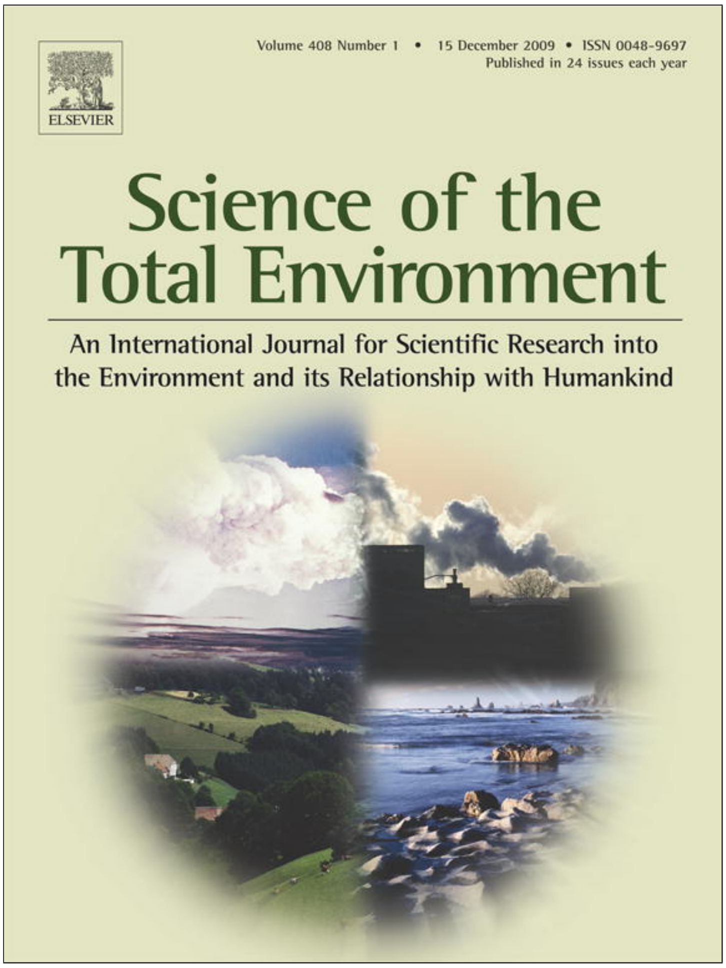
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Rural areas affected by the Chernobyl accident: Radiation exposure and remediation strategies

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ABSTRACT

Main objectives of the present work were to develop an internationally agreed methodology for deriving optimized remediation strategies in rural areas that are still affected by the Chernobyl accident, and to give an overview of the radiological situation in the three affected countries, Belarus, Russia and Ukraine. Study settlements were defined by having in 2004 less than 10,000 inhabitants and official dose estimates exceeding 1 mSv. Data on population, current farming practices, contamination of soils and foodstuffs, and remedial actions previously applied were collected for each of such 541 study settlements. Calculations of the annual effective dose from internal radiation were validated with extensive data sets on whole body counter measurements. According to our calculations for 2004, in 290 of the study settlements the effective dose exceeded 1 mSv, and the collective dose in these settlements amounted to about 66 person-Sv. Six remedial actions were considered: radical improvement of grassland, application of ferrocyn to cows, feeding pigs with uncontaminated fodder before slaughter, application of mineral fertilizers for potato fields, information campaign on contaminated forest produce, and replacement of contaminated soil in populated areas by uncontaminated soil. Side effects of the remedial actions were quantified by a 'degree of acceptability'. Results are presented for two remediation strategies, namely, Strategy 1, in which the degree of acceptability was given a priority, and Remediation Strategy 2, in which remedial actions were chosen according to lowest costs per averted dose only. Results are highly country-specific varying from preference for soil replacement in populated areas in Belarus to preference for application of ferrocyn to cows in Ukraine. Remedial actions in 2010 can avert a large collective dose of about 150 person-Sv (including averted doses, which would be received in the following years). Nevertheless, the number of inhabitants in Belarusian and Russian settlements with annual doses exceeding 1 mSv remains large. Compared to international values for the cost-effectiveness of actions to reduce occupational exposures, the recommended remediation strategies for rural areas affected by the Chernobyl accident are quite cost-effective (about 20 k€/person-Sv).

1. Introduction

Huge amounts of radioactive materials have been released during the reactor accident of Chernobyl in 1986. Large areas of agricultural land in Belarus, Russia and Ukraine were severely contaminated. Due to radioactive decay and remediation, the contamination levels in foodstuffs decreased significantly during the first two decades after the accident (Balonov, 2007). Nevertheless, there are still a few hundreds of settlements, in which annual effective doses of the population due to ionizing radiation caused by the accident exceed 1 mSv.

In the three countries, there are laws or acts of governmental authorities requesting or recommending relocation of the population from settlements with annual doses exceeding 5 mSv. In the dose range of 1 to 5 mSv, remedial actions should be optimized. However, an agreed strategy of optimization has been lacking for a long time. Therefore, the International Atomic Energy Agency initiated the project *Radiological support for the rehabilitation of the areas affected by the Chernobyl nuclear power plant accident*. In the frame of this project, a software tool called *ReSCA — Remediation Strategies after the Chernobyl Accident* has been developed (Ulanovsky et al., submitted for publication). The software is based on two decades of experiences with agricultural countermeasures against radioactive contaminations in the aftermath of the Chernobyl accident (Fesenko et al., 2007). A main feature of *ReSCA* is the use of settlement-specific levels of ground contaminations and activity

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contents in food stuffs, a method which has been introduced by Jacob et al. (2001). *ReSCA* is already in official use in Ukraine for deriving optimized remediation strategies. In Russia and Belarus it is on its way of being introduced.

Several decades after the Chernobyl accident, the only radionuclide relevant for the resulting population exposure is ^{137}Cs (IAEA, 2006; Ylipieti et al., 2008). Consequently, only exposures caused by ^{137}Cs are considered in *ReSCA*. Relevant exposure pathways are external radiation from the decay of caesium atoms in the environment and internal radiation after incorporation of caesium with foodstuffs, especially milk and forest produce. According to the recommendations of the International Commission on Radiological Protection (ICRP, 2007, p.86), doses are assessed for a hypothetical representative person, who receives a dose that is representative of the more highly exposed individuals in the population.

In the present study, radioecological information has been collected for all rural settlements (less than 10,000 inhabitants), in which the annual effective dose exceeds 1 mSv according to the official dose catalogues for the year 2004 (Russian Government, 2006; Likhtarev et al., 2005). Based on these data, annual effective doses were calculated with *ReSCA* and validated with results of whole body counter (WBC) measurements. Dose distributions in 2010 and 2020 were predicted. Possible remediation strategies, their costs and impacts on the dose distribution are discussed for settlements with effective doses in 2010 exceeding 1 mSv.

2. Materials and methods

2.1. Study settlements

For the present analysis, study settlements have been defined as settlements with less than 10,000 inhabitants and for which official values for the dose in 2004 from ^{137}Cs exceeds 1 mSv. For Russia and for Ukraine, so called dose catalogues (Russian Government, 2006; Likhtarev et al., 2005) were used to identify the study settlements. At the time of our analysis, no official dose catalogue was published for Belarus. In order to identify the Belarusian study settlements, the Institute of Radiology performed *ReSCA* calculations for the radiation exposure in the year 2004 in 2889 Belarusian settlements, for which sufficient radiological data were available. Those settlements with dose estimates exceeding 1 mSv were chosen as study settlements.

