137Cs Soil-to-plant Transfer for Individual Species in a Semi-natural Grassland. Influence of Potassium Soil Content

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Soil-to-plant relationship/Transfer factor/Radiocaesium/Radiopotassium.

In the present study we assessed the radiocaesium uptake by plants in order to piece together information on factors affecting the uptake processes, particularly K supply and plant species differences. Vegetation uptake from soil contaminated by the Chernobyl accident was compared at two semi-natural grasslands. The Cs/K discrimination factor (DF), which is often used to evaluate a plant’s efficiency in absorbing nutrients from soil, was estimated. The obtained DF values (0.01 to 0.8) vary with K soil concentrations and plant species, indicating that the 40K is more efficiently absorbed than 137Cs. The soil-to-plant relationship was evaluated by means of the transfer factor (TF). The 137Cs TFsp values obtained from separated plant species varied within the range of 0.016 to 0.400 (site 1) and 0.017 to 0.171 (site 2). When mixed grass samples were considered a large variation was observed, mainly for site 1. The 137Cs TFmix ranges were: 0.018 to 0.250 for site 1 and 0.017 to 0.167 for site 2. These values fall within the range of TFs commonly reported (0.0001–1). Our present data suggest that these pastures are apt for forage use. Different plant species presented different individual behavior regarding their 137Cs TFsp when the 40K soil activity concentration was taken in account. For most of the species analyzed, we observed a gradual decrease in the individual 137Cs TFsp when the 40K soil activity concentration was increased, with the exception of Taraxacum officinale at one of the sampling sites.

INTRODUCTION

The uptake of radionuclides by plant roots constitutes the main pathway for the migration of radiocaesium from soil to humans, via food chains. Semi-natural environments are extensively used as pasture for cattle, sheep and goat. Radiocaesium present in animals has been one of the most important sources of dietary radiation dose to certain human groups after the Chernobyl accident.

Everything in our environment, including food, contains trace amounts of radioactivity. This means that this trace amount (about 150 to 200 becquerels) of natural radioactivity (from elements such as potassium) is unavoidable in our daily diets.1) Radioactive foods, on the other hand, are those that have become accidentally contaminated by radioactive substances from weapon testing or nuclear reactor accidents.

It is well accepted that the absorption of K+ by plant roots is a consequence of two different, but parallel, mechanisms for K+ uptake present on plasma membranes. (i) The high affinity, energized transporter system works at low K+ concentration, within the micromolar range. This is a saturable system; it moves K+ against an electrochemical gradient, and it probably the dominant mechanism for K+ uptake, since K+ concentrations in soil do not normally exceed 1 nM. (ii) The low affinity mechanism is usually associated with ion channels, and is a non-saturate process. This mechanism works at the millimolar range and seems not to be energized. The presence of these two systems ensures a large flexibility for plants to acquire K+ under conditions where soil free K+ in soil can vary between micromolar and millimolar levels.2)

While Rb+ uptake is similar to K+ uptake, Cs+ acts as a channel blocker or inhibitor of K+ channels. Maathuis et al. showed that millimolar Cs+ in plant growth media severely impairs plant growth, possibly through adverse effects on plant K+ levels. They also suggested that Cs+ toxicity may originate from K+ starvation. Cs+ toxicity in plants is believed to cause cellular K+ shortage. These studies come to reinforce a great number of field experiences which suggest a selective uptake of K+ vs. Cs+ by plant roots.3–5)

Radiocaesium bioavailability in soil is a function of the soil properties (e.g. pH, soil solution chemistry, clay content, soil organic matter) and biological processes which can be controlled by factors, such as genotypic differences in nutrient acquisition

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and plant age. Radioacesium bioavailability has been widely studied both in soil and hydroponic experiments with special reference to potassium competition, since potassium is generally considered to be an effective inhibitor for radioacesium uptake by plant roots.7,8

A number of field studies in contaminated areas have been conducted since the Chernobyl accident in order to better understand the behavior of 137Cs in soil-plant systems.9-13 In previous studies we performed an analysis of the soil-to-plant relationship in alpine pastures, and compared our results with a similar area in Germany. We observed a very strong negative correlation between the 40K soil activity and the 137Cs plant activity for both pastures. This observation indicates that when a large variety of different plant species is considered, radioacesium and radiopotassium do not necessarily behave in an analogous way.14

Our observations in semi-natural grassland suggest that the TF is a highly variable parameter that appears to be independent of the radionuclide activity in soil.15 The variability observed for 137Cs TF values do suggest that other variables, besides soil concentration, would influence the amount of radionuclide to be uptaken by plants.

The present study assessed the radioacesium uptake in plants in order to piece together information on factors affecting the uptake processes, particularly K supply and differences among different plant species. 137Cs uptake was assessed for different plant species from two sites located at a semi-natural grassland, at the Giulia Alps, Italy. The soil-to-plant relationship for radioacesium is also discussed because of its direct importance regarding human exposure to radioacesium through the food chain.

