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Impact of Agro-Technical Measures on the Strontium Uptake of Agricultural Crops

Silvia Haneklaus and Ewald Schnug [1]

Abstract

Contamination of food with radio-nuclides after nuclear disasters is one of the major threats to human health. The Cernobyl accident in 1986 was an event which affected regions all over the world, it highlighted uncertainty about appropriate measures to be employed in order to reduce the entry of radio-nuclides into the food chain.

Generally oilseed rape showed three to six times higher Sr contents of the vegetative and generative plant parts than cereals. In pot, lysimeter and field trials the following measures were tested: liming (Ca supply versus pure increase of pH value), sulphate and phosphate fertilisation; mixing depth of Sr (surface contamination (0-1 cm) versus mixing of Sr in the plough layer (0-30cm)). In all experiments the seed and grain Sr concentrations, respectively remained more or less unaffected by the different treatments. Sr transfer into vegetative plant parts of fodder plants was distinctly reduced by liming or gypsum fertilisation whereby this influence seems to be widely independent of the soil type.

A differentiation of liming into a Ca and pH effect showed that an increase in pH had little effect on the Sr uptake while the Ca supply resulted in a significant decrease in the Sr uptake due to Ca/Sr antagonism. The application of extremely high amounts of phosphorus to a soil low in plant available phosphorus decreased the Sr contents of oilseed rape and cereals efficiently in a pot experiment, but hardly any influence of common P applications on the Sr uptake can be expected. Only extraordinarily high amounts of sulphate were able to reduce the Sr uptake, too.

The mixing of Sr within the whole ploughed layer (0-30 cm) decreased Sr contents of *Dactylis glomerata* L. by up to 29 % in comparison with Sr added to the soil surface (0-1 cm). Therefore deep and homogenizing soil tillage operations are a further important measure for the reduction of Sr uptake of plants.

Key words: Cernobyl, nuclear accidents, fertilisation, soil tillage

Zusammenfassung

Einfluss agro-technischer Maßnahmen auf den Strontiumgehalt landwirtschaftlicher Kulturpflanzen

Die Kontamination von Nahrungsmitteln mit Radionukliden nach kerntechnischen Unfällen ist eine wesentliche Bedrohung für die Gesundheit des Menschen. Der Reaktorunfall von Tschernobyl 1986 war solch ein Ereignis, welches Regionen in allen Teilen der Welt beeinträchtigte und zugleich die Notwendigkeit verdeutlichte, agro-technische Maßnahmen hinsichtlich ihrer Wirksamkeit zu prüfen, um Landwirten geeignete Handlungsempfehlungen geben zu können.

Raps reagierte in allen Versuchen durchschnittlich mit sechsfach höheren Sr-Gehalten in vegetativen und dreifach höheren Gehalten in generativen Pflanzenteilen als Getreide. In Gefäß- Lysimeter- und Feldversuchen wurden die folgenden Maßnahmen getestet: Kalkung (Ca-Zufuhr versus pH-Effekt), Sulfat- und Phosphatdüngung; Einarbeitungstiefe (oberflächig (0-1cm) ausgebrachtes Sr versus auf Pflugtiefe (0-30 cm) eingearbeitetes Sr). In allen Versuchen zeigte sich, daß die Behandlungen mehr oder weniger keinen Einfluß auf die Samen- bzw. Korngehalte ausübten. Der Sr-Transfer in vegetative Pflanzenteile von Futterpflanzen wurde durch Kalkung und Gipsdüngung deutlich reduziert, wobei dieser Effekt weitgehend unabhängig vom Bodentyp zu sein scheint.

Eine Differenzierung von Ca- und pH-Effekt zeigte deutlich, daß letzterer keinen signifikanten Einfluß auf die Sr-Aufnahme ausübte, während eine erhöhte Ca-Zufuhr, bedingt durch den Ca/Sr-Aufnahmeantagonismus, zu einer signifikanten Abnahme der Sr-Gehalte führte. Extrem hohe, nicht praxisübliche Phosphat- und Sulfatgaben führten zu einer Reduzierung der Sr-Aufnahme.

Das Einmischen von Sr in der vollen Bearbeitungstiefe (0-30 cm) führte zu einer Abnahme der Sr-Gehalte von Knaulgras um bis zu 29 %, verglichen mit einer oberflächigen Sr-Ausbringung (0-1 cm). Daher stellen tiefe, mischende Bodenbearbeitungsmaßnahmen eine wichtige Maßnahme zur Reduzierung der Sr-Aufnahme durch landwirtschaftliche Kulturpflanzen dar.

Schlüsselworte: Tschernobyl, Nuklearunfälle, Düngung, Bodenbearbeitung

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1 Introduction

Contamination of food with radio-nuclides after nuclear disasters is one of the major threats to human health. The Cernobyl accident in 1986 was an event which affected regions all over the world, it highlighted uncertainty about appropriate measures which were to be employed in order to minimise the entry of radio-nuclides into the food chain. Thereafter many efforts were made to establish rules on how to maintain agricultural production techniques after nuclear disasters in order to keep the contamination of food as low as possible (Anon, 1994; Ponchet & Metivier, 1994; Anon, 1999).

Contaminations with ^{90}Sr are particularly dangerous because of its similarity with Ca; ^{90}Sr may replace Ca in biological structures such as human bones. This explains the exceptionally hazardous potential of ^{90}Sr, a ß-radiation emitter with a half-life time of 28 years. The ß-decay of ^{90}Sr makes this radio-nuclide also difficult to determine in experimentation, because its analysis requires radio-chemical methods (Kampe 1986; Rink & Sauer, 1986). Therefore, experiments investigating the transfer of ^{90}Sr in the food chain are limited. A solution to this problem is the analysis of stable Sr which behaves identically to ^{90}Sr in the environment. However, even more often the Ca uptake has been determined in order to evaluate the ^{90}Sr uptake (Coughtrey & Thorne, 1983) because of the similarities of both elements. Thus, the fate of ^{90}Sr cannot be isolated from that of stable Sr and Ca.