The data collected for a study settlement *i* include

- the number of inhabitants, N_i
- the mean ^{137}Cs ground contamination density, $q_{i,s}$ (kBq m^{-2})
- the mean ^{137}Cs concentrations, $q_{i,f}$ (Bq kg^{-1}), in foodstuffs for *f* equal to 'pork', 'potatoes' and 'mushrooms'
- the average consumption of locally collected mushrooms relative to the average consumption of mushrooms in the country, μ_i
- the number of grassland areas for cows.

The data for a grassland area *j* include

- the number of cows, N_j^c
- information about countermeasures previously or presently applied
- the mean ^{137}Cs concentrations, $q_{j,f}$ (Bq L^{-1} or Bq kg^{-1}), in milk and beef
- the distribution of soil types.

Soil properties influence the bioavailability of radionuclides (IAEA, 1996, 2006, 2009) and, hence, the effectiveness of remedial actions in terms of dose reduction.

In Belarus, data on the number of inhabitants in the study settlements were obtained from regional statistics committees. Data on settlement areas and the distribution of their territories in terms of soil types were supplied by regional land tenure organizations. Documents on the number of private cows were obtained from the regional agricultural committees. Values of ^{137}Cs ground contamination densities were based on measurements performed by the Hydrometeorological Service of Belarus. Data on the ^{137}Cs concentration in food products produced in the private sector and in mushrooms were collected by the radiological department of the regional sanitary-epidemiological services.

For Russian study settlements, data on the ^{137}Cs ground contamination density of the Russian dose catalogue (Russian Government, 2006) were used. Data on the population density were taken from the corresponding statistical bulletin (Statistical Bulletin, 2005). Data on the contamination of potatoes are from the Bryansk center "Agrochemradiology" of the RF Ministry of Agriculture (Panov et al., 2007; Prudnikov et al., 2007). Data on the contamination of animal products (milk, meat), as well as forest products are from a periodic radiation control of agricultural and natural foodstuffs carried out by the Bryansk radiological veterinary laboratory of the RF Ministry of Agriculture (Panov et al., 2007; Prudnikov et al., 2007). Measurement results were not available for all foodstuffs in all settlements. As a surrogate, foodstuff contaminations were assessed in these cases from the soil activity and average transfer factors according to soil type (Bogdevitch et al., 2002; Fesenko et al., 2007).

Data for the Ukrainian study settlements were obtained by the Ukrainian Institute of Agricultural Radiology (UIAR) within the framework of the National Project "Scientific and methodological support of the agricultural production at the territory contaminated with radionuclides as a result of the Chernobyl catastrophe" (UIAR, 2004). In 2004, in the study settlements samples of soil, mushrooms and agricultural production (including cow milk and soil from each pasture) were collected, as well as information was acquired about the population, number of cows, and countermeasures applied.

2.2. Dose calculations

The *ReSCA* methodology (Ulanovsky et al., submitted for publication) was applied to calculate effective doses in 2004.

The annual effective dose due to external exposure of the representative person in a study settlement, *i*, has been estimated according to

$$D_{E,i} = C_E q_{i,s}, \tag{1}$$

where C_E is the average annual external dose per ^{137}Cs ground contamination density for the upper 10% of the dose distribution. For C_E a value of 2.2 µSv per kBq m^{-2} has been derived from the literature (Golikov et al., 2002). The corresponding value for the average dose in the settlement has been assumed to be by a factor of 1.8 smaller. This factor expresses the variability of individual doses, which are due to site-specific differences in

- migration of caesium into the soil
- decreases of caesium activities due to run-off and decontamination
- individual occupancy times at locations with, e.g., high contaminations as forests, or low dose levels in paved areas.

The annual effective dose due to internal exposure of a representative person in a settlement was calculated according to

$$D_{I,i} = C_I \sum_f F_{i,f} \times \begin{cases} \sum_j N_j^c Q_{j,f} \Big/ \sum_j N_j^c, \text{for} f \text{ equal}'\text{milk}'\text{and}'\text{beef}' \\ Q_{i,f}, \text{ for} f \text{ equal}'\text{pork}', '\text{potatoes}' \text{ and}'\text{mushrooms}' \end{cases} \tag{2}$$

where

- C_I is the effective dose per unit intake of ^{137}Cs averaged over the age-dependent coefficients as specified by ICRP (1996), and has a value of 1.2 10^{-5} mSv Bq^{-1}
- $F_{i,f}$ is the country-specific annual consumption of foodstuff *f* (Table 1), multiplied in the case of mushrooms with μ_i. The

Table 1
Average consumption rates in rural areas of the affected countries (BRIR, 1990; Jacob et al., 2001).

Foodstuff	Consumption rates (kg y^{-1} or L y^{-1})		
	Belarus	Russia	Ukraine
Private milk	260	200	234
Beef	6	8	3
Pork	50	20	48
Potato	240	190	131
Mushrooms	4	5	3.5

consumption rates take into account foodstuffs not explicitly mentioned as, e.g., milk products (included in $F_{i,\text{milk}}$) or forest berries (included in $F_{i,\text{mushrooms}}$)

- The summation j is over all grassland areas related to settlement i
- $Q_{j,f} = q_{j,f} / (1 - \varphi_j + \varphi_j / R_{FA,f})$, for f = 'milk' or 'beef', where φ_j is the fraction of cows to which ferrocyn has been applied in 2004, and $R_{FA,f}$ is the reduction of the ^{137}Cs concentration in milk and beef, respectively, due to the application of ferrocyn (see below)
- $Q_{i,f}$ equals to $q_{i,f}$ for f = 'pork' and 'potatoes'
- $Q_{i,\text{mushrooms}}$ was assumed to be by a factor of 2 smaller than the measured concentration $q_{i,\text{mushrooms}}$, because the ^{137}Cs concentration in consumed mushrooms is due to culinary practices lower than the concentration in fresh mushrooms.

The average of the internal dose in each of the settlements was assumed to be by a factor of 3 smaller than the dose to the representative person.

Predictions of future doses were based on the assumption of

- an ecological half-life of 50 years corresponding to an effective half-life of 18.8 years for external exposures (Golikov et al., 1999)[1]
- an ecological half-life of 30 years corresponding to an effective half-life of 15 years for agricultural products (Jacob et al., 2001)
- an ecological half-life of 100 years for forest products. The latter value was chosen as a typical value in the large range of 22 to 800 years for different species of mushrooms (IAEA, 2009). Correspondingly, a value of 23 years was used for the effective half-life of forest products.

Assessments of collective doses were based on the product of the number of inhabitants and the average dose in each of the affected settlements.

2.3. Affected settlements and dose validation

All study settlements, in which the effective dose of the representative person exceeds 1 mSv in 2004, are called here affected settlements. In order to predict the rural population in settlements, in which the annual dose still exceeds in future years 1 mSv, it is assumed that the population in the affected settlements is the same as in 2004.

The coefficient, C_E, used for the external dose calculations has been validated with TLD measurements in an earlier work (Golikov et al., 1999). The value was also confirmed by measurements of the external dose in contaminated settlements in the year 2001, according to which the average annual effective dose was in the range of 0.39 to 1.34 µSv per kBq m^{-2} (Ramzaev et al., 2006).

WBC measurements in settlements, for which *ReSCA* calculations resulted in values of the annual internal dose exceeding 0.5 mSv, and which had more than 50 inhabitants, were used for validation of internal dose calculations. For 17 Belarusian settlements, results of WBC measurements were obtained from the Center of Radiation Medicine, Gomel. The measurements were partly performed in local clinics, partly by mobile teams. For the present study, a seasonal factor was used to convert the seasonal dependent results to an annual dose.

For the Russian settlements, two data sets with annual dose values derived from WBC measurements were available: results of local clinics for 52 settlements, and results of the Institute of Radiation Hygiene for 45 settlements.