MATERIALS AND METHODS

Study area

The area of study was situated in the Tarvisio Woodlands in the North-East of Italy. Sampling of natural soils and plants was conducted at two sites (site 1 and site 2) of semi-natural grassland contaminated by the fallout of the Chernobyl accident (mean deposition of approximately 40 kBq m–2).16,17 Regarding forage production, two yearly harvests can be done in this area. The sampling was carried out during the period of the first harvest, namely the growing season.

As is typical for pasture sites, a large variety of different plants are growing in place. The dominant species belong to the Graminaceae family and the area is characterized by Asteraceae Taraxacum officinale G.H. Weber, Leguminosae, Trifolium pratense (L.) and Trifolium repens (L.), Plantaginaceae (Plantago sp.), Borrago sp. and other species.

Field sampling

Soil and grass were sampled simultaneously—within an area of one hectare along three equidistant transects—on the same day for each site: June 28th and July 13th 1999, for sites 1 and 2 respectively.

Grass samples were collected by cutting the total herbage growing at each 1 × 1-m plot, 2 cm above ground, while avoiding contamination with soil. A fraction of each vegetation sample was taken and separated by plant species, which were classified and processed separately. The aboveground plant material was weighed, dried at 105°C until constant weight and milled before radioactivity quantification.

Soil samples (at both sites): monoliths of 15 × 15 cm were collected to a depth of 10 cm. Soil samples were air-dried, ground to pass through a 2-mm sieve, homogenized and weighed.

Dried soil and grass samples were analyzed for 137Cs and 40K by gamma spectrometry with a high purity Germanium detector (HPGe). The 137Cs activity was decay-corrected to the date of the Chernobyl accident, May 1986.

Statistical analysis

The Kolmogorov-Smirnov test (KS-test)18 was applied with the purpose to determine whether the two data sets (sites 1 and 2) differ significantly. Statistical analysis were performed using Statgraphic plus 3.1 (1997, Manugistic, Inc.). The KS-test is non-parametric test, and uses the cumulative frequency to compare the theoretical distribution against the observed one. The test is based on an estimation of the major vertical deviation (DN) between both distributions. DN is defined as:

\[ DN = \max \left\{ F_1(X) - S_1(X) \right\} \]

where:

\[ F_1(X) \]

is a function of the cumulative frequency distribution specified; and \( S_1(X) \) is the cumulative frequency distribution observed for a random sample of \( N \) observations.

Thus, the critical values of DN are as follows: with \( p = 0.05 \), if \( N = 25 \), then \( DN = 0.27 \); if \( N = 17 \) then \( DN = 0.318 \).

The Mann-Whitney W test was subsequently applied in order to compare the medians of both sites, as the latter might represent different populations.

RESULTS

Soil characteristics

The 137Cs and 40K activity concentration experimental values obtained from soil at the two alpine pastures under study are given in Table 1, where the geometric mean, median and range are included.

<table>
<thead>
<tr>
<th>Site</th>
<th>Geometric mean (137Cs Bq kg–1)</th>
<th>Median (137Cs Bq kg–1)</th>
<th>Range (137Cs Bq kg–1)</th>
<th>Distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>403</td>
<td>397</td>
<td>264 to 613</td>
<td>Log-normal</td>
</tr>
<tr>
<td>2</td>
<td>289</td>
<td>288</td>
<td>220 to 367</td>
<td>Log-normal</td>
</tr>
<tr>
<td>Site</td>
<td>Geometric mean (40K Bq kg–1)</td>
<td>Median (40K Bq kg–1)</td>
<td>Range (40K Bq kg–1)</td>
<td>Distribution</td>
</tr>
<tr>
<td>1</td>
<td>398</td>
<td>399</td>
<td>356 to 461</td>
<td>Normal</td>
</tr>
<tr>
<td>2</td>
<td>401</td>
<td>392</td>
<td>358 to 474</td>
<td>Normal</td>
</tr>
</tbody>
</table>
For a comparison of both sites, the KS-test was applied to the 137Cs soil activity concentration and the maximum deviation (DN) obtained was 0.59. There is a statistically significant difference between the both distributions ($p = 0.001$; 95.0% confidence level). In Fig. 1 (top) the density distribution for this variable was represented.

The frequency distributions of 137Cs soil activity concentration (Bq kg$^{-1}$) showed that both sites can be adequately modeled by either normal or lognormal distributions. The probability (P-value) that the data conform to a lognormal distribution is, however, somewhat higher because the obtained maximum deviation values are below to the critical value when a $p = 0.05$ is considered.

