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Plant uptake of radioactive corrosion products in a field study

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Abstract The root uptake by wheat of three activation products (^{57}Co, ^{54}Mn and ^{65}Zn) was studied in a 3-year field experiment. The aim of the investigation was to calculate the soil–plant transfer factors of these nuclides and to verify the role played by different soil treatments (Ca and K) on the uptake. The uptake of ^{54}Mn and ^{65}Zn, relevant for the plant, was higher than that of ^{57}Co (physiologically unimportant). The temporal distribution of the uptake showed a decreasing trend, while the treatments containing Ca led to lower transfer factors for ^{54}Mn and ^{65}Zn, which varied between 0.67 and 3.68. The variations exhibited by the different nuclides were discussed, as well as the differences between the treatments.

Keywords Radioactive corrosion products · Activated metal particles · Transfer factors · Radioactive pollution · Radioecology

Introduction

The production of energy through nuclear power has stressed the importance of investigating the consequences of the release of radioactive substances in the environment. In a nuclear reactor neutron activated metal particles (corrosion products) are normally set in circulation in the coolant and even if advanced design and extensive treatment systems are devoted to avoid leakage of radionuclides, small quantities may still reach the environment. In terms of releases, this possibility exists under normal operating conditions, yet increases substantially in the case of anomalous function, and most seriously, in the case of an accident. These substances, once released in the environment, will ultimately deposit and accumulate in terrestrial and aquatic ecosystems.

From the point of view of food production, the dispersion and the accumulation of radioactive substances in the soil constitute by far the major sources of concern. The ready uptake of radionuclides by plants can lead to their distribution in a wide variety of foodstuffs, whilst the permanence of these contaminants in the root zone makes them available for transfer to the human food chain for a long time. Attention has therefore been focused on the transport from soil to plant, this being the key process governing contamination of food and animal feed. The kinetics of the transfer of several radionuclides have been investigated in many experiments, but the majority of these studies relate to short-term pot experiments where the root systems have access only to contaminated soil. The results of these experiments often exhibit poor agreement with those obtained under field conditions, where the roots are in a heterogeneously contaminated soil profile and nutrient uptake from subsoil dilutes the uptake from surface and plough layers [1].

For this reason, a 3-year investigation was carried out in Sweden under field conditions to study the uptake by spring wheat (*Triticum aestivum*) of three activation products, ^{57}Co, ^{54}Mn and ^{65}Zn. The objective of the experiment was to determine transfer factors of the examined nuclides and to study how different nutrient treatments affected the root uptake of an important agricultural crop such as spring wheat.

Experimental

The radionuclides were applied in a top soil with three different treatments allocated on four replicates. The experiment

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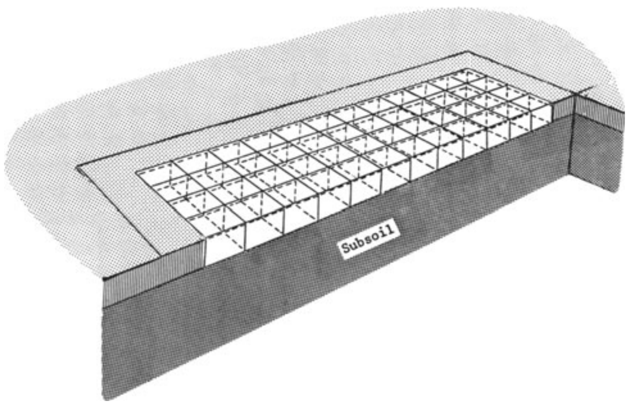

Fig. 1 Cross-section of the plot enclosures placed on top of the subsoil

Table 1 Plan of the experiment

Treatment	Rate	
	g/plot	Kg/ha
NPK (control)	15	600
NPK + CaO	15 + 150	600 + 6,000
NPK + KCl	15 + 12	600 + 480

was carried out in the open field at an experimental station with the soils placed in plots on top and in contact with local subsoil. Each plot consisted of a square cell contained in a metal frame 0.5 × 0.5 × 0.3 m designed as a type of lysimeter open underneath and with the top soil contaminated to a depth of 20 cm. A cross-section of the field set-up with 48 plots is shown in Fig. 1. With this arrangement, originally introduced by Fredriksson [2], the soil material of each replicate is subject to identical conditions (as in pot experiments), while climate and subsoil status are as relevant as in a field situation, thus taking advantage of both types of experimental approaches.