One measure to lower the amounts of ^{90}Sr entering the food chain is the selection of the crop type. Sr uptake of dicotyledonous crops is for example distinctly higher than that of monocotyledonous crops due to the higher cation exchange capacity of these plants (Ananyan & Sarkisyan, 1976; Szabo et al., 1977; Andersen, 1973). Changes in the production technique are required whenever a choice of the crop species is not possible and may be used as an additional measure to reduce ^{90}Sr turnover. The Sr content of plants varies depending on the plant available content in the soil, root uptake and growth stage and agro-technical measures focus on a decrease of the Sr availability. The mechanisms rely for example on a Sr/Ca uptake antagonism or immobilisation as carbonates, sulphates or phosphates. A deeper, homogenising cultivation during soil tillage operations yields a dilution effect (Andersen, 1967; Grzybowska, 1973; Korneey et al., 1976; Korneeva et al., 1976; Cline & Rickard, 1972). Other procedures such as leaching by means of water, acids or alkalines (Fuller et al., 1966; Martin & Turner, 1966; Spalding, 1980) provided unsatisfactory results and long term negative effects of these treatments on pH and stability of soil structure can be expected. The removal of the upper top soil layer reduced the uptake of radio-nuclides by up to 99 % (Anon, 1994; Menzel & James, 1971; Howorth & Sandalls, 1987). The practicability of this technique on agricultural production fields is questionable because of the enormous amounts of contaminated soil for disposal, about 700 - 1500 t ha^{-1} need to be picked up when a soil layer of 5-10 cm is removed by scraping (Andersson, 1996). A further problem may be that the entire, fertile humus layer could be removed by this measure.

It has been the aim of the investigations presented here to compare the efficacy of different agro-technical methods to reduce the Sr uptake of different agricultural crops in pot, lysimeter and field trials.

2 Materials and Methods

Pot trials were conducted for evaluating the maximum potential of agro-technical methods to reduce the Sr uptake of agricultural crops. Lysimeter experiments better reflect natural growth conditions, but only field trials permit the estimation of the true efficiency of treatments. The impact of the following agro-technical measures on the Sr uptake of agricultural crops were studied:

- Increasing Ca applications (pH indifferent) and increasing rates of liming (pH increasing) to winter wheat and oilseed rape on a low pH parabrown earth and marsh soil
- Increasing sulphate applications to oats and oilseed rape on a fluvial and a sea marsh soil
- Increasing phosphate amendments to cereals and oilseed rape on a parabrown earth with a low content of plant available phosphorus
- cultivation forms (mixing of increasing Sr rates in two soil depths: 0-1 cm and 0-30 cm) on a fluvial marsh soil with a perennial forage crop (*Dactylis glomerata L.*)

Pot and lysimeter experiments

The soil capacity of the pots was 1.6 kg pot^{-1} and 60 kg per lysimeter, respectively. Basic fertilisation was applied in amounts that warranted nutrient element concentrations at shooting stage comparable to those under field conditions. In pot trials, phosphate was applied as ammonium-phosphate solution (N-balance by ammonium-nitrate), sulphate as potassium-sulphate (K-balance by potassium chloride) and calcium as calcium-oxide. In lysimeter trials, sulphate was applied as gypsum (calcium balance by calcium oxide). In order to test the effect of cultivation, Sr was applied at 2 depths (0-1 cm; 0-30 cm) and in different amounts (0-3 g Sr $lysimeter^{-1}$).

Field experiment

A field trial with increasing amounts of calcium and sulphate was conducted on a marsh soil at Bordelumer Koog, near Bredstedt (8° 55.8' E; 54° 36.3' N) with a high lime requirement. The pH optimum was determined according the Jensen method, with soil samples being homogenously mixed with increasing amounts of lime (Haneklaus & Schnug, 2000). After adjustment of the actual pH value,

Table 1
Descriptive data for soils used in pot, lysimeter and field trials

Parameter	Pot	Lysimeter	Field
Soil type	Parabrown earth	Fluvial marsh soil	Sea marsh soil
pH ($CaCl_2$)	5.7	5.5	5.3
CEC (mg $100g^{-1}$)	12.7	21.4	18.2
Clay content (%)	12	25	19
Total contents			
N (mg g^{-1})	0.7	1.2	1.3
$C_{org.}$ (%)	1.2	2.3	3.4
Sr (mg kg^{-1})	83	70	99
Available contents			
Phosphorus (mg kg^{-1})	52	39.0	83.0
Potassium (mg kg^{-1})	168	67	200
Sulphate-S (mg kg^{-1})	4.9	22.4	18.3
Sr (mg kg^{-1}) [1]	11.5	17.2	14.2
Sr (mg kg^{-1}) [2]	3.4	1.8	4.0

[1] in 1N NH_4-acetate, pH 7; [2] in 0.025N $CaCl_2$

necessary amounts for liming were calculated. Relevant characteristics of soils used in pot, lysimeter and field trials are summarised in table 1.

Soil analysis

The following methods were employed: C - conductometrically using the Stroehlein analyser; N - according to Kjeldahl; S_{total} - by X-ray fluorescence spectroscopy; clay content - using the sieve and pipette method according to Koehn; ECE according to Mehlich; pH - potentiometrically in 0.025N $CaCl_2$; $CaCO_3$ - volumetrically according to Scheibler; Sr_{total} - by X-ray fluorescence spectroscopy; P and K - in the DL-extract according to Egner-Riehm; exchangeable Sr and Ca in 1N NH_4-acetate according to Nishita et al.,1958; rapidly exchangeable Sr in 0.025N $CaCl_2$ according to Schachtschnabel. For details and references see Schlichting & Blume (1966) and Haneklaus (1989).

Plant analysis

Total Sr and Ca concentrations in plant material (younger, fully differentiated leaves of oilseed rape and the whole above-ground plant material of cereals at stem extension and straw and grain material of cereals at harvest) were determined by X-ray fluorescence spectroscopy (X-RF) according to Schnug & Haneklaus (1999).

3 Results and Discussion

Evaluation and differentiation of the effect of liming and Ca applications on the reduction of the Sr uptake of oats and oilseed rape in pot experiments

Ca applications to soils are supposed to have the greatest influence on the Sr uptake of plants as Ca and Sr show the same uptake and metabolic characteristics in plants. On production fields the Ca supply is usually adjusted by liming so that it is not possible to distinguish between Ca and pH effect. A pot trial was therefore designed, particularly to distinguish between both effects. The results are summarised in table 2.

