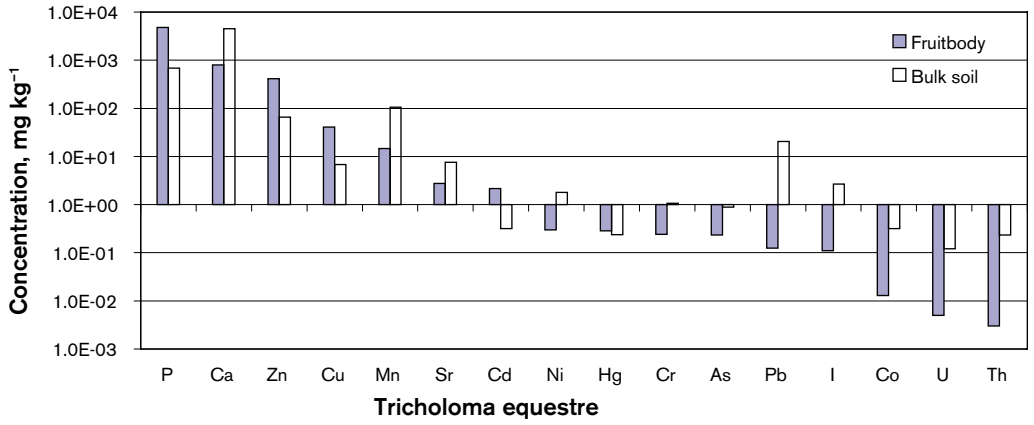


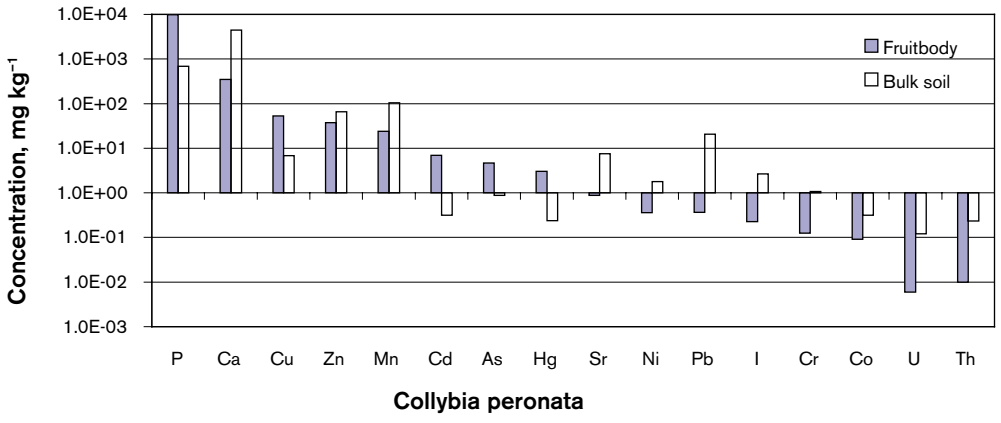
Cortinarius sp.



Sarcodon imbricatus







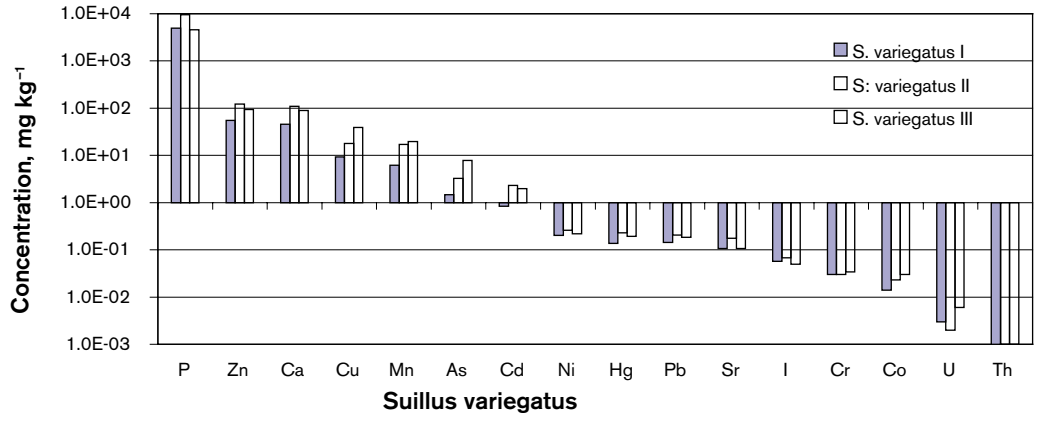


Figure 3-5. *Concentrations of elements in bulk soil and fruitbodies of fungi, mg per kg dw.*

3.6 Relations between uptake of the elements by mycelium and by fruitbodies of fungi

Correlation coefficients between elements taken up by mycelium were calculated (Table 3-13). Phosphorus uptake by mycelium correlated with Cu and Pb uptake ($P < 0.05$). Calcium uptake correlated with Sr and U ($P < 0.05$). Good correlations were observed between uptake of Cr and Co, Ni, I and Th ($P < 0.01$). Manganese uptake correlated with uptake of Cu and Zn ($P < 0.05$). There were good relationship between uptake of Co and Ni ($P < 0.01$) as well as between Co uptake, I and Th uptake ($P < 0.05$). Nickel uptake by fungal mycelium correlated well with uptake of Cu and Sr ($P < 0.05$), as well as I ($P < 0.01$) and Th uptake ($P < 0.05$). Positive correlations were also observed between uptake of Sr, Th and U ($P < 0.05$), as well as between Cd and Hg ($P < 0.05$) (Table 3-13). Our findings showed that fungal mycelium tend to accumulate Ca as well as Sr. Concentration ratios (CRs) defined as concentration of element in mycelium, mg kg^{-1} divided by concentration of element in bulk soil, mg kg^{-1}, were found to be 1.8 and 1.4 respectively. Uptake of Ca correlated fairly well with Sr uptake in mycelium ($r = 0.77$, $P < 0.05$). Uptake of Hg correlated well with Cd uptake ($r = 0.89$) (Table 3-13).

Table 3-13. Correlation coefficients between concentrations of elements in mycelium.

	P	Ca	Cr	Mn	Co	Ni	Cu	Zn	As	Sr	Cd	I	Hg	Pb	Th
Ca	0.62														
Cr	–0.07	0.38													
Mn	–0.03	–0.41	–0.14												
Co	0.62	–0.06	0.83**	–0.31											
Ni	0.26	0.51	0.96**	–0.14	0.82**										
Cu	0.80*	0.43	0.59	0.76*	0.43	0.76*									
Zn	–0.14	–0.71	–0.16	0.67*	–0.09	–0.06	0.18								
As	0.17	0.49	0.42	–0.58	0.64	0.52	0.52	–0.25							
Sr	0.14	0.77*	0.66	–0.58	0.51	0.68*	0.39	–0.59	0.49						
Cd	–0.25	–0.50	–0.28	–0.10	0.21	–0.14	0.06	0.53	0.35	–0.31					
I	0.45	0.01	0.89**	0.03	0.67*	0.89**	0.61	–0.01	0.13	0.59	–0.24				
Hg	–0.36	–0.47	–0.30	–0.05	0.09	–0.19	–0.04	0.57	0.32	–0.26	0.89*	–0.35			
Pb	–0.78*	–0.62	0.15	–0.30	0.58	0.14	–0.18	0.23	0.24	0.03	0.65	0.10	0.57		
Th	–0.43	0.27	0.83**	–0.30	0.70*	0.74*	0.24	–0.28	0.41	0.71*	–0.32	0.58	–0.17	0.29	
U	0.69	0.86*	0.43	–0.17	0.14	0.51	0.47	–0.33	0.13	0.79*	–0.34	0.60	–0.32	–0.34	0.28

* $P < 0.05$, ** $P < 0.01$

Correlation coefficients between concentrations of the elements in fruitbodies of fungi were also calculated (Table 3-14). Although the fruitbodies of analysed fungi belong to different species some correlations between concentrations of various elements in fruitbodies were found.

Table 3-14. Correlation coefficients among concentration of elements in fruitbodies.

