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Transfer of ^{134}Cs and ^{85}Sr to *Pleurotus eryngii* Fruiting Bodies Under Laboratory Conditions: A Compartmental Model Approach

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In order to analyse in detail the different transport routes for caesium and strontium to fungi, and reduce as far as possible the variability of the uptake of radionuclides in natural ecosystems (Heinrich, 1992), we studied their dynamics under controlled laboratory conditions (Baeza et al., 2000) for *Pleurotus eryngii*. This species of mushroom was chosen as it is a basidiomycetic saprophyte of frequent consumption in the Mediterranean region (Moreno et al., 1986) and grows on the remains of organic material, generally in grassland ecosystems. It is thus a good representative of a saprophytic mushroom for which there exist proven techniques for its culture (Ferri, 1985). The analysis of the different routes of incorporation of the radionuclides allowed us to identify the direct deposition route of ^{85}Sr and ^{134}Cs onto the fruiting bodies as being more important than routes in which the radioactive contamination originates in the mycelium or in the surface layer of the soil. For these latter two routes, we found that there is an evolution of the transfer which depends on the developmental stage of the fungus. To correctly interpret the experimentally observed dynamics (Baeza et al., 2000), in the present study we developed a specific compartmental model to analyse the dynamics followed by ^{85}Sr and ^{134}Cs in reaching the fruiting bodies of *Pleurotus eryngii* in the following two situations: when the origin of the radioactive contamination is in the substrate layer where the mycelium will be grown, and when it comes from the surface layer of the soil.

MATERIALS AND METHODS

Mushrooms of the edible species *Pleurotus eryngii*, a representative of the saprophytic nutritional mechanism, were grown under controlled laboratory conditions (Baeza et al., 2000) . The procedure consisted of two consecutive phases: a) Spread of the mycelium in the substrate from which it will obtain its nourishment. This is contained in a Ø=14 cm diameter and 2 cm deep Petri dish, and consists of 50% wheat grain, 25% straw, 8.3% wheat flour, and 16.7% calcareous soil. The pH of this soil is 7.2 and the ^{137}Cs and ^{40}K activities are (1.5 ± 0.5) and (785 ± 69) Bq/kg d.w. respectively. b) Moving the substrate with the mycelium to a soil bed for the subsequent formation of the fruiting bodies. In this

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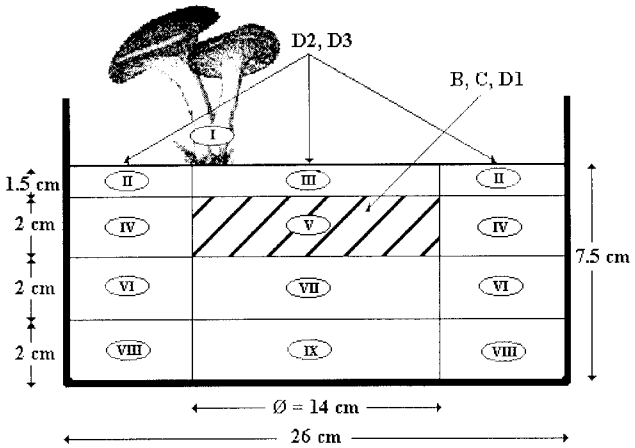

Figure 1. Schematic diagram of the culture of *Pleurotus eryngii*. The letters B to D identify the contamination routes studied. The compartments analysed are identified by I to IX.

phase, the humidity is maintained at 75% by spraying twice daily with 80 ml of distilled/irrigation water, the photoperiod is 16 h., with temperatures of 18 °C in the light period and 14 °C during darkness.

To carry out this study, known activities of ^{85}Sr and ^{134}Cs (Baeza et al., 2000) were incorporated at different clearly identifiable moments of the growth of the fungus. Figure (1) shows a schematic diagram of the routes by which the radioactive contamination is incorporated into the system. All experiments were performed in triplicate, and are identified on the figure by letters. The radionuclides in previously sterilized solutions were conditioned to a neutral pH at the time of their addition to the culture medium, so as not to damage the growth. The method of incorporation was by means of a great many small droplets uniformly distributed over the specific compartment being contaminated in each experiment. Experiments B, C, and D1 were performed during the phase of spread of the mycelium, before moving the substrate/mycelium between soil layers, as shown in Figure (1), compartment V. Experiment B: the substrate was contaminated 20 days before inoculation of the mycelium, or 75 days before harvesting the mushrooms. Experiment C: the radioactive contamination was deposited onto the substrate at the moment of mycelium inoculation, or 55 days before harvest. Experiment D1: the radionuclides were added onto the surface of the substrate/mycelium when the mycelium was in the phase of spreading, 10 days after its inoculation, or 45 days before harvest. As one sees in Figure (1), in experiments D2 and D3 the radionuclides were added homogeneously to the surface of the soil. Experiment D2: 30 days after inoculation or 25 days before harvest, at the moment of moving the substrate/mycelium, compartment V, to the soil on which the fruiting bodies were to form. Experiment D3: the radionuclides were deposited onto the surface of the soil, 40 days after mycelium inoculation or

