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ORIGINAL PAPER

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Soil-to-grain transfer of fallout ^{90}Sr for 28 winter wheat cultivars

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Abstract In order to identify wheat cultivars with minimum soil-to-grain transfer of fallout ^{90}Sr, 28 winter wheat cultivars were investigated at three different sites with different soil types in Upper Bavaria. Each cultivar was grown on an area of 10 m^2 and harvested in August 1999. Mean soil-to-grain concentration ratios (C_r) were 0.151 ± 0.029, 0.205 ± 0.035 and 0.060 ± 0.012, respectively. The C_r values obtained varied by factors of up to 2.6 for the different cultivars at a given site, and by factors of up to 5.0 for the different sites and a given cultivar. Site-averaged normalized concentration ratios (SANC$_r$) ranged from 0.666 ± 0.062 to 1.503 ± 0.161. The cultivars Convent, Ludwig, and Semper, showed the lowest uptake of ^{90}Sr compared to the mean of all cultivars at each site. A cultivar that shows both minimum uptake of ^{90}Sr and ^{137}Cs could not be identified. The results suggest that ^{90}Sr rather than ^{137}Cs might be the limiting radionuclide concerning the use of contaminated land for wheat production. Thus, more efforts might be necessary identifying wheat cultivars with minimum ^{90}Sr uptake.

Introduction

The input of fission products into the atmosphere reached its maximum in 1962, due to fusion bomb tests performed by the USSR at Novaya Zemlya and the USA at Johnston and Christmas Island [1]. Concerning the radiological impact, ^{90}Sr was one of the most important fallout radionuclides, due to its long half-life, the high-energy beta radiation of its daughter ^{90}Y, its similar behaviour to calcium in the food chain, and its long-term accumulation in the human body. Aiming at minimization of the internal dose after ingestions via the food chain, research was therefore initiated to identify crop species with low uptake of ^{90}Sr. As a consequence of the Chernobyl accident in 1986, large areas in the former Soviet Union were contaminated with high activities of ^{137}Cs and ^{90}Sr, which made agricultural use impossible. The Chernobyl accident revived the need and interest in research on crops with low ^{137}Cs and ^{90}Sr uptake. In 2005, 444 nuclear power plants in 31 countries with an aggregate electrical power of 370 GW$_e$ were in operation, four new reactors went into operation, and 23 new power plants in ten countries were under construction [2]. With respect to the growing importance of nuclear energy [3–5], concepts for the management of contaminated landscapes are required. Different strategies for countermeasures that would allow food production on contaminated areas have been summarized recently by Howard and co-workers within the STRATEGY project [6]. Twenty-nine agricultural countermeasures were selected after critically reviewing of the literature. The cultivation of certain species of crops was not recommended, however, because the authors felt that the available data were not sufficient to allow for an appropriate crop cultivar selection. However, the uptake of ^{90}Sr and ^{137}Cs by different varieties of crops should be studied in more detail because 'the proper selection of plant varieties is one of the simplest, most effective, and least expensive measures in reducing the contamination of agricultural products' [7]. Especially when other cultivars of a crop type are used that already had been cultivated in a certain area prior to a nuclear accident, social and economic consequences could be reduced significantly compared to the application of most other types of countermeasures.

Wheat is one of the most important foodstuff. For this reason, its uptake of ^{90}Sr and ^{137}Cs has already been studied in the 1950s (e.g. [8]). Recently, our group

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published the results of a study on the soil-to-plant transfer of fallout ^{137}Cs in 28 winter wheat cultivars, each of them grown in 1999 at three different locations in Upper Bavaria, Germany [9]. In this study it was shown that the concentration ratio C_r (Eq. 1) of ^{137}Cs depends primarily on the sites where the wheat was grown, which can be explained by locally different soil characteristics.

$$C_r = \frac{a_{grain}}{a_{soil}} \quad (1)$$

where C_r is the concentration ratio for a given wheat cultivar, and a_{grain} and a_{soil} are the activity concentrations in grain and soil, both given on a dry-mass basis.

