Conclusions

Cesium (^{137}Cs and ^{133}Cs) and Alkali Metals

The concentrations of the three stable alkali elements K, Rb, and ^{133}Cs and the activity concentration of ^{137}Cs have been determined in various components of Swedish forest − bulk soil, rhizosphere, soil-root interface fraction, fungal mycelium, and fungal sporocarps (Vinichuk et al. 2010b). The soil-root interface fraction is distinctly enriched with K and Rb, compared with bulk soil. Potassium concentration increases in the order bulk soil < rhizosphere < fungal mycelium < soil-root interface < fungal sporocarps, whereas, Rb concentration increases in the order bulk soil < rhizosphere < soil-root interface < fungal mycelium < fungal sporocarps. Cesium is generally evenly distributed within bulk soil, rhizosphere, and soil-root interface fractions, indicating no ^{133}Cs enrichment in these forest compartments.

The uptake of K, Rb, and ^{133}Cs during the entire transfer process between soil and sporocarps occurs against a concentration gradient. For all three alkali metals, the levels of K, Rb, and ^{133}Cs are at least one order of magnitude higher in sporocarps than in fungal mycelium. Potassium uptake appears to be regulated by fungal nutritional demands for this element and fungi have a high preference for the uptake of Rb and K than for Cs. According to the efficiency of uptaking by fungi, the three elements can be ranked in the order $Rb^+ > K^+ > Cs^+$, with a relative ratio of 100:57:32.

Although the mechanism of Cs uptake by fungi may be similar to that of Rb, the uptake mechanism for K appears to be different. The variability in isotopic (atom) ratios of ^{137}Cs/K, ^{137}Cs/Rb, and ^{137}Cs/^{133}Cs in the fungal sporocarps suggests they are not species specific. The relationships between the concentration ratio $^{137}Cs/^{133}Cs$ and K, Rb, and ^{133}Cs in fungal sporocarps have wide and inconsistent variation, and the concentration of K, Rb, and ^{133}Cs in sporocarps appears to be independent of the $^{137}Cs/^{133}Cs$ isotopic ratio.

The study of *S. variegatus* sporocarps (Vinichuk et al. 2011a) sampled within 1 km^2 forest area with high ^{137}Cs fallout from the Chernobyl accident confirms ^{133}Cs and ^{137}Cs uptake is not correlated with uptake of K; whereas, the uptake of Rb is closely related to the uptake of ^{133}Cs. Furthermore, the variability in ^{137}Cs and alkali metals (K, Rb, and ^{133}Cs) among genotypes in local populations of *S. variegatus* is high and the variation appears to be in the same range as found in species collected at different localities. The variations in concentrations of K, Rb, and ^{133}Cs and ^{137}Cs activity concentration in sporocarps of *S. variegatus* appear to be influenced more by local environmental factors than by genetic differences among fungal genotypes.

Cs (^{137}Cs and ^{133}Cs), K and Rb in *Sphagnum* Plants

The distribution of ^{137}Cs within *Sphagnum* plants (down to 20 cm depth) (Vinichuk et al. 2010a) is similar to stable K, Rb, and ^{133}Cs. The ^{137}Cs activity concentrations and concentrations of K, Rb, and ^{133}Cs are highest in the uppermost 0-10 cm segments of *Sphagnum* (in the capitula and the subapical segments) and gradually decrease in older parts of the plant. Such distribution can be interpreted as dependent on the living cells of capitula and living green segments in the upper part of *Sphagnum*. The ^{137}Cs appears to be taken up and relocated by *Sphagnum* plants in similar ways to the stable alkali metals, as concentrations of K, Rb, and ^{137}Cs activity concentrations in *Sphagnum* segments are similar to the depth of about 16 cm, and display a slightly different pattern in the lower part of the plant.

Alkali Earth Metals Ca and Sr

Concentrations of Ca and Sr in soil fractions: bulk soil, rhizosphere, soil-root interface, fungal mycelium and fruit bodies of fungi are relatively high. The concentration of Ca and Sr is found to be higher in the rhizosphere fraction Fungal sporocarps contained noticeably less calcium and strontium than mycelium and the mechanism of Ca and Sr exclusion appears efficient.

Fungal sporocarps varied in their ability to accumulate alkaline earth metals, although the concentration of calcium within fruit bodies of different species was several orders of magnitude higher than the concentration of strontium.

Calcium uptake correlates fairly well with Sr uptake in fungi: the Pearson correlation of Sr and Ca in fruit bodies of fungi is 0.904 (P-value = 0.000).