	P	Ca	Cr	Mn	Co	Ni	Cu	Zn	As	Sr	Cd	I	Hg	Pb	Th
Ca	–0.07														
Cr	0.01	0.33													
Mn	0.28	0.46	0.06												
Co	0.03	0.27	0.53*	0.39											
Ni	0.09	0.31	0.21	0.60*	0.67**										
Cu	0.27	0.31	0.23	0.56*	0.43	0.40									
Zn	–0.05	0.64**	0.37	0.47	0.36	0.44	0.42								
As	0.45	0.23	0.76**	0.21	0.66**	0.25	0.30	0.17							
Sr	–0.06	0.92**	0.35	0.35	0.17	0.19	0.40	0.79**	0.18						
Cd	0.30	0.26	0.05	0.85	0.44	0.50*	0.45	0.35	0.28	0.15					
I	–0.04	–0.11	–0.06	–0.19	–0.15	–0.08	–0.22	–0.09	–0.07	–0.04	–0.10				
Hg	0.46	0.02	–0.10	0.60*	0.29	0.35	0.69**	0.10	0.25	0.02	0.78**	–0.02			
Pb	0.37	0.52*	0.30	0.57*	0.48	0.65**	0.55*	0.26	0.49	0.37	0.32	–0.21	0.31		
Th	0.13	0.18	0.04	0.04	0.03	0.01	0.01	–0.10	0.18	0.17	0.10	0.86**	0.21	0.07	
U	–0.18	0.62**	0.01	0.03	0.02	–0.02	–0.21	–0.04	0.03	0.35	0.03	–0.10	–0.14	0.19	0.11

* P < 0.05, ** P < 0.01

Concentration of Ca seems to be well correlated with concentration of Zn, Sr, U ($P < 0.01$) as well as with Pb concentration ($P < 0.05$). Concentration of Cr in fruitbodies correlated well with Co ($P < 0.05$) and As concentration ($P < 0.01$). Manganese concentration in fungi correlated with that of Ni, Hg and Pb concentration ($P < 0.05$). Good correlations were found between Co, Ni and As concentrations ($P < 0.05$), Ni and Pb concentration ($P < 0.01$), Cu and Hg concentration ($P < 0.01$). Cadmium concentration in fruitbodies also correlated well with that of mercury ($P < 0.01$). Mercury concentration in fruitbodies of fungi correlated relatively weakly with Cu ($r = 0.69$, $P < 0.01$). Rather good correlation was also observed between concentration of Th and I ($r = 0.86$, $P < 0.01$).

Table 3-15. Correlation coefficients between concentration of elements in mycelium and fruitbodies with concentration in bulk soil.

P	Ca	Cr	Mn	Co	Ni	Cu	Zn	As	Sr	Cd	I	Hg	Pb	Th	U
						Mycelium:Bulk soil									
–0.04	0.63	0.98**	0.06	0.53	0.33	0.32	0.77*	0.08	0.33	0.26	–0.45	0.46	0.31	0.79*	0.71*
						Fruitbodies:Bulk soil									
0.43	0.45	–0.35	0.88**	–0.21	–0.44	–0.26	0.87**	–0.05	0.59	0.27	–0.29	0.63	0.43	0.63	0.91**

* P < 0.05, ** P < 0.01

Concentrations of the examined metals in bulk soil correlated well with concentrations in mycelium (Table 3-15). Good and significant correlations were found between concentration of Cr, Zn, Th and U in bulk soil and concentration in mycelium. Only weak (not significant) correlations were found for Ca, Co and Hg. No correlations were found for P, Mn, Ni, Cu, As, Sr, Cd, I and Pb. Manganese, zinc and uranium concentrations in fruitbodies correlated significantly with concentration of those elements in bulk soil. However, most of the elements studied did not show any correlation between concentration in bulk soil and that in fruitbodies of fungi.

4 Discussion

The concentration of potassium in the rhizosphere and soil-root interface fraction as higher compared to the concentration of potassium in bulk soil. A significant difference between K concentrations in rhizosphere and soil-root interface compared to K concentration in bulk soil was observed ($P < 0.05$ and $P < 0.001$, respectively). Concentrations of potassium and rubidium in mycelium and fruitbodies compared to concentrations in bulk soil were significantly higher ($P < 0.001$). Caesium concentration in fruit bodies was higher compared to concentration in bulk soil ($P < 0.01$). Statistically significant higher concentration of potassium in rhizosphere and especially soil-root interface can be explained by presence of mycorrhizae. As reported by /Yoshida and Muramatsu, 1998/ concentration ratio of potassium (mg per kg in mushrooms or plants dw divided by mg per kg in upper 0–5 cm layer of soil dw) was higher, 1.4, in mushrooms compared to that in plants, 0.4, growing in the same forest. Our data indicate a concentration ratio for potassium in mycelium of 4.5 and even higher, 65.3 for fruitbodies of fungi. Studies of /Olsen et al. 1990/ show, that fungal biomass as part of mycorrhizae comprise about 40% of the dry weight. Such substantial amount may contribute to higher potassium concentration in rhizosphere and soil-root interface compared to that in bulk soil.

Accumulation of potassium by fungi is well documented. As pointed out by /Tyler, 1982/ the high concentration of K in fruitbodies of fungi may reflect a demand for K as a main cation in osmoregulation. The relative constancy and high CR for K may also indicate that K is an important element in regulating productivity of sporophore formation in fungi /Tyler, 1982/.

In our study the median K concentration in fruitbodies, 39,500 mg kg^{-1} was higher than that obtained by /Yoshida and Muramatsu, 1998/ (median value for 29 species is 27,200 mg kg^{-1}) and /Tyler, 1980/ (32,000 mg kg^{-1} for 200 mushrooms belonging to 130 species). /Seeger, 1978/ reported K level in many fungal species between 1.5 and 117 g of K per kg dry matter and found that the CR for K (fruitbodies/soil) ranged from 20 to 40. We also found higher median concentration for Rb – 191 mg kg^{-1} in comparison with /Yoshida and Muramatsu, 1998/, median value for 29 species is 87.6 mg kg^{-1}, and /Tyler, 1980/ (140 mg kg^{-1}). For stable Cs, the median concentration in fruitbodies was found to be 3.9 mg kg^{-1}, which is also higher than reported by /Yoshida and Muramatsu, 1998/ (1.01 mg kg^{-1}). An average level of 7 mg kg^{-1} of non–radioactive Cs with the highest value in *Cortinariaceae* – 308 mg kg^{-1} were reported by /Seeger and Schweinshaut, 1981/ in mushrooms.

The accumulation of Rb seems to be very pronounced in fruitbodies. /Tyler, 1982/ found mean concentration ratio for Rb to be 41 for the litter decomposing fungus *Collybia peronata*. However, Rb was concentrated to an even greater extent (mean ratio > 100) in *Amanita rubescens*, which is probably mycorrhizal with beech (*Fagus sylvatica* L.). In similar studies /Yoshida and Muramatsu, 1998/ found much lower CR for mushrooms 1.4, 1.6 and 0.80 correspondingly for K, Rb and stable Cs. However, as reported by other authors, CR for ^{137}Cs for mushrooms was higher than those for stable Cs, which is due to the fact that stable Cs is originally contained in the mineral components and therefore is more difficult for mushrooms to take up. As reported by /Oughton et al. 1992/ a higher fraction of ^{137}Cs was extractable compared with stable Cs.

Our data indicate that there is a significant correlation between concentration of Rb and Cs in mycelium ($r = 0.79$, $P < 0.05$). Potassium concentration in fruitbodies of fungi correlates with Rb concentration ($r = 0.51$, $P < 0.05$). Strong correlation was also found between concentration of Rb and Cs in fruitbodies of fungi ($r = 0.1$, $P < 0.01$). It is interesting to point out, that more or less the same correlation coefficient for mushrooms between concentrations of K and Rb ($r = 0.26$) and Rb and Cs ($r = 0.82$) were reported by /Yoshida and Muramatsu, 1998/. They also reported rather week correlation between K and Cs in fruitbodies, 0.23 0.26 and they concluded, that the mechanisms of the Cs uptake by fungi may be different from that of K. Our data seemed to confirm such statement, since we also found a rather weak correlation between K and Cs uptake by fruitbodies ($r = 0.26$) and this correlation was not significant. No correlation between ^{137}Cs and K in mushrooms was also found in studies of 28 species in Austria /Ismail, 1994/. Our studies also confirm the hypothesis that Rb showed intermediate behaviour between K and Cs, since correlation coefficient was found to be, $r = 0.51$, which was statistically significant. Since Rb uptake by fungal fruitbodies correlates rather well with Cs uptake ($r = 0.91$) we assume that uptake mechanism for those two elements might be rather similar. /Gaso et al. 2000/ also found that uptake of Rb by fungi rather well correlates with Cs uptake ($R^2=0.90$). Correlations between K, Rb and Cs uptake for fruitbodies were found to be more pronounced, than that of mycelium, which is very likely due to the fact, that concentration ratios for fruitbodies were at least one order of magnitude higher than that for mycelium, as we discussed before.

Concentration ratios in this study were calculated using dry weight of bulk soil, rhizosphere, and soil root interface fractions, as well as on dry weight of mycelium and fruitbodies of fungi. The carbon content (median values) in bulk soil was 39% of dry matter, 43% in rhizosphere fraction, 48% in soil-root interface fraction and 46% in mycelium and fruitbodies of fungi. Calculation of CRs based of carbon content resulted in a slightly lower values of CRs compared to CRs calculated using dry weight. For potassium, CRs calculated using carbon content were found to be 1.2 in rhizosphere fraction, 1.1 in soil-root interface fraction, 3.9 in mycelium and 55 in fruitbodies of fungi. The corresponding CRs calculated using dry weight were found to be 1.3 in rhizosphere fraction, 1.4 in soil root-interface fraction, 4.5 in mycelium and 65 in fruitbodies of fungi. Our conclusion is that the CRs based on dry weight is adequate to use and is also generally accepted in radioecology.