The obtained mean C_r values were 0.00049 ± 0.00016 in Gereuth, 0.00075 ± 0.00009 in Pettenbrunn, and 0.00042 ± 0.00008 in Pulling, respectively. The maximum-to-minimum ratio (MMR) of the C_r for ^{137}Cs was 3.1, 1.5 and 2.2 at the three sites, respectively. For a better comparison of the cultivars normalized soil-to-grain ratios NC_r's (Eq. 2) and site-averaged normalized soil-to-grain ratios site-averaged normalized concentration ratios ($SANC_r$'s) (Eq. 3) were calculated, to eliminate the influence of the different local soil characteristics.

$$NC_r = \frac{C_r}{\overline{C}_r} = n \frac{a_{grain}}{\sum_{i=1}^{n} a_{grain,i}} \quad (2)$$

where NC_r is the normalized soil-to-grain ratio for a given wheat cultivar i at a site and n the total number of cultivars

$$SANC_r = \frac{1}{3} \sum_{j=1}^{3} NC_{r,j} \quad (3)$$

where $SANC_r$ is the site-averaged normalized soil-to-grain ratio for a given wheat cultivar, and j is the index of the site.

The cultivars Flair ($SANC_r$ = 0.74 ± 0.13), Kornett (0.76 ± 0.14), and Previa (0.79 ± 0.08), were found to show $SANC_r$ values significantly lower than the mean $SANC_r$ of all cultivars. In other words, these species showed a smaller uptake of ^{137}Cs than the other cultivars.

Apart from ^{137}Cs, the strontium isotope ^{90}Sr is the radionuclide of major importance to the radiological long-term hazard of fallout from nuclear accidents, as was pointed out for example by Mück [10]. Therefore, the aim of this work was to determine the soil-to-grain-transfer of ^{90}Sr in the 28 wheat cultivars from the three sites in Bavaria that were described above, and to identify cultivars with significantly lower uptake of ^{90}Sr compared to other winter wheat cultivars. Concerning their possible practical application in food production on contaminated farmland, cultivars with both minimum uptake of ^{90}Sr and of ^{137}Cs would be ideal.

Materials and methods

Details of the sampling strategy and location, soil properties, grain yields and the determination of ^{137}Cs have already been described elsewhere [9]. Briefly, the sampling locations were near the villages Gereuth, Pettenbrunn, and Pulling, which are located within a radius of about 10 km around the city of Freising (Upper Bavaria, Germany). Selected soil parameters of the sampling locations are given in Table 1. As can be seen from Table 1 the soils were well supplied with nutrients [11]. About 1 kg of grains were air-dried, cleaned, sieved, and ashed at a temperature of 400°C. Soil samples (about 2 kg) were dried and sieved (2 mm), four sub-samples of 50 g were used for ^{90}Sr analysis. ^{137}Cs and ^{40}K were determined by gamma spectrometry. After these measurements the samples were ashed at 550°C and leached with 65% nitric acid. ^{90}Y was extracted with tributyl phosphate (TBP) and purified by hydroxide and oxalate precipitation and, if necessary, by the removal of thorium isotopes by means of anion exchange chromatography. Finally, ^{90}Y was determined by proportional or Cherenkov counting. The radiochemical purity of the counting samples was assured by controlling the ^{90}Y decay curves. The chemical yield of Y, determined gravimetrically and by complexometric titration with ethylenediamine tetraacetic acid (EDTA), was in the range of 90%. Minimum detectable activities (MDAs) were calculated according to [12]. Typical MDA's were in the range of 7–12 mBq per sample. Quality assurance was done by participating national round-robin tests.

Table 1 Selected soil parameters of the Ap horizons in Gereuth, Pettenbrunn and Pulling [9]

Site	Gereuth	Pettenbrunn	Pulling
Soil type	Kolluvisol	Parabrownearth	Pararendzina
Soil texture	Silty loam	Silty loam	Clayey loam
pH	6.7 ± 0.1	6.1 ± 0.1	7.3 ± 0.1
Clay (%)	25 ± 1	20 ± 1	43 ± 1
Silt (%)	47 ± 1	59 ± 1	50 ± 1
Sand (%)	28 ± 1	21 ± 1	7 ± 1
K^+ ($mMol_c\ kg^{-1}$)	6.5 ± 0.5	7.5 ± 1.1	4.8 ± 0.3
Mg^{2+} ($mMol_c\ kg^{-1}$)	26.5 ± 0.4	9.7 ± 0.2	43.2 ± 2.0
Ca^{2+} ($mMol_c\ kg^{-1}$)	138 ± 3	79 ± 4	322 ± 4
K_2O ($mg\ kg^{-1}$)	250 ± 10	210 ± 10	120 ± 10
P_2O_5 ($mg\ kg^{-1}$)	250 ± 10	80 ± 10	190 ± 10

Calibrations were performed with certified reference standard solutions purchased from the physikalisch–technische bundesanstalt (PTB), Braunschweig, Germany. Details of the radiochemical procedure are described in [13]. Statistical data analysis was performed with the software package STATISTICA 7.1 (Statsoft, Tulsa, USA, 2005)