Transition Metals Cr, Co, Ni, Cu, Zn, Cd, Hg, and Pb

The capability of mycorrhizal fungi sporocarps to accumulate copper is higher than in mycelium: fungal sporocarps have statistically higher concentrations of Cu than the bulk soil (Vinichuk, 2012b, 2013). Zinc concentration in fungal mycelium is 2-fold higher than in bulk soil and 3-fold higher in sporocarps. The accumulation of cadmium is pronounced in both mycelium and fungal sporocarps: Cd concentration in mycelium is about 5 times higher than in bulk soil and about 2 times higher in sporocarps than in mycelium extracted from soil in the same plots where fungal sporocarps were sampled. Accumulation of Cd by fungal sporocarps is apparently species dependent.

Zinc concentration in sporocarps, and to a lesser extent in mycelium, depends on the concentration of Zn in the soil, whereas, the uptake of Cu and Cd by both sporocarps and mycelium does not correlate with their concentration in soil.

Thus, the uptake of Zn and Cu by fungi is balanced, implying similarities in the uptake mechanism.

The uptake of Cu, Zn, and Cd during the entire transfer process between soil and sporocarps occurs against a concentration gradient. For all three metals, the levels of Cu, Zn, and Cd in sporocarps is about two times higher than in fungal mycelium. Thus, fungi (mycelium and sporocarps) preferentially bioaccumulate Cd over Zn and Cu, and the bioconcentration values can be ranked in the order: $Cd^{2+} > Zn^{2+} > Cu^{2+}$, with a relative ratio of 100:41:38.

The concentration of Co and Ni in mycelium (Vinichuk, 2012a) is similar to the concentrations in other soil fractions (bulk soil, rhizosphere, soil-root interface); whereas, the concentrations in sporocarps are about 5-9 times lower than in mycelium. The concentration of Pb in mycelium is about 1.5 times lower than in other soil fractions (bulk soil, rhizosphere, soil-root interface) and about 50 times lower than in mycelium. The mycorrhizal fungi (mycelium and sporocarps) only absorb Co, Ni, and Pbbut do not accumulate these metals in tissue.

Fungal mycelium of upper forest soil layer may comprise 2.9-5.8% of chromium and 2.7-5.4% of nickel from their total content in soil. Fungal mycelium can also comprise between 4.6-9.1% of the total Cu in soil, 5.4-10.9% of the total Zn in the soil, and 15.5-31.7% of the total Cd in the soil. In fungal mycelium, the accumulation is estimated to be 3.5-6.9% for cobalt, 2.0-3.9% for Pb and 4.0-8.0% for Hg. In the mycelium of fungi in the upper (0-5 cm) layer of forest soil can be allocated 2.9-5.8% of the total amount of chromium in soil.

Semimetals (As)

No difference in As concentration in bulk soil and rhizosphere has been found, when soil-root interface fraction contains lower amounts of the elements (Unpublished data). The concentration of arsenic in mycelium was about the same as concentration in the soil and about 1.5 times higher in fruit bodies than in mycelium. Thus, arsenic does not appear to be accumulated by mycelium and only moderately by fruit bodies of fungi. Fungal mycelium accumulates between 3.0 and 6.1% of the total As in soil.

Actinides Th and U

Thorium concentration varies from of 0.0041 mg kg^{-1} dry weight in fruit bodies of fungi to 1.45 mg kg^{-1} dry weight fraction in the rhizosphere (Vinichuk, 2012c). Uranium concentration varies from 0.026 mg kg^{-1} dry weight in fruiting bodies of fungi to 9.36 mg kg^{-1} dry weight fraction in the rhizosphere. Both natural isotopes do not accumulate in either mushroom mycelium or their fruit bodies: bioconcentration ratios in fruit bodies are on average 0.006 for Th and 0.035 for U. Concentrations of Th and U isotopes in fruit bodies of fungi are about 270 times lower than in the bulk soil. The content of Th and U in mushroom mycelium and fruiting bodies depends on the concentration of these elements in the soil: as the concentrations of these elements in the soil increases, their content in mushrooms also increases. Mycelia of upper (0-5 cm) layers of the forest soil can comprise up to 5.0% of total thorium and 3.0% of total uranium content in soil.

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Mykhailo Vinichuk is Professor in Ecology, Zhytomyr State Technological University, Zhytomyr, Ukraine. His research interests are behavior of radionuclides in both natural (forest, peatland) and agricultural ecosystems with special emphasis on the role of ectomycorrhizal fungi in radionuclides transfer.

Klas Rosén is Associate Professor at Department of Soil & Environment, Swedish University of Agricultural Sciences SLU, Sweden. His research interests are both in terrestrial radioecology and radiation safety with various countermeasures in agricultural, forest and urban areas.

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