15 days before harvest, while there were still no visible fruiting bodies above the soil.

The fruiting bodies were harvested by cutting the stalk slightly above soil level so as to have no soil particles adhered to the samples to be analysed. The mushroom, soil, and substrate/mycelium (mycelium together with remains of the substrate) samples were oven dried, homogenized and packed in 52 mm diameter and 13 mm depth Petri-dish type capsules for gamma spectrometric analysis. The measurement of the γ emissions of all the samples was performed using an n-type intrinsic Ge detector with a 25.6% efficiency, a 1.85 keV resolution, and a peak-Compton ratio of 57:1 for the 1.33 MeV ^{60}Co γ emission. The method followed in performing the spectrometric analyses has been described in detail elsewhere (Baeza et al., 2000). In all cases, the measurement time was less than 48 h and the detection limits were 24, 21, 1.8 and 119 mBq for ^{85}Sr, ^{134}Cs, ^{137}Cs and ^{40}K, respectively.

RESULTS AND DISCUSSION

In order to explain the values of the ^{85}Sr and ^{134}Cs transfer to *Pleurotus eryngii* reported previously (Baeza et al., 2000), we studied the dynamics followed by both radionuclides using a specific compartmental model for each of the following two sets of experiments: the contamination was localized in the substrate where the mycelium will be grown (experiments identified as B, C and D1 above), and the contamination was by surface deposition onto the soil (experiments D2 and D3). In both cases, we assume that the system satisfies the following working hypothesis (Kirchner, 1998): 1. Fluxes between compartments are governed by the concentration of the donor compartment. 2. The concentrations in each compartment are uniform. 3. The transport coefficients λ_{ij} between compartments i and j are independent of time. 4. The absorption of radionuclides in a compartment is an instantaneous process.

In modelling the transfer to the mushroom's fruiting body of the radionuclides existing in the substrate/mycelium compartment, experiments B, C and D1 in Figure (1), we have only considered the fruiting bodies (I), the substrate/mycelium itself (V) and the soil compartments that are in direct contact with the substrate/mycelium (compartments III, IV and VII), given that, because of the large area in contact with the substrate/mycelium, they have a high radionuclide transfer probability. Indeed, we found that the sum of the total activities (specific activity by mass) that were detected in the compartments analysed (I, III, IV, V and VII) represents 95% of the total ^{85}Sr and ^{134}Cs activity initially added. Results obtained by various workers (Schell et al., 1996) have shown that the lateral transfer of the radioactive contamination originating in the surface soil is negligible, unless there is a significant slope, which was not the case in our experimental design. Nevertheless, we have taken this lateral transfer formally into account because of the relatively large area of contact between the substrate/mycelium (compartment V) and the surrounding soil layer (compartment IV).

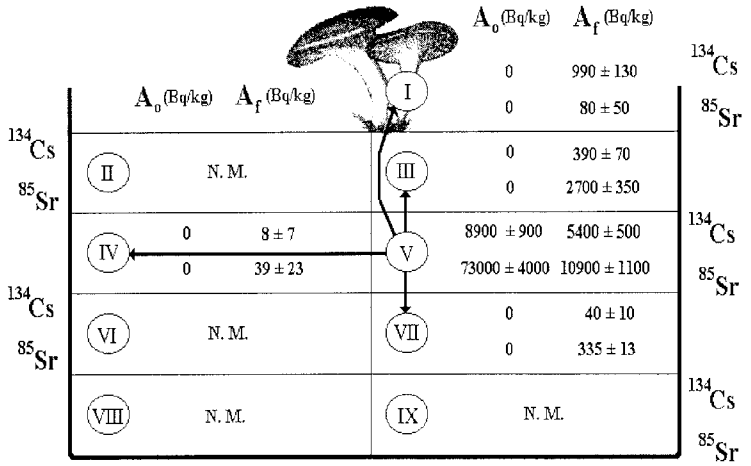

Figure 2. Average specific activities and associated standard deviations, both expressed in $Bq \cdot kg^{-1}$ (d.w.), for the initial A_o and final A_f times of experiment B in the compartments considered. Arrows identify the radionuclide fluxes used in the model. NM = compartments whose final activities were not measured.