Results

Table 2 shows the ^{90}Sr and ^{137}Cs activity concentrations and the $^{137}Cs/^{90}Sr$ activity ratios of the Ap soil horizons at the three locations. The ^{90}Sr activity concentrations range from 1.08 to 2.06 Bq kg^{-1}, which corresponds to 314–514 Bq m^{-2}. The corresponding $^{137}Cs/^{90}Sr$ activity ratios range from 14 to 20 which are typical values for the region near Munich. The small standard deviations of the ^{90}Sr concentrations in the soil indicate a small spatial variability of the local ^{90}Sr fallout at the study sites, as was also found for ^{137}Cs [9]. Table 3 shows the ^{90}Sr activity concentrations of the wheat grains. For better comparability with literature data, Table 3 also includes the corresponding mean Tag values (Bq kg^{-1} grain/Bq m^{-2} soil) which are often used in the Russian literature. Mean ^{90}Sr activity concentrations in the grains were 0.163, 0.286 and 0.123 Bq kg^{-1}, respectively (for Gereuth–Pettenbrunn–Pulling; unless otherwise stated, all following data on the three experimental sites will be reported in this order). For all sites the ^{90}Sr activity concentrations were log-normal distributed (Shapiro–Wilkinson). There was no correlation found between the grain yields and the ^{90}Sr activity concentrations in the grains, at any site. Based on the data shown in Tables 2 and 3, concentration ratios C_r (Eq. 1) for each variety at each site, and their MMR were calculated (s. Table 4). Mean C_r were 0.151 ± 0.029, 0.205 ± 0.035 and 0.060 ± 0.012, respectively. As shown by the MMR, the C_r for a given cultivar varied by a factor from 2.46 to 5.00 between the sites. The C_r values between the cultivars at a given site varied by factors of 2.57, 1.89 and 2.48, respectively.

In order to eliminate the site-specific influences on the uptake of ^{90}Sr, for each cultivar NC_r values (Eq. 2) were calculated for each site, as well as the corresponding $SANC_r$ values (Eq. 3). The resulting NC_r and $SANC_r$ values are shown in Figs. 1 and 2, for all cultivars. In Fig. 2, the culivars were sorted by increasing $SANC_r$ values, which ranged from 0.6656 ± 0.0617 to 1.5027 ± 0.1610.

Table 2 ^{90}Sr and ^{137}Cs [9] activity concentrations (±combined standard uncertainty) and $^{137}Cs/^{90}Sr$ activity ratios (±1 standard deviation) in the investigated Ap soil horizons

	Gereuth	Pettenbrunn	Pulling
^{90}Sr (Bq kg^{-1})	1.08 ± 0.07	1.40 ± 0.11	2.06 ± 0.14
^{90}Sr (Bq m^{-2})	314 ± 23	514 ± 42	409 ± 30
^{137}Cs (Bq kg^{-1})	20.1 ± 1.1	27.9 ± 1.6	29.4 ± 1.3
^{137}Cs (Bq m^{-2})	5,800 ± 300	10,300 ± 600	5,800 ± 300
$^{137}Cs/^{90}Sr$	18.6 ± 1.6	20.0 ± 1.9	14.2 ± 1.1

Discussion

The C_r values for ^{90}Sr obtained in the present work agree very well with the mean recommended value of 0.15 given in [14, 15] for the soil-to-grain transfer of cereals grown on loamy soils, and with the corresponding mean concentration ratios (identical with transfer factors) recently published by the German Federal Ministry for Environment, Nature Conservation and Nuclear Safety (BMU) [16]. From Table 4 it becomes obvious that the uptake of ^{90}Sr by wheat grains mainly depends on the site characteristics, and to a lesser degree on the wheat cultivars. The mean C_r values for ^{90}Sr are clearly but negatively associated with the Ca^{2+} content in the soil (Table 1). Although it was often observed that the uptake of strontium by crops is suppressed by calcium [17], an evaluation of a big pool of

Table 3 Activity concentrations (Bq kg^{-1} dry mass) of ^{90}Sr (±combined standard uncertainty) in wheat grains