The soil pH value increased from 5.7 to 7.8 at the highest liming rate, but this had no significant influence on the Sr contents in the vegetative plant tissue of oats and oilseed rape. Consequently no significant correlation was found between pH value and plant Sr and Ca concentrations, respectively. In comparison, the Sr content of oats decreased significantly from 13 to 5 mg Sr kg^{-1} and that of oilseed rape from 94 to 34 mg kg^{-1} Sr with increasing Ca supply. Increasing Ca amendments reduced the Sr uptake of oilseed rape of up to 65 % and of oats of up to 60 %. A similar, but positive effect of the treatment on the Ca contents was observed (table 2). There was a close negative relationship between Ca supply and Sr concentration in oilseed rape ($Y = -0.5*X + 104.1$; r^2=75 %), while this effect was less pronounced in oats ($Y = -0.086*X + 15.8$; r^2=43 %).

The results of the pot trials with oats and oilseed rape revealed that the anatgonistic effect of Ca reduced the Sr uptake while changes in soil pH had obviously no effect on the Sr uptake.

Among all agro-technical measures liming proved to be the most effective way to reduce the Sr uptake of crops; reductions of 15 % to 80 % were recorded (Andersen, 1963; Gulyakin et al., 1976; Haghiri & Himes, 1974; Szabo, 1980). In some investigations the Sr content was set into direct relation to soil pH values (Abazov et al., 1978; Haghiri & Sayre, 1961; Schroeder et al., 1962; Uhler & Hungate, 1960); other studies indicated that the liming effect was restricted to acid soils (Abazov et al., 1978; Frederiksson et al., 1970; Haak & Lnsj, 1975; Klechkovskii et al., 1973; Mistry & Bhjubal, 1973) i. e., only if a Ca deficit existed at the clay minerals, liming reduced the Sr uptake (Abazov et al., 1978; Browman & Spalding, 1984).

4 Influence of liming on the Sr uptake of oats and oilseed rape in a lysimeter experiment

Growth conditions in lysimeters are closer to those in the field (Steffens et al., 1988) and therefore more effective for testing agro-technical methods. The soil used in a lysimeter trial was a fluvial marsh soil with high clay con-

Table 2
Influence of pH-value and Ca application on Sr (mg kg-1) and Ca concentrations (mg g-1) of the vegetative plant tissue of oats and summer oilseed rape at stem extension

Liming effect pH-level[1]	Oats			Oilseed rape		
	Soil pH	Ca (mg g-1)	Sr (mg kg-1)	Soil pH	Ca (mg g-1)	Sr (mg kg-1)
1	5 .7	12 .4	16 .7	5 .5	29 .7	84 .0
2	6 .2	13 .4	19 .3	6 .1	29 .5	94 .2
3	6 .3	12 .6	16 .4	6 .4	30 .3	88 .4
4	6 .4	12 .4	17 .8	6 .9	29 .8	88 .5
5	6 .5	12 .4	18 .1	7 .1	29 .5	88 .0
6	6 .9	13 .9	19 .1	7 .4	29 .3	89 .9
7	7 .1	11 .9	19 .1	7 .5	29 .6	93 .2
8	7 .2	12 .6	19 .0	7 .6	30 .4	91 .1
9	7 .3	12 .5	20 .0	7 .7	32 .6	90 .2
10	7 .8	12 .6	17 .2	8 .0	29 .8	88 .8
Calcium effect Ca as CaCl2 (mg 100g-1)						
0	5 .6	7 .9	12 .9	6 .0	12 .5	93 .7
50	5 .9	10 .0	13 .2	5 .7	19 .1	97 .3
55	5 .9	12 .2	11 .7	5 .7	23 .3	79 .4
65	5 .5	11 .1	11 .3	5 .6	30 .6	73 .0
85	5 .7	12 .0	10 .9	5 .6	32 .8	62 .0
95	5 .8	15 .4	5 .8	5 .8	36 .8	67 .0
105	5 .4	16 .1	5 .0	5 .4	40 .4	31 .3
110	5 .8	16 .4	5 .6	5 .7	38 .9	48 .6
130	5 .7	17 .2	6 .4	5 .8	42 .2	43 .2
145	5 .6	18 .6	5 .4	5 .7	45 .5	34 .2
LSD 5 % TUKEY-HSD test	0 .2	2 .9	5 .2	0 .2	6 .3	31 .2

[1] lime (CaO) was amended to level soil pH and Ca was balanced as $CaCl_2$ so that equal amounts of Ca were applied

tent of 25% and low pH value of 5.5 (table 1) indicating a high Ca deficit or lime requirement with the pH optimum value being pH 7.0. Increased Ca rates yielded increased Ca contents in the vegetative plant tissue of oats and oilseed rape, while the Ca concentration in the grain of oats was not affected by the treatment (table 3).

The Sr content of the vegetative plant tissue was reduced efficiently in both crops, while the effect on the Sr content of the grain was not significant (table 3).

The calculation of concentration factors (CF) for the Sr transfer from soil to plant requires the determination of plant available Sr contents in the soil and total Sr concentrations in plants on dry weight basis. These CFs are directly comparable with transfer factors for ^{90}Sr (Heine & Wiechen, 1978). CFs may vary widely in dependence on species and treatment. The CF of oilseed rape was 17.1 in the control and 5.9 at the highest Ca supply which is about a third of the original value. For the transfer of Sr into the grain of oats, the highest CF was found in the control with 1.3 and the lowest at pH 7 with 0.5.

The influence of liming on the reduction of Sr concentrations in the vegetative tissue of oats and oilseed rape is shown in figure 1 and compared to the effect of sulphate amendments. Sulphate was applied in rates from 0–66 g lysimeter^{-1} SO_4-S as gypsum and the Ca input was balanced by CaO.

The effect of Ca was always distinctly higher than that of sulphate (table 4). By means of the quotients of the regression coefficients for the Ca and sulphate effect, a Ca:S impact factor of 1:0.3 for reducing Sr concentrations was determined when equivalent amounts of nutrients were applied.