The compartmental model that we have developed is therefore defined by Eqs. (1) to (5), where A_i represents the total activity (in Bq) of compartment i, λ_D the decay corresponding to each radionuclide, and λ_{ij} the transport coefficient from compartment i to j.

$$\frac{dA_V(t)}{dt} = -\lambda_{V,I}\, A_V(t) - \lambda_{V,III}\, A_V(t) - \lambda_{V,IV}\, A_V(t) - \lambda_{V,VII}\, A_V(t) - \lambda_D\, A_V(t) \qquad (1)$$

$$\frac{dA_I(t)}{dt} = \lambda_{V,I}\, A_V(t) - \lambda_D\, A_I(t) \qquad (2)$$

$$\frac{dA_{III}(t)}{dt} = \lambda_{V,III}\, A_V(t) - \lambda_D\, A_{III}(t) \qquad (3)$$

$$\frac{dA_{IV}(t)}{dt} = \lambda_{V,IV}\, A_V(t) - \lambda_D\, A_{IV}(t) \qquad (4)$$

$$\frac{dA_{VII}(t)}{dt} = \lambda_{V,VII}\, A_V(t) - \lambda_D\, A_{VII}(t) \qquad (5)$$

To solve this compartmental model, we transformed the above differential equations to their incremental form, and then calculated the different transport coefficients λ_{ij} between the compartments (Bunzl et al. 1995; Baeza et al., 2001). In the calculation we took the two reference times shown in Figure (2): the initial time (o) at which the deposition of the radionuclides onto the substrate/mycelium compartment took place; the final time (f) at which the fruiting bodies were harvested.

Table 1. Mean values and standard deviations of the transport coefficient λ_{ij}, expressed in days^{-1}, for the experiments B, C and D1. The compartment number V or substrate/mycelium is labelled *subs*.

Experiment	*B (Δt=75 d)*		*C(Δt=55 d)*		*D1(Δt=45 d)*	
Radionuclide	^{134}Cs	^{85}Sr	^{134}Cs	^{85}Sr	^{134}Cs	^{85}Sr
Subs.→Soil above $\lambda_{V,III}$ ($d^{-1} \cdot 10^{-3}$)	5.2±0.8	14±3	6.3±1.3	12±10	9±5	22±6
Subs.→Soil below $\lambda_{V,VII}$ ($d^{-1} \cdot 10^{-3}$)	4.1±1.9	8±6	2.5±1.4	11±5	3.9±2.1	11±7
Subs.→Soil lateral $\lambda_{V,IV}$ ($d^{-1} \cdot 10^{-3}$)	1.5±1.0	5±3	1.5±0.8	4±2	2.8±1.9	4±3
Subs.→Soil λ_V^* ($d^{-1} \cdot 10^{-3}$)	9±4	25.7±1.9	10.4±2.4	26±17	16±6	37±14
Subs.→fruiting body $\lambda_{V,I}$ ($d^{-1} \cdot 10^{-5}$)	48±14	0.58±0.07	60±50	2.1±1.4	53±33	15±2

Table 1 gives the mean values of the transport coefficients for the experiments in which the contamination is originated from the substrate in which the mycelium is developed. On analysing the transport coefficients, $\lambda_{V,III}$, from the substrate/ mycelium to the layer of soil covering it, one observes that the ^{85}Sr value is usually greater than the ^{134}Cs value for all three experiments (B, C, and D1). One also notes that as the time interval from the moment of contamination of the mycelium to the harvesting of the mushrooms, Δt, becomes shorter (specifically $\Delta t_{(B)}$=75 d, $\Delta t_{(C)}$ = 55 d, and $\Delta t_{(D1)}$ = 45 d), the average value of the transport coefficient for each radionuclide seems to rise slightly. Indeed, the correlation coefficients between the mean value of the coefficient $\lambda_{V,III}$ and the time, Δt, are –0.91 and –0.62 for ^{134}Cs and ^{85}Sr, respectively. Nevertheless, the associated dispersion does not allow us to state this with total confidence. Similar result was obtained with respect to the transport of ^{85}Sr from the substrate/mycelium to the soil layer below it, $\lambda_{V,VII}$, with correlation coefficient of –0.94. The transport coefficients from the substrate/mycelium to the soil layer located laterally, $\lambda_{V,IV}$, while slightly smaller, are nevertheless qualitatively analogous in value to those already discussed. Three aspects of the analysis of the transport from the substrate/mycelium layer to the fruiting bodies, $\lambda_{V,I}$, should be emphasized. Firstly, their values are systematically less than for the substrate/mycelium to soil vertical transfer. Secondly, the value of the ^{134}Cs transport coefficient is clearly greater than for ^{85}Sr in each experiment. Lastly, only in the case of ^{85}Sr was observed any dependence between the times at which the radionuclides were