Based on the data obtained in this study, we conclude that concentrations of Ca, Mn, Sr, I, Cr, U Th and Co were higher in the rhizosphere compared to bulk soil (Table 3-8, Appendix VII). However, due to the large variation in concentrations between the sites investigated the differences for those elements were not statistically significant. Lead and mercury concentrations were found to be higher in bulk soil compared to concentrations of these elements in rhizosphere and soil-root interface. Concentrations of P, Zn and Cd were found to be significantly higher ($P < 0.05$) in soil-root interface compared to concentrations in bulk soil and in rhizosphere. Concentrations of Pb, Ni, Co, Cr and Th were found to be significantly lower ($P < 0.05$; 0.05; 0.05; 0.01; 0.01) in soil-root interface compared to concentrations in bulk soil.

Data obtained in this study showed that fungi accumulate appreciable amounts as essential as well as nonessential elements. Fungal mycelium seemed to accumulate the following elements listed in decreasing order: P, Cd, Cu, Ca, Zn, Sr, Co, As and Hg. Concentrations of P, Zn and Cd in mycelium differed significantly ($P < 0.05$; 0.05 and 0.01) compared to that in bulk soil. Fruitbodies of fungi accumulate: P, Cd, Cu, Zn, As and Hg. Concentrations of those elements were found to be higher in fungi compared to concentration in bulk soil.

Phosphorus is an essential nutrient element and fungi have relatively large requirements for phosphorus. Uptake of phosphorus can be related to involvement of this element to the energy metabolism processes. It is known that mycorrhizal fungi are involved in the uptake of phosphates by plant roots and phosphates from the soil are absorbed into the fungal

sheath were much of it is accumulated /Smith and Read, 1997/. Phosphorus is taken up by mycelium very efficiently. Concentration ratio for mycelium compared to bulk soil was found to be 7.4. Even higher accumulation (CR 8.5) was observed for fruitbodies of fungi. *Lactarius scrobiculatus* and litter decomposing fungus *Collybia peronata* were species with highest ability to accumulate phosphorus within their fruitbodies. CRs for fruitbodies of those species were 20.7 and 17.2 respectively. In mycelium, phosphorus uptake correlates rather well with that of Cu ($r = 0.80$, $P < 0.05$). No correlation between P and any other elements studied was found in fruitbodies of fungi. No correlation was found between concentration of phosphorus in bulk soil and mycelium as well as in fruitbodies.

Fungi did not accumulate Ca and the role of Ca^{2+} in fungal growth is not well understood. However, Ca is highly important in fungi and is required by fungi in the same order as micronutrients /Jackson and Heath, 1993/. Ca is found in all fungal cells and has induced diverse effects on growth, differentiation and sporulation /Gow and Gadd, 1995/. In fruitbodies of the studied fungal species, CR (Ca in fruitbodies/Ca in bulk soil) was found to be about 0.03. Some of the fungal species (fruitbodies), investigated in this study, i.e. *Suillus granulatus* and *Boletus edulis*, showed very low Ca concentration, giving CR less then 0.01. Appreciable amounts of Ca were recorded in fruitbodies of some of the species, e.g. *Cortinarius odorifer* and *Tricholoma equestre* (955 and 840 mg kg^{-1}), however these concentrations were still much lower compared to the concentration of Ca in corresponding bulk soil samples (Figure 3-5). /Tyler, 1980/ found that low Ca concentrations were common for most agarics and several other taxa of macrofungi, although higher levels were encountered in some of the *Polyporaceae*. Our data indicated some accumulation of Ca by mycelium. Concentration ratio for Ca in mycelium was found to be 1.8. In vascular plants, where Ca always constitutes a macro constituent, it is mainly found in the structural parts of the tissue or in inorganic precipitates, e.g. oxalate. Structural functions of Ca in fungi are not known. It was shown /Tyler, 1982/ that in e.g. agarics, Ca was only a trace element in fungal nutrition. Since Ca easily forms complexes with phosphate and thereby may affect the energy metabolism, an active efflux mechanism is therefore important for Ca /Greger, 2004/. In such a way Ca is restricted to the apoplast and large calcium-rich crystals deposited on the surface of mycelium may be observed. Such crystals have been reported by /Wallander et al. 2003/ on the surface of rhizomorphs in *Suillus granulatus*. It has been suggested /Jennings, 1996/ that formation of calcium oxalate may be significant in calcium homeostasis in fungi. Considering a very high level of Ca in bulk soil the mechanism of Ca exclusion seems to be quite efficient. Our data revealed only relatively weak correlation between Ca concentration in bulk soil and that in mycelium ($r = 0.63$, not significant) and even weaker ($r = 0.45$) for fruitbodies of fungi. Ca uptake correlates rather well with strontium uptake ($r = 0.77$, $P < 0.05$) and even better with uranium ($r = 0.86$, $P < 0.05$) in mycelium. In fruitboides of fungi Ca and Sr concentrations were found tightly correlated ($r = 0.92$, $P < 0.01$). Correlation between Ca and U was found to be weaker ($r = 0.62$) but highly significant ($P < 0.01$). Relatively weak correlations ($r = 0.64$, $P < 0.01$ and $r = 0.52$, $P < 0.05$) were found between concentrations of Ca and Zn and concentrations of Ca and Pb in fruitbodies of fungi.

Concentration ratio for chromium was found to be very low for mycelium (CR = 0.5) as well as for fruitbodies of fungi (CR = 0.02), indicating effective exclusion of this element from fungi. Data obtained in this study indicate that chromium uptake by mycelium is highly dependent upon the concentration of this element in bulk soil ($r = 0.98$, $P < 0.05$). Concentrations of Cr in fruitbodies were not correlated with Cr concentration in soil ($r = –0.35$). Chromium uptake by mycelium correlated rather well with uptake of Ni ($r = 0.96$, $P < 0.01$), I uptake ($r = 0.89$, $P < 0.01$), Co and Th uptake ($r = 0.83$, $P < 0.01$). In fruitbodies of fungi Cr concentration correlated only weakly with concentration of As ($r = 0.76$, $P < 0.01$) and concentration of Co ($r = 0.53$, $P < 0.05$).

Appreciable amounts of manganese were found in fungi. Manganese is required for fungi since it is essential element for fungal growth. According to our data mycelium contained 96 mg kg^{-1} of Mn, and 17.3 mg kg^{-1} was found in fruitbodies. However, in bulk soil samples higher amounts of Mn were found, giving concentration ratio 0.9 in mycelium and 0.17 in fruitbodies. In spite of the fact that manganese is a plant micronutrient, no accumulation of this element by fungi was observed in this study. According to /Rácz and Oldal, 2000/ cultivated mushrooms behave as a filter for Mn, since no accumulation of this element was observed. In soils with relatively high pH, manganese availability may be limited. Higher manganese availability was found in acid and flooded soil /Greger, 2004/. Mn uptake by mycelium correlated with uptake of Cu and Zn uptake ($r = 0.76$ and 0.67, $P < 0.05$) respectively. In fruitbodies of fungi Mn concentration correlated only weakly with concentration of Cu ($r = 0.56$, $P < 0.05$), Pb ($r = 0.57$, $P < 0.05$), Ni and Hg ($r = 0.60$, $P < 0.05$). Manganese concentration in fruitbodies correlated well ($r = 0.88$, $P < 0.01$) with concentration of Mn in bulk soil, however no correlation was found for mycelium (Table 3-15).

Cobalt was only moderately accumulated by fungal mycelium (CR = 1.4) and efficiently excluded from fruitbodies, since median CR in studied fruitbodies was found to be 0.06. At least some of the fungal species (fruitbodies) demonstrated extremely efficient excluding mechanism for cobalt indicated by very low CR values. For example in *Lactarius deterrimus* and *Suillus granulatus* CRs were found to be less than 0.005. Cobalt uptake by mycelium correlated well with Ni, I, Cr and Th uptake (Table 3-6). Co concentration in fruitbodies correlated only weakly with Ni, Cr and As concentrations (Table 3-13). Cobalt concentration in soil did not correlate with that in fruitbodies and only weakly (not significant) with that in mycelium ($r = 0.53$).

