Accumulation of ^{137}Cs and ^{40}K in aboveground organs of tropical woody fruit plants

R. M. Anjos · M. Rizzotto · N. Sanches · H. Velasco · D. L. Valladares · K. D. Macario

Abstract Distribution of ^{40}K and ^{137}Cs in tissues of the *Citrus aurantifolia* was measured by gamma spectrometry. A simple theoretical model is also proposed to describe the temporal evolution of ^{40}K activity concentration in such tropical woody fruit species. This model exhibits close agreement with the ^{40}K experimental results, in the leaf growing and fruit ripening processes of lemon trees.

Keywords ^{137}Cs · ^{40}K · Plant internal distribution · Fruits · Leaves

Introduction

In South America, studies on biogeochemical cycles of radiocaesium have been carried out for tropical plants after the Goiânia radiological accident [1, 2]. Based on the study of contaminated plants, our results have shown a significant correlation between activity concentrations of ^{137}Cs and ^{40}K in different compartments of plants [1, 2]. Similar findings have been suggested during the investigation on the distribution and uptake of ^{137}Cs and the alkali metals in plants [3–5]. Despite there are large differences in the degree of translocation of inorganic cations in the above-ground parts of different species, depending upon physiological habits of the plants [4], some works have suggested the possibility of using the behaviour of alkali metals to predict the ^{137}Cs behaviour in soil–plant systems [3, 5].

In this paper, the activity concentrations of ^{137}Cs and ^{40}K from root to shoot for a tropical woody fruit species (*Citrus aurantifolia*) were evaluated in order to improve the understanding on the behaviour of monovalent inorganic cations in plants as well as its capability to store these elements. A theoretical model was also developed in order to describe the temporal evolution of their activity concentrations in different organs of tropical plants.

Experimental

Sampling details

Samples of roots, stems, barks, branches, twigs, leaves and fruits were taken from six specimens of lemon tree (*C. aurantifolia*). They were 5-years-old. Three of them were cropped on ^{137}Cs accidentally contaminated soil and the other ones on uncontaminated soil. The amounts of ^{137}Cs and ^{40}K in the samples were determined by standard gamma spectrometry using HPGe and NaI(Tl) detectors. Details of sample collection, preparation, experimental set up and analysis are explained elsewhere [1, 2].

The capability of plants to store ^{137}Cs and ^{40}K can be estimated through their respective accumulation rates in different compartments of the plant. The stem-to-compartment concentration ratios can be defined as:

$$CR_j = \frac{C_j}{C_{stem}} \tag{1}$$

where C_j is the activity concentration of the radionuclide in a given plant compartment j (root, stem, bark, twig, etc.).

R. M. Anjos (✉) · N. Sanches · K. D. Macario
Instituto de Física, Universidade Federal Fluminense, Av. Gal. Milton Tavares de Souza, s/n, Gragoatá, CEP 24210-346 Niterói, RJ, Brazil
e-mail: meigikos@if.uff.br

M. Rizzotto · H. Velasco · D. L. Valladares
Grupo de Estudos Ambientales (GEA), Instituto de Matemática Aplicada San Luis (IMASL), Universidad Nacional de San Luis, Ejército de los Andes 950, D5700HHW San Luis, Argentina

C_{stem} represents the activity concentration of the radionuclide in the main stem. The ^{40}K/^{137}Cs discrimination ratio can be calculated from the division of the ^{40}K and ^{137}Cs concentration ratios in a given plant compartment j.

Theoretical model

Usually the mathematical models used to describe the evolution of radionuclide activity concentrations, in reference to time, consist of a dynamic system of coupled ordinary differential equations. Each differential equation describes the temporal behaviour of the activity concentration in each compartment of the considered system, with coupling terms accounting for the possibility of radionuclide transfer among the compartments [6].

In this work we use a three-compartment model to describe the radionuclide circulation in the trunk-leaf-fruit system, for tropical woody fruit plants. The number of compartments and the coupling terms take into account the particular situation to be described: the temporal evolution of ^{40}K concentrations along a single growth period, of fruits and leaves. The input of radionuclides into the plant is assumed to be only through the root system, i.e. no surface absorption is considered for fruits and leaves. In addition, we assume a logistic model to describe the fruit and leaf growth [7]. In situ experimental evidence demonstrates that this hypothesis is applicable for fruits and leaves in the considered plants. The model does not consider variations in the activity concentration due to radionuclide physical decay processes, given that the simulation time period is short.