added with their transport coefficients: its transport coefficient increased as the time interval Δt decreased. In this case, the correlation coefficients of $\lambda_{V,I}$ with Δt are -0.58 and –0.82 for ^{134}Cs and ^{85}Sr, respectively. The substrate/mycelium to fruiting body transport coefficient, $\lambda_{V,I}$, must be directly related to the incorporation of radionuclides to the fruiting bodies. However, to correctly analyse the accumulation of radionuclides in the fruiting bodies, one must take into account their retention by the substrate/mycelium layer, since if a radionuclide is retained to a greater degree it will have a greater probability of being transferred to the fruiting bodies. One can take this retention into account by means of an effective transport coefficient, λ^*_V in Table 1, defined as the sum of the transport coefficients from the substrate/mycelium to the rest of the compartments except the fruiting bodies, equation (6):

$$\lambda^*_V = \lambda_{V,III} + \lambda_{V,VII} + \lambda_{V,IV} \qquad (6)$$

so that the lower this effective coefficient, the greater will be the retention by the substrate/mycelium. In Table 1, one sees that the values λ^*_V are systematically greater for ^{85}Sr than for ^{134}Cs. This result can be verified from the means and standard deviations of the quotients of λ^*_V between the two radionuclides (^{85}Sr /^{134}Cs). These values for each of the three replicates of the experiments B, C, and D1, are (3.4 ± 1.6 (S.D.)), (2.3 ± 1.1 (S.D.)) and (2.296 ± 0.013 (S.D.)), respectively. Taking into account therefore the greater transport of ^{134}Cs than of ^{85}Sr from the substrate/mycelium layer to the fruiting bodies, and the greater degree of retention of the former isotope by this layer, one may conclude that when the radioactive contamination comes from the substrate/mycelium the fruiting bodies accumulate proportionally more ^{134}Cs than ^{85}Sr. This explains satisfactorily the experimental values obtained previously (Baeza et al., 2000), which showed a greater incorporation of ^{134}Cs than of ^{85}Sr into the fruiting bodies when these radionuclides were added to the substrate/mycelium.

Given the design of the experiments carried out for the analysis of the transport of the radionuclides deposited onto the surface layer of the soil, see experiments D2 and D3 in Figure (1), we considered two different cases: the contaminants were deposited onto the layer of soil situated immediately above the substrate/mycelium (compartment III), or onto the rest of the soil surface (compartment II). Figure (3) shows the mean values of the initial, A_o, and final, A_f, specific activities for the experiment D2. One observes that there is a notable difference between the final activities detected in the soil compartments situated in the vertical of the substrate/mycelium (compartments identified as III, VII and IX) as against the rest (compartments identified as II, IV, VI and VIII). In particular, it shows that the substrate/mycelium, compartment V, is relatively less permeable than the other soil compartments considered, thus impeding percolation of the radionuclides through it. This difference in behaviour is a consequence of the radionuclide flux being greater vertically than horizontally as can be seen in Figure (2) on comparing the smaller final activity from compartment V to IV than between the compartments vertically above and below the substrate/mycelium (compartments III and VII). Nevertheless, the greater level of activity in compartment IX is due to the accumulation in it of the irrigation water used in the culture and hence of the dissolved radionuclides.