5 Influence of sulphate fertilisation on the Sr uptake of oats and oilseed rape in lysimeter experiments

While Romney et al. (1957) determined an average reduction of the Sr concentrations of 20 %, Andersen (1973) observed no effect by sulphate amendments. The results of the lysimeter trial reveal that even high amounts of sulphate reduced Sr concentrations in oats and oilseed rape only slightly, though significantly (table 4). Grain Sr concentrations were not affected by the sulphate treatment (table 4).

Table 3
Influence of increasing liming rates (g lysimeter^{-1} Ca) on the Sr (mg kg^{-1}) and Ca (mg g^{-1}) content of straw and grain of oats at harvest and of leaf tissue of oilseed rape at stem extension, and plant available Sr contents (mg kg^{-1}) in soil

	Oats						
	Straw		Grain		Soil		
Treatment (g lysimeter^{-1} Ca)	Ca (mg g^{-1})	Sr (mg kg^{-1})	Ca (mg g^{-1})	Sr (mg k^{-1})	Soil pH	Sr (mg kg^{-1})	CFseed/soil
0	7.1	16.5	0.5	7.4	5.5	5.7	1.3
9	8.7	16.4	0.6	7.8	5.8	7.4	1.1
28	9.0	16.0	0.7	7.7	6.3	8.9	0.9
46	8.1	14.3	0.6	7.0	6.7	10.9	0.6
64	9.1	12.9	0.6	6.7	7.0	12.5	0.5
			Oilseed rape				
			Leaves		Soil		
0			25.7	95.7	5.5	5.6	17.1
9			26.9	83.0	6.3	11.4	7.3
28			28.1	78.4	6.2	8.9	8.8
46			27.5	77.6	6.0	8.2	9.5
64			31.5	77.7	6.2	9.6	8.1

[1] Ca supply as CaO; [2] exchangeable Sr content in the soil in the NH_4-acetate extract; [3] CF-concentration factor

No clear effect of the sulphate supply on CF of oats could be determined. Decrease and fluctuation of the CF of oilseed rape is presumably caused by the variation of the exchangeable Sr contents in soil resulting from the Ca balance in the form of lime.

The effects of liming and sulphate fertilisation on Sr concentrations of oats and oilseed rape are compared in figure 1. The results reveal that there was a close relationship between Ca supply/lime rate and Sr contents of oats and oilseed rape. In comparison the sulphate effect was only small.

6 Influence of liming and sulphate fertilisation on Sr uptake of oilseed rape on an acid marsh soil in a field experiment

Field trials allow a bias-free evaluation of the effectiveness of agro-technical methods to reduce the Sr uptake of crops. A marsh soil with high clay content (19 %), but a low soil pH value of 5.3 (table 1) was chosen to test the combined applications of calcium (as lime) and sulphate (as gypsum) in order to reduce the Sr uptake of oilseed rape. The results of this trial are summarised in figure 2.

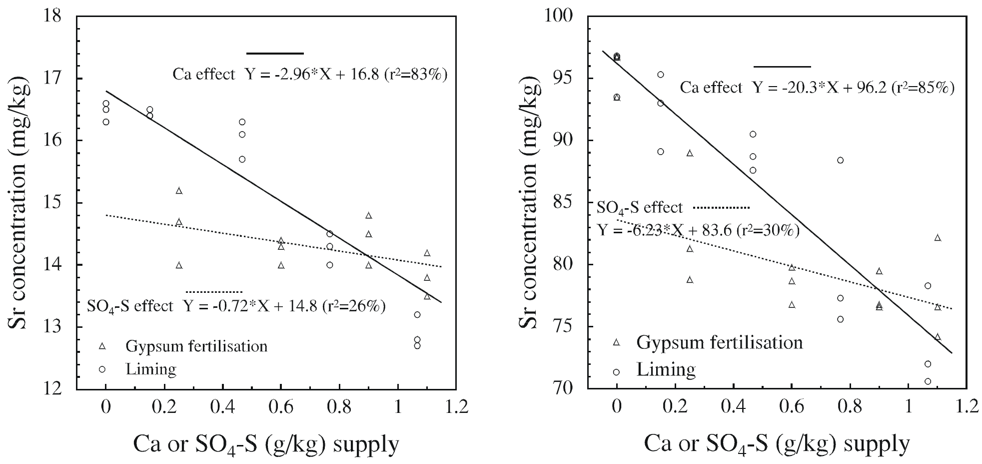

Fig. 1
Left: Relationship between increasing gypsum (g kg^{-1} SO_4-S) and liming (g kg^{-1} Ca) rates and Sr concentrations (mg kg^{-1}) of straw of oats at harvest. Right: Relationship between increasing gypsum (g kg^{-1} SO_4-S) and liming (g kg^{-1} Ca) rates and Sr concentrations (mg kg^{-1}) of younger leaves of oilseed rape at stem extension

Table 4
Influence of increasing sulphate fertilisation as gypsum (g $lysimeter^{-1}$ SO_4-S) on the Sr (mg kg^{-1}) and Ca (mg g^{-1}) concentration of straw and grain of oats at harvest and of leaf tissue of oilseed rape at stem extension and exchangeable Sr contents (mg kg^{-1}) in the soil

	Oats						
	Straw		Grain		Soil		
Treatment (g $lysimeter^{-1}$ SO_4-S)	Ca (mg g^{-1})	Sr (mg kg^{-1})	Ca (mg g^{-1})	Sr (mg kg^{-1})	Soil pH	Sr (mg kg^{-1})	CFseed/soil
0	7.1	16.5	0.5	7.4	5.5	5.7	1.3
15	9.4	14.6	0.5	7.4	6.6	10.4	0.7
36	9.2	14.3	0.7	7.3	6.2	8.7	0.8
54	9.4	14.4	0.8	7.1	5.8	7.1	1.0
66	9.4	13.8	0.9	7.1	5.7	5.4	1.3
			Oilseed rape				
			Leaves			Soil	
0			25.7	95.7	5.5	5.6	17.1
15			26.9	83.0	6.3	11.4	7.3
36			28.1	78.4	6.2	8.9	8.8
54			27.5	77.6	6.0	8.2	9.5
66			31.5	77.7	6.2	9.6	8.1

[1] sulphate supply as gypsum with Ca balance by CaO; [2] exchangeable Sr content in the soil in the NH_4-acetate extract; [3] CF-concentration factor

A distinct reduction of the Sr concentrations of up to 21 % compared to the control was observed, whereby a mixture of lime and gypsum (1.5 + 4.6 t ha^{-1}) yielded best effects, presumably due to the additional immobilising effect of sulphate. About 1t ha^{-1} Ca or 1.4 t ha^{-1} CaO proved to be at least necessary to reduce Sr concentrations significantly.