For the Ukrainian settlements, a data set on annual dose values derived from WBC measurements was obtained for 22 settlements from the Ukrainian Research Center of Radiation Medicine. The measurements were partly performed in local clinics, partly by mobile teams.

2.4. Remediation strategies

Six types of remedial actions are considered in the program system *ReSCA* (Ulanovsky et al., submitted for publication):

- Radical improvement of grassland (RI)
- Application of ferrocyn to cows (FA)
- Feeding pigs with uncontaminated fodder before slaughter (FP)
- Application of mineral fertilizers for potato fields (MF)
- Information campaign on mushrooms and other forest produce (IM)
- Replacement of contaminated soil in populated areas by uncontaminated soil (RS).

A detailed description of the agricultural countermeasures including necessary resources, limitations of the application, costs and times of effectiveness has been given by Fesenko et al. (2007). Radical improvement of grassland (RI) includes removing vegetation, ploughing, liming, fertilization and reseeding. Typically, ferrocyn (a mixture of 5% $KFe[Fe(CN)_6]$ and 95% $Fe_4[Fe(CN)_6]$) is administered to cows (FA) as an additive to concentrate feed with a rate of 0.5 kg of concentrate per cow daily. Feeding pigs with uncontaminated fodder (FP) was assumed to start two months before slaughter (Pröhl et al., 1993; Jacob et al., 2001). The use of mineral fertilizers for potato fields to reduce root uptake of radiocaesium is based on decreasing the Cs:K ratio in the soil solution while maintaining optimal growth conditions for plants (Fesenko et al., 2007). The optimum ratio of minerals was determined to be a N:P:K ratio of 1:1.5:2. No quantitative information was available for information campaigns on contaminated mushrooms and forest produce (IM). Since, however, such a remedial action was considered as potentially important, it was included in the study by making a subjective choice of effectiveness, costs, etc.

The implementation of the remedial action 'Replacement of contaminated soil in populated areas by uncontaminated soil' (RS) has been described by Ulanovsky et al. (submitted for publication). Replacement of soil around the houses of in total ten inhabitants in the area with the highest contamination is considered as one remedial action, followed eventually by the houses of further ten inhabitants in the area with the next highest soil contamination, and so on.

Quantitative characteristics of the remedial actions are summarised in Table 2. The reduction factors given in Table 2 apply to realistic field conditions. The reduction factor of 1.5, e.g., for replacement of soil is an intermediate value of what has been achieved by large scale decontamination work in 1989 (Golikov et al., 1999) and by careful decontamination work under optimized conditions (Roed et al., 2006).

The estimated costs include all direct costs as expenses for work power, machines, materials and waste disposal. Side effects of remedial actions, as, e.g., the increase of potato yield by applying mineral fertilizers, have been considered in *ReSCA* by defining a degree of acceptability of the remedial actions (see below).

The dose, D_{ijr}, averted by remedial action r (RI or FA) for grassland area j in a settlement i was calculated by

$$D_{ijr} = C_I N_j^c \sum_f (1 - 1/R_{jrf}) Q^*_{j,f} Y_{j,f} T_r, \quad (3)$$

[1] An ecological half-life describes the attenuation of a dose contribution due to ecological processes, e.g., due to migration into the soil or fixation to the soil matrix. An effective half-life describes the total attenuation rate taking radioactive decay into account.

Table 2
General characteristics of the remedial actions considered.

Remedial action	Reduction factor	Time of effectiveness	Costs (€)[a]	Degree of acceptability
Radical improvement (RI)	1.7–8[b]	4 or 7 years[c]	350–2350[d]	1.0
Ferrocyn application to cows (FA)	2 or 3[e]	Time of application	30–60[d]	0.75
Clean feed for pigs (FP)	3	Time of application	6–20[f]	0.6
Mineral fertilizer for potatoes (MF)	2	1 year	0.8–2.5[f]	1.0
Information on mushrooms (IM)	1.5	2 years	3[f]	0.5
Replacement of contaminated soil (RS)	1.5	Infinite	525[f]	0.1

More specific information is given by Fesenko et al. (2007) and Ulanovsky et al. (submitted for publication). For agricultural remedial actions, the reduction factors apply to the contamination of foodstuffs, for replacement of soil to the reduction to the external exposure of the population.
[a] Costs relate to the year 2004.
[b] Depending on soil type, previous applications of RI, and whether it includes drainage.
[c] 4 years for RI without drainage, 7 years for RI with drainage.
[d] Costs per cow, costs depending on country, and in case of RI whether it includes drainage.
[e] 3 for milk and 2 for beef.
[f] Costs per inhabitant, costs depending on country.

where

- the index f is for 'milk' and 'beef'
- R_{jrf} the reduction factor for remedial action r for foodstuff f in grassland area j
- $Q^{*}_{j,f}$ is the activity in foodstuff f in grassland area j, eventually reduced, if the other of the two remedial actions against milk and beef contaminations is already part of the remediation strategy (see below)
- $Y_{j,f}$ is the annual yield of milk or beef per cow
- T_r is the time of effectiveness of remedial action r.

The dose averted by remedial action r (FP, MF or IM) was calculated by

$$D_{ijr} = C_I N_i \sum_f (1 - 1/R_{rf}) Q_{i,f} F_{i,f} T_r, \tag{4}$$

where

- the index f is for 'pork', 'potatoes' and 'mushrooms'
- R_{rf} the reduction factor for remedial action r for foodstuff f.

The calculation of the dose averted by replacement of contaminated soil in populated areas was described by Ulanovsky et al. (submitted for publication).

In building remediation strategies, *ReSCA* chooses sequentially remedial actions with the largest value of

$$\beta \times \frac{\min(CD_{ijr})}{CD_{ijr}} + (1-\beta) \times DA_r, \tag{5}$$

where

- DA_r is the degree of acceptability of remedial action r
- CD_{ijr} are the costs per averted dose for the application of a remedial action r in settlement i or on grassland j
- $\min(CD_{ijr})$ are the costs per averted dose for the application of that combination of a remedial action r and a settlement i or a grassland j, which is not already part of the strategy and which has the lowest costs per averted dose
- β is a positive weighting factor, which has to be specified by the user and has to be smaller or equal to 1.0. This weighting factor expresses the importance given by the user to the costs per averted dose relative to the degree of acceptability.

If in a settlement the annual effective dose to the reference person is reduced by a remediation strategy below 1 mSv, then no further remedial actions are considered in that settlement.

Results on interviews of inhabitants of rural settlements and local stakeholders of the most contaminated regions of the three countries (the Bryansk region of the Russian Federation, the Gomel and Mogilev regions of Belarus and the Rovno region of Ukraine) were used for estimating degrees of acceptability of the various remedial actions (Fesenko et al., 2007). In spite of high local variations across individual settlements (see also Howard et al. 2005), data averaged over vast areas were quite consistent across the three countries. The population preferred actions allowing an increase or maintenance in the productivity of plants or animals such as radical improvement, clean feed for pigs or fertilization of potato fields, while the stakeholders gave preferences to the measures that can provide maximum reduction of radionuclide transfer to agricultural products with minimum costs (Fesenko et al., 2007). The values chosen in the present analysis were confirmed in a number of stakeholder workshops involving local and regional decision makers and their staff in the contaminated areas of the three countries.

For simplicity, the remedial actions are assumed to be applied within one year. Correspondingly, averted doses, costs and costs per averted dose are calculated for one year for remedial actions, which have to be applied continuously (e.g. application of ferrocyn), and for the period of effectiveness for the other remedial actions (e.g., four years for radical improvement). Averted doses and costs of remedial actions, which have to be performed subsequently, are not considered in our calculations.