According to the experimental data available, the activity concentration of radionuclides in trunks, C_T (Bq kg^{-1}), has no relevant alteration during a growth period. Consequently, only changes in mass and concentration activity are considered through the following coupled differential equations.

For the leaf compartment:

$$\frac{dC_L}{dt} = \lambda_{TL}C_T - \lambda_{LF}C_L \tag{2}$$

For the fruit compartment:

$$\frac{dC_F}{dt} = \lambda_{TF}C_T + \lambda_{LF}C_L \tag{3}$$

where λ_{TL} (d^{-1}), λ_{TF} (d^{-1}) and λ_{LF} (d^{-1}) represent the trunk to leaf, trunk to fruit, and leaf to fruit transfer rates, respectively. The magnitudes C_L (Bq kg^{-1}) and C_F (Bq kg^{-1}) describe the leaf and fruit radionuclide activity concentrations, respectively.

Previous papers [8] suggest including the possibility of activity transfer from leaf to fruit compartments, based on the demand of fruits for nutrients and photosynthetic products. Consequently, the model includes this transfer process (coupling term, λ_{LF}, in Eqs. 2 and 3). This term was also crucial to simulate changes in activity concentration in fruits along the growth period.

When we include logistic growth models in Eqs. 2 and 3, and then apply mathematical procedures, we obtain the following differential equations for the activity concentrations in leaf and fruit compartments, respectively:

$$\frac{dC_L}{dt} = \frac{\lambda_{TL}\theta_L C_T}{f_L} - [\lambda_{LF} + \alpha_L(1 - f_L)]C_L \tag{4}$$

$$\frac{dC_F}{dt} = \frac{\lambda_{TF}\theta_F C_T}{f_F^3} + \lambda_{LF}\frac{\theta_F f_L}{\theta_L f_F^3}C_L - 3\alpha_F(1 - f_F)C_F \tag{5}$$

where the constants θ_L and θ_F are, respectively, the ratio between the trunk compartment mass, and the leaf compartment mass, and fruit compartment mass at the end of the growth process; the functions f_L and f_F describe

Table 1 Mean values of activity concentrations (Bq kg^{-1} dry weight) of ^{137}Cs and ^{40}K from lemon trees contaminated by caesium

Lemon tree (*Citrus aurantifolia*)

Compartment	Concentrations		Stem-to-compartment j Concentration ratios		^{40}K/^{137}Cs Discrimination ratios
	^{137}Cs (Bq kg^{-1})	^{40}K (Bq kg^{-1})	$CR[^{137}Cs]$	$CR[^{40}K]$	$\frac{CR[^{40}K]}{CR[^{137}Cs]}$
Main root	97(10)	236(20)	1.0(0.1)	1.0(0.1)	1.0(0.2)
Main stem	90(7)	230(20)	0.9(0.1)	1.0(0.1)	1.1(0.2)
Bark	245(31)	600(48)	2.5(0.4)	2.5(0.3)	1.0(0.2)
Branch	183(20)	432(37)	1.9(0.3)	1.8(0.2)	1.0(0.2)
Twig	281(17)	723(54)	2.9(0.3)	3.1(0.3)	1.1(0.2)
Old leaves	420(26)	1216(91)	4.3(0.5)	5.2(0.6)	1.2(0.2)
New leaves	581(47)	1249(106)	6.0(0.8)	5.3(0.6)	0.9(0.2)
Mature fruit	301(24)	759(76)	3.1(0.4)	3.2(0.4)	1.0(0.2)
Green fruit	395(22)	1049(55)	4.1(0.4)	4.4(0.6)	1.1(0.2)

Values in parentheses represent one standard deviation from the mean based on 10 measurements

the leaf and fruit compartments growth according to the logistic model:

$$f_L(t) = \frac{m_L(t)}{m_L^{max}} = \frac{a_L}{(1 - a_L)\, e^{-\alpha_L t} + a_L} \quad (6)$$

$$f_F(t) = \frac{R_F(t)}{R_F^{max}} = \frac{a_F}{(1 - a_F)\, e^{-\alpha_F t} + a_F} \quad (7)$$

where $m_L(t)$ (kg) is the mass of leaf compartment at time t (d), m_L^{max} (kg) is the mass of the leaf compartment at the end of the growth process, $a_L = \frac{m_L(0)}{m_L^{max}}$, α_L (d^{-1}) is the leaf growth parameter, $R_F(t)$ (cm) is the characteristic linear dimension of the fruit at time t, R_F^{max} (cm) is the characteristic linear dimension of the fruit at the end of the growth process, $a_F = \frac{R_F(0)}{R_F^{max}}$, and α_F (d^{-1}) is the fruit growth parameter. In each case, the integration of differential equations 4 and 5 were performed using a computational algorithm based on the explicit Runge–Kuta formula.

