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# Evaluation of the effectiveness of countermeasures in contaminated forests

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**Abstract.** In many regions subjected to the contamination after the ChNPP accident forest products play an important role in radiation impact on the population. The decision making framework to optimise implementation of forest countermeasures in the long term after the ChNPP accident is described. The approach is based on the analysis of the main exposure pathways related to contaminated forest and application of different criteria (reduction of individual dose, cost for implementation; cost of averted dose of 1 man-Sv; secondary ecological effect and psycho-social impact) for the selection of optimal countermeasures strategies. Results of the application of the approach proposed for the study area (Novozybkov district, Russian Federation) are presented. The results emphasize the effectiveness of the application of a flexible decision support technologies for the optimization of countermeasures taking into account radioecological and economic features of contaminated forests.

## 1. INTRODUCTION

In many areas contaminated after the Chernobyl accident, forests and forest products are an important source of internal and external exposure of the population [1]. In the first period after the ChNPP accident, the contribution of agricultural products (mainly milk) to the internal dose was much higher than that of forest products. In the long term after the ChNPP accident, the importance of forests in exposure of the population increases and in some situations doses from consumption of forest products are comparable with agricultural ones [2]. Therefore, according to the experience gained after the ChNPP accident, serious attention should be given to forest countermeasures, and remediation strategies in terrestrial ecosystems should be selected on the basis of a comparative analysis of the effectiveness of forest and agricultural countermeasures.

Forest countermeasures have to be considered under four aspects: radiological, economic, environmental or ecological and social. Economic and social consequences are connected with the restrictions of access which should be applied in the contaminated forests as well as with extra expenses for the countermesure implementation. The restrictions result in losses of forest products in which radionuclide contents exceed permissible levels (PLs). This has negative economic consequenses and leads to negative psychological impact on the population which considers a forest as a source of risk. Besides, countermeasures can be optionally applied in areas where dose to the population exceeds 1 mSv $a^{-1}$; countermeasures are necessary when doses are exceeding 5 mSv per year. In the dose range from 1 to 5 mSv countermeasures should be applied on an optimised basis.

However, these aspects are not still adecvately considered in the current guides on implementation of countermeasures in contaminated forests. Overall, this indicates a need for the improvement of the current approaches to the selection of optimal countermeasures options in contaminated forest.

## 2. GENERAL APPROACH

The justification of countermeasure strategies implementation in contaminated forests can be considered in several steps (Figure 1). The first step is the evaluation of the necessity of countermeasures application. Its objective is to identify forest areas where forest products exceed PLs and settlements where annual effective doses are above the radiation safety standard of 1 mSv per year.