In the present report, two remediation strategies for the year 2010 were derived. Remediation Strategy 1 was derived for β equal to 0.1, i.e., the degree of acceptability of the remedial actions was considered to be important for developing the strategy. Remediation Strategy 2 was derived for β equal to 1.0, i.e., only costs per averted dose are taken into account in the process of optimisation.

3. Results

3.1. Affected settlements

In total, 541 study settlements fulfilled the criteria for inclusion in the analysis, 78 in Belarus, 261 in Russia and 202 in Ukraine (see electronic supplementary material, Table S1). The Russian catalogue (Russian Government, 2006) lists in total 428 settlements with a dose in 2004 exceeding 1 mSv. We considered, however, only settlements, which have not been abandoned (264), and excluded 3 towns with more than 10,000 inhabitants (Klimovo, Klintsy and Novozybkov).

The Belarusian study settlements are mostly located in Gomel and Mogilev oblasts, the Russian settlements in Bryansk oblast, and the Ukrainian settlements in Zhitomir, Kiyv, Rivne and Volyn oblasts (Fig. 1).

The study settlements in Ukraine had ^{137}Cs ground contamination densities less than 555 kBq m^{-2} (15 Ci/km^2), because the population of higher contaminated settlements has been resettled in 1991 according to the Laws of Ukraine (Supreme Council of Ukraine, 1991a,b). Settlements in which some persons have illegally returned were not considered.

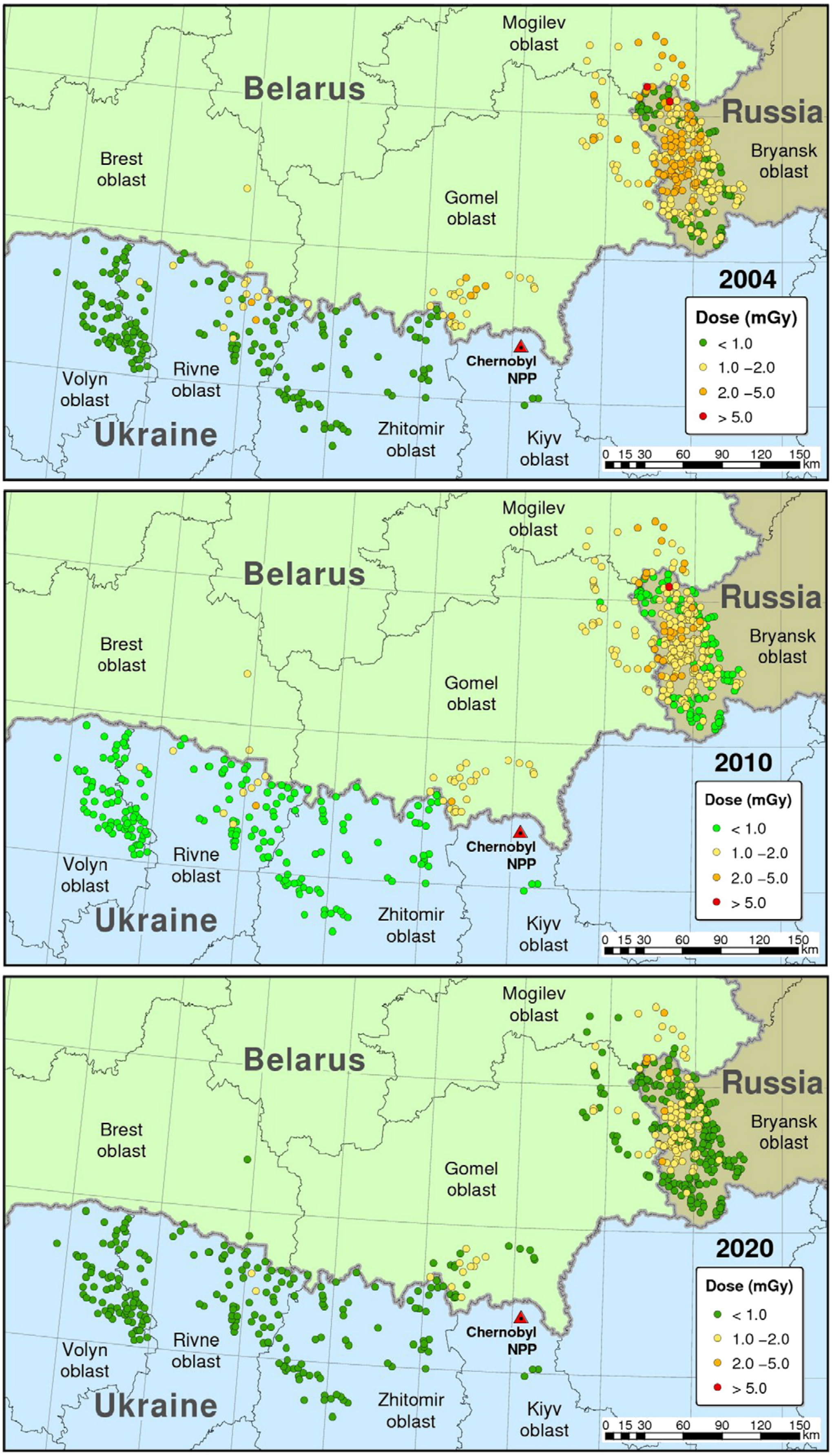

Fig. 1. Map of the 541 study settlements, coloured according to the dose of the representative person from ^{137}Cs as calculated with *ReSCA* for 2004 (upper panel) and predicted for 2010 and 2020 (middle and lower panel).

According to the present *ReSCA* calculations for 2004, the effective dose of the representative person exceeded 1 mSv only in 54% of the study settlements. The population in these 290 affected settlements was 78,172, most of them living in Russian settlements (Table S2).

According to the Russian catalogue, there are quite a number of settlements which had doses exceeding 5 mSv. According to the present calculations, however, there are only two such settlements, Zaborye with a dose of 7.4 mSv and Nikolaevka with a dose of 5.6 mSv (Fig. 1).

It is predicted for the year 2010 that without remedial actions the number of settlements with annual doses exceeding 1 mSv will still be 251 (Table S2). However, the number of settlements with annual doses from ^{137}Cs exceeding 2 mSv will be reduced by natural processes and radioactive decay from 91 in 2004 to 33 in 2010.

The number of settlements with annual doses exceeding 1 mSv is predicted for 2020 to be 121. Those with annual doses from ^{137}Cs exceeding 2 mSv will be substantially reduced to 6.

3.2. Dose calculations

Overall, the *ReSCA* calculations of internal doses were confirmed by the WBC measurements (Table S3). The number of settlements, in which the *ReSCA* estimation of the internal dose to the representative person (average dose of upper 10% percent of dose distribution) is larger than the threefold of the measured average dose, is about the same as the number of settlements, in which the *ReSCA* estimation is smaller (Fig. 2). The calculations overestimate the dose to the representative person slightly: the median of the calculated to measured dose ratio in the 76 settlements with WBC measurements was 1.16 (90% range: 0.48 to 3.4). The overestimation by more than a factor of three in a very small fraction of the settlements (5%) may be explained by a smaller fraction of local food products in the diet, or by lower contamination levels in the locally produced and consumed foodstuffs, if compared to the *ReSCA* calculations.

The collective dose assessed for 2004 in the affected settlements amounts to about 66 person-Sv (Table 3). About 78% of the collective dose occurs in Russia. This is mainly due to the large proportion of inhabitants in affected settlements residing in Russia (74%). But also the average dose in 2004 in the affected settlements in Russia (0.9 mSv) is higher than, e.g., in Ukraine (0.6 mSv).[2]

According to the predictive calculations, the collective dose in the affected settlements will reduce due to natural reduction processes and radioactive decay until 2010 to about 52 person-Sv and until 2020 to about 36 person-Sv.