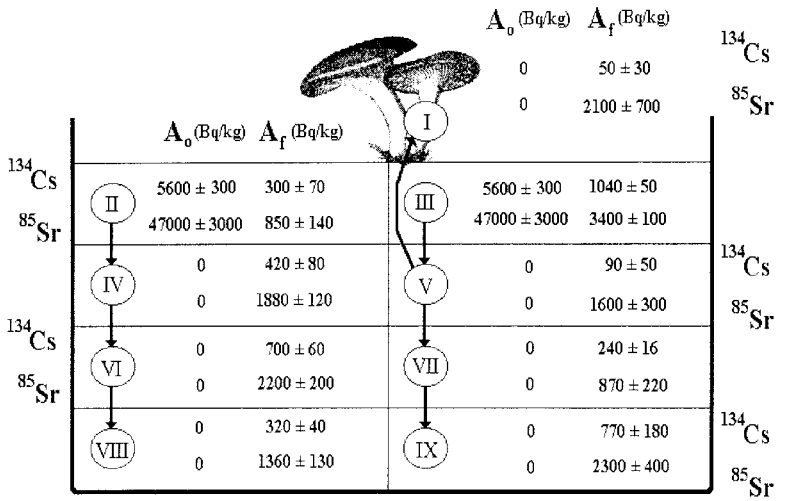

Figure 3. Average specific activities and associated standard deviations, both expressed in $Bq \cdot kg^{-1}$ (d.w.), for the initial A_0 and final A_f times of experiment D2 in the compartments considered. Arrows identify the radionuclide fluxes used in the model.

To analyse the dynamics followed by ^{85}Sr and ^{134}Cs in the two experiments D2 and D3, we developed a compartmental model consisting of two well-differentiated parts. The first considers exclusively the transport between the compartments I, III, V, VII, and IX which model the dynamics followed by the radionuclides deposited onto the part of the soil surface which covers the substrate/mycelium layer. On the basis of our working hypothesis, these are the only contaminants that may to some degree become incorporated into the fruiting bodies, compartment I. The second part of the model represents the behaviour of the radionuclides deposited onto the soil surface layer that does not lie over the substrate/mycelium, compartment II. For both parts, we set up a set of differential equations which are analogous to equations (1-5), and that allow us to calculate the values of the transport coefficients from the total activities in each of the compartments considered. Table 2 lists the mean values of the transport coefficients, λ_{ij}, for the three replicates constituting experiments D2 and D3. On analysing the transport coefficients from the soil above the substrate/mycelium to this latter compartment, $\lambda_{III,V}$, one sees that for both experiments (D2 and D3) they are similar in value for ^{134}Cs and for ^{85}Sr, taking into account the dispersion associated with the respective mean values. The mean value of the transport coefficients from the substrate/mycelium layer to the soil situated immediately below it, $\lambda_{V,VII}$ in Table 2, for ^{134}Cs are an order of magnitude greater than that for ^{85}Sr in both experiments. This indicates that ^{134}Cs is more readily transported from the substrate/mycelium to the aforementioned soil layer than is the case for ^{85}Sr. For this coefficient, $\lambda_{V,VII}$, there was also observed to exist a dependence on the time that has elapsed since the radionuclide deposition: the shorter this interval Δt, the greater the mean values of the transport coefficients.

Table 2. Mean values and standard deviations of the transport coefficients λ_{ij}, for the experiments D2 and D3. The compartment number V or substrate/mycelium is labelled *subs*.

Experiment	*D2 (Δt=25 d)*		*D3 (Δt=15 d)*	
Radionuclide	^{134}Cs	^{85}Sr	^{134}Cs	^{85}Sr
Soil above → Subs. $\lambda_{III,V}(d^{-1} \cdot 10^{-2})$	3.4 ± 0.4	3.69 ± 0.25	2.5 ± 1.3	3.5 ± 1.6
Subs. →Soil bellow $\lambda_{V,VII}(d^{-1} \cdot 10^{-2})$	214 ±19	44 ±9	1100 ±300	130 ±60
Soil→Soil $\lambda_{II,IV}(d^{-1} \cdot 10^{-2})$	16 ±5	11.5 ±2.6	10 ±4	8 ±3
Sub.→fruiting body $\lambda_{V,I}(d^{-1} \cdot 10^{-2})$	0.60 ±0.17	2.2 ± 1.0	4.4 ± 1.2	6 ± 4