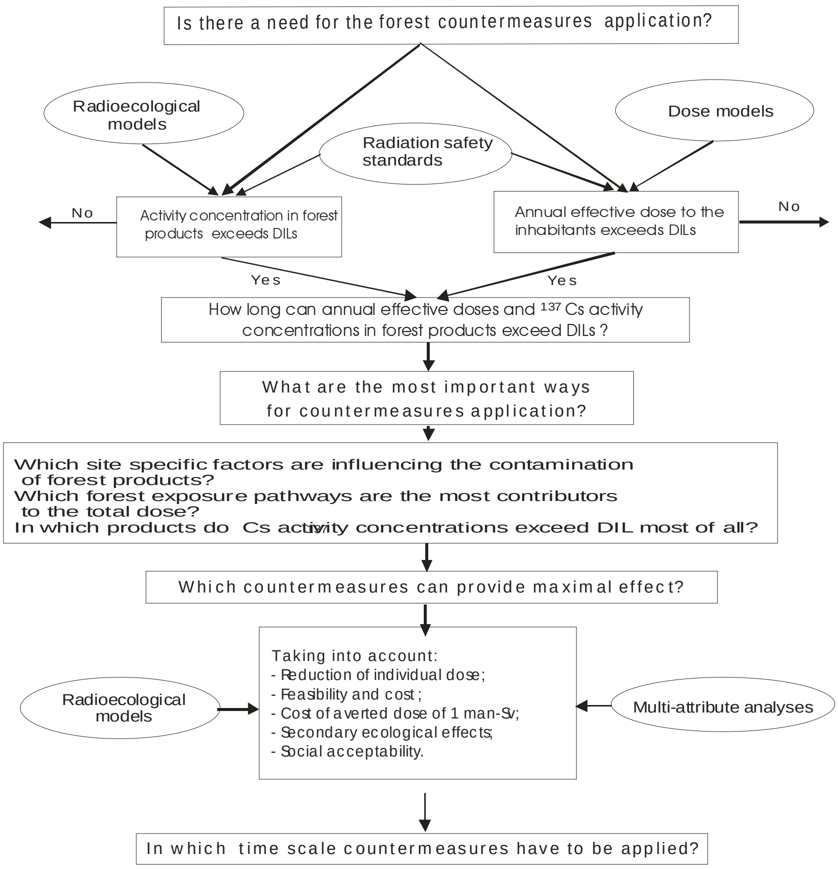


Figure 1. Framework of decision making on forest countermeasures application

In the case if at least one of these criteria is observed, the duration of the period when there is a need for countermeasures application should be evaluated and conclusion about the necessity in forest countermeasures should be documented. The objective of the second step is to justify the most important ways for the countermeasures implementation. The analysis of the importance of the exposure pathways is a necessary step before applying countermeasures, because their effectiveness in terms of dose reduction is the greater, the higher is the significance of exposure pathway for which countermeasures are applied. Besides, it is not possible to propose the same countermeasures for areas with different contamination levels or forest properties and classification of forests is needed to provide realistic countermeasures options. Density of contamination of forests, type of forest and type of forest soil should be considered among these factors and selection of optimal countermeasures strategies should be done for forest areas with more or less uniform properties governing concentrations of radionuclides in forest products or doses resulting from contaminated forest.

The main objective of the third step is the identification of countermeasures strategies, which can provide maximal effect. This step includes a comparative analysis of the effectiveness of possible countermeasures and evaluation of secondary ecological (indirect) effects, which are specific for each forest area. The peculiarity of forests as a subject for countermeasures application is the complexity of criteria used for the evaluation of their effectiveness and reduction of individual dose; cost of countermeasures implementation; cost of averted dose of 1 man-Sv and social acceptability should be listed. Because of diversity of these criteria, modern decision support technologies based on multi-attribute analysis have to be applied to identify optimal countermeasure options.

The final step is justification of the time scale in which forest countermeasures should be applied taking into account results of cost-benefit analyses.

## 3. EVALUATION OF THE EFFECTIVENESS OF FOREST COUNTERMEASURES

The Novozybkov district located 180 km northeast of the Chernobyl NPP was selected as a case study area for the application of the approach described above. The average deposition density of $^{137}$Cs on the territory of this district was about 750 kBq m$^{-2}$ while contamination of forest soils varied in a range from 150 to 2500 kBq m$^{-2}$. The data obtained for the study area were united within zones with different levels of contamination (above 1480 kBq m$^{-2}$ - zone A, between 555 and 1480 kBq m$^{-2}$ - zone B and between 185 and 555 kBq m$^{-2}$ - zone C) and, consequently, with different scales of countermeasures application. The more detailed description of this area is given elsewhere (Fesenko et al., 2000).

Official information regarding internal and external doses to inhabitants of the settlements located on the contaminated territory is available for several years after the accident and was published in recent years. Mean data of annual effective doses in the settlements of different zones calculated on the basis of information available from dose catalogues as well as on results of the FORESTLAND model [3] predictions are shown in Fig. 2. The time-dependent experimental data on concentrations of $^{137}$Cs in berries and mushrooms are available for the study area for 1987 – 1996 [2]. The predictions made with the aid of FORESTLAND model indicate that $^{137}$Cs activity concentrations in mushrooms and berries can exceed PLs (500 Bq kg$^{-1}$ and 160 Bq kg$^{-1}$) for extremely long time: up to 2077 and 2087, 2055 and 2073, 2038 and 2037 in zones A, B and C, respectively.

These results indicate that the application of countermeasures is of importance up to 2025, 2015 and 2005 in zones A, B and C, however, countermeasures on restriction or optimisation of mushrooms and berries consumption can be considered even outside these time periods.

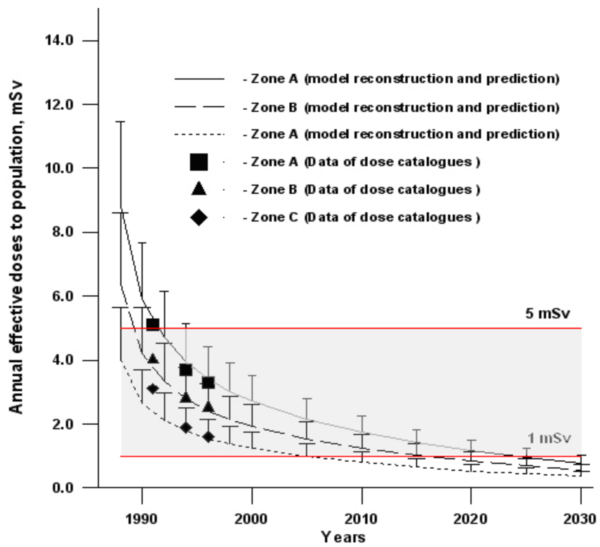


**Figure 2.** Variation with time of average effective doses to the population of the study area. Bars reflect dose variability across zones A, B and C dependent on exposure of the population in individual settlements. Dose range where countermeasures should be applied on an optimised basis is shown by shadow.