A comparison of the frequency distributions of the $^{40}$K soil activity concentration (Bq kg$^{-1}$) of both sites, using the KS-test, evidenced a non significant difference between both distributions (DN = 0.23; $p = 0.66$; 95.0% confidence level). Figure 1 (bottom) shows the density distribution for this variable.

Concerning the Mann-Whitney W test for $^{137}$Cs soil activity deposition at both sites, we found a statistically significant difference between the medians ($p < 0.05$; 95% confidence level). For $^{40}$K soil activity concentration at both sites, there was not a statistically significant difference between the medians ($p \geq 0.05$; 95% confidence level).

**Cs/K discrimination factor (DF)**

$^{137}$Cs $^{40}$K discrimination factor (DF) is efficiently transported by the high affinity K$^+$ uptake transporter of wheat root cells, and experimental observations suggest that K$^+$ strongly suppress Cs$^+$ uptake.\textsuperscript{2,19,20} Plant roots absorb caesium less efficiently than its nutrient analogue, potassium. This is illustrated by the so-called Cs/K discrimination factor (DF). DF values below unity indicate that K is more efficiently absorbed than Cs.

The present experimental data were taken under field conditions throughout the growing season. Due to these experimental conditions, we estimated the discrimination factor as follows:

$$DF = \frac{\text{137Cs in plant} [\text{Bq kg}^{-1}]/\text{40K in plant} [\text{Bq kg}^{-1}]}{\text{137Cs in soil} [\text{Bq kg}^{-1}]/\text{40K in soil} [\text{Bq kg}^{-1}]}$$

In agreement with previous reports from several authors,\textsuperscript{19} our estimated DF values for different plant species are below 1 (Table 2).

**Soil-to-plant relationship for $^{137}$Cs**

The soil-to-plant relationship is evaluated by means of the transfer factor, which is usually expressed as: $^{137}$Cs TF = $^{137}$Cs activity per dry grass mass (Bq kg$^{-1}$)/$^{137}$Cs activity in dry soil (Bq kg$^{-1}$).\textsuperscript{20} The soil activity concentration to a depth of 10 cm was used in the calculation. $^{137}$Cs TF values were estimated for separated plant species (TF$_{sp}$) and for mixed grass samples (TF$_{mix}$).

$^{137}$Cs TF$_{sp}$ values varied within the range of 0.016 to 0.400 at...
clear tendency towards a decrease in the 137Cs TFsp values was observed when 40K soil content was increased. However, we have not found a statistically significant relationship between the variables. The obtained TFsp variability for this plant species was 24%. However, for Graminaceae, Plantago sp. and Trifolium spp. the correlation coefficients were –0.31, 0.01 and 0.35 respectively, indicating a relatively weak relationship between the variables. We found no statistically significant relationship between the 137Cs TFsp and 40K soil activity concentration (p ≥ 0.10; 95% confidence level). The 137Cs TFsp variability for these three plant species was 10%, 0.016% and 12%, respectively.

**DISCUSSION**

In the present study we analyzed the behavior of 137Cs and the natural isotope 40K in relation to soil and plant activities for either mixed or individual plant species.

In the first part we compared the 137Cs and 40K activity concentrations obtained from soil samples at two semi-natural grassland sites by using the K-S test and Mann-Whitney W test. 137Cs soil activity concentration at site 1 (Fig. 1; top, solid curve) exhibits higher dispersion and a maximum of density at about 320 Bq kg⁻¹; while site 2 (dotted curve) shows lower dispersion and a maximum of density at about 280 Bq kg⁻¹. Thus, the present data allow us to state that the 137Cs soil samples from the two sites do not belong to the same population, meaning that both sites can be differentiated by their 137Cs soil activity concentration.

Regarding 40K soil activity concentration (Fig. 1, bottom), the values from both sites exhibited similar dispersion, as well as a similar density maximum value of about 390 Bq kg⁻¹. Thus, no difference in 40K soil activity concentration was observed, as compared at both sites. This observation agrees with the fact that 40K is a natural radioactive element with a homogeneous distribution in nature.

In addition, the comparison of density distributions for 137Cs and 40K revealed differences in their variation range. In the case of 137Cs, the range is markedly larger, but the maximum density is about three-times lower than the corresponding to 40K.

In agreement with earlier reports from several authors², our estimated DF values are below unity (Table 2). The obtained Cs/K DF values typically ranged between 0.01 and 0.8, and varied according to K concentrations and plant species.

The DF values obtained from our experimental data confirm that under field conditions K⁺ is more efficiently absorbed than Cs⁺ by the different plant species studied at both semi-natural grasslands.

Smolders et al.² performed in-solution culture studies of spring wheat at different K concentrations. Under these conditions, the authors reported DF values for entire plants, which ranged between 0.04 and 0.26. In the present study we considered only mature edible parts of grass, and the DF values obtained under field experimental conditions fall in a range comparable to the above mentioned. It is remarkable that in-solution culture experiences provide values that are comparable to field experimental data.