With respect to the transport coefficients between the different soil layers, it is noteworthy that the values for the two radionuclides are very similar. However, there also seems to be a decline in both transport coefficients as the time elapsed between the contamination and the harvesting, Δt, becomes shorter: the linear correlation coefficients for the trend followed by the six individual values of experiments D2 and D3 are 0.66 and 0.80 for ^{134}Cs and ^{85}Sr, respectively. Our interpretation of this result is on the basis of the part played by the irrigation water as transmitter of the radioactive contamination between the different soil layers. Therefore, as the contamination in experiment D3 is later than in D2, the radionuclides in the former are subjected to fewer irrigations than in the latter. Lastly, we calculated the transport coefficients between the substrate/mycelium layer and the fruiting bodies, $\lambda_{V,I}$ in Table 2. We obtained that the mean value for ^{85}Sr was systematically greater than that for ^{134}Cs in both experiments, the mean value of the quotient $^{85}Sr/^{134}Cs$ for the above cited coefficient being (7 ± 5 (S.D.)) and (1.7 ± 0.9 (S.D.)) for the three replicates of experiments D2 and D3, respectively. It is also worthy of note that the shorter the time lapse, Δt, between the deposition of the radionuclides and the harvesting of the mushrooms, the greater the values of $\lambda_{V,I}$, and hence those of the transfer of the two radionuclides to *Pleurotus eryngii*, although the associated dispersion to these values are too large to be able to affirm this trend unequivocally.

To analyse the dynamics of the radionuclide transport from their initial deposition in the soil's surface layer to the fungus's fruiting bodies, as well as the transport coefficient between the substrate/mycelium and the fruiting bodies, $\lambda_{V,I}$, one must also take into account the transport from the soil to the substrate/mycelium layer, $\lambda_{III,V}$, since the compartments affected in the transit are: soil (compartment III),

substrate/mycelium (V) and fruiting bodies (I). The transport coefficient from substrate/mycelium to soil, $\lambda_{V,VII}$, must also be included, since the smaller this is, the greater will be the retention of each radionuclide by the substrate/mycelium. In our case, given that the transport from the soil to the substrate/mycelium, $\lambda_{III,V}$, is approximately the same for the two radionuclides, the incorporation to the fruiting bodies will mainly be governed by the transport from the substrate/ mycelium to the fruiting bodies, $\lambda_{V,I}$, and by the retention of these radionuclides in the substrate/mycelium. In particular, as the value of $\lambda_{V,I}$ is greater for ^{85}Sr than for ^{134}Cs in both experiments, and as the retention by the substrate/mycelium of ^{85}Sr is also greater than that of ^{134}Cs, one may conclude that, in the case of surface contamination of the soil, the fruiting bodies preferentially accumulate ^{85}Sr relative to ^{134}Cs. This result is in perfect accord with that obtained experimentally (Baeza et al., 2000), in which there was found to be a greater incorporation of ^{85}Sr than of ^{134}Cs to the fruiting bodies when these radionuclides were incorporated into the culture by deposition onto the surface layer of soil.

An overall comparison of the coefficients corresponding to the vertical migration of the radionuclides from the substrate/mycelium to the layers of soil when the contamination was originated in the substrate/mycelium, see Table 1, with those when the contamination was deposited on the surface soil layer, see Table 2, shows there to be a clear difference. Indeed, the transport coefficients, $\lambda_{V,VII}$, obtained for both isotopes in experiments D2 and D3 are orders of magnitude greater than those for experiments B, C, and D1. Also, in experiments D2 and D3, ^{134}Cs migrates more easily from the substrate/mycelium to the soil below, $\lambda_{V,VII}$, than does ^{85}Sr, whereas the behaviour in experiments B, C and D1 is precisely the contrary. We interpret these differences on the basis of a combination of two factors. Firstly, there are different mechanisms for the incorporation of the radionuclides in the two groups of experiments. In experiments B, C, and D1, the radionuclides are added directly to the substrate on which the mycelium is to grow, and remain longer than in experiments D2 and D3 in which the isotopes were deposited onto the surface layer of soil. Consequently, in the B, C and D1 experiments, ^{85}Sr and ^{134}Cs have more time to form chemical compounds that bind them to the organic fraction of the substrate, as indeed has been observed by various workers (Shand et al., 1994) for radiocesium. Secondly, the times at which the radionuclides were incorporated into the system were different in terms of the phase of development of the fungus and thus of its nutritional requirements. Hence, the present results seem to indicate greater uptake of strontium than of caesium by the fruiting bodies when the fungus was in the mushroom-forming stage, which corresponded to the dates on which experiments D2 and D3 were carried out.