Nickel is a nutrient element for plants /Greger, 2004 and references herein/. Our data did not show any accumulation of this element by fungi. Median concentrations of Ni in mycelium were found to be similar to that in bulk soil (2.7 and 2.5 mg kg^{-1}) and much lower concentration was detected in fruitbodies (0.4 mg kg^{-1}). CRs for mycelium and fruitbodies were 0.9 and 0.4 respectively. Nickel concentration varied only moderately between sites in bulk soil as well as in fungi. As an exception relatively low concentration of Ni was detected in fruitbody of *Suillus granulatus* (0.059 mg kg^{-1}), compared to median value in all fruitbodies – 0.4 mg kg^{-1}. Nickel uptake by mycelium seems to be only weakly correlated with Ni concentration in soil ($r = 0.33$) and even less correlation was found for fruitbodies ($r = 0.15$). Ni uptake by mycelium was tightly correlated with Cr uptake ($r = 0.96$, $P < 0.01$), iodine uptake ($r = 0.89$, $P < 0.01$), Co uptake ($r = 0.82$, $P < 0.01$) as well as with uptake of Cu ($r = 0.76$, $P < 0.05$), uptake of Th ($r = 0.74$, $P < 0.05$) and uptake of Sr ($r = 0.68$, $P < 0.05$). In fruitbodies relatively weak correlation was observed between concentrations of Ni and concentrations of Co ($r = 0.67$, $P < 0.01$), Pb ($r = 0.65$, $P < 0.01$), Mn ($r = 0.60$, $P < 0.05$) and Cd ($r = 0.50$, $P < 0.05$).

Fungi accumulate copper very efficiently. Fungi require copper, as it is an essential element for fungal growth. Our data indicate that appreciable amounts of Cu were detected in fungal mycelium as well as in fruitbodies of fungi. Concentration ratio for mycelium was found to be 3.0, and 5.9 for fruitbodies, indicating that copper concentration increase in the order bulk-soil-mycelium-fruitbodies. Our data do not indicate any significant correlation between Cu uptake and another elements investigated by fungal mycelium. Cu concentration in fruitbodies of fungi correlated only weakly with Hg ($r = 0.69$, $P < 0.01$) and Pb ($r = 0.55$, $P < 0.05$). No correlation was found between copper concentration in bulk soil and in fungi. We also found that Cu accumulated to high extent by litter decomposing fungus *Collybia peronata* (CR = 7.2), some of the *Cortinarius* sp. (CR = 3.9–6.7), *Tricholoma equestre* (CR = 5.5), *Cantharellus tubaeformis* (CR = 4.4) and *Lactarius trivialis* (CR = 3.3). Copper is a nutrient element and high concentration of Cu

in mushrooms may reflect the demand for this metal in enzymes /Malmström and Rydén, 1968/. On the other hand a model experiment with microscopic fungi indicate that fungi could influence the mobility of the copper, nickel and zinc compounds in polluted Al-Fe humus podzols /Bespalova et al. 2002/. It was suggested that increased mobility of metals was primarily due to the decomposition of soil organic matter. Ectomycorrhizal fungi act as protector for host plant against copper toxicity. Protection of *Pinus sylvestris* against copper toxicity by the ectomycorrhizal fungi *Suillus bovines* and *Thelephora terrestris* was reported by /Van Tichelen et al. 2001/. The mechanism of protection was thought to be binding of the Cu in extraradial mycelium. Root growth and P nutrition were severely inhibited in non-mycorrhizal pines at elevated Cu concentration compared with mycorrhizal plants and excess of Cu had little effect on the development of mycorrhizal roots and mycelia. Sorption and accumulation of Cu by extraradical mycelium of arbuscular mycorrhizal fungi was also demonstrated by /Gonzales-Chaves et al. 2002/.

Fungi also accumulate zinc. Zinc is also required for fungi since it is essential element for fungal growth. It was appeared from the data we obtained, that CR for zinc was found to be 1.6 in mycelium and 2.3 in fruitbodies of fungi. *Sarcodon imbricatus* is an fungi showing high Zn accumulation (CR = 8.4). Zinc concentrations in fruitbodies of *Cortinarius* sp. and *Tricholoma equestre* were about five times higher compared to concentration in corresponding bulk soil samples. Litter decomposing fungi *Hypholoma capnoides* and *Collybia peronata* did not accumulate Zn. Concentration ratios for those species were found to be about 0.5. Zn uptake by mycelium correlates with Mn uptake ($r = 0.67$, $P < 0.05$). In fruitbodies Zn concentration correlated rather well with alkaline earth elements Ca and Sr concentration ($r = 0.64$ and 0.79, $P < 0.01$). Zinc uptake by fungi was correlated with concentration of this element in soil. Our data revealed that Zn concentration in bulk soil correlated well with that in mycelium ($r = 0.77$, $P < 0.05$). Correlation between Zn concentration in bulk soil and fruitbodies was even better and significant ($r = 0.87$, $P < 0.01$). /Thomet et al. 1999/ found that concentration of Zn in mushrooms was strongly correlated with concentration of chemically related Cd. Accumulation of Zn by mycorrhizas was reported by /Turnau et al. 2001/, which observed strong accumulation of Zn within the fungal mantle and in the rhizomorphs in *Suillus luteus* mycorrhizas. /Berthelsen et al. 1995/ found a mean Zn concentration in mycorrhizas to be 456 ± 201 μg g^{-1} mycorrhizas, which at least several times higher compared to data obtained in this study.

Arsenic is an element which accumulate rather moderately by mycelium (CR =1.4) as well as by fruitbodies (CR = 1.3). Litter decomposing fungus *Collybia peronata*, and *Cortinarius* sp. tend to accumulate higher amounts of As, compared to other species. Concentration ratios for the above-mentioned species (fruitbodies) were found to be about 7.0. On the other hand, *Cantharellus tubaeformis* was an example, where As concentration was very low, giving CR 0.05. Our data did not revealed any correlation between As and other elements uptake by mycelium. In fruitbodies of fungi As concentration correlated with concentration of Cr and Co (Table 3-14). No correlation was found between concentration of As in soil and fungi.

Strontium accumulated very moderately by fungal mycelium and efficiently excluded from fruitbodies. Concentration ratio mycelium:bulk soil for Sr was found to be 1.4 and fruitbodies:bulk soil – 0.04. Median Sr concentration in mycelium was much higher – about 20.0 mg kg^{-1} – compared to the concentration in fruitbodies – 0.54 mg kg^{-1}. /Yoshida and Muramatsu, 1998/ and /Ban-nai et al. 1994/ reported similar CRs for Sr in mushrooms – 0.03. Low ^{90}Sr concentration in mushrooms was observed by /Mascanzoni, 1990/ after the Chernobyl accident. Increased uptake of ^{90}Sr by ectomycorrhizal fungi was reported by /Entry et al. 1994/. Seedlings inoculated with ectomycorrhizal fungi accumulated between 3.0 to 6.9% of the ^{90}Sr compare to non-mycorrhizal 0.6 –0.7%.

Apparently Sr uptake is species-specific. Data obtained in this study revealed relatively high Sr concentration in some species (fruitbodies) i.e. *Tricholoma equestre* (2.74 mg kg^{-1}), *Cortinarius odorifer* (1.63 mg kg^{-1}) and *Cortinarius* sp. (1.56 mg kg^{-1}). At least one order of magnitude lower Sr concentration was recorded e.g. in *Boletus edulis* (0.14 mg kg^{-1}). In mycelium Sr uptake correlates with U uptake ($r = 0.79$, $P < 0.05$), Th ($r = 0.71$, $P < 0.05$), Ca ($r = 0.77$, $P < 0.05$) and Ni ($r = 0.68$, $P < 0.05$). In fruitbodies Sr concentration showed good correlated with Ca concentration ($r = 0.92$, $P < 0.01$) and Zn concentration ($r = 0.79$, $P < 0.01$). Very weak correlation was found between Sr concentration in bulk soil and that in mycelium ($r = 0.33$) and between Sr concentration in bulk soil and that in fruitbodies ($r = 0.59$). Based on the data above it might be assumed that in fungi Sr following similar uptake mechanism as Ca.