Cultivar	Gereuth	Pettenbrunn	Pulling
Aristos	0.172 ± 0.010	0.293 ± 0.013	0.126 ± 0.006
Asketis	0.155 ± 0.007	0.266 ± 0.015	0.122 ± 0.008
Aspirant	0.128 ± 0.010	0.236 ± 0.010	0.126 ± 0.006
Astron	0.163 ± 0.011	0.326 ± 0.015	0.125 ± 0.006
Atlantis	0.256 ± 0.016	0.377 ± 0.029	0.199 ± 0.015
Batis	0.196 ± 0.009	0.358 ± 0.016	0.142 ± 0.006
Borneo	0.165 ± 0.011	0.297 ± 0.019	0.141 ± 0.009
Caesar	0.156 ± 0.009	0.286 ± 0.013	0.106 ± 0.005
Certo	0.163 ± 0.009	0.240 ± 0.013	0.097 ± 0.007
Classic	0.201 ± 0.013	0.374 ± 0.023	0.153 ± 0.007
Contra	0.147 ± 0.007	0.200 ± 0.009	0.120 ± 0.006
Contur	0.153 ± 0.007	0.257 ± 0.012	0.114 ± 0.005
Convent	0.100 ± 0.007	0.210 ± 0.010	0.080 ± 0.004
Dream	0.148 ± 0.009	0.350 ± 0.019	0.136 ± 0.010
Drifter	0.170 ± 0.011	0.321 ± 0.014	0.154 ± 0.010
Flair	0.173 ± 0.011	0.296 ± 0.013	0.128 ± 0.009
Glockner	0.166 ± 0.008	0.339 ± 0.015	0.102 ± 0.005
Habicht	0.112 ± 0.005	0.293 ± 0.013	0.092 ± 0.005
Hybnos	0.142 ± 0.008	0.274 ± 0.012	0.128 ± 0.008
Kornett	0.220 ± 0.010	0.299 ± 0.014	0.138 ± 0.006
Ludwig	0.140 ± 0.006	0.250 ± 0.011	0.092 ± 0.007
Mewa	0.176 ± 0.008	0.308 ± 0.017	0.091 ± 0.005
Olivin	0.152 ± 0.009	0.245 ± 0.011	
Petrus	0.169 ± 0.008	0.282 ± 0.013	0.148 ± 0.010
Previa	0.171 ± 0.008	0.321 ± 0.020	0.127 ± 0.006
Semper	0.128 ± 0.008	0.232 ± 0.014	0.105 ± 0.007
Tambor	0.169 ± 0.008	0.236 ± 0.019	0.118 ± 0.006
Toni	0.165 ± 0.011	0.243 ± 0.011	0.113 ± 0.005
Mean	0.163	0.286	0.123
Median	0.164	0.289	0.125
Standard deviation	0.031	0.048	0.034
Minimum	0.100	0.200	0.080
Maximum	0.256	0.377	0.199
Coefficient of variation	19.0	16.9	20.2

data by the BMU revealed a significant negative correlation only for sandy, but not for loamy soils [16].

As mentioned above, research on the uptake of ^{90}Sr by different wheat cultivars was already initiated decades ago. However, results reported in the literature are difficult to compare, due to inconsistent data presentation or different experimental conditions. For example, it was shown recently that the mean transfer factors for radiocaesium and radiostrontium strongly depend on the experimental setups (Table 5) [16]. However, in most cases it was possible to calculate MMR values of different cultivars of wheat grown up under identical conditions. As shown in Table 6, MMR values of different wheat cultivars vary by factors between about 1.6 and 4.2. The MMR values presented in this work for the three sites (2.57, 1.89 and 2.48) agree very well with data already published in the literature. The observed variability of ^{90}Sr uptake by wheat is in the same range as the variability between different types of cereals. This has to be taken into account when comparing the uptake of these radionuclides by different types of crops. In 1965, Lee and Sosulski [18] already concluded that 'the validation of determining differences between crops on the basis of single varieties to represent each crop may be questionable'. Malikov and co-workers [19] found an MMR value of 2.0, while Green and co-workers [20] found MMR values of 3–4 and pointed out that these factors are comparable to the differences of the same cultivar in different years. Unfortunately, Green's data only refer to cereals as a group, including wheat, barley and oats.

Putyatin and co-workers [21] compared the uptake of ^{137}Cs and ^{90}Sr in six cultivars of spring wheat. They identified cultivars with significantly lower uptake and reported MMR values to be 1.6 for both radionuclides. A short summary of the variability of the uptake of ^{90}Sr by wheat grains is given in Table 7. These data again support Green's statement that the MMR of different cereals in one year are in the same range as the MMR of the same cultivar in different years. Thus, more effort has to be done to quantify this variation, in order to identify suitable wheat cultivars for mid- and long-term application.