Prior to putting it into the plots, the soil was air-dried, weighed, homogenized and fertilized with macronutrients (NPK 16-7-13), Ca and K according to Table 1. Ca and K were added since they have shown to play an important role in the uptake of many radionuclides. The NPK-fertilizer was added annually in spring and during dry periods the natural water regime was supplemented with irrigation. Normal agricultural practices were used, with sowing in May and harvest in September. The soil was homogeneously contaminated with the different nuclides diluted in 0.2 N HCl solutions at a level of 4 MBq/plot, corresponding to about 70 kBq/kg dry soil. Physical and chemical properties of the experimental soil, as well as the subsoil, are given in Table 2.

At harvest, the plants were cut 5–6 cm above the soil surface, dried for 12 h at 105 °C and the edible plant part (grain) was ground into a homogeneous powder. Quantities of 10 g wheat grain were weighed and placed into plastic vials for radioassay. Great care was used to fill the vials uniformly and to exact volumes, in order to produce consistent and reproducible geometries. Gamma radiation was measured with a NaI(Tl) 3″ × 3″ well-type scintillation detector assembled in a 12 cm thick low-activity lead shield. The photopeaks selected for measurement of the gamma emission were 122, 835 and 1.11 MeV for ^{57}Co, ^{54}Mn and ^{65}Zn respectively. Since the investigation covered a period of 3 years, the measurements were carried out at different times and therefore the results were decay-corrected to a common time in order to render them comparable with each other.

Results and discussion

In environmental modelling, for the purpose of describing the radionuclide migration in soil, agricultural land is often categorized as a well-mixed type to simulate land subject to frequent ploughing and cultivation [3]. The parameter commonly used for describing the radioactive transport between the compartments "soil" and "plant" is the soil–plant transfer factor (TF_{sp}), defined as [4]:

$$TF_{sp} = \text{Activity in plant dry matter (Bq/kg)}/\text{Activity in dry soil (Bq/kg)}.$$

Transfer factors were calculated for the uptake of ^{57}Co, ^{54}Mn and ^{65}Zn by the grain of spring wheat as influenced by the different nutrient treatments. Mean values over the four replicates with standard deviations are presented in Table 3. Regardless of the treatment type, the distribution pattern of the TF_{sp}-values was similar, while variations occurred to a greater extent between nuclides. The mean TF_{sp}-values decreased in the order: ^{65}Zn>^{54}Mn>>^{57}Co.

Table 2 Physical and chemical properties of the soil used

Soil classification[a]	Dry weight (kg/plot)	Ph	Organic matter (%)	Base saturation (%)	Soluble nutrients (mg/100 g dry soil)				
					P_{AL}	K_{AL}	Ca_{AL}	P_{HCL}	K_{HCL}
Loamy sand	68	5.6	4.3	83	13.2	16.0	189	56	110
Clay	(Subsoil)	7.7	–	80	–	–	–	–	–

[a] According to USDA standard

Table 3 TF_{sp}-values obtained for the uptake of ^{57}Co, ^{54}Mn and ^{65}Zn by wheat grain with different nutrient treatments, mean values over the four replicates and standard deviations