Cadmium is an element, which was accumulated very efficiently by fungal mycelium and difference in cadmium concentration between bulk soil, and mycelium was statistically significant. Concentration ratio for Cd was 3.0 in mycelium and 5.8 in fruit bodies. The extent of Cd transfer from soil to fruitbodies was species-specific. At least some of the species of fungi showed very high preference for Cd accumulation (Figure 3-5 and Table 3-12). Cd accumulation was very pronounced for *Cortinarius armeniacus*, *Cortinarius sp*., *Sarcodon imbricatus*, *Cortinarius odorifer* and *Lactarius scrobiculatus* and also for the liter decomposing fungus *Collybia peronata*. Those species of fungi showed concentration ratio for Cd between 7 and 33. Concentration ratio for Cd in *Cortinarius armeniacus* was found to be 33.3, compared to 4 for Cu and 3.6 for Zn. This fungus showed about 8 times higher ability to accumulate Cd compared to ability to accumulate Cu. High level of Cd accumulation in fruitbodies was reported by /Tüzen, 2003/ and /Rácz and Oldal, 2000/. /Blaudez et al. 2000/ and /Ott et al. 2002/ reported high ability to accumulate Cd by ectomycorrhizal fungus *Paxillus involutus*. The highest mean values of cadmium were found in *Boletus edulis* (10.3 mg kg^{-1} dry matter), *Xerocomus chrysenteron* (10.0) and *Lycoperdon perlatum* (9.7) /Zimmermannova et al. 2001/. High cadmium and arsenic concentrations were found to be characteristic of genus *Agaricus* /Vetter, 1994/. /Alonso et al. 1996/ found *Agaricus macrosporus* as the most important accumulative species (0.966–0.543 mg kg^{-1} dry weight of cadmium as mean value in the hymenium. /Tyler, 1982/ assumed that Cd in fruitbodies is sometimes accumulated along with Cu or Zn due to inability of the fungus to discriminate between those two metals. However, this explanation seems inadequate, as certain species appear to have a preference for Cd. Our findings indicate only rather weak and not significant correlation between concentration of Cd and Cu and concentration of Cd and Zn in fruitbodies of fungi ($r = 0.45$ and 0.42) respectively. /Tyler, 1982/ reported that accumulation of Cd correlated with that of Cu ($r = 0.82$) and with Zn ($r = 0.58$). /Thomet et al. 1999/ showed that concentrations of Cd in isolated wild mycelium of *Agaricus macrosporus* and *Agaricus silvicola* and stems of corresponding fruiting bodies were strongly correlated with chemically related Zn. Our findings instead indicate very good correlation between uptake of Cd and Hg uptake in mycelium ($r = 0.89$, $P < 0.05$) as well as in fruitbodies of different species studied ($r=0.78$, $P < 0.01$). Uptake of Cd by fungi was not correlated with the concentration of this element in soil. Only very weak correlation ($r = 0.26–0.27$) was observed between Cd concentration in bulk soil and fungi (Table 3-8). Cd seems to be unequally distributed between fungal biomass. Results obtained in this study revealed rather active transfer of Cd within a fungus from mycelium to fruitbodies. About two times higher Cd concentrations was found in fruitbodies of fungi compared to that in mycelium. As reported by /Turnau et al. 2002/ in *Hebeloma* and *Inocybe* mycorrhizas Cd was present in higher amount in the extra-matrical mycelium, whereas no or only low amounts of this element were detected within fungal mantles. /Berthelsen et al. 1995/ analyzed soil samples and samples of different morphological types of ectomycorrhiza with respect to Cd and found that the mean Cd concentration in mycorrhiza was 4.6 ± 1.9 µg g^{-1}, which may contribute for about 33% of the soil level of this element. The biosorption of Cd by mycelium was observed

in laboratory experiment /Siminovicova et al. 2002/, where Cd sorption varied between 64.6 and 100% of the content of metal applied to the medium. Accumulation of Cd by fungi has been suggested to protect of the host plant against Cd toxicity. /Colpaert and Vanassche, 1993/ reported that a dense extrametrical mycelium increase potential for Cd retention, providing protective effect against cadmium toxicity in the host, since Cd uptake was highest in the non-mycorrhizal seedlings. Taking into account the high toxicity of this element, the reason for high accumulation of Cd by fungal mycelium is still not clear.

Iodine concentrations were lower in mycelium – 1.5 mg kg^{-1} compared to 2.7 mg kg^{-1} in bulk soil and even much lower in fruitbodies of fungi – 0.06 mg kg^{-1}, clearly indicating that no accumulation of this element takes place. Concentration ratio for iodine in mycelium was 0.6, and 0.02 in fruitbodies of fungi. Highest iodine concentration was recorded for *Lactarius deterimus* – 0.816 mg kg^{-1}, followed by litter decomposing fungus *Collybia peronata* – 0.226 mg kg^{-1}. Low negative correlations were found between iodine concentration in bulk soil and fungi ($r = –0.45$ in mycelium and –0.29 in fruitbodies), indicating that iodine uptake by fungi is not affected by concentration of this element in soil. Iodine uptake by mycelium correlates rather well with Cr and Ni uptake ($r = 0.89$, $P < 0.01$) and Co uptake ($r = 0.67$, $P < 0.05$). In fruitbodies of fungi iodine concentration was correlated with concentration of Th ($r = 0.86$, $P < 0.01$).

Generally, mercury is not accumulated by fungal mycelium; giving CR about 1.1 Fruitbodies showed slightly higher ability to accumulate Hg (CR = 1.5) and this ability seemed to be species-specific. High Hg accumulation was observed for *Collybia peronata* (CR = 11.7), *Sarcodon imbricatus* (CR = 9.2) and *Cortinarius armeniacus* (CR = 5.9), *Cortinarius* sp. (CR = 2.3). Mercury concentrations in the other investigated species were found to be more or less the same as in the bulk soil, indicating no accumulation. Mercury uptake by mycelium was rather well correlated ($r = 0.89$, $P < 0.05$) with Cd uptake. Mercury concentration in fruitbodies correlated with concentration of Cd ($r = 0.78$, $P < 0.01$) and concentration of Cu ($r = 0.69$, $P < 0.01$). Mercury uptake by fungi depends very little upon the concentration of this element in bulk soil ($r = 0.46–0.63$). High ability of cultivated mushrooms to accumulate mercury has been reported by /Rácz and Oldal, 2000/. /Falandysz et al. 2003/ reported the greatest concentration of Hg for *Boletus edulis*, *Lycoperdon perlatum* and *Clitocybe revulosa*.

In our study fungi did not accumulate Pb. Concentration ratio for Pb in mycelium was found to be 0.6, and 0.1 in fruitbodies. Pb concentration in bulk soil was 20.4 mg kg^{-1} as median value (Table 3-8, Appendix VII). In mycelium Pb concentration was found to be 12.4 mg kg^{-1} and 0.18 mg kg^{-1} in fruitbodies. These findings suggest that Pb is rather efficiently excluded from fungi. A biofiltering effect of Pb by the fungal mantle was observed in the case of suilloid mycorrhizas /Turnau et al. 2002/. /Rácz and Oldal, 2000/ found that cultivated mushrooms behaved as a filter for Pb, resulting in no accumulation of this element. Studies of /Marschner et al. 1996/ showed that ectomycorrhizal fungi differ in their Pb accumulation and important factor is the binding capacity of the extramatrical mycelium. For the microscopic fungus *Trichoderma viride* the sorption of Pb in laboratory experiment was reported to be between 50 and 60%, and for Hg from 1.4 to 7.2% of the available concentration (Siminovicova et al. 2002). Studies by /Berthelsen et al. 1995/ revealed only low degree of Pb accumulation (arithmetic mean = 35 ± 6 µg g^{-1} mycorrhiza), indicating that Pb was almost excluded by the mycorrhizas. Lead accumulation in the fungal biomass may account to only about 2% of the soil level of this element. Pb concentration varied significantly among investigated species of fungi. In this study relatively low Pb concentration was found in *Lactarius deterimus* (0.06 mg kg^{-1}) and *Suillus granulatus* (0.08 m g kg^{-1}). Lead concentration in *Lactarius trivialis* fruitbody was almost one order of magnitude higher – 0.617 mg kg^{-1}. Lead uptake by fungi was not affected by concentration of this element in soil. Correlation coefficient between Pb concentration

in bulk soil and fungi was rather low. Uptake of Pb by fungal mycelium was not correlated with uptake of any elements investigated in this study. In fruitbodies of fungi concentration of Pb was only weakly correlated with concentration of Ni ($r = 0.65$, $P < 0.01$), Mn ($r = 0.57$, $P < 0.05$), Cu ($r = 0.55$, $P < 0.05$) and Ca ($r = 0.52$, $P < 0.05$).

Thorium concentration in fungal fruitbodies was found exceptionally low and Th seemed to be excluded from fungal mycelium (CR = 0.5) as well as from fruitbodies. The exclusion of Th from fruitbodies seemed to be very efficient – CR for studied fungal species varied between 0.001 and 0.16. /Mietelski et al. 2002/ observed thorium in fruitbodies of mushrooms in measurable amounts. Thorium uptake by mycelium was dependent upon concentration of this element in soil ($r = 0.79$, $P < 0.05$). However for fruitbodies of fungi the correlation was less pronounced ($r = 0.63$). Thorium uptake by mycelium correlated with Cr uptake ($r = 0.83$, $P < 0.01$), Ni uptake ($r = 0.74$, $P < 0.05$), Sr uptake ($r = 0.71$, $P < 0.05$) and Co uptake ($r = 0.70$, $P < 0.05$). In fruitbodies significant correlation between Th and I concentrations was detected – $r = 0.86$, $P < 0.01$.

Uranium seemed to show similar behaviour. The median concentration of this element was higher in bulk soil – 1.85 compared to concentration in mycelium – 1.03 mg kg^{-1}. In fruitbodies uranium was found only in small amounts – 0.006 mg kg^{-1} – which indicates rather low uptake rate of this element by fruitbodies and very efficient exclusion of U from fungi. However, higher U content in *Cortinarius odorifer* fruitbody was found – 0.216 mg kg^{-1}. Data obtained in this study showed that uranium uptake by fungi depends upon the U concentration in soil. Highly significant correlations ($r = 0.71$, $P < 0.05$ and 0.91, $P < 0.01$) were found between uranium concentration in bulk soil and mycelium as well as in bulk soil and in fruitbodies (Table 3-15). Uptake of uranium by mycelium correlates well with calcium and strontium uptake ($r = 0.86$ and 0.79, $P < 0.05$). Uranium concentration in fruitbodies of fungi correlated with Ca concentration ($r = 0.62$, $P < 0.01$). /Mietelski et al. 2002/ observed uranium in fruitbodies of mushrooms in measurable concentration, however, no uranium accumulated in the examined mushroom species. Uranium uptake and translocation by the arbuscular mycorrhizal fungus *Glomus intraradices* under root-organ culture conditions were reported by /Rufyikiri et al. 2002/. However, no accumulation of this element was observed either.