With respect to the reduction of internal doses due to the uptake of ^{137}Cs and ^{90}Sr it would be desirable to identify wheat cultivars with minimum uptake of both ^{90}Sr and ^{137}Cs. Table 8 compares the $SANC_r$ for ^{90}Sr obtained in this work with those for ^{137}Cs reported in [9], for each cultivar. Some cultivars showed $SANC_r$ values significantly lower than one for ^{90}Sr, others for ^{137}Cs. However, none of the investigated cultivars showed both a significantly lower uptake of ^{90}Sr as well as of ^{137}Cs. In Fig. 3, the $SANC_r$ values for ^{90}Sr as determined in this work are plotted against those for ^{137}Cs [9]. In addition we also calculated normalized concentration ratios based on the data published by Malikov and co-workers (Table 3 in [19]) and by Putyatin and co-workers (Table 1 in [21]). These are the only publications known to us which deal with the variety of both ^{90}Sr and ^{137}Cs in different wheat cultivars. Figure 3 supports the hypothesis that there is no correlation between the uptake of ^{137}Cs and ^{90}Sr by wheat grains. This missing correlation is expected because ^{90}Sr, an earth alkali metal, and ^{137}Cs, an alkali metal, show different properties, as far as their fixation to soil particles and the mechanisms governing plant uptake are concerned. Since the uptake of ^{90}Sr and ^{137}Cs is shown to be independent parameters, it should be possible to optimize (decrease) them both by specific breeding. Putyatin and co-workers identified a certain cultivar (Quattro) which had a 'significantly' lower uptake of ^{90}Sr as well as ^{137}Cs. This cultivar also fits our criterion ($SANC_r$ value +1 standard deviation $\leq$ 0.9) for 'significantly lower' uptake. However, by considering all available data shown in Fig. 3 this appears to be a fortunate coincidence.

Table 4 Concentration ratios C_r (Bq kg^{-1} dry mass/Bq kg^{-1} Ap soil horizon) of ^{90}Sr (±combined standard uncertainty) in wheat grain and MMR between the C_r of the three sites

Cultivar	Gereuth	Pettenbrunn	Pulling
Aristos	0.159 ± 0.013	0.210 ± 0.018	0.061 ± 0.005
Asketis	0.144 ± 0.011	0.190 ± 0.018	0.059 ± 0.005
Aspirant	0.118 ± 0.012	0.169 ± 0.015	0.061 ± 0.005
Astron	0.151 ± 0.014	0.233 ± 0.020	0.061 ± 0.005
Atlantis	0.237 ± 0.021	0.270 ± 0.029	0.097 ± 0.010
Batis	0.182 ± 0.014	0.256 ± 0.022	0.069 ± 0.005
Borneo	0.152 ± 0.014	0.213 ± 0.021	0.068 ± 0.006
Caesar	0.145 ± 0.012	0.204 ± 0.018	0.051 ± 0.004
Certo	0.151 ± 0.013	0.172 ± 0.016	0.047 ± 0.004
Classic	0.186 ± 0.016	0.268 ± 0.026	0.074 ± 0.006
Contra	0.136 ± 0.011	0.143 ± 0.013	0.058 ± 0.005
Contur	0.142 ± 0.011	0.183 ± 0.016	0.055 ± 0.004
Convent	0.092 ± 0.008	0.150 ± 0.013	0.039 ± 0.003
Dream	0.137 ± 0.012	0.251 ± 0.023	0.066 ± 0.007
Drifter	0.157 ± 0.014	0.230 ± 0.020	0.075 ± 0.007
Flair	0.160 ± 0.015	0.211 ± 0.018	0.062 ± 0.006
Glockner	0.154 ± 0.012	0.243 ± 0.021	0.049 ± 0.004
Habicht	0.103 ± 0.008	0.209 ± 0.018	0.045 ± 0.004
Hybnos	0.131 ± 0.011	0.196 ± 0.017	0.062 ± 0.006
Kornett	0.203 ± 0.016	0.214 ± 0.019	0.067 ± 0.005
Ludwig	0.129 ± 0.010	0.179 ± 0.016	0.045 ± 0.004
Mewa	0.163 ± 0.013	0.220 ± 0.020	0.044 ± 0.004
Olivin	0.141 ± 0.012	0.175 ± 0.015	
Petrus	0.157 ± 0.012	0.202 ± 0.017	0.072 ± 0.007
Previa	0.158 ± 0.012	0.230 ± 0.022	0.062 ± 0.005
Semper	0.119 ± 0.010	0.166 ± 0.016	0.051 ± 0.005
Tambor	0.156 ± 0.012	0.169 ± 0.019	0.057 ± 0.005
Toni	0.153 ± 0.014	0.174 ± 0.015	0.055 ± 0.004
Mean	0.151	0.205	0.060
Median	0.152	0.207	0.061
Standard deviation	0.029	0.035	0.012
Minimum	0.092	0.143	0.039
Maximum	0.237	0.270	0.097
MMR	2.57	1.89	2.48