Nuclide	Experimental year	TF_{sp}		
		Control	CaO	KCl
^{57}Co	I	0.0038 ± 0.0004	0.0036 ± 0.0004	0.0042 ± 0.0004
	II	0.0028 ± 0.0003	0.0023 ± 0.0002	0.0025 ± 0.0002
	III	0.0029 ± 0.0003	0.0024 ± 0.0003	0.0027 ± 0.0003
^{54}Mn	I	3.02 ± 0.27	1.27 ± 0.13	2.76 ± 0.29
	II	2.22 ± 0.21	0.67 ± 0.07	2.05 ± 0.21
	III	2.11 ± 0.22	0.73 ± 0.08	2.27 ± 0.22
^{65}Zn	I	3.49 ± 0.33	1.87 ± 0.18	3.68 ± 0.34
	II	2.74 ± 0.28	1.22 ± 0.11	2.91 ± 0.27
	III	2.96 ± 0.27	1.29 ± 0.12	2.84 ± 0.29

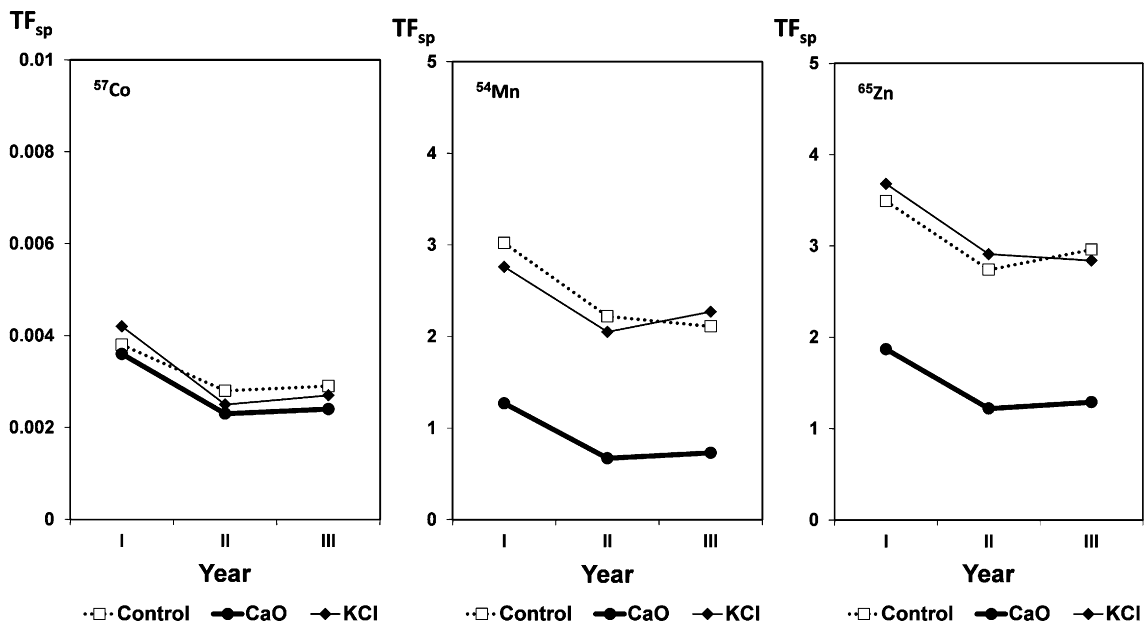

Fig. 2 Mean values on time of the transfer factors for the uptake of ^{57}Co, ^{54}Mn and ^{65}Zn by the grain of spring wheat with different nutrient treatments

The TF_{sp} of ^{54}Mn and ^{65}Zn ranged between 0.67 and 3.68, while for ^{57}Co the TF_{sp} were 2–3 orders of magnitude lower. The transfer levels were in agreement with established data for the soil and the crop used as obtained in similar field experiments [4–6]. A thoroughly review of how the uptake varies with plant and soil type can be found elsewhere [7].