Evaluated on the basis of the results given in [2] contributions of different pathways to the exposure of critical population group members and for the rest population are given in Table 1.

**Table 1.** Contributions of exposure pathways in zones with different contamination levels, %.

| | Zone A | | Zone C | |
|---|---|---|---|---|
| | Normal population | Critical group | Normal population | Critical group |
| External dose within the forest | 3 | 1-18 | 4 | 2-17 |
| External dose within the settlement | 41 | 11–17 | 44 | 17–24 |
| Internal dose from milk and meat consumption | 33 | 58–66 | 35 | 54–60 |
| Internal dose from mushrooms consumption | 19 | 11-14 | 13 | 1–12 |
| Internal dose from berries consumption | 2 | 1-2 | 1 | 1–2 |
| Internal dose from the other products consumption | 2 | 1-2 | 4 | 1-2 |
| Contribution of the internal dose to the total one | 56 | 71-83 | 52 | 66-75 |
| Contribution of forest pathways to the total dose | 24 | 83-88 | 18 | 75-83 |

In terms of individual exposure pathways, the highest contribution to the total dose to the population is the external dose within (or near) settlements, followed by internal doses with milk and meat products, mushrooms, and finally berries and external dose associated with the forest contamination.

For critical population group members the forest pathways play a dominant role (exceeding 70% of the total dose) and it might be expected that application of forest countermeasures is the most effective way in decreasing the contamination impact. The most important pathway is related to the consumption of “forest milk”. However, even when using alternative feedstuff this pathway would be excluded, the contribution of other forest pathways (such as mushrooms consumption and external irradiation of foresters within contaminated forest) is rather important vary in a range from 23 (only mushrooms and berries) to 57% (all forest exposure pathways).

Based on these results, the potential effectiveness of forest countermeasures in terms of dose to critical population group reduction can be ranked as follows: “forest milk consumption”>”mushrooms consumption”>”external dose in the forest (to foresters)”>”berries consumption”>“visiting forest for recreation and mushrooms (berries) gathering”.

The effectiveness of forest countermeasures in terms of percentage of the total dose reduction estimated based on data of Table 1 as well as related cost per hectare of forested area, their acceptability and cost of one man-Sv averted are given in Table 2. Collective doses, which can be averted due to forest countermeasures application were calculated based on the approach presented elsewhere (Fesenko et al., 2000) and the cost of the countermeasures was taken from studies carried out in this region and includes the necessary resources, manpower, equipment, consumable [4].

**Table 2.** Effectiveness of forest countermeasures in terms of annual effective dose reduction, cost, acceptability and cost of one man-Sv being averted after countermeasures application for 2003, thousand USD.

| Countermeasures | Decrease of | effect. dose, % | Cost US $ | Accept- | Cost of |
|---|---|---|---|---|---|
| | Critical population group | The rest population | per ha | Ability | 1 man-Sv averted |
| Restrictive countermeasures | | | | | |
| A. Abandonment | 83-88 | 18-24 | 105-107 | Very low | 297-866 |
| B. No foresters access | 79-84 | - | 109-111 | Low | 231-770 |
| C. No public access | | 18-24 | 103-104 | Low | 295-861 |
| D. Restriction on grazing of domestic animals or using forest grass for fodder | 54-58 | - | 4.3 | Moderate | 16.5-53.7 |
| E. Restriction on mushroom collection | 9-11 | 13-19 | 24-26 | Low | 14.2-53.4 |
| F. Restriction on berries collection | 0.9-1.8 | 1-2 | 14-15 | Low | 87.8-305 |
| Optimisation in forest management | | | | | |
| G. Limitation of tree harvesting to the areas with low doses | 2-5 | - | 0.48 | Very high | 246-785 |
| H. Limitation on mushrooms collections to the species with low accumulation | 3-4 | 3-4 | 0.64 | Moderate | 5.8-21.6 |
| I. Mushrooms processing before consumption | 3-4 | 3-4 | 0.46 | Moderate | 6.6-24.6 |
| Application of Cs binders | | | | | |
| J. Decrease of contamination of “forest milk” | 30-49 | - | 0.14 | High | 1.5-5.2 |
| Soil based countermeasures (only for berries) | | | | | |
| K. Liming | 0.5-1.0 | 0.6-1.2 | 12.7 | Low | >1000 |
| L. Application of potassium | 0.4-0.9 | 0.5-1.0 | 130 | Low | >1000 |

It can be seen (Table 2) that the most effective way to reduce the impact of contaminated forests on the population is the application of options for reducing exposure from mushrooms consumption. As for the critical population group, this pathway is also important, however, as outlined earlier, a more effective option is to decrease the “forest milk” exposure pathway. The lowest effectiveness in terms of dose reduction as well as the highest cost and low acceptability are typical for soil-based countermeasures, which excludes these options from the further analysis.