Comparing pot, lysimeter and field trials, the amounts of Ca needed to induce the same decrease of Sr uptake were: two (for oilseed rape) to threefold (for cereals) higher amounts of Ca in lysimeter than in pot trials and again 1.6-fold (for oilseed rape) higher Ca rates under field conditions.

A comparison of lysimeter and field trials revealed that twice as much sulphate was necessary under field conditions compared to lysimeters in order to achieve the same reduction of the Sr uptake. The lower effectiveness of sulphate compared to Ca is probably due to the fact that sulphate is highly mobile within the soil and anion adsorption is negligable on agricultural production fields (Bloem, 1998).

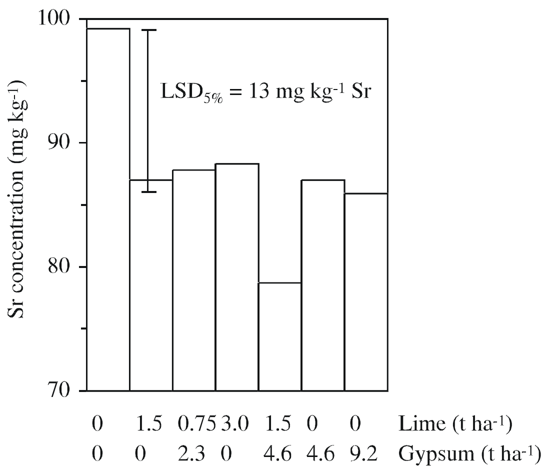

Fig. 2
Influence of combined liming as CaO (kg ha^{-1}) and gypsum (kg ha^{-1}) fertilisation on the Sr concentration (mg kg^{-1}) of younger leaves of oilseed rape at stem extension

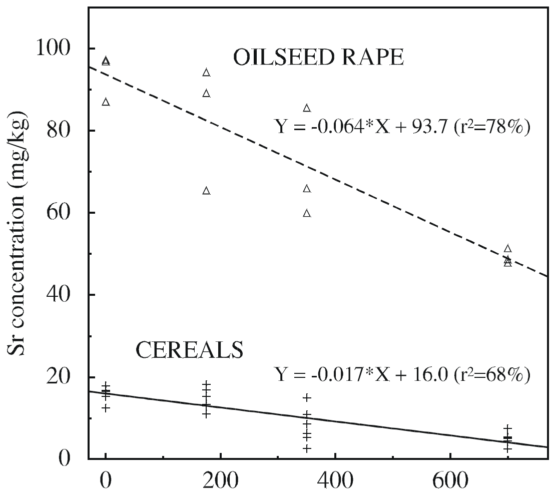

Fig. 3
Relationship between phosphate fertilisation (mg kg^{-1} P) and Sr concentrations (mg kg^{-1}) of younger leaves of oilseed rape and cereals at stem extension

Table 5
Influence of increased phosphate fertilisation (mg kg^{-1} P) on the Sr (mg kg^{-1}), Ca (mg g^{-1}) and P (mg g^{-1}) content of the vegetative plant tissue of oats, wheat and oilseed rape at stem extension

Treatment	Oats			Wheat		
P rate (mg kg^{-1} P)	P (mg g^{-1})	Ca (mg g^{-1})	Sr (mg kg^{-1})	P (mg g^{-1})	Ca (mg g^{-1})	Sr (mg kg^{-1})
0	2.4	12.3	15.9	2.5	9.7	15.7
175	5.7	10.8	13.1	5.6	12.3	16.2
350	7.3	9.4	8.7	8.1	11.9	7.5
700	9.3	10.2	4.4	10.4	11.6	5.6
	Oilseed rape					
0	3.0	32.2	93.8			
175	6.5	30.2	83.0			
350	8.1	30.7	70.5			
700	10.1	30.8	49.3			

Table 6
Influence of increasing Sr supply (g $lysimeter^{-1}$ Sr as $SrCl_2$) on the Sr content (mg kg^{-1}), Sr uptake (mg) and yield (g $lysimeter^{-1}$) of a forage crop (*Dactylis glomerata* L.) in dependence on the depth of mixing

Sr supply (g $lysimeter^{-1}$)	Sr content (mg kg^{-1}) 0-1 cm	Sr content (mg kg^{-1}) 0-30 cm	Relative mixing effect (%) (B/A*100) [1]	Yield (g $lysimeter^{-1}$) 0-1 cm	Yield (g $lysimeter^{-1}$) 0-30 cm	Sr uptake (mg) 0-1 cm	Sr uptake (mg) 0-30 cm
1. Cutting							
0	23.7	23.8	100	162	163	3.8	3.9
0.3	24.1	21.7	89	157	155	3.8	3.4
0.6	26.0	23.9	91	165	159	4.3	3.8
1.5	29.0	24.6	84	166	159	4.8	3.9
3.0	35.8	26.1	73	158	161	5.7	4.2
2. Cutting							
0	38.5	31.2	100	116	130	4.5	4.1
0.3	39..9	27.7	86	112	105	4.5	4.1
0.6	41.4	33.8	100	121	112	5.0	3.8
1.5	47.0	32.4	85	132	119	6.2	3.9
3.0	56.4	34.3	75	112	123	6.3	4.2
3. cutting							
0	45.1	38.7	100	98	98	4.4	3.8
0.3	45.5	36.0	92	91	87	4.1	3.1
0.6	50.9	39.2	89	94	94	4.8	3.7
1.5	55.0	39.3	84	99	102	5.4	4.0
3.0	69.1	41.9	71	101	96	7.0	4.0
4. cutting							
0	50.6	41.1	100	72	68	3.6	2.8
0.3	50.7	36.8	90	65	68	3.3	2.5
0.6	54.8	41.6	94	65	53	3.6	2.2
1.5	61.4	43.2	87	68	72	4.2	3.1
3.0	75.8	43.9	71	71	67	5.4	2.9