Conclusion

It was shown that ^{90}Sr is accumulated in grains of wheat with a mean C_r value of 0.14, varying by factors up to 2.6 from cultivar to cultivar at a given site, and by fac-

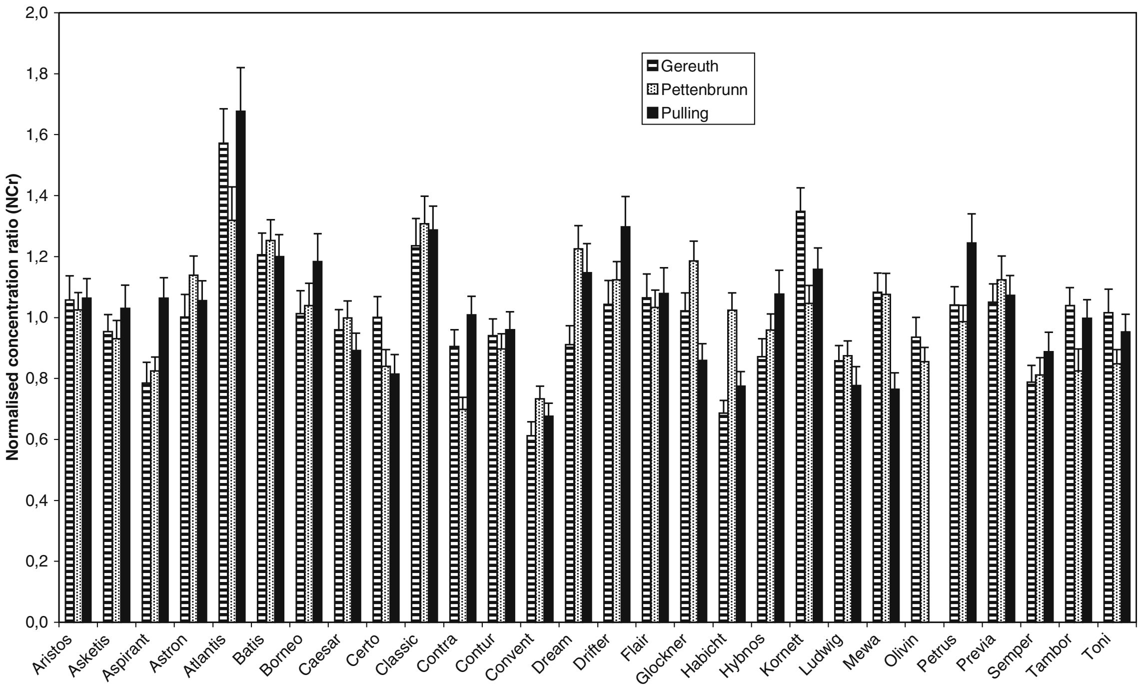

Fig. 1 Normalized concentration ratios (NC_r) for the soil-to-grain-transfer of ^{90}Sr in Gereuth, Pettenbrunn and Pulling