A decision analytic tool based on a *PRIME* (*P*reference *R*atios *I*n *M*ulti *A*ttribute *E*valuations) technique was applied to justify optimal countermeasure strategies, [5]. In the frame of this technique the following steps allowing the identification of a reasonable decision are considered:

- Identification of the alternatives and their attributes;
- Preference assessment;
- Determination of the best alternative.

The objectives of the first step are identification and description of possible alternatives. Within this step, each countermeasure listed in Table 2 (or their combinations) have been considered as an alternative, and the above mentioned criteria were taken as their attributes which were defined for each alternative from Table 2. Levels of acceptability were transformed into numeric scale: “Very low” -5, “Low” - 25, “Moderate” - 50, “High” - 75 and “Very high” - 90.

The objective of the preference assessment is to identify priorities in the selection of optimal forest countermeasures strategies. The first phase in preference assessment is to assess the weights of the attributes. The weight ranging from 0 to 100 is a subjective ranking based on expert judgement taking into account general preferences related to forest countermeasures application.

Two main possible strategies of forest countermeasure application in the long term after the ChNPP accident can be considered: the first one (dose reduction strategy) is based on the preference of maximal reduction of effective dose and the second one (acceptability strategy) is aimed on maximal acceptability of countermeasures. Taking into account these preferences, attributes were weighted in two following ways: reduction of effective dose (100-100)>acceptability (70-90)> cost of 1 man-Sv averted (60-80) and cost for countermeasure application (40-50); reduction of the effective dose (70-90)> acceptability (100-100)>cost of 1 man-Sv averted (60-80) and finally cost for countermeasure application (40-50).

The third step directly concentrates on the selection of optimal alternatives and includes analysis of “value intervals” and decision rules, which allow the selection of the optimal alternative (countermeasures). The notion of the value interval of an alternative refers to the alternative’s value interval of the main goal, since it contains the total value of an alternative (Fig. 2).

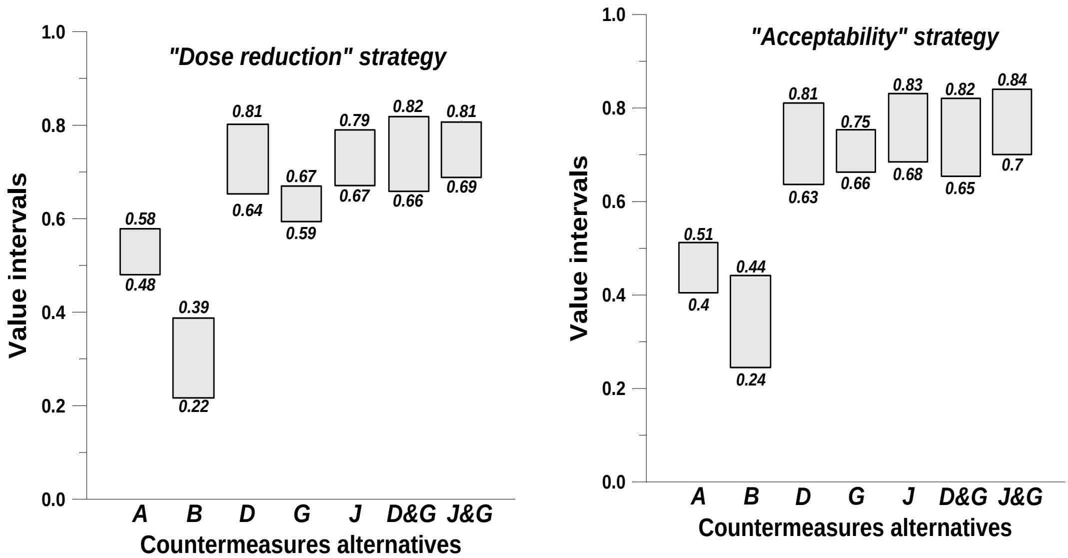


**Figure 3.** Value intervals of alternatives in forest countermeasures applications (critical population group).

It can be seen on the basis of these results that the restriction on using forest grass for fodder (alternative D) or using Prussian blue to decrease “forest milk” contamination (J) in combination with limitation of tree harvesting to the area with low doses (alternatives D&G and J&G) are likely dominating in the selection of optimal countermeasures options for critical population groups but this information doesn’t allow making the final decision. As for the rest population, the results have shown that a combination of forest countermeasures such as “Limitation on mushrooms and berries collections to the species with low accumulation in the combination” and “Mushrooms processing before consumption” (alternative “H&I”) has likely a good chance to be selected as the best option.