Results and discussion

Activity concentrations of ^{137}Cs and ^{40}K from root to shoot for a tropical woody fruit species were evaluated as well as the capability of this plant to store these elements. Table 1 shows the mean values of activity concentrations of ^{137}Cs and ^{40}K along the main trunk, bark, branches, twigs, leaves and fruits from lemon trees. These data refer to the mean of 10 samples from each plant compartment. Given the homogeneity of the results, two clusters were identified of younger (fruit, leaf, twig, branch and bark) and older parts (main stem). The results indicate that tissues with low ^{137}Cs activity concentration (on a dry weight basis) had low ^{40}K activity concentration as well, in such a way that both ^{137}Cs and ^{40}K had simultaneously higher activity concentrations in the new parts than in the older parts. Concentration ratio values for ^{137}Cs and ^{40}K indicate that both elements have similar behaviour in different organs of the same tree. This result can be better observed from the ^{40}K/^{137}Cs discrimination ratio results for each compartment j (main stem, bark, old and new branches, twig, old and new leaves, mature and green fruits), since the ^{40}K/^{137}Cs values were approximately equal to unity for the different compartments of lemon trees studied in this work.

These findings suggest, therefore, the possibility of using a few radioisotopes to predict the behaviour of monovalent cations in tropical woody fruit plants. However, it is noteworthy that while some plants are able to replace high proportions of potassium with sodium, without any effect on growth, other plants can undergo additional growth stimulation through Na that cannot be achieved by increasing the plants K content [9]. Growth stimulation by Na is caused mainly by its effect on cell

expansion, and on the water balance of plants. Such observations would indicate that Na$^+$, K$^+$ and Cs$^+$ may compete during the plants uptake, and that radioisotopes possibly could also be used to trace the plants Na nutrition, presenting, therefore, an important tool for studies on plant
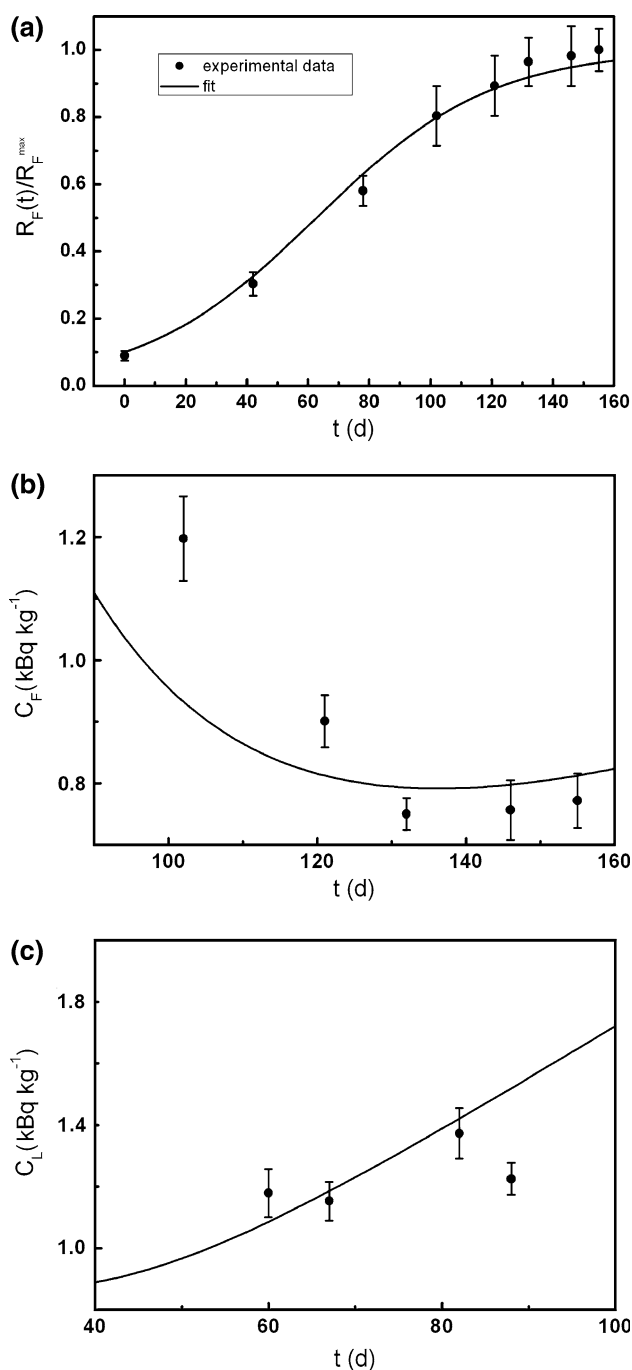