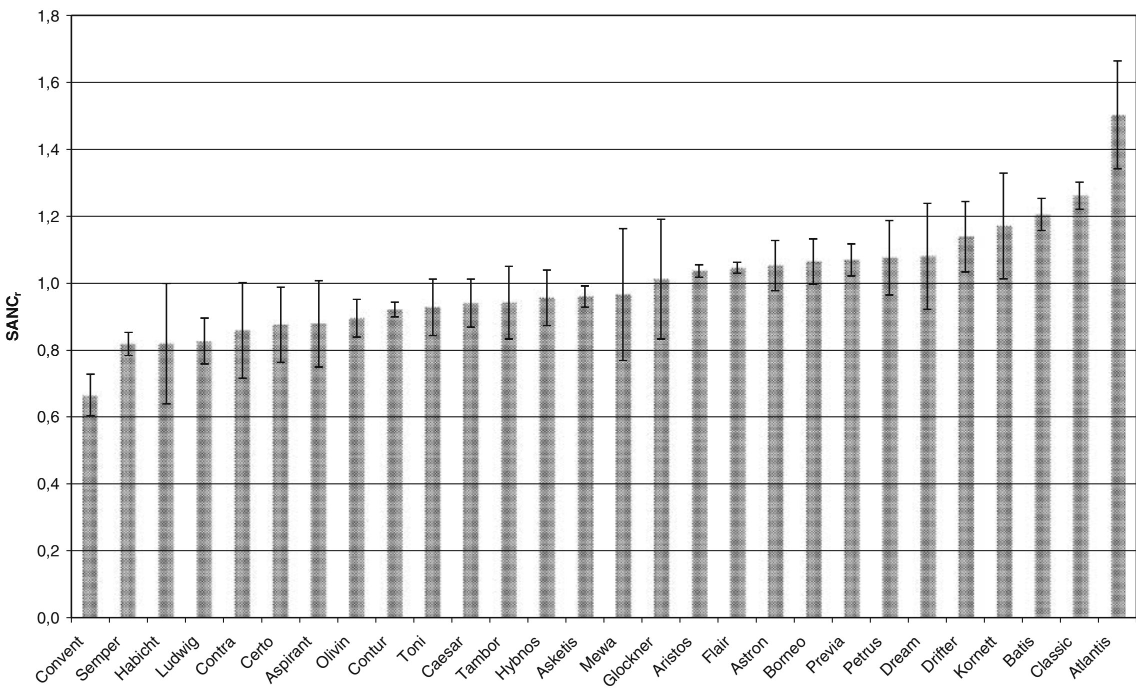

Fig. 2 Site averaged normalized concentration ratios ($SANC_r$) for the soil-to-grain-transfer of ^{90}Sr in Gereuth, Pettenbrunn and Pulling

tors up to 5.0 for a given cultivar from site to site. No correlation could be found between the uptake of ^{137}Cs and ^{90}Sr. Thus, when cultivating wheat cultivars at highly contaminated sites, a decision might be required on the selection of cultivars with minimum ^{90}Sr uptake or minimum ^{137}Cs uptake. Based on the C_r values presented in this work and on those presented by Putyatin and co-workers [21], maximum acceptable ^{137}Cs and ^{90}Sr soil activity concentrations for contaminated farmland can be calculated. For this purpose we used the sanitary standard 10-117-99 of Belarus [22], as an example. For the European Union no applicable regu-

Table 5 Mean transfer factors for the soil-to-grain transfer of radiostrontium

	Soil type	
	Sand	Loam
Type of experiment		
Field	0.60	0.43
Lysimeter	1.09	
Greenhouse	0.41	0.05
Contaminant		
Global fallout	0.61	0.39
Chernobyl		
Artificial	0.78	0.05

Dependence on experimental setup and radionuclide source in Germany [16]

Table 6 Ratios between wheat cultivars with maximum and minimum uptake of radiostrontium

Number of compared wheat cultivars	Experimental setup	MMR	Reference
50	^{89}Sr, green house	3.6–3.8	[35]
12	^{85}Sr, green house	4.2	[18]
10 (Winter wheat)	^{90}Sr, field experiments	2	[19]
6 (Spring wheat)	^{90}Sr, field experiments, Belarus	1.6	[21]
28 (Winter wheat)	^{90}Sr, field experiments at three sites in Bavaria, 1999	2.6/1.9/2.5	This work

Table 7 Variability of the MMR of the uptake of radiostrontium in wheat grains

Conditions	^{90}Sr	Reference
One cultivar, one location, different years	4.80	[36]
One cultivar, different locations, 1 year	2.46–5.00	This work
Different cultivars, one location, 1 year	1.6–4.2	This work [18, 19, 21, 35]

lation exists. Other prescriptive limits for ^{90}Sr and ^{137}Cs in wheat grains used for human nutrition production were not known to us. Using our mean C_r values of 0.00055 for ^{137}Cs and 0.14 for ^{90}Sr, wheat grown on a soil contaminated by more than 79 Bq kg^{-1} ^{90}Sr or 164 kBq kg^{-1} ^{137}Cs would show higher activity concentrations than allowed by the sanitary standard 10-117-99 of Belarus. Based on the deduced concentration ratios this corresponds to a ^{137}Cs/^{90}Sr ratio of 2,080. Using the C_r values given in [19] this ratio would be 220 (Table 9). Such high ratios are generally not found in soil contaminated by the Chernobyl fallout for which typical ratios significantly below 100 were reported [1, 23–34]. This suggests that investigations on identifying, cultivation and breeding of wheat cultivars with minimum uptake of radionuclides should focus on ^{90}Sr. However, since in other countries other limits have to be taken into account, the national regulations as well as