Concentration of Ra was found below the detection limit, which makes impossible to draw any conclusion on possible concentration and accumulation of this element in studied biological material.

The studied elements showed different distribution within the fungal biomass. Phosphorus, Cd, Cu, Zn, Hg and As concentrations were higher in fruitbodies compared to that in mycelium, giving fruitbodies to mycelium concentration ratios 4.1, 2.2, 1.7, 1.4, 1.4 and 1.3 correspondingly. Concentrations of these elements increase in the following order: bulk soil-mycelium-fruitbodies. Obviously transfer of these elements from mycelium to fruitbodies takes place and there should be rather effective transport mechanism, resulting in accumulation of the elements within fruitbodies of fungi. Highest accumulation of P in fruitbodies was shown by *Lactarius scrobiculatus* (CR = 20.7), for Cd by *Cortinarius armeniacus* (CR = 33.2), for Cu and Hg by litter decomposing fungus *Collybia peronata* (CR = 7.2 and 11.7), for Zn by *Sarcodon imbricatus* (CR = 8.4), for As by *Collybia peronata* and *Cortinarius* sp. (CR = 7.1). Concentrations of Ca, U, Th, Pb, Cr, Sr, Co, I, Ni and Mn were found to be higher in fungal mycelium, compared to concentrations in fruitbodies. Calcium was an exception in this case, since Ca could be deposited only on the surface of mycelium, forming large calcium-rich crystals /Wallander et al. 2003/. This explanation seems to be very likely in this case, since the investigated soils were rather rich in calcium. Strontium was often associated with Ca and sometimes also with Mg, and the ratio between Sr and Ca was relatively stable in biosphere /Greger, 2004/.

In fact, Ca and Sr uptake by fungi was correlated very tightly ($r = 0.77$, $P < 0.05$) in mycelium and even more strongly in fruitbodies ($r = 0.92$, $P < 0.01$). Apart of Ca and Sr the above mentioned elements may be ranked in the following order, reflecting decreasing effectiveness of their retention by mycelium: U > Th > Pb > Cr > Co > I > Ni > Mn.

It is accepted /Lodenius et al. 1981/ that saprophytic fungi accumulate much higher levels of heavy metals (Hg, Pb, Cd) than mycorrhizal fungi, which is probably due to saprophytic fungi using wood as nutrient source and that heavy metals are firmly bound and highly accumulated in cell walls of plants. Our data indicate that not only saprophytic fungi but also mycorrrhizal species may accumulate appreciable amounts of heavy metals. In this study we investigated fruitbodies of two saprophytic fungi *Hypholoma capnoides* and *Collybia peronata*. *Collybia peronata* fruitbodies accumulate much greater amounts of As, Hg, Cu and Cd compared to *Hypholoma capnoides* as well as mycorrhizal species. Some of the mycorrhizal species e.g. *Cortinarius* sp. accumulates greater amounts of Cd, As and Cu whereas e.g. *Sarcodon imbricatus* showed high accumulation of Hg. Mycorrhizal fungi were found as much prone to accumulate Zn compared to saprophytic species.

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Appendix I

Concentration of K, Rb and Cs in bulk soil, rhizosphere, soil root-interface and mycelium, mg kg^{-1} dw.

Sites	Bulk soil	Rhizosphere	Soil-root interface	Mycelium
Potassium				
1	745	1,490	4,240	3,060
2	370	839	3,330	2,590
3	429	752	3,230	2,270
4	719	896	3,860	1,690
5	528	647	2,790	3,660
6	485	772	1,840	2,480
7	916			4,070
8	986			3,240
9	605			2,750
Mean	642.6	899.3	3,215	2,867.8
Median	605	805.5	3,280	2,750.0
SD	214.6	301.4	842.8	727.5
Rubidium				
1	10.1	13.3	6.09	23.1
2	3.74	7.06	6.85	13.00
3	4.97	5.27	8.88	20.90
4	2.34	2.26	8.82	5.67
5	1.48	1.19	4.54	8.38
6	2.27	3.32	5.86	12.80
7	6.05			23.30
8	2.36			7.68
9	2.52			9.71
Mean	3.98	5.4	6.84	13.84
Median	2.52	4.3	6.47	12.80
SD	2.72	4.41	1.73	6.88
Caesium				
1	0.683	0.85	0.231	0.980
2	0.299	0.539	0.208	0.507
3	0.402	0.41	0.239	1.020
4	0.207	0.141	0.18	0.339
5	0.097	0.048	0.089	0.183
6	0.186	0.238	0.198	0.675
7	0.66			2.820
8	0.112			0.170
9	0.08			0.206
Mean	0.3	0.37	0.19	0.77
Median	0.21	0.32	0.2	0.51
SD	0.23	0.29	0.05	0.84

Appendix II

Concentration of K, Rb and Cs in fungal fruit bodies, mg kg^{-1} dw.

Sites	Species	K	Rb	Cs
1	Lactarius deterrimus	22,300	174	1.76
2	Suillus granulatus	21,700	155	4.41
3	Lactarius scrobiculatus	29,100	130	1.49
4	Boletus edulis	45,100	181	7.74
5	Cortinarius odorifer	37,900	105	3.37
5–7	Sarcodon imbricatus	53,700	1,000	25.1
6	Cantharellus tubaeformis	50,800	249	2.88
6	Lactarius trivialis	37,600	288	9.71
7	Cortinarius armeniacus	61,800	421	12.7
8	Cortinarius *sp.*	89,600	371	1.66
8–10	Hypholoma capnoides*	25,800	30.8	0.776
8–10	Tricholoma equestre	65,700	178	1.72
10	Collybia peronata*	23,300	17.5	0.089
Stalbo-K3	Suillus varegatus	35,600	201	5.32
Stalbo-K3	Suillus variegatus	41,100	337	9.58
Stalbo-K3	Suillus variegatus	78,200	469	9.39
Mean		44,956	269.2	6.1
Median		39,500	191.0	3.9
SD		20,446	234.1	6.4

* Saprophytes

Appendix III

C and N content in forest soil and fungal mycelium, % of dry weight.

Sites	Bulk soil	Rhizosphere	Soil-root interface	Mycelium
Carbon				
1				38.72
2	17.20	28.57	45.47	38.31
3	14.39	35.02	47.78	44.35
4	46.98	49.76		
5	45.03	47.23	49.44	47.66
6	39.26	43.15	48.86	46.92
7				
8				
9				
10				48.11
Mean	32.6	40.7	47.9	44.0
Median	39.3	43.2	48.3	45.6
SD	15.6	8.8	1.8	4.5
Nitrogen				
1				1.521
2	0.713	1.238	1.038	1.587
3	0.447	0.978	0.968	1.630
4	1.413	1.221		
5	1.865	1.639	1.375	2.248
6	1.426	1.513	1.191	1.709
7				
8				
9				
10				2.072
Mean	1.173	1.318	1.143	1.795
Median	1.413	1.238	1.115	1.670
SD	0.579	0.261	0.181	0.295

Appendix IV

C and N content in fruitbodies, % of dry weight.

Sites	Species	C	N
1	Lactarius deterrimus	46.11	2.654
2	Suillus granulatus	46.70	2.620
3	Lactarius scrobiculatus	45.56	3.355
4	Boletus edulis	46.97	4.593
5	Cortinarius odorifer	45.48	3.598
5–7	Sarcodon imbricatus	45.07	4.429
6	Cantharellus tubaeformis	46.28	3.265
6	Lactarius trivialis	45.71	2.960
7	Cortinarius armeniacus	46.36	4.104
8	Cortinarius *sp.*	44.75	3.916
8–10	Hypholoma capnoides *	43.39	4.013
8–10	Tricholoma equestre	42.46	2.138
10	Collybia peronata*	44.70	5.074
Stalbo-K3	Suillus variagatus	47.79	3.684
Stalbo-K3	Suillus variagatus	46.37	4.417
Stalbo-K3	Suillus variagatus	44.23	4.647
Mean		45.50	3.717
Median		45.64	3.800
SD		1.37	0.837

* Saprophytes

Appendix V

Concentration ratio fruitbodies (mg kg^{-1} dw) / bulk soil (mg kg^{-1} dw) for K, Rb and Cs.