[1] A = relative Sr content in 0-1 cm soil depth = 100 %; B = relative Sr content in 0-30 cm soil depth

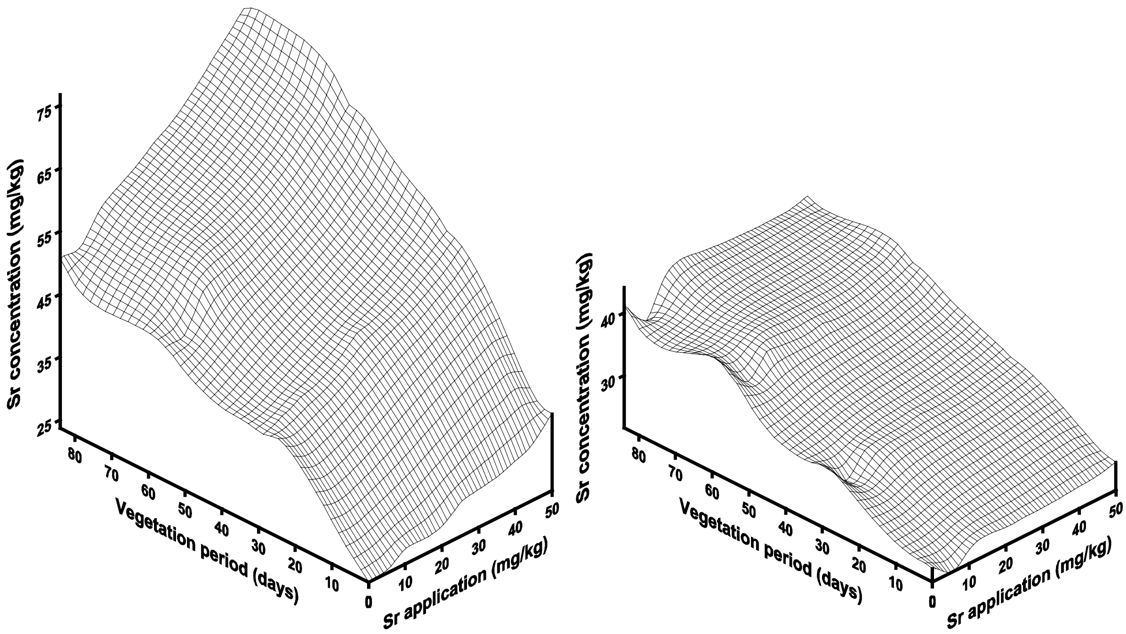

Fig. 4
Left: Influence of the Sr applications (mg kg^{-1} Sr) mixed at 0-1 cm soil depth and harvest date on the Sr content (mg kg^{-1}) of *Dactylis glomerata* L.; Right: Influence of the Sr applications (mg kg^{-1} Sr) mixed at 0-30 cm soil depth and harvest date on the Sr content of *Dactylis glomerata* L.
[1. cutting after 0 days; 2. cutting after 28 days; 3. cutting after 65 days; 4. cutting after 89 days]

7 Influence of phosphate fertilisation on Sr uptake of cereals and oilseed rape in a pot experiment

The immobilisation of Sr as phosphates was proposed as a possibility to reduce Sr uptake of crops through high phosphate input. The influence of increasing phosphate applications as $NH_4(H_2PO_4)$ on the Sr uptake of cereals and oilseed rape is presented in table 5 and figure 3.

The results in table 5 show that phosphate applications resulted in a steep increase in the P contents of the plant tissue. The relative reduction of the Sr concentrations was distinctly higher in cereals than oilseed rape. Compared to the control, the reduction of the Sr contents was 72 % for oats, 64 % for winter wheat and 52 % for oilseed rape at the highest P rate.

The use of a phosphate solution presumably contributed largely to the high efficacy of this measure as Andersen (1973) showed that the magnitude of the effect increased from the application of dissolved phosphate > top dressing of phosphate > mixing of phosphate in the topsoil. Uhler & Hungate (1960) observed a 50 % decrease of the Sr uptake after phosphorus fertilisation. A repressive effect was also determined by Wallace et al. (1974), Andersen (1973) and Yudintseva et al. (1983). The amounts of phosphate applied in the experiment reported here were extremely high with rates corresponding to 440 kg ha^{-1} P for oilseed rape and 280 kg ha^{-1} P for cereals in the field. On production fields much lower application rates (< 50 kg ha^{-1} P) are usually applied. Additionally, as the liming experiments have already revealed even higher rates would be required under field conditions in order to yield similar effects. Although efficient in reducing the ^{90}Sr uptake of plants, high phosphate applications would be an unsuitable measure, from both an economic and ecological point of view.

8 Influence of soil tillage operations on the Sr uptake of a forage crop (*Dactylis glomerata*) in a lysimeter experiment

Mixing of the soil material yields a dilution effect and thus may reduce Sr contents of vegetative plant tissue by up to 50-75 % and that of generative plant parts by up to 20% (Cline & Rickard, 1972; Grzybowska, 1973 and Korneev et al., 1976) so that deep, homogenising soil tillage operations are promising agro-technical methods and preferable to minimum cultivation techniques.

In a lysimeter experiment increasing amounts of Sr were mixed in the topsoil at two different soil depths, 0-1cm and 0-30 cm. The cultivation of a forage crop allowed follow up of the Sr uptake at different harvest dates throughout the vegetation period. The results are shown in table 6 and figure 4.

Mixing of Sr at 0-1 cm soil depth resulted in a steep and significant rise in Sr content within the plant tissue at all harvest dates during the growth period. At the first harvest date the Sr contents increased by 9 % if mixed at 0-1 cm soil depth. Mixing of the Sr at 0-30 cm soil depth reduced the Sr uptake by 34 %. A maximum reduction of the Sr uptake by 25-29 % was achieved through mixing of Sr at a deeper soil depth (0-30 cm).