In total, about 60% of the collective dose is due to external radiation and 40% due to incorporation of ^{137}Cs with contaminated foodstuffs. However, the distribution of the dose to the representative person on external exposures and internal exposures varies between the affected settlements of the three countries (Fig. 3). In Belarus, in nearly all of the affected settlements the external exposure exceeds the internal exposure. This is probably due to relocations of the inhabitants from settlements with high transfer factors and previous agricultural remediation activities. In Russia, there is about an equal number of settlements with external dose exceeding the internal dose and of settlements with internal dose exceeding external dose. In the Ukrainian settlements, the internal dose is considerably larger than the external dose, which is due to very high transfer factors in the affected area. Although the effective half-lives for the various pathways differ, the general picture of the dose distribution on external and internal exposure does essentially stays the same until 2020 (Table 3).

Overall, the annual dose from mushrooms is comparable to the annual dose from milk in the Belarusian and Russian affected settlements (Fig. S1). In Ukraine, however, milk dominates the internal exposure in most of the affected settlements. Due to the longer effective

[2] Note that the dose to the representative person is higher than the average dose.

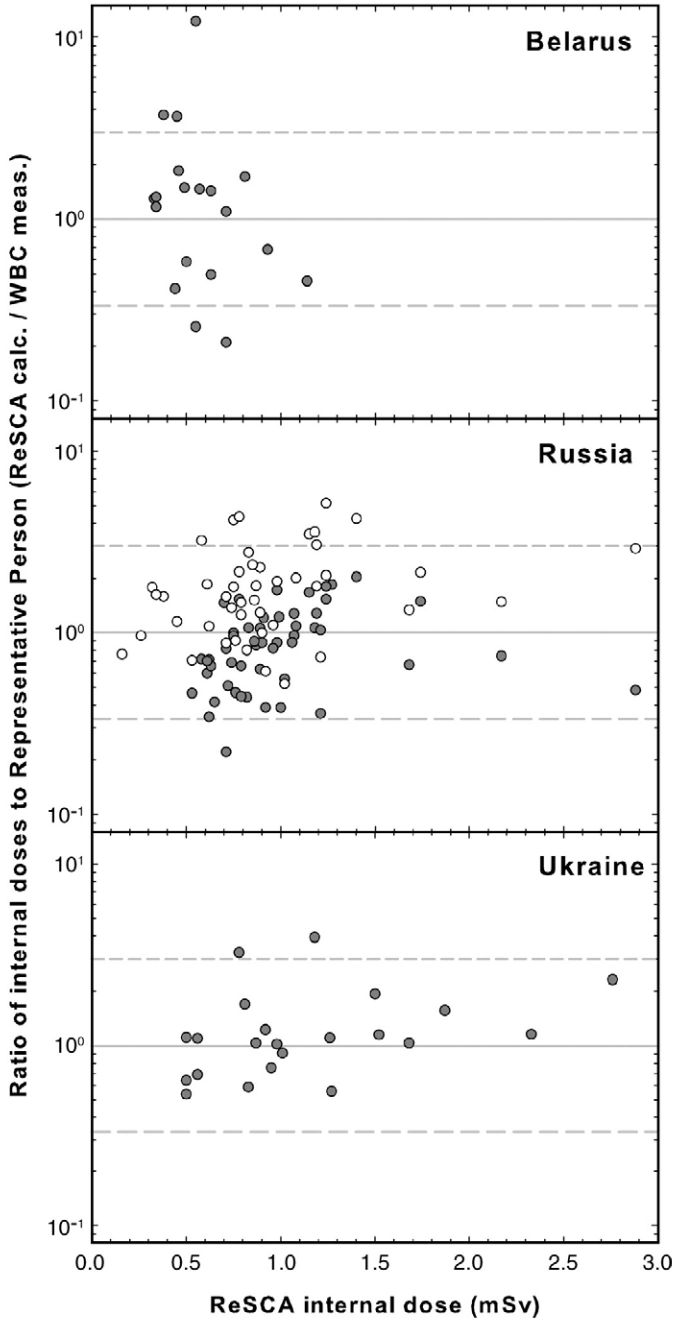

Fig. 2. Ratio of internal doses to the representative person in 2004 as estimated by *ReSCA* and as estimated on the base of WBC measurements (threefold of the average dose), upper panel for Belarus, middle panel for Russia (filled circles: measurements of local clinics, open circles: measurements of Institute of Radiation Hygiene), and lower panel for Ukraine.

Table 3
Collective dose in 2004, 2010, and 2020 in the affected settlements.

Country (population in affected settlements)	Collective annual dose (person-Sv) from								
	External radiation			Internal radiation			Both pathways		
	2004	2010	2020	2004	2010	2020	2004	2010	2020
Belarus (9615)	6.4	5.1	3.5	1.7	1.3	0.9	8.0	6.4	4.4
Russia[a] (57 960)	33.3	26.7	18.5	17.8	13.9	9.3	51.1	40.6	27.8
Ukraine (10 597)	0.8	0.7	0.5	5.8	4.4	2.8	6.6	5.1	3.3
All[a] (78 172)	40.5	32.5	22.5	25.2	19.6	13.0	65.7	52.2	35.5

[a] Excluding the three Russian towns Klimovo, Klintsy and Novozybkov.

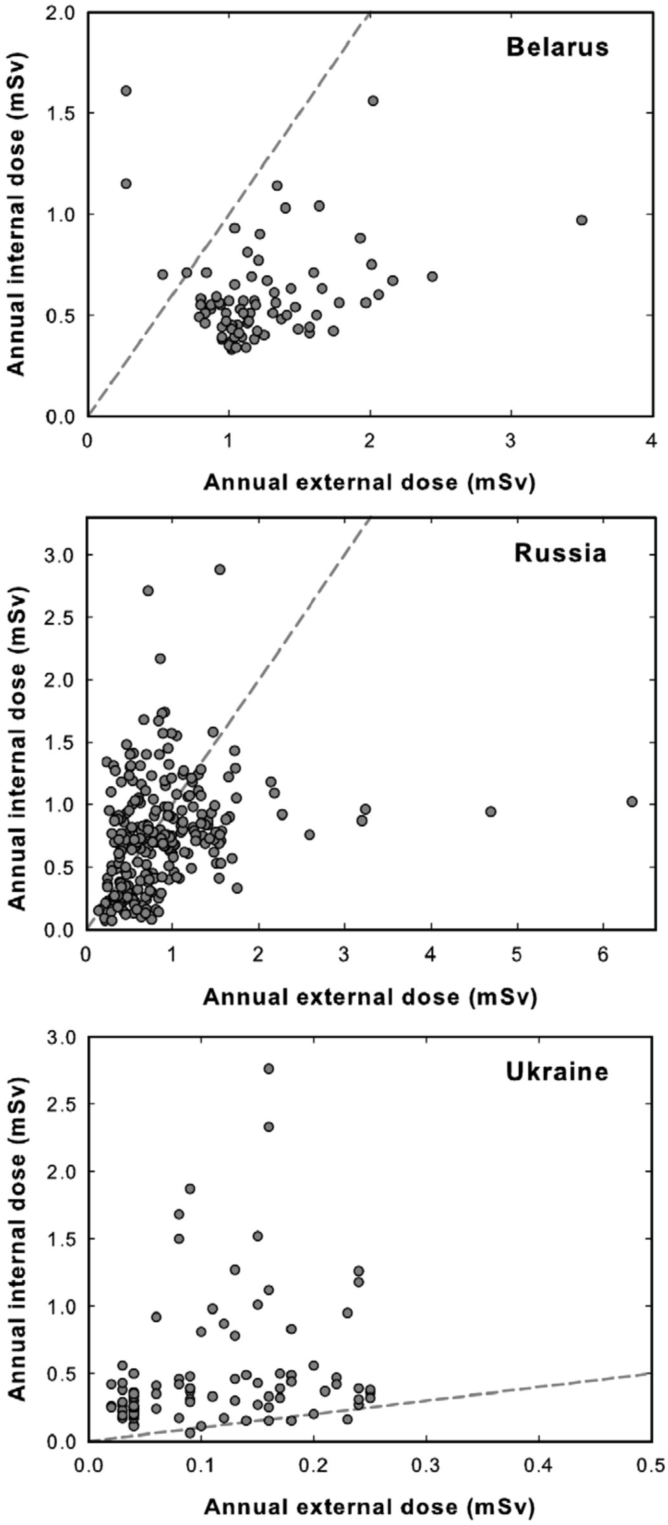

Fig. 3. Annual effective dose from internal radiation versus dose from external radiation in the affected settlements in 2004.

half-life of the caesium contamination in mushrooms compared to milk, the relative contribution of mushrooms to the internal dose increases slowly with time.