Sites	Species	K	Rb	Cs
1	Lactarius deterrimus	29.9	17.2	2.6
2	Suillus granulatus	58.6	41.4	14.7
3	Lactarius scrobiculatus	67.8	26.2	3.7
4	Boletus edulis	62.7	77.4	37.4
5	Cortinarius odorifer	71.8	70.9	34.7
5–7	Sarcodon imbricatus	101.7	675.7	258.8
6	Cantharellus tubaeformis	104.7	109.7	15.5
6	Lactarius trivialis	77.5	126.9	52.2
7	Cortinarius armeniacus	67.5	69.6	19.2
8	Cortinarius sp.	90.9	157.2	14.8
8–10	Hypholoma capnoides	26.6	13.1	6.9
8–10	Tricholoma equestre	66.6	75.4	15.4
Mean		68.9	121.7	39.7
Median		67.7	73.2	15.5
SD		24.1	179.9	70.6

Appendix VI

Transfer factors (TF, Bq kg^{-1} dw / Bq m^2) of ^{137}Cs activity concentration for fruitbodies of fungi.

Sites	Species	Bq kg^{-1} dw	Bq m^2	TF
1	Lactarius deterrimus	749	5,667	0.13
2	Suillus granulatus	1,371	5,667	0.24
3	Lactarius scrobiculatus	504	5,667	0.09
4	Boletus edulis	4,863	5,667	0.86
5	Cortinarius odorifer	16,650	5,667	2.94
5–7	Sarcodon imbricatus	2,831	5,667	0.50
6	Cantharellus tubaeformis	4,151	5,667	0.73
6	Lactarius trivialis	11,511	5,667	2.03
7	Cortinarius armeniacus	31,513	5,667	5.56
8–10	Hypholoma capnoides	2,387	5,667	0.42
8'–11	Tricholoma equestre	5,228	5,667	0.92
Mean		7,433		1.31
Median		4,151		0.73
SD		9,379		1.66

Appendix VII

Concentration of elements in forest soil and fungal mycelium, mg kg^{-1} dw.

Sites	Bulk soil	Rhizosphere	Soil-root interface	Mycelium
Phosphorus				
1				
2	345	493	752	
3	217	490	774	1,470
4	575	699	901	789
5	732	536	761	1,670
6	549	576	644	995
7	684			1,100
8	801			1,330
9	572			1,200
Mean	559.4	558.8	766.4	1,222.0
Median	573.5	536.0	761.0	1,200.0
SD	195.4	85.9	91.4	296.7
Calcium				
1				
2	14,500	26,100	17,200	
3	5,350	9,660	6,270	27,500
4	6,350	6,350	3,320	15,200
5	38,400	26,400	19,100	31,100
6	11,100	11,700	6,680	14,500
7	9,630			4,420
8	5,080			8,410
9	3,870			9,330
Mean	11,785	16,042	10,514	15,780
Median	7,990	11,700	6,680	14,500
SD	11,335	9,513	7,122	9,992
Chromium				
1	6.990	9.840	2.360	8.910
2	3.750	6.670	1.500	4.100
3	4.390	4.330	1.210	4.490
4	2.200	1.140	0.227	2.510
5	1.770	0.790	0.415	0.376
6	2.140	3.070	0.577	1.110
7	1.750			1.300
8	1.180			0.508
9	0.953			0.523
Mean	2.79	4.31	1.05	2.65
Median	2.14	3.70	0.89	1.30
SD	1.94	3.47	0.81	2.81

Sites	Bulk soil	Rhizosphere	Soil-root interface	Mycelium
Manganese				
1	71.0	130.0	92.5	177.0
2	80.0	155.0	105.0	156.0
3	55.5	68.4	65.9	49.5
4	54.6	96.9	76.7	66.7
5	260.0	139.0	131.0	95.9
6	140.0	97.8	85.0	42.3
7	735.0			189.0
8	102.0			89.1
9	108.0			546.0
Mean	178.5	114.5	92.7	156.8
Median	102.0	113.9	88.8	95.9
SD	218.1	32.2	23.0	155.7
Cobalt				
1	1.400	1.800	0.616	2.220
2	0.931	1.630	0.710	0.953
3	1.320	1.240	0.995	1.300
4	0.373	0.232	0.119	0.950
5	1.210	0.678	0.470	0.243
6	0.621	0.780	0.658	1.280
7	0.652			1.300
8	0.345			0.349
9	0.288			0.181
Mean	0.79	1.06	0.59	0.98
Median	0.65	1.01	0.64	0.95
SD	0.44	0.60	0.29	0.65
Nickel				
1	4.79	7.26	3.25	7.33
2	3.97	6.83	2.49	3.96
3	2.91	3.36	1.48	4.11
4	2.25	2.07	0.77	2.44
5	8.28	5.01	2.94	2.53
6	2.72	3.18	1.11	1.87
7	2.54			3.01
8	1.95			1.48
9	1.63			1.46
Mean	3.45	4.62	2.01	3.13
Median	2.72	4.19	1.99	2.53
SD	2.06	2.11	1.03	1.85
Copper				
1	9.58	19.60	18.00	25.20
2	8.75	14.10	11.80	15.70
3	6.35	9.35	12.80	19.60
4	6.70	6.25	5.91	8.40
5	30.70	19.30	15.00	20.40
6	10.10	9.82	7.92	8.56
7	7.47			19.00
8	6.23			13.70
9	7.38			12.00
Mean	10.36	13.07	11.91	15.84
Median	7.47	11.96	12.30	15.70
SD	7.75	5.54	4.46	5.70

Sites	Bulk soil	Rhizosphere	Soil-root interface	Mycelium
Zinc				
1	17.1	34.0	47.9	73.0
2	12.7	25.3	42.8	62.1
3	16.3	31.5	48.1	49.7
4	38.0	46.7	49.2	61.0
5	22.7	18.6	42.0	57.0
6	37.5	35.5	35.1	43.6
7	70.8			112.0
8	50.2			72.2
9	81.1			96.8
Mean	38.49	31.93	44.18	69.71
Median	37.50	32.75	45.35	62.10
SD	24.65	9.56	5.36	22.13
Arsenic				
1	0.616	0.969	0.424	1.190
2	0.677	1.340	0.388	0.775
3	0.709	0.864	0.706	1.540
4	0.606	0.519	0.437	0.945
5	1.520	1.050	1.100	1.110
6	1.820	1.470	0.873	1.040
7	0.988			1.300
8	1.110			0.538
9	0.658			0.368
Mean	0.967	1.035	0.655	0.978
Median	0.71	1.01	0.57	1.04
SD	0.44	0.34	0.29	0.37
Strontium				
1	14.0	23.3	23.1	25.5
2	15.5	30.0	26.3	25.9
3	8.0	14.1	11.1	20.0
4	14.3	12.0	7.2	21.2
5	38.5	26.4	25.0	22.1
6	28.5	29.5	19.4	17.0
7	20.3			12.4
8	11.0			11.6
9	4.2			6.0
Mean	17.14	22.55	18.68	17.97
Median	14.30	24.85	21.25	20.00
SD	10.64	7.77	7.85	6.76
Cadmium				
1	0.120	0.316	0.652	0.774
2	0.183	0.341	0.574	0.734
3	0.108	0.225	0.947	0.761
4	0.353	0.263	0.604	0.855
5	0.463	0.496	0.544	1.100
6	0.399	0.471	1.550	2.410
7	0.331			5.610
8	0.264			1.210
9	0.369			0.503
Mean	0.29	0.35	0.81	1.55
Median	0.33	0.33	0.63	0.86
SD	0.13	0.11	0.39	1.62

Sites	Bulk soil	Rhizosphere	Soil-root interface	Mycelium
Iodine				
1	1.880	4.180	2.660	5.420
2	1.820	4.130	2.730	3.710
3	1.630	2.930	1.130	1.710
4	2.690	2.450	0.585	1.010
5	6.800	4.890	2.950	1.190
6	4.150	4.390	1.880	1.290
7	2.990			1.460
8	2.780			1.490
9	2.550			1.290
Mean	3.03	3.83	1.99	2.06
Median	2.69	4.16	2.27	1.46
SD	1.61	0.93	0.96	1.49
Mercury				
1	0.050	0.094	0.057	0.143
2	0.082	0.169	0.097	0.229
3	0.066	0.144	0.097	0.227
4	0.224	0.169	0.074	0.282
5	0.241	0.169	0.125	0.200
6	0.227	0.204	0.124	0.221
7	0.280			0.507
8	0.213			0.197
9	0.260			0.193
Mean	0.183	0.158	0.096	0.244
Median	0.224	0.169	0.097	0.221
SD	0.090	0.037	0.027	0.105
Lead				
1	6.69	9.31	4.02	15.30
2	9.31	15.40	6.89	10.90
3	8.58	15.30	8.23	8.30
4	31.00	25.20	8.38	16.80
5	20.40	11.40	7.29	6.55
6	25.20	22.30	11.40	16.70
7	23.60			19.40
8	16.50			12.40
9	24.60			7.38
Mean	18.43	16.49	7.70	12.64
Median	20.40	15.35	7.76	12.40
SD	8.62	6.16	2.40	4.65
Thorium				
1	2.94	2.87	0.577	1.870
2	1.420	2.510	0.446	0.931
3	1.950	2.250	0.359	1.110
4	0.903	0.203	0.046	1.730
5	0.501	0.152	0.102	0.214
6	1.020	0.696	0.121	0.338
7	0.681			0.311
8	0.336			0.107
9	0.134			0.064
Mean	1.10	1.45	0.28	0.74
Median	0.90	1.47	0.24	0.34
SD	0.89	1.23	0.22	0.70