Fig. 1 a Experimental data and logistic model fitting of fruit radius evolution over time; b Experimental data and theoretical prediction for ^{40}K activity concentration (kBq kg^{-1} dry weight) in fruits from lemon trees; c Experimental data and theoretical prediction for ^{40}K activity concentration (kBq kg^{-1} dry weight) in leaves from lemon trees

physiology. Concerning radioecology, ^{40}K could be used as a radiotracer for studying the transport and accumulation of radiocaesium in the different organs of tropical plants.

The model was calibrated with experimental data, as follows: Figure 1a shows $\frac{R_F(t)}{R_F^{max}}$ vs. t for lemon fruit. Dots represent the experimental data with the corresponding error bar, and the continuous line represents the fit using Eq. 7, using α_F as a free parameter. Theoretical and experimental fit is very good. The same procedure was followed to obtain α_L.

Replacing these parameter values in Eqs. 4 and 5, we obtain the ^{40}K activity concentration for fruits and leaves, as a function of time (Fig 1b, c). In these figures, dots symbolize the experimental data and the continuous lines represent the theoretical approach. The agreement between the model and experimental data is reasonable for the considered time period.

Conclusions

^{137}Cs and ^{40}K showed very similar distributions, exhibiting, therefore, similar behaviour. Their activity concentrations were age-dependent and decreased with increasing age of leaves and fruits. A very simple three compartment model was proposed, which was calibrated with ^{40}K experimental data. The agreement between the model and experiment is reasonable. Further research is necessary in order to encompass the complete growing period, and thus improve the performance of the model. Particularly, it is necessary to obtain more experimental data covering the early growing periods for fruits and leaves. The availability of a theoretical approach to simulate the input of radionuclides into the edible parts of plants is important, given that the assessment of population dose rates is a vital food chain model issue.

References

1. Anjos, R.M., Mosquera, B., Sanches, N., Cambuí, C.A., Mercier, H.: Caesium, potassium and ammonium distributions in different organs of tropical plants. Environ. Exp. Bot. **65**, 111–118 (2009)
2. Sanches, N., Anjos, R.M., Mosquera, B.: ^{40}K/^{137}Cs discrimination ratios to the aboveground organs of tropical plants. J. Environ. Radioact. **99**, 1127–1135 (2008)
3. Yoshida, S., Muramatsu, Y.: Concentrations of alkali and alkaline earth elements in mushrooms and plants collected in a Japanese pine forest, and their relationship with ^{137}Cs. J. Environ. Radioact. **41**, 183–205 (1998)
4. Chao, J.H., Chiu, C.Y., Lee, H.P.: Distribution and uptake of ^{137}Cs in relation to alkali metals in a perhumid montane forest ecosystem. Appl. Radiat. Isot. **66**, 1287–1294 (2008)
5. Lovrencic, I., Volner, M., Barisic, D., Popijac, M., Kezic, N., Seletkovic, I., Lulic, S.: Distribution of ^{137}Cs, ^{40}K and ^{7}Be in silver fir-tree (*Abies alba* L.) from Gorski Kotar, Croatia. J. Radioanal. Nucl. Chem. **275**, 71–79 (2008)
6. Mitchell, N.G.: Models for radionuclide transfer to fruits and data requirements. J. Environ. Radioact. **52**, 291–307 (2001)
7. Yu, K.N., Mao, S.Y., Joung, E.C.M.: Assessment of the transfer of ^{137}Cs in three types of vegetables consumed in Hong Kong. Appl. Radiat. Isot. **49**, 1695–1700 (1998)
8. Carini, F.: Radionuclide transfer to fruit in the IAEA TRS 364 Revision. J. Environ. Radioact. (2008). doi:10.1016/j.jenvrad.2008.10.001
9. Markert, B.: Instrumental Element and Multielement Analysis of Plant Samples—Methods and Applications. John Wiley and Sons, Chichester, New York (1996)