3.3. Preferred remedial actions in the remediation strategies

Remediation strategies have been evaluated using expected annual doses in 2010. In Remediation Strategy 1, high weight is given to the degree of acceptability of the remedial actions. Radical improvement (RI) is favoured in this strategy because of its high degree of acceptability. For nearly all settlements in all three countries, RI is recommended as the first remedial action (Table S4). The cost-effectiveness of RI depends on

- the level of milk contamination: the higher the milk contamination, the better is the cost-effectiveness because more dose is averted for the same amount of resources
- the soil type: the activity reduction factor is considerably higher for peat than for other soil types
- whether or not RI has been applied before: if RI has been applied during the past three years, then it makes no sense to repeat the action in the present year. If RI has been applied a longer time ago, then the contamination has already been distributed to deeper soil layers so that a further reduction of the grass contamination is only achieved by fertilizing and sowing grass species with low caesium uptake.

Table 4 gives an overview about the first ten remedial actions in Remediation Strategy 2 in Russia (more extensive data on most important remedial actions are given in Table S5). In Remediation Strategy 2, only costs per averted dose are considered. Clearly application of ferrocyn (FA) is favoured in this strategy. Replacement of contaminated soil (RS) in the most contaminated spots in highly contaminated settlements (e.g. Svetilovichi in Belarus, and Zaborye and Yalovka in Russia) turns out to be as cost effective as FA. RS has the advantage of creating a clean populated area, however, it also creates radioactive waste disposals.

Comparing the first remedial actions in the two strategies, it may be noted that not only the remedial actions, but also the sequence of settlements, for which remedial actions are recommended, is different. While according to Strategy 2 it is recommended to perform FA in the settlements with the highest milk contaminations in the first place, Strategy 1 takes into account the reduction factor of milk contamination by RI, which depends on soil type and previous applications of RI.

3.4. Overall costs, averted doses and costs per averted dose

As to be expected, generally the cost-effectiveness of the remediation strategies decreases with increasing invested resources thus with increasing averted doses (Fig. 4). Other observations for the situation in 2010 are country-specific:

- In Belarus, the first remedial actions have a cost-effectiveness of about 25 k€/person-Sv. Led by the high degree of acceptability, Remediation Strategy 1 then selects remedial actions (mainly RI in lower contaminated sites) with a low cost-effectiveness. If more than 500 k€ can be spent, however, then also in Remediation Strategy 1 remedial actions with a lower degree of acceptability (RS and FA) are chosen, and the cost-effectiveness increases again. If about 1 M€ are spent in 2010, then the dose averted by Strategy 2 is about 6 person-Sv more than in Strategy 1.
- In Russia, a large number of remedial actions with a very high cost-effectiveness of about 10 k€/person-Sv can still be applied. This is explained by the relative high contamination of milk in a larger number of Russian settlements, if ferrocyn would not be applied. In a number of settlements, the estimated milk contamination without ferrocyn application was larger than 300 Bq L^{-1}. Noticeable differences of the two strategies in cost-effectiveness are only observed for investments larger than 0.5 M€.
- In Ukraine, the annual dose to the reference person can be reduced below 1 mSv in all settlements with relative modest resources of less than 0.4 M€ in 2010 (Strategy 2). However, in the following years, additional resources are needed for continuing the application of ferrocyn to cows. In Strategy 1, the more expensive and less

Table 4
First ten remedial actions (RA) according to Remediation Strategy 2 ($\beta = 1.0$, only costs per averted dose are considered) for the year 2010 in Russia.

Settlement	Area number(s)	Remedial action	Annual dose before RA (mSv)	Annual dose after RA (mSv)	Costs (k€)	Averted dose (person-Sv)	Costs per averted dose (k€/person-Sv)
Dobrodeevka	309–311	FA	3.46	2.29	2.6	0.830	3.2
Zaborye	–	RS (0.065)[a]	5.88	5.57	3.3	0.715	4.6
Unecha	331–333	FA	2.36	1.54	1.1	0.250	4.6
Smyalch	21–27	FA	2.08	1.46	5.7	0.950	6.0
Dobrodeevka	309–311	RI	2.29	1.89	17.2	2.822	6.1
Guta Koretskaya	370–371	FA	1.84	1.27	2.9	0.438	6.6
Novonovitskaya	59–62	FA	1.88	1.32	1.6	0.245	6.6
Krasnaya Krynitsa	483	FA	2.05	1.50	0.1	0.009	6.7
Yalovka	–	RS (0.02)[b]	3.35	3.30	3.3	0.485	6.7
Popovka	51–54	FA	1.84	1.29	2.4	0.354	6.8

[a] Decontamination of most contaminated part (6.5%) of Zaborye, corresponding to environment of houses for 10 people.
[b] Decontamination of most contaminated part (2%) of Yalovka, corresponding to environment of houses for 10 people.