During the growth period an enrichment of Sr and decline of yield was observed so that the Sr removal remained nearly constant. Increased amounts of Sr only slightly influenced the Sr removal if it was mixed deeply into the soil while a direct positive relationship existed between Sr removal and amount of Sr applied when mixed in the upper soil surface.

The influence of harvest date and Sr application rate on the Sr content of *Dactylis glomerata* L. in dependence on the mixing depth is shown in figure 4. When Sr was mixed at 0-1 cm soil depth, the dominant factor was the number of cuttings, but the amount of Sr applied also had a significant influence on the Sr content of the plant (figure 4, left). When Sr was mixed at 0-30 cm soil depth, the dominant factor on the Sr content was just the number of cuttings (figure 4, right).

The results proved that the depth of soil tillage will have a strong influence on Sr uptake of plants which have an intensive root density in the top soil like *Dactylis glomerata* L. and is therefore a suitable tool to reduce their uptake. The mixing effect will be higher, the more of the root system is in the upper layer of the soil.

9 Conclusions

Particularly long-living radio-nuclides such as ^{90}Sr and ^{137}Cs with a half-life period of 28 and 30 years, respectively are ecologically and radiologically critical as the environmental burden will be persistent over a long period of time. Only the removal of the upper top soil layer may reduce the contaminated soil surface efficiently (Anon, 1994; Menzel & James, 1971; Howorth & Sandalls, 1987) but this procedure is not only time-consuming and costly, but also yields enormous amounts of soil material for disposal and the fertile humus layer of the soil may be removed completely. In comparison, deep, homogenising soil tillage operations reduced the Sr uptake by only up to 29 % (table 6).

The results of the experiments presented here together with already published data reveal that the efficacy of other agro-technical methods to reduce the Sr uptake of agricultural crops is very limited (Howorth & Sandalls, 1987; Ponchet & Metivier, 1994; Anon 1994; Anon, 1999). Generally, the effect of different fertiliser amendments on the Sr contents was low and on an average 7.7 t ha^{-1} S, 2.3 t ha^{-1} P and 6.3 t ha^{-1} Ca are estimated to be necessary in order to reduce the Sr uptake of oilseed rape by 10% under field conditions (Haneklaus, 1989). No significant effect of liming and sulphate fertilisation on the Sr content of grain of cereals under controlled growth conditions in lysimeters was observed (Haneklaus, 1989).

Strong differences exist in the Sr uptake between monocotyledonous and dicotyledonous crops as well as vegetative and generative plant parts which ought to be considered when grown on contaminated soils (Andersen, 1973; Bollard & Butler, 1966; Haneklaus, 1989; Menzel, 1965; Montford et al., 1980; Vetter & Haraszti, 1981; Wirth, 1980).

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References

Abazov M, Dergunov I D and Mikulin R (1978) Effect of soil properties on the accumulation of Sr-90 and Cs-137 in crops. Soviet Soil Sci 10: 52-56

Ananyan V L and Sarkisyan G A (1976) Uptake of radioactive Sr, calcium and potassium by some types and groups of herbaceous plants of Armenia. Biol Zh Arm 292: 77-82

Andersen A J (1963) Influence of liming and mineral fertilization on plant uptake of radiostrontium from danish soils. Soil Sci 96: 52-59

Andersen A J (1967a) Investigations on the plant uptake of fission products from contaminated soils I. Influence of plant species and soil types on the uptake of radioactive strontium and caesium. Risoe Report 170

Andersen A J (1967b) Investigations on the plant uptake of fission products from contaminated soils II. The uptake of radioactive strontium placed at different depths in the soils. Risoe Report 174

Andersen A J (1973) Plant accumulation of radioactive strontium with special reference to the strontium-calcium relationship as influenced by nitrogen. Risoe Report 278

Andersson K G (1996) Evaluation of early phase nuclear accident clean-up procedures for nordic residential areas. NKS/EKO 5(96): 18

Anon (1994) Guidelines for agricultural countermeasures following an accidental release of radionuclides. IAEA, Vienna

Anon (1999) Uebersicht über Maßnahmen zur Verringerung der Strahlenexposition nach Ereignissen mit nicht unerheblichen radiologischen Auswirkungen (Maßnahmenkatalog). Bonn, Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit, Oktober 1999

Bloem E (1998) Schwefel-Bilanz von Agrarökosystemen unter besonderer Berücksichtigung hydrologischer und bodenphysikalischer Standorteigenschaften. Landbauforsch Voelkenrode SH 192 [Dissertation]

Bollard E G, Butle G W (1966) Mineral nutrition of plants. Ann Rev Plant Physiol 17: 76-112

Browman M G, Spalding B P (1984) Reduction of radiostrontium mobility in acid soils by carbonate treatment. J. Environm Quality 13 (1): 166-172

Cline J F, Rickard W H (1972) Radioactive strontium and caesium in cultivated and abandonned field plots. Health Phys. 23: 317-324

Frederiksson A, Eriksson E, Haak E (1970) Plant uptake of fission products: II. Uptake of 90Sr by Trifolium as influenced by the calcium and phosphate status in the soil. Landbrukhgskolans Ann. 36: 19-39

Fuller W H, Hardcastle J E, Hannapel R J (1966) Calcium-45 and strontium-89 movements in soils and uptake by barley plants as affected by $Ca(Ac)_2$ and $Sr(Ac)_2$ treatment of the soil. Soil Sci 101: 472-484

Gulyakin I V, Yudintseva E V, Levina E M (1976) Effect of soil moisture on uptake of strontium-90 and caesium-137 by plants. Agrokhimiya 2: 102-107

Grzybowska D (1973) Uptake of 90Sr and 137Cs by plants from contaminated soils. Nukleonika. 17: 331-340

Haak E, Lnsj H (1975) Studies on plant accumulation of fission products under swedish conditions: XVI. Uptake of ^{90}Sr by barley and peas from 12 different soils combined with 2 subsoils in a long term microplot experiment. Rep 30 Uppsala 1975. ISBN 91-7088-416-1

Haghiri F (1974) Decontamination of surface soil containing strontium-90. Agronomy J. 66: 330-331

Haghiri F, Himes F L (1974) Removal of radiostrontium by leaching, runoff, and plant uptake as influenced by soil and crop management practices. Ohio Agric Res and Development Centre, Res. Bull. 1072.