The results obtained reflect the functions that the different nuclides fulfil in plants. The uptake of ^{54}Mn and ^{65}Zn was higher since these elements are micronutrients and, as such, essential for the plant and readily absorbed by the roots. Although the role of manganese in plant metabolism is not completely understood, its importance for a plant's vital functions is widely acknowledged. Manganese plays a role in photosynthesis and is a constituent of several enzymes which function in vital plant cycles [8, 9]. Zinc is known to be essential for the transformation of carbohydrates and the consumption of sugars, being part of the enzyme systems which regulate plant growth [10]. In contrast, the uptake of ^{57}Co was considerably lower, owing to the minor (or null) significance of this element for the plant [11]. As a consequence, its uptake is a passive process exposed to great extent to the antagonism of other substances in the system [7].

On the whole, the transfer factors exhibited a decreasing trend from experimental year I to III. This observation is consistent with the assumption that at the early stage of the experiment the topsoil, from which the root system absorbed the necessary nutrient substances, had not yet settled and exhibited poor contact with the subsoil. In this situation, the nuclides were still held in exchangeable form and exhibited a higher uptake which later decreased, when availability diminished, presumably due to formation of insoluble compounds [3, 12]. This was particularly noticeable with ^{54}Mn and ^{65}Zn, thus reflecting the need of these elements by the plant and their prompt uptake as soon as they are available in an exchangeable form.

The effect of the different nutrient treatments is visualized in Fig. 2, where the mean values on time of the transfer factors for ^{57}Co, ^{54}Mn and ^{65}Zn are presented in graphic form. The treatments containing Ca led to a lower TF_{sp} for ^{54}Mn and ^{65}Zn. This result confirms previous findings showing that the uptake of essential elements such as manganese and zinc and chemically similar to calcium is reduced by the concurrent presence of available Ca-ions in the soil [7, 13]. A similar reduction due to the Ca-treatment was not observed in the uptake of ^{57}Co. Furthermore, it was noticed that the K-treatment did not affect the uptake of any of the employed nuclides, confirming the findings that the effect of calcium cannot be reproduced by potassium [14, 15].

Conclusions

A 3-year investigation on the transport from soil to plant of radioactive corrosion products was carried out in the open field using an improved plot technique. Compared with pot experiments, the results obtained with this technique are more consistent and have the advantage of estimating the plant uptake in a real world situation. The results obtained in this study show that after the homogeneous incorporation of activation products in the plough layer of the soil, the activity in wheat grain varied owing to nuclide characteristics and fertilizer levels. Elements such as ^{54}Mn and ^{65}Zn, relevant for the plant, were absorbed readily, while the uptake of ^{57}Co (physiologically unimportant) was considerably lower. The temporal distribution of the soil–plant transfer of the investigated nuclides emphasizes the importance of treating the TF_{sp}-values obtained during the first year after a contamination with caution. It should be kept in mind that, if employed in environmental modelling, the initial transfer values describe the uptake in a particular situation (early uptake) and are by no means representative for evaluating the transport in the long term.

The treatments receiving Ca reduced the uptake of ^{54}Mn and ^{65}Zn, indicating that their availability appears to be associated with that of the components of the mineral fraction, which compete effectively with both nuclides for the root absorption. In contrast, the K-treatment did not affect the uptake of any of the investigated nuclides, indicating that the effect of calcium fertilization cannot be replaced by potassium. The results obtained stress the importance of maintaining an appropriate nutrient status in agricultural soils with particular regard to calcium. This nutrient was found to play an important role in the uptake of ^{54}Mn and ^{65}Zn, thus suggesting a way of lowering the root absorption of these nuclides in the case of a release and reducing the contamination of the human food chain. This issue assumes even greater importance when considering the possibility of long-term alterations of the soil Ca-level caused by persistent acid precipitations.

In conclusion, it is clear that the prediction of radionuclide movements from soil to plant not only relies on knowledge of chemical and physiological uptake mechanisms, but also on adequate determination of the soil nutrient conditions. Full information on these parameters could guide quicker analysis of nuclide translocation through terrestrial systems, thereby improving the possibilities of forecasting the implications for the human food chain.

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