Figure (4) shows the evolution of the transport coefficients, $\lambda_{V,I}$, from the substrate/mycelium to the fruiting bodies versus the time interval Δt between the contamination and the harvesting of the fruiting bodies. One sees that the two radionuclides, ^{134}Cs and ^{85}Sr, show similar evolution, with a greater incorporation into the fruiting bodies when the time of the deposition is close to harvesting. Nonetheless, the temporal evolution of these coefficients is far more marked for

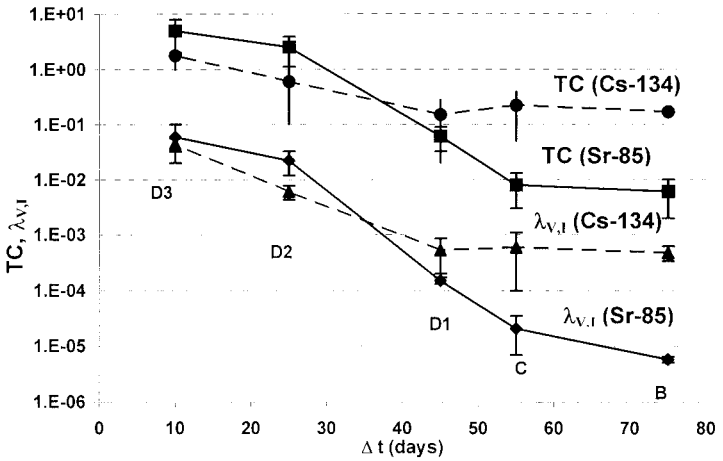

Figure 4. Evolution of the transport coefficients, $\lambda_{V,I}$ and transfer coefficients, TC, for ^{85}Sr and ^{134}Cs versus the time interval, Δt.

^{85}Sr than for ^{134}Cs. Consequently, one observes that in the depositions performed close to the time of harvesting the mushrooms (experiments D2 and D3), ^{85}Sr is incorporated to a greater degree, while in the contaminations at more distant dates the radionuclide that is more efficiently incorporated is ^{134}Cs. This difference in behaviour depending on the time at which the deposition took place with respect to the stage of development of the fungus seems again to reflect a change in the fungus's nutritional requirements. This result fits in perfectly with observations in various studies in the field, in which radiocaesium was found to have a greater activity level than radiostrontium in the fruiting bodies of fungi collected several years after the Chernobyl Nuclear Power plant accident in Sweden (Mascanzoni, 1990), since that situation was one in which the medium, specifically the soil, had been contaminated before the appearance of the fruiting bodies, analogous to our experiments B, C and D1.

To evaluate the transfer of radionuclides from the soil to the fruiting bodies of fungus, one traditionally uses the concept de transfer coefficients, TC, for which there exist different definitions (Shutov et al., 1996; Vaszari et al., 1992). Given the characteristics of the design of the present experiments in which the substrate/mycelium layer is completely localized in the growth medium, compartment V in Figure (1), for the calculation of the transfer coefficients, TC, we compared the activity incorporated into the fruiting bodies of the fungus with that existing in the substrate/mycelium layer:

$$TC = \frac{Bq\ /\ kg\ d.w.\ mushrooms}{Bq\ /\ kg\ d.w.\ substrate\ /\ mycelium} \quad (7)$$

We show in Figure (4) the mean values and standard deviations obtained for the transfer coefficients, TC, of ^{85}Sr and ^{134}Cs, as a function of the time interval Δt

between the moment of the contamination and the harvesting of the mushrooms. An overall analysis allows us to affirm that they reproduce the conclusions based on the transport coefficients, $\lambda_{V,I}$, obtained by solving the corresponding compartmental model. Thus one sees that in the experiments where the substrate/mycelium was contaminated, B, C and D1, the transfer coefficients for ^{134}Cs are systematically greater than those found for ^{85}Sr, with there only being a clear temporal evolution of these coefficients for this latter isotope in the sense that the transfer coefficients increase as the time interval, Δt, decreases. In the experiments where the contamination originated in the surface soil layer, see D2 and D3 in Figure (4), the TC coefficients for ^{134}Cs are systematically lower than those for ^{85}Sr, and there is a clear temporal evolution for both isotopes, with the coefficients increasing for decreasing time interval Δt. Considering the temporal variation of the transfer coefficients for both isotopes in the five experiments carried out, it should be noted that while the evolution is only by an order of magnitude for ^{134}Cs, in the case of ^{85}Sr the variation is practically by three orders of magnitude.