The 137Cs TF values obtained for mixed grass samples as well

![Fig. 2. Scattergram of 137Cs TF vs. 40K soil activity concentration for mixed grass samples, site 1 (top) and site 2 (bottom).](image-url)
Fig. 3. Scattergram of $^{137}$Cs TF vs. $^{40}$K soil activity concentration for different plant species on site 1.

Fig. 4. Scattergram of $^{137}$Cs TF vs. $^{40}$K soil activity concentration for different plant species on site 2.
as for separated plant species, from both semi-natural grasslands, are within the range of $^{137}$Cs TF values for mature edible parts recommended by Nisbet and Woodman (0.0001–1 range).\(^{11}\)

Nisbet and Woodman\(^{11}\) built a database of soil-to-plant transfer factors for radioesium, compiled for arable crops. This database was sub-divided into 28 soil-crop combinations covering four soil types and seven crop groups. We compared our data with two groups included in the above mentioned study: cereals and green vegetables. The mean $\text{TF}_{\text{mix}}$ values obtained for mixed grass samples were higher than those informed by Nisbet and Woodman for cereals in organic soils (0.043). However, $\text{TF}_{\text{mix}}$ values for mixed grass samples are lower than the values reported for green vegetables in organic soils (0.29).\(^{11}\)

In order to evaluate the influence of the plant species, we performed a parallel study using mixed grass and individual plant species simultaneously. 85 samples were analyzed for individual species and 41 samples were used for mixed grass, at both sites. The study of the dependence of the $^{137}$Cs $\text{TF}_{\text{mix}}$ on $^{40}$K soil activity concentration at both sites provides a non significant relationship between the variables for mixed grass samples. As compared to individual plant species, mixed grass samples showed lower variability for TF values, as a function of the $^{40}$K soil activity concentration.

However, when individual plant species were considered, we found that the correlation coefficients varied between –0.46 and 0.06 for site 1, and between –0.49 and 0.35 for site 2. Although only a few cases—such as $\text{T. officinale}$, in site 2—exhibited a significant negative correlation, the high dispersion of the correlation coefficients suggest that different plant species behave in different ways.

$\text{T. officinale}$ and Graminaceae showed $\text{TF}_{\text{sp}}$ values with a clear negative tendency when $^{40}$K soil activity concentration was increased. Figures 3 and 4 show that for most species there is a decrease in $^{137}$Cs TFs when there is an increase in $^{40}$K soil activity concentration. This observation suggests the influence of the $^{40}$K soil concentration on the $^{137}$Cs uptake capacity of plant roots.

The difference in the $^{137}$Cs $\text{TF}_{\text{sp}}$ values might be explained based on different plant physiology and soil characteristics.

CONCLUSIONS

This study provides evidence on plant efficiency in absorbing nutrients from soil under field conditions for different plant species. It is generally accepted that Cs enters plants mainly via K transport systems, namely K transporters and channels operating at different external potassium concentrations. K therefore appears to be one of the major factors influencing radioesium uptake in plants. Cs/K DF was estimated in both study sites, indicating that K is more efficiently absorbed from soil—under field conditions—by different plant species. It is remarkable that in solution culture experiences provide DF values comparable with to field experimental data.

In mixed grass samples we observed that $^{137}$Cs uptake by plants decreases with the increase in the $^{40}$K soil content. The analyzed individual species, that were taken from the same samples as mixed grass, presented a similar behavior in function of the $^{40}$K soil content of both sites.

The $^{137}$Cs $\text{TF}_{\text{sp}}$ values obtained in grass lay within the recommended range for mature edible parts. These results suggest that these pastures are apt for forage use.

The $^{137}$Cs $\text{TF}_{\text{sp}}$ variability in Graminaceae and in $\text{T. officinale}$ is 10% and more than 20%, respectively, can be explained by $^{40}$K soil content.

A comparison between different plant species from both sites evidenced that Graminaceae and $\text{T. officinale}$ exhibit different behaviors regarding Cs absorption when we analyzed the $^{137}$Cs $\text{TF}_{\text{sp}}$ and the $^{40}$K soil activity concentration. These results suggest that the plant efficiency in absorbing Cs varies according to the K soil concentration and plant species. It is clear that in mixed grass samples the effect of the $^{40}$K soil activity on TF is mitigated, while this behavior is more marked for particular plant species. Graminacea and $\text{T. officinale}$, species which account for 65% of the mixed grass samples, exhibited a clear negative tendency in $^{137}$Cs uptake with increased $^{40}$K soil content.

Bioremediation is emerging as an alternative approach to reduce the contamination level of $^{137}$Cs, such as applications of minerals or chemical fertilizers in agricultural production systems with low levels of contamination. However, further investigation is still needed to optimize these countermeasures.

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