Decision rules are assisting the decision maker in the determination of the best alternative. *PRIME* Decisions [5] provides four decision rules that apply to different situations. The available rules are maxi-max, maxi-min, central values, and mini-max regret [6].

Mini-max regret takes a different approach and calculates the possible loss of value for each alternative by using dominance data. Thus, this technique selects the alternative with the minimal possible loss of value. The results of such calculations have shown that for both "Dose reduction" and "Acceptability" strategies alternative J&G for the critical population group and H&I for the rest population are marked as the most appropriate practically and possible loss of value calculated on the basis of mini-max regret technique is shown in Fig. 3 to confirm this conclusion.

The final step in the methodology suggested for the evaluation of the effectiveness of forest countermeasures is the estimation of time periods when they should be applied. The ICRP Publication No. 37 (ICRP, 1983) considers measures justified when the cost of reducing the collective dose by 1 man-Sv is within the range of 10-20 thousand US $. Results of such calculations for the countermeasures identified as an appropriate are given in Fig. 4.

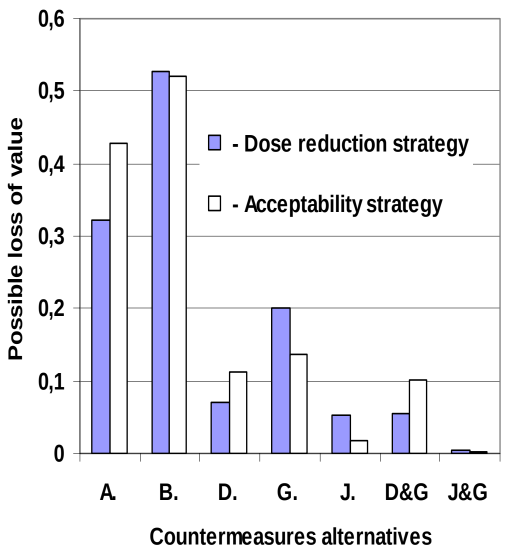


**Figure 4.** Loss of value for alternatives in application of forest countermeasures (critical population group).

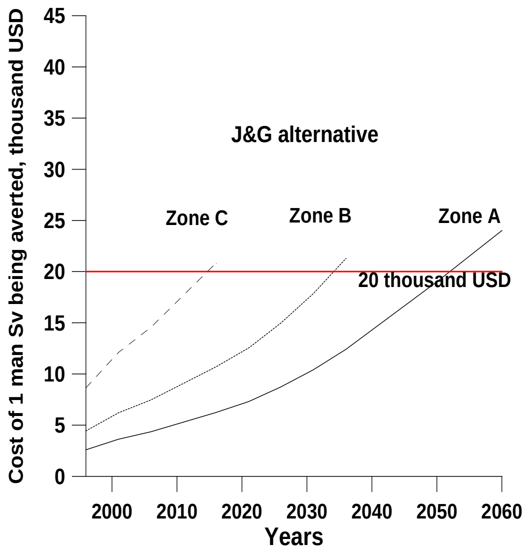


**Figure 5.** Variation with time of the cost of 1 man-Sv being averted (critical population group).

The information presented in Fig. 4 indicates that combined application of Prussian Blue to decrease exposure of the critical population group members and limitation of tree harvesting to the area with low doses is also in agreement with cost of 1 man-Sv requirements and hence completely justified. However, in this case the cost of 1 man-Sv being averted will exceed 20 thousand USD only in 2015, 2034 and 2053 in zones A, B and C, respectively and application of the countermeasures suggested might be continued outside the periods when average annual effective dose is less than 1 mSv $a^{-1}$.

The results obtained allow the conclusions that application of forest countermeasures in the most contaminated areas of Russia will be necessary for at least several more decades and an application of the decision-making framework based on combined consideration of radioecological, social and economic features of forests countermeasures is useful for the selection of optimal long-term actions. It has been also found that restrictive options as well as soil based forest countermeasures are not applicable in the long term after the Chernobyl accident and more attention in the long term after the Chernobyl accident should be given to the optimisation in forest and forest products usage.

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