Analyzing together the mean values of the substrate/mycelium to mushroom transport coefficients, $\lambda_{V,I}$, (see Tables 1, 2 and Figure (4)), and those of the transfer coefficients, TC, (see Figure (4)) one may highlight the following results: Firstly, both groups of coefficients show the same decreasing trend as Δt increases. Secondly, the transport coefficients, $\lambda_{V,I}$, are systematically lower in value than the corresponding transfer coefficients, TC. This is a consequence of the conceptual difference underlying the definitions of the two sets of coefficients. Thirdly, both sets of coefficients clearly show the different nutritional requirements of the fungus at different stages of its development (spread of the mycelium in the substrate and formation of the aerial part of the mushroom). Thus one sees in Figure (4) that at the time of initiation of fruiting body formation, between 25 and 30 days before the date of harvesting of the mushrooms, there is an inversion of the trend in the values of the coefficients for ^{85}Sr and ^{134}Cs. Now strontium is preferentially taken up at this stage of fruiting body formation, doubtless due to the greater calcium requirements of the fungus at this time relative to potassium.

In order to check our results for the transfer coefficients, we compared them with those reported by other authors. Rühm et al., (1998) quantified the ^{134}Cs transfer as the ratio between the activity detected in the mushroom and that in the soil layer containing the mycelium, with a mean value of 5.4 for the transfer factor within the range (0.5 – 29.0) for saprophytic mushrooms. Results of a comparable order of magnitude have also been reported by other authors for ^{137}Cs transfer to various saprophytic fungi (Heinrich, 1992; Vaszari et al., 1992). The good agreement presented by the transfer coefficients for the case of saprophytic fungi, independently of whether their conditions of growth were natural or under controlled laboratory conditions as in our case, is a validation of our experimental design for the detailed analysis of the dynamics of the transfer of different radionuclides to different types of fungi.

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REFERENCES

Baeza A, Guillén J, Paniagua J, Hernández S, Martín JL, Díez J, Manjón JL, Moreno G, (2000) Radiocaesium and radiostrontium uptake by fruitbodies of *Pleurotus eryngii* via mycelium, soil and aerial absorption. Appl Radiat Isotopes 53: 455-462

Baeza A, Paniagua J, Rufo M, Guillén J, Sterling A (2001) Seasonal variations in radionuclide transfer in a Mediterranean grazing-land ecosystem. J Environ Radioactiv 55: 283-302.

Bunzl K, Kracke W, Schimmack W, Auerswald K (1995) Migrations of fallout $^{239+240}$Pu, ^{241}Am and ^{137}Cs in the various horizons of a forest soil under pine. J Environ Radioactiv 28: 17-34.

Ferri F I (1985) Funghi: Micologia Isolamiento, Coltivaziones. Edagricole, Bologna.

Heinrich G (1992) Uptake and transfer factors of ^{137}Cs by mushrooms. Radiat Environ Bioph 31: 39-49.

Kirchner G (1998) Applicability of compartmental models for simulating the transport of radionuclides in soil. J Environ Radioactiv 38: 339-352.

Mascanzoni D (1990) Uptake of ^{90}Sr and ^{137}Cs by mushrooms following the Chernobil Accident. In: Desmet G, Nassimbeni P, Belli M. (ed) Proceedings workshop transfer of radionuclides in natural and semi-natural environments. Elsevier Applied Science, London, p 459.

Moreno G, Manjon JL, Zugaza Z (1986) Guía de los Hongos de la Península Ibérica. I.N.C.A.F.O., Madrid.

Rühm W, Steiner M, Kammerer L, Hiersche L, Wirth E (1998) Estimating future radiocaesium contamination of fungi on the basis of behaviour patterns derived from past instances of contamination. J Environ Radioactiv 39: 129-147.

Shutov VN, Bruk GY, Basalaeva LN, Vasilevitskiy VA, Ivanova NP, Kaplem, IS (1996) The role of mushrooms and berries in the formation of the internal exposures doses to the population of Russia after the Chernobyl accident. Radiat Prot Dosim 67: 55-64.

Schell WR, Linkov I, Myttenaere C, Morel B (1996) A dynamic model for evaluating radionuclide distributions in forests from nuclear accidents. Health Phys 70: 318-335.

Shand C, Cheshire M, Smith S (1994) Distribution of radiocaesium in organic soils. J Environ Radioactiv 23: 285-302.

Vaszari EE, Tóth V, Tarján S (1992) Determination of radioactivities of some species of higher fungi. J Radioanal Nucl Ch 165: 345-350.