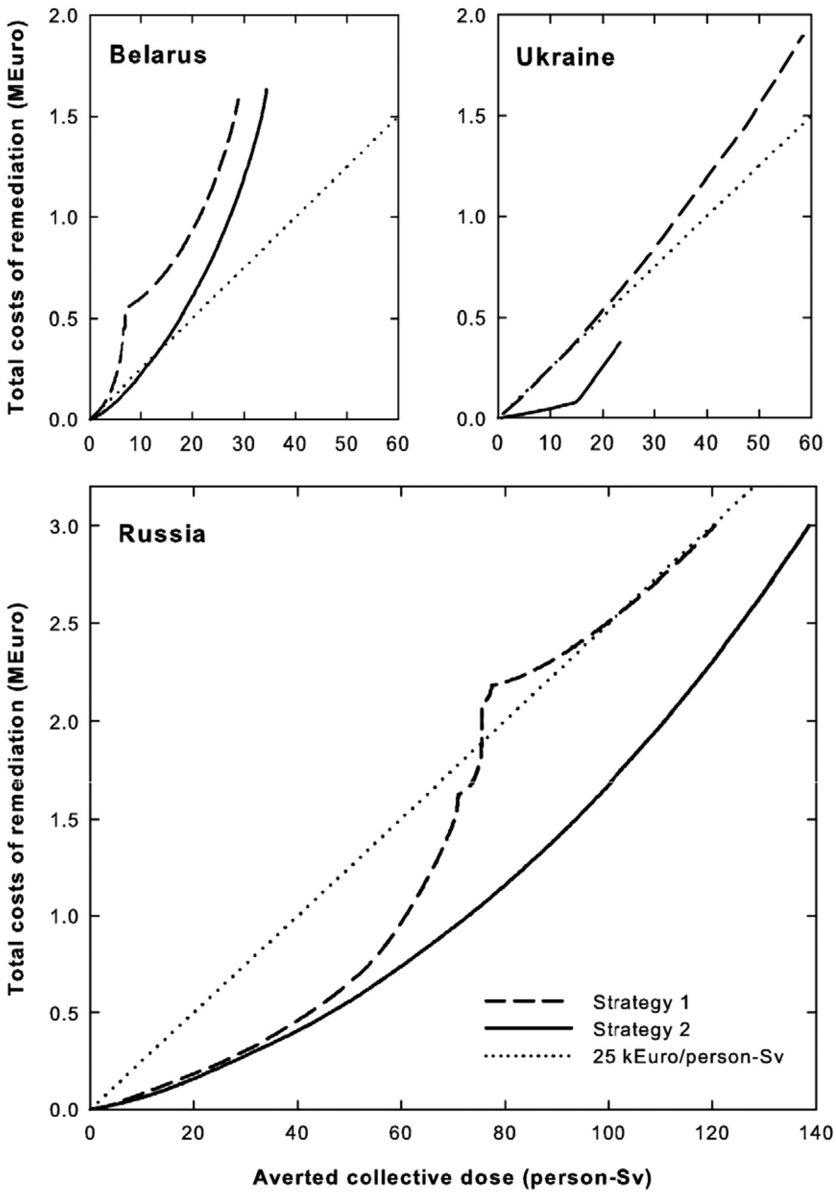

Fig. 4. Costs of remediation in dependence on collective dose averted in Belarus (upper left panel), in Russia (lower panel), and in Ukraine (upper right panel), dashed line for Remediation Strategy 1 ($\beta = 0.1$, degree of acceptability is important), solid line for Remediation Strategy 2 ($\beta = 1.0$, only costs per averted dose are considered). The dotted line with a constant slope (25 k€/person-Sv) has been introduced as a guide of the eye.

cost-effective RI (partly including drainage) is recommended, which reduces the annual dose well below 1 mSv in quite a number of settlements.

Also, the distribution of resources on agricultural remedial actions and remedial actions against external exposures (RS) is quite country-specific (Table 5) In Belarus, Strategy 1 shares the resources between agricultural remedial actions and RS, while Strategy 2 focuses on RS. In Russia, Strategy 1 focuses on agricultural actions, while Strategy 2 shares the resources between agricultural actions and RS. For Ukraine, only agricultural actions are recommended.

A large dose in the order of 150 person-Sv can be averted by remedial actions in 2010. This is more than twice the collective dose in 2010, demonstrating that to a considerable degree both strategies include the application of remedial actions, which are effective for a larger number of years. The number of settlements with annual doses exceeding 1 mSv after application of the two remediation strategies is quite similar (Fig. 5).

Although the collective dose which can be averted by the strategies is quite high, the number of inhabitants in Belarusian and Russian settlements with annual doses exceeding 1 mSv remains large (Table S7). In Belarus, reducing the annual dose below 1 mSv in all settlements, in which this is possible, and applying all six remedial actions in the remaining settlements, costs 1.6 M€ and leaves 1700 people living in settlements with annual doses to the representative person exceeding 1 mSv. In Russia, even the investment of 5 M€ leaves the annual dose in settlements with nearly 29,000 inhabitants being larger than 1 mSv.

4. Discussion

4.1. Main results

The results of the present study based on extensive radioecological data for 541 rural settlements, in which according to official data the effective dose in 2004 caused by the Chernobyl accident exceeded 1 mSv. According to the present study, the number of settlements with the dose to the representative person exceeding a value of 1 mSv is considerably smaller. Reasons for this discrepancy may be manifold, including differences in input data and dose calculation methodologies. The present analysis focussed as much as possible on settlement-specific data.

The 290 affected settlements had 78,172 inhabitants, 57,960 of them lived in Russian settlements. In addition, there are three towns (Klimovo, Klintsy and Novozybkov) with a total of 133,000 inhabitants, in which according to the official dose catalogue the annual dose exceeded 1 mSv (Russian Government, 2006).

Compared to Russia, in Belarus and Ukraine the number of affected settlements with a dose to the representative person in 2004 exceeding 1 mSv was small. Possible reasons include:

- in Belarus and Ukraine, more remediation work was implemented in the decade before 2004 than in Russia
- there is a difference in the criterion for relocation: 40 Ci km^{-2} in Russia (Russian Government, 1991; Russian Ministry of Health, 1999), and 15 Ci km^2 in Belarus (Belarusian Government, 1991) and Ukraine (Supreme Council of Ukraine, 1991a,b). Thus, in Belarus and Ukraine more of the highly contaminated settlements have been resettled than in Russia.

In Ukraine, a reduction of annual doses below 1 mSv can be achieved in all study settlements with relatively small resources. In Russia, however, there are still a larger number of settlements with high contamination levels and larger efforts are needed to remediate the situation.

Even more than two decades after the accident, a considerable collective dose can be averted by quite cost-effective remediation strategies. The costs per averted dose are about 20 k€/person-Sv in Russia and Ukraine and about 40 k€/person-Sv in Belarus. These values are considerably lower than international values for reducing occupational exposures. Hardemann et al. (1998), for example, recommended values of 85 kUS$/person-Sv in the dose range of 1–2 mSv, and 350 kUS$/person-Sv in the dose range of 2–5 mSv. On the other hand, the remedial actions considered in our analysis cannot avoid that the number of inhabitants of settlements with annual doses exceeding 1 mSv continues to be high. Relocation has not been considered in this study, because ICRP (2007, p. 117) recommended this countermeasure only for much higher dose values.

Remedial actions to reduce the caesium contamination of milk remain a key factor in remediation strategies. In Belarus, however, and also in Russia, replacement of contaminated soil in populated areas needs to be included in the remediation strategies, because of the importance of the external radiation from radiocaesium that has been deposited in the settlements.

Although the ingestion of contaminated mushrooms and other forest produce is of increasing importance for the internal dose in affected settlements in Belarus and Russia, countermeasures against this pathway are not an essential part of the remediation strategies derived in this study. The reason is that no effective and cost-effective countermeasure other than an information campaign about this pathway is known to the authors.

Table 5
Summary for arbitrarily chosen funds available in 2010: Strategy 1 corresponds to $\beta=0.1$ (degree of acceptability of the remedial actions important), Strategy 2 to $\beta=1.0$ (only costs per averted dose are considered).

Strategy/ country	Costs (k€)			Averted dose (person-Sv)			Costs per averted dose (k€/person-Sv)		
	RI + FA	RS	All	RI + FA	RS	All	RI + FA	RS	All
Strategy 1									
Belarus	467	452	1003	6.9	14.1	21.4	68	32	47
Russia	1721	–	2024	75.0	–	75.6	23	–	27
Ukraine	1372	–	1372	45.3	–	45.3	30	–	30
All	3560	452	4399	127.2	14.1	142.3	28	32	31
Strategy 2									
Belarus	116	884	1002	3.7	23.5	27.3	31	38	37
Russia	850	1151	2001	56.7	54.2	110.9	15	21	18
Ukraine	378	–	378[a]	23.5	–	23.5	16	–	16
All	1344	2035	3381	83.9	77.7	161.7	16	26	21

'RI' stands for radical improvement of grassland, 'FA' for application of ferrocyn to cows and 'RS' for replacement of contaminated soil in populated areas. The other three remedial actions play only minor roles.

[a] The effective dose to the representative person in 2010 can be reduced below 1 mSv in all settlements by investing 378 k€ according to Remediation Strategy 2.