Sites	Bulk soil	Rhizosphere	Soil-root interface	Mycelium
Uranium				
1	5.090	6.680	5.150	5.680
2	14.20	22.100	16.200	10.300
3	1.850	2.180	0.509	2.360
4	0.304	0.099	0.031	0.965
5	36.700	21.200	12.200	7.190
6	2.850	3.880	0.663	1.030
7	0.404			0.307
8	0.171			0.131
9	0.070			0.040
Mean	6.85	9.36	5.79	3.11
Median	1.85	5.28	2.91	1.03
SD	12.06	9.77	6.89	3.72
Radium–226				
1	< 0.005	< 0.005	< 0.005	< 0.005
2	< 0.005	< 0.005	< 0.005	< 0.005
3	< 0.005	< 0.005	< 0.005	< 0.005
4	< 0.005	< 0.005	< 0.005	< 0.005
5	< 0.005	< 0.005	< 0.005	< 0.005
6	< 0.005	< 0.005	< 0.005	< 0.005
7	< 0.005			< 0.005
8	< 0.005			< 0.005
9	< 0.005			< 0.005
Radium–228				
1	< 0.005	< 0.005	< 0.005	< 0.005
2	< 0.005	< 0.005	< 0.005	< 0.005
3	< 0.005	< 0.005	< 0.005	< 0.005
4	< 0.005	< 0.005	< 0.005	< 0.005
5	< 0.005	< 0.005	< 0.005	< 0.005
6	< 0.005	< 0.005	< 0.005	< 0.005
7	< 0.005			< 0.005
8	< 0.005			< 0.005
9	< 0.005			< 0.005

Appendix VIII

Concentration of elements in fungal fruitbodies, mg kg^{-1} dw.

Sites	Species	P	Ca	Cr	Mn	Co	Ni	Cu	Zn
1	Lactarius deterrimus	4,170	118	0.061	3.01	0.005	0.351	6.3	61.5
2	Suillus granulatus	3,590	64.7	0.030	3.54	0.005	0.059	16.9	35.8
3	Lactarius scrobiculatus	4,500	145	0.030	4.18	0.261	0.468	20.8	40.4
4	Boletus edulis	5,350	68.3	0.030	4.96	0.005	0.624	8.16	59
5	Cortinarius odorifer	4,330	955	0.038	16.70	0.041	0.397	12.8	87.5
5–7	Sarcodon imbricatus	6,170	284	0.035	19.90	0.220	1.120	64.1	190
6	Cantharellus tumaeformis	3,250	390	0.084	20.30	0.031	0.325	44.3	83.6
6	Lactarius trivialis	6,680	462	0.044	19.70	0.039	0.839	33.6	110
7	Cortinarius armeniacus	4,810	495	0.051	42.00	0.229	1.230	29.7	255
8	Cortinarius phlemacium	5,480	678	1.170	19.20	0.374	0.877	42.0	258
8–10	Hypholoma capnoides	5,390	93.9	0.475	8.60	0.007	0.355	22.3	42
8–10	Tricholoma equestre	4,820	804	0.241	14.70	0.013	0.298	40.9	410
10	Collybia peronata	9,810	346	0.125	23.80	0.091	0.357	53.4	37.3
Stalbo-K3	Suillus variegatus	4,960	45.6	0.030	6.17	0.014	0.201	9.2	54.8
Stalbo-K3	Suillus variegatus	9,520	123	0.030	17.90	0.023	0.258	17.2	109
Stalbo-K3	Suillus variegatus	4,570	93.4	0.030	19.70	0.050	0.219	39.1	89.1
Mean		5,463	323	0.16	15.27	0.09	0.50	28.8	120.2
Median		4,890	215	0.04	17.30	0.04	0.36	26.0	85.6
SD		1,854	287	0.29	10.14	0.12	0.34	17.3	105.7

Continuation

Sites	Species	As	Sr	Cd	I	Hg	Pb	Th	U	$^{226.228}$Ra
1	Lactarius deterrimus	0.201	0.365	0.467	0.816	0.071	0.060	0.013	0.006	< 0.005
2	Suillus granulatus	0.819	0.176	0.167	0.044	0.069	0.076	0.001	0.012	< 0.005
3	Lactarius scrobiculatus	1.660	0.211	0.747	0.035	0.069	0.140	0.003	0.019	< 0.005
4	Boletus edulis	0.716	0.14	1.190	0.043	0.432	0.116	0.001	0.009	< 0.005
5	Cortinarius odorifer	0.909	1.630	3.330	0.059	0.233	0.323	0.005	0.216	< 0.005
5–7	Sarcodon imbricatus	1.250	0.721	4.570	0.073	2.210	0.420	0.002	0.014	< 0.005
6	Cantharellus tumaeformis	0.090	0.924	0.436	0.062	0.203	0.265	0.003	0.004	< 0.005
6	Lactarius trivialis	0.786	0.957	1.760	0.058	0.280	0.617	0.003	0.006	< 0.005
7	Cortinarius armeniacus	1.220	0.876	11.0	0.115	1.650	0.305	0.004	0.006	< 0.005
8	Cortinarius phlemacium	7.840	1.55	4.550	0.085	0.499	0.499	0.004	0.036	< 0.005
8–10	Hypholoma capnoides	0.849	0.189	0.837	0.054	0.099	0.092	0.002	0.003	< 0.005
8–10	Tricholoma equestre	0.234	2.74	2.140	0.111	0.284	0.125	0.003	0.005	< 0.005
10	Collybia peronata	4.640	0.875	6.930	0.226	3.040	0.366	0.010	0.006	< 0.005
Stalbo-K3	Suillus variegatus	1.460	0.107	0.835	0.057	0.136	0.144	0.001	0.003	< 0.005
Stalbo-K3	Suillus variegatus	2.300	0.175	3.280	0.068	0.231	0.207	0.001	0.002	< 0.005
Stalbo-K3	Suillus variegatus	0.185	0.194	7.770	0.034	1.970	0.107	0.001	0.006	< 0.005
Mean		1.57	0.74	3.13	0.12	0.72	0.24	0.004	0.02	
Median		0.88	0.54	1.95	0.06	0.26	0.18	0.003	0.01	
SD		2.00	0.73	3.14	0.19	0.94	0.17	0.003	0.05	

Appendix IX

Observed vegetation on the sampling sites

Sites 1, 2, 3 and 4

N 60° 22’ 45.41’’; E 18° 13’ 20.12’’

Dominating trees: Norway spruce 80% and Scots pine 20% both at an age of 80 to 100 year.

Field layer: Pteridium aquilinum, Tussilago farfara, Filipendula ulmaria, Paris quadrifolia, Rubus saxatilis, Vaccinium myrtillus, Fragaria vesca, Maiathemum bifolium, Hepatica nobilis, Oxalis acetosella. Melampyrum silvaticum, Convallaria majalis, Trientalis europaea, Melica nutans, Dactylis glomerata, Deschampsia cespitosa. Monotropa hypopitus,

Sites 5, 6 and 7

N 60° 22’ 47.45’’; E 18° 13’ 19.17’’

Dominating trees: Norway spruce 80% and Scots pine 20% both at an age of 80 to 100 years.

Field layer: Pteridium aquilinum, Vaccinum myrtillus, Rubus saxatilis, Fragaria vesca, Melampyrum pratense, Melica nutans, Tussilago farfara, Filipendula ulmaria. Hepatica nobilis, Oxalis acetosella. Maianthemum bifolium, Trientalis eurpaea, Vaccinium vitis-idaea. Solidago virgaurea.

Site 8 and 9

N 60° 22’ 35.66’’; E 18° 11’ 53.94’’

Dominating trees: Scots pine 90% and Norway spruce 10%.

Field layer: Vaccinium myrtillus (dominating), Vaccinium vitis-idaea, Empetrum nigrum. Trientalis europaea, Maianthemum bifolium. Lycopodium annotinum

Site 10

N 60° 22’ 41.23’’; E 18° 13’ 20.31’’

Dominating trees: Scots pine 90% and Norway spruce 10%. Scots pine about 100 years old. Below the pine young spruce at a height of 3 to 6 metres.

Field layer: Vaccinium myrtillus, Pteridium aquilium. Hepatica nobilis, Trientalis europaea, Melica nutans, Maianthemum bifolium, Fragaria vesca, Convallaria majalis, Oxalis acetosella, Deschampsia cespitosa.

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