Haghiri F, Sayre J D (1961) Sr-90 uptake by plants as influenced by soil types and liming. Soil Sci Soc Am Proc 25: 120-123

Haneklaus S (1989) Strontiumgehalte in Pflanzen und Böden Schleswig-Holsteins und Bewertung von Düngungsmaßnahmen zur Verminderung der Strontiumaufnahme von Kulturpflanzen. PhD, University Kiel, Germany

Haneklaus S, Schnug E (2000) Spatial variability of soil acidity and its impact on production technology. Proc Int Sci Conf Soil Acidification and Liming: Fundamental and Technological Researches. Klaipeda (Lithuania): 67-73. ISBN 9986-527-66-X

Heine K, Wiechen A (1978) Determination of concentration factors of elements in the food chain soil-plant-milk. Milchwissenschaft 33: 230-232

Howorth J M, Sandalls F J (1987) Decontamination and reclamation of agricultural land following a nuclear accident: a literature review. AERE – R 12666

Kampe W (1986) Auswirkungen radioaktiver Stoffe auf landwirtschaftliche Produktion und Nahrungsqualität. Obstbau 11 (19): 442-443

Klechkovskiiv M, Fedorov E A, Arkhipov N P, Romanov G N, Aleksakhin R M (1973) Trends in the uptake of radioactive strontium by crop plants from the soil and foliar application. Pochvovedenie 5: 38-47

Korneev N A, Korneeva N Y, Popova T P (1976) Accumulation of strontium-90 in forage crops when radionuclide was incorporated into the ploughed layer of the soil and below it. Doklady Vaskhnil. 2: 26-27

Korneeva N Y, Korneev N A, Aleksakhin R M (1976) Effect of deep incorporation of ^{90}Sr into the soil and species and cultivars of spring wheat on accumulation of ^{90}Sr in grain. Agrokhimiya. 3: 102-110

Martin W E, Turner F B (1966) Transfer of ^{89}Sr from plants to rabbits in a fallout field. Health Phys 12: 621-631

Menzel R G (1965) Soil-plant relationships of radioactive elements. Health Phys 11: 1325-1332

Menzel R G, James P E (1971) Treatments for farmland contaminated with radioactive material. Agricultural Handbook No 395, Washington

Mistry K B, Bhjubal B M (1973) Effect of calcium and organic matter additions on the uptake of radiostrontium and radium by plants from Indian soils. Agrichimica 18 (1/2): 173-183

Montford M A, Shank K E, Hendricks C, Oakes T W (1980) Concentrations of stable elements in food products. CONF-8000643-1

Šnie N H, Hull C H, Jenkins J G, Steinbrenner K, Bent D H (1975) SPSS-Statistical package for the social sciences. 2nd edition. Mc Graw-Hill. New York

Nishita H, Steen A J, Larson K H (1958) Release of Sr-90 and Cs-137 from vina loam upon prolonged cropping. Soil Sci 86: 195-201

Nishita H, Wallace A, Romney E M (1978) Radionuclide uptake by plants. US Nucl Reg Com/CR-0336. UCLA 12: 1158

Ponchet M, Metivier H (1994) Agriculture, environment et nucleaire: comment réagir en cas d'accident. Institut de protection et de surete nucleaire FNSEA – CNIEL. IPSN – Mission Communication, Fontenay, France

Rink K, Sauer, R (1986) Radioaktivitaetsmessungen nach dem Reaktorunfall von Tscherenobyl. Kali-Briefe (Buentehof). 18 (5): 397-412

Romney E M, Neel J W, Nishita H, Olafson J H, Larson, K H (1957) Plant uptake of Sr-90, Y-91, Ru-106, Cs-137 and Ce-144 from soils. Soil Sci 83: 369-376

Schlichting E, Blume H P (1966) Bodenkundliches Praktikum. Berlin/Hamburg, Parey 209 p

Schnug E, Haneklaus S (1999) Diagnosis of the nutritional status and quality assessment of oilseed rape by X-ray spectroscopy. [CD-ROM] Proc. 10th Int Rapeseed Congress, Sept 26-29 1999 Canberra pp 67 - 73

Schroeder D, von Reichenbach H, von dem Bussche-Huennefeld, G (1962) The dependence of Sr sorption by soils on pH. Naturwissenschaften 49: 137-138

Spalding B P (1980) Adsorption of radiostrontium by soil treated with alkali metal hydroxides. Soil Sci Am. J, 44: 703-709

Steffens W, Fuehr F, Mittelstaedt W, Klaes J, Foerstel, H (1988) Untersuchungen des Transfers von ^{90}Sr, ^{137}Cs, ^{60}Co, und ^{54}Mn vom Boden in die Pflanze und der wichtigsten, den Transfer beeinflussenden Bodenparameter. Berichte der Kernforschungsanlage Jülich ISSN 0366-0885

Szabo A S (1980) Investigation of the Cs-137 and Sr-90 uptake from the soil of maize, wheat and beans. Radiochem. Radioanal Lett 38: 283-288

Szabo A, Bende E, Kovacs A (1977) Study on caesium and Sr uptake of maize. wheat and bean. Agrokemia es Talajtan. 26 (1/2): 55-62

Uhler R L, Hungate P (1960) Relative availability of some Sr-90 compounds in soil. Nature 187: 252-253

Vetter J, Haraszti E (1981) Strontium and caesium content of certain fodder plants. Botanikai Kozlemeneyk 68 (3/4): 205-212

Wallace A, Elgazzar A, Cha J W, Alexander G V (1974) Phosphorus levels versus concentrations of zinc and other elements in bush bean plants. Soil Sci 117 (6): 347-351

Wirth E (1980) Literaturstudie zur Problematik des Transfers langlebiger Radionuklide aus dem Boden in die Pflanze. S T H Berichte 1980,1

Yudintseva E V, Zhigareva T L, Pavlenko L I (1983) Forms of ^{90}Sr and ^{137}Cs in a limed and fertilized sod-podzolic soil. Soviet Soil Sci 15 (5): 84-90