Table 8 Site average normalised concentration ratios (SANC$_r$) of ^{90}Sr and ^{137}Cs [9]

Cultivar	^{90}Sr	^{137}Cs
Aristos	1.04 ± 0.02	1.16 ± 0.31
Asketis	0.96 ± 0.03	1.01 ± 0.14
Aspirant	0.88 ± 0.13	1.09 ± 0.24
Astron	1.05 ± 0.08	0.89 ± 0.21
Atlantis	1.50 ± 0.16	0.92 ± 0.18
Batis	1.21 ± 0.05	1.16 ± 0.11
Borneo	1.06 ± 0.07	1.09 ± 0.50
Caesar	0.94 ± 0.07	1.17 ± 0.18
Certo	0.88 ± 0.11	0.96 ± 0.14
Classic	1.26 ± 0.04	1.13 ± 0.18
Contra	0.86 ± 0.14	0.85 ± 0.24
Contur	0.92 ± 0.02	0.86 ± 0.29
Convent	*0.67 ± 0.06*	0.92 ± 0.16
Dream	1.08 ± 0.16	0.95 ± 0.20
Drifter	1.14 ± 0.11	1.07 ± 0.24
Flair	1.05 ± 0.02	*0.74 ± 0.13*
Glockner	1.01 ± 0.18	1.17 ± 0.12
Habicht	0.82 ± 0.18	0.92 ± 0.26
Hybnos	0.96 ± 0.08	1.04 ± 0.27
Kornett	1.17 ± 0.16	*0.76 ± 0.14*
Ludwig	*0.83 ± 0.07*	0.97 ± 0.25
Mewa	0.97 ± 0.20	0.95 ± 0.13
Olivin	0.90 ± 0.06	1.17 ± 0.19
Petrus	1.08 ± 0.11	1.30 ± 0.19
Previa	1.07 ± 0.05	*0.79 ± 0.08*
Semper	*0.82 ± 0.03*	0.87 ± 0.18
Tambor	0.94 ± 0.11	0.96 ± 0.17
Toni	0.93 ± 0.08	1.16 ± 0.37

(SANC$_r$ + SD) ≤ 0.9 are shown in italics letters

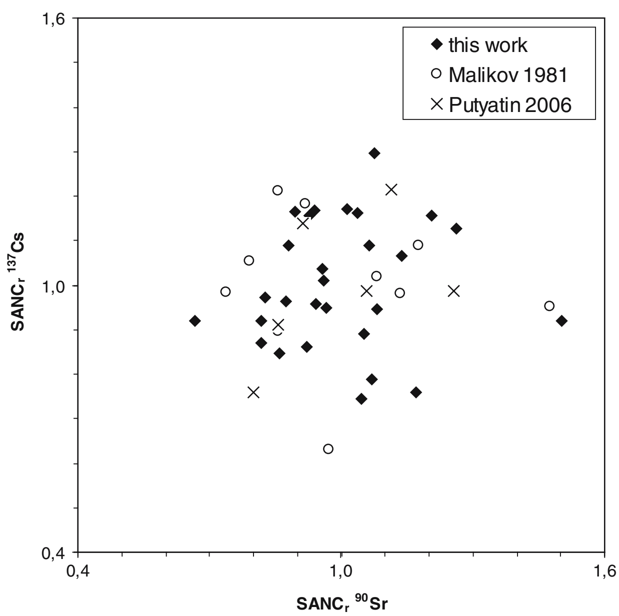

Fig. 3 Comparison of the SANC$_r$ of ^{90}Sr and ^{137}Cs obtained in this work, and reported by Schimmack [9], Malikov [19] and Putyatin [21]

Table 9 Maxima for the $^{137}Cs/^{90}Sr$ activity ratio for soils containing the maximum possible ^{90}Sr activity concentrations calculated with different concentration ratios

Nuclide	Grain max. activity conc. (Bq kg^{-1})	C_r (kg/kg)	Reference	Soil max. activity conc. (Bq kg^{-1})	$^{137}Cs/^{90}Sr$ max. activity ratio
^{90}Sr	11	0.14	This work [9]	79	2,080
^{137}Cs	90	0.00055		164,000	
^{90}Sr	11	0.35	[21]	31	220
^{137}Cs	90	0.013		6,920	

the local $^{137}Cs/^{90}Sr$ activity ratios have to be considered when selecting the best wheat cultivar.

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