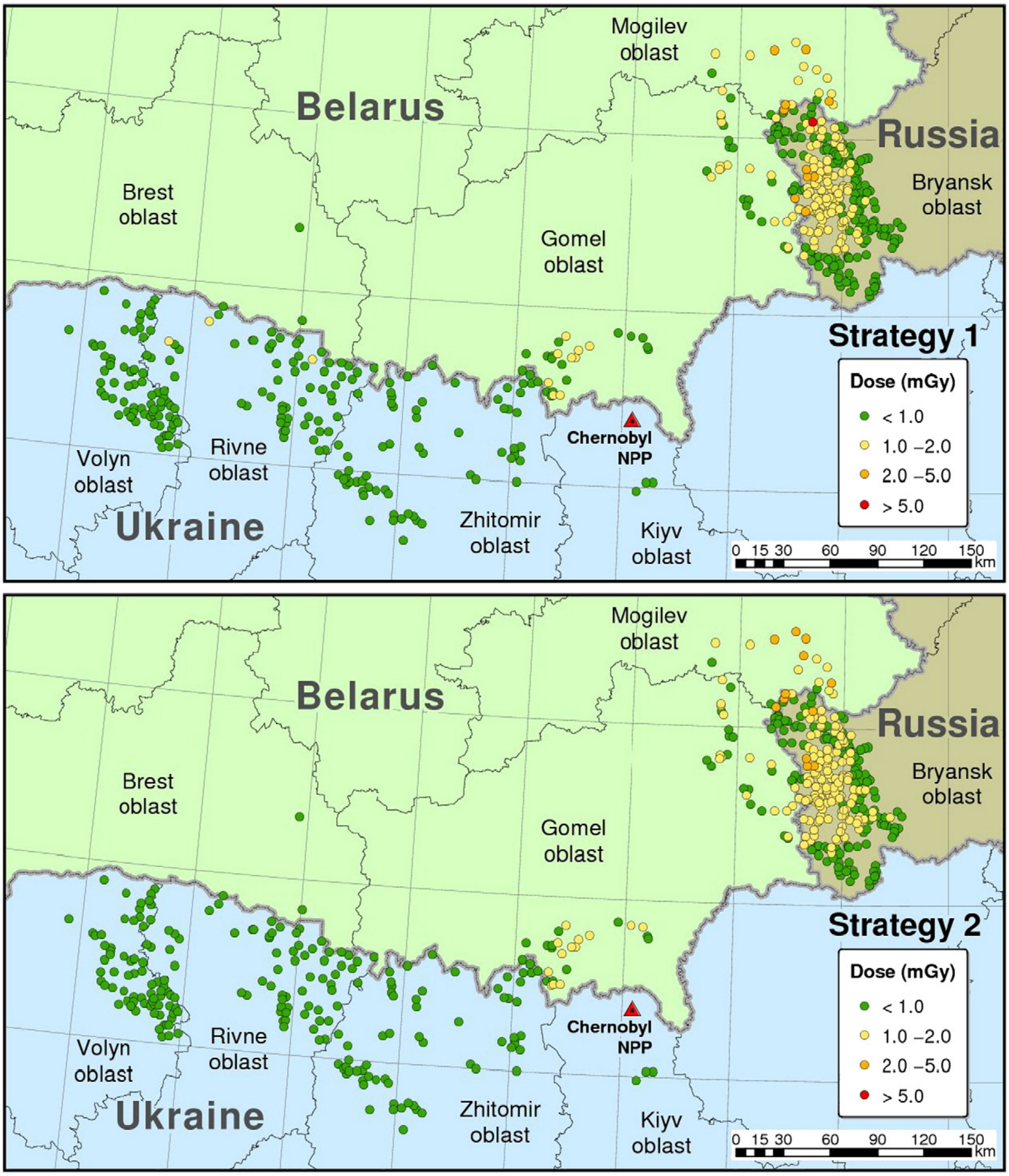

Fig. 5. Maps of the 541 study settlements coloured according to the dose from ^{137}Cs as calculated with *ReSCA* for available resources as given in Table 5: Upper panel for application of Remediation Strategy 1 ($\beta = 0.1$, degree of acceptability important), lower panel for application of Remediation Strategy 2 ($\beta = 1.0$, only costs per averted dose are considered).

4.2. Strengths and limitations of the present study

The strengths of the present study are:

- a procedure for assessing the dose to the representative person, which has been validated by a huge data base of TLD (external exposure) and WBC (internal exposure) measurements
- a methodology that allows taking into account settlement-specific radioecological conditions and that can be applied at the same time to the whole of the affected area in the three countries
- a first assessment of the radiological situation in the three countries affected by the Chernobyl accident that is based on settlement-specific data
- a simple algorithm that allows putting arbitrary weight on the side effects of the countermeasures
- a unitary approach for Belarus, Russia and Ukraine to recommend remediation strategies in the rural settlements still affected by the Chernobyl accident.

Limitations of the study include:

- incompleteness: there may be a small number of affected settlements, which have not been included in the study, because their 2004 catalogue dose is below 1 mSv (this applies only to Russia and Ukraine)
- too generic input data for a decision on remedial actions in a given settlement. This is particularly the case for the costs for drainage of wet

peat and for replacement of contaminated soil. Also, degrees of acceptability of the various remedial actions may vary in the different contaminated areas (Fesenko et al., 2007; Howard et al., 2005)
- subjective choice of parameter values for an information campaign on mushrooms and other forest produce
- time dependencies have been only taken into account in so far as averted doses are considered for the whole period, for which remedial actions are effective. The application of remedial actions, that need to be applied continuously (e.g., FA), is considered only for one year. Costs and averted doses of such remedial actions in the following years are not taken into account
- use of data for the year 2004. Radiological conditions might have changed since then
- uncertainties have not been taken into account. However, the authors believe the settlement- and area-specific variability to be considerably higher than the uncertainty of the representative values chosen in the present calculation.

Generally, it should be kept in mind that *ReSCA* is only a support for decision making. Although settlement-specific parameters are used, more local conditions will have to be taken into account in decisions on remediation strategies.

4.3. Comparison with a previous study

An earlier study on remediation strategies for rural territories contaminated by the Chernobyl accident (Jacob et al., 2001) made a prediction of the population in affected rural settlements that was based on the official dose catalogues for 1996 (1995 in Belarus). It is noticeable that the results for all three countries differ considerably from the results of the present study (Table 3). Compared to the earlier study, the assessed number of inhabitants in affected rural settlements is according to the present study

- considerably lower in Belarus and Ukraine, which is at least partially due to remedial actions, which have been applied in the meantime
- considerably higher in Russia, which is due to a change of the official dose calculation procedures in Russia.

The earlier study was based on radioecological data for 70 settlements and an extrapolation to the whole of the affected area (Jacob et al., 2001), whereas the present study used radioecological data for all affected settlements. Another difference is that the present study takes more explicitly into account side effects of the remedial actions. Nevertheless, qualitatively main results (see above) of both studies were the same. This includes the general conclusion that it is still quite cost-effective to apply remedial actions in the areas affected by the Chernobyl accident.

There are, however, quantitative differences, which are mainly due to the time that elapsed between the two studies. Whereas the earlier study assessed that in 1996 about 2000 person-Sv could still be averted, it is assessed in the present study that according to the conditions in 2010 only about 150 person-Sv could be averted at reasonable costs. A part of this difference has indeed been averted by remedial actions applied in the countries during this time period.

Whereas the earlier study assessed that in 1996 a cost-effectiveness of about 7 k€/person-Sv could be achieved, remediation strategies derived in the present study for conditions as in 2010 have an overall cost-effectiveness of about 20 k€/person-Sv in Russia and Ukraine, and a higher value in Belarus. This demonstrates the importance of implementing remediation strategies as soon as possible.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi: 10.1016/j.scitotenv.2009.09.006.

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