SITE CHARACTERIZATION TECHNIQUES USED IN RESTORATION OF AGRICULTURAL AREAS ON THE TERRITORY OF THE RUSSIAN FEDERATION CONTAMINATED AFTER THE ACCIDENT AT THE CHERNOBYL NPP

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ABSTRACT

The experience gained in the aftermath after the heavy radiation accidents shows the need for improvement in site characterisation techniques and methodology in order to provide a link between site characterisation and the selection of restoration strategies. This paper gives an overview of the site characterisation techniques used in restoration of contaminated agricultural lands on the territory of the Russian Federation. The approach used for site characterisation and selection of restoration strategies is described. The main site specific factors influencing the choice of restoration options are identified. Data on the efficiency of major restoration measures used for the remediation of agricultural lands after the Chernobyl Nuclear Power Plant and the Kyshtym accidents are given. A description of the decision support system FORCON, designed to simplify the selection of restoration options, is presented.

1. INTRODUCTION

The accident at the Chernobyl Nuclear Power Plant (NPP), both in times of released activity and the area subjected to contamination, was the most serious ever to have occurred in the history of nuclear energy. Those countries most seriously affected include the republics of Russia, Belarus and the Ukraine, which are estimated to have received about 70% of the fallout [1]. As a result in the first time in history vast areas were heavily contaminated, and a large proportion of them require large scale restoration.

In this context, agricultural ecosystems are among those environments of considerable interest. It has been shown that in many cases the contribution from internal irradiation is comparable to that of external irradiation. Thus, in the first year after the accident at the Chernobyl NPP the contribution of internal irradiation to the total equivalent effective radiation dose for the population of the Confederation of Independent States (CIS) countries amounted to 45% (that of external to 52%), and for the life time dose these values were 39% and 60%, respectively [2]. In regions with high mobility of radionuclides in the soil, where the contribution of internal irradiation predominates, the restoration of agricultural lands should have priority in restoration policy. On the contrary, in such areas where external irradiation exceeds considerably the internal one, attention can be paid to the more costly options based on the decontamination of the territory.

The experience gained in the aftermath of the heavy radiation accidents shows that, in the case of large scale contamination, the limitation of internal radiation doses to people living in areas subject radioactive contamination by means of restoration of agricultural lands is economically more realistic, than to decrease dose burdens from external irradiation. Therefore, the problems connected with the optimal restoration strategies of agricultural land subject to radioactive contamination were of crucial importance from the point of view of providing safe living conditions for the population in the regions affected after the Chernobyl and Kyshtym accidents. A necessary component in the decision making for the selection of optimal restoration options is the site characterisation of agricultural areas and the evaluation of factors controlling the accumulation of radionuclides in agricultural products.

The objectives of this paper are to present the analysis of the site specific factors considered in selecting the remediation options in regions contaminated after the accident at the ChNPP and to give an overview of site characterisation techniques used in restoration of agricultural areas on the territory of the Russian Federation heavily contaminated by the radiation accidents.

2. APPROACH USED FOR THE SELECTION OF OPTIMAL RESTORATION OPTIONS FOR REMEDIATION OF AGRICULTURAL LANDS

The general objectives of the agricultural land restoration can be formulated as follows:

- To provide opportunities for the production of agricultural products which can be used without any restrictions;
- To provide radiation safety standards for people involved in agricultural production.

Formally, justification of restoration strategies in the agricultural production could be presented in several steps:

(1) Site characterisation of contaminated agricultural lands;

(2) Evaluation of the need for restoration;

(3) Assessment of the effectiveness of different restoration options under particular conditions;

(4) Comparative analysis and ranking of the restoration options;

(5) Justification of the most effective restoration measures with taking into account costs, availability of resources, possible limitations and socio-economic impacts.

The general logic of making decisions concerning the application of restoration options on agricultural lands in the contaminated regions of the Russian Federation is outlined in Figure 1. It is clear that all steps concerning justification of the restoration options depend directly or indirectly on the quality of the site characterisation. So, evaluation of the necessity for restoration, of the effectiveness of the restoration options, and of their ranking has to take into account many site specific factors, which control the mobility of radionuclides in agro-ecosystems, and the significance of different pathways for irradiation of the population.

The specific peculiarity of agricultural areas as a subject for remediation is the complexity of criteria used for the evaluation of restoration options. So, on the one hand, agro-ecosystems are important contributors to the collective dose for the population living outside of the contaminated area (imported dose). On the other hand, very often they determine the dose of irradiation the rural population involved in the food production receives. These result are different criteria for the restoration of agricultural land used for producing exported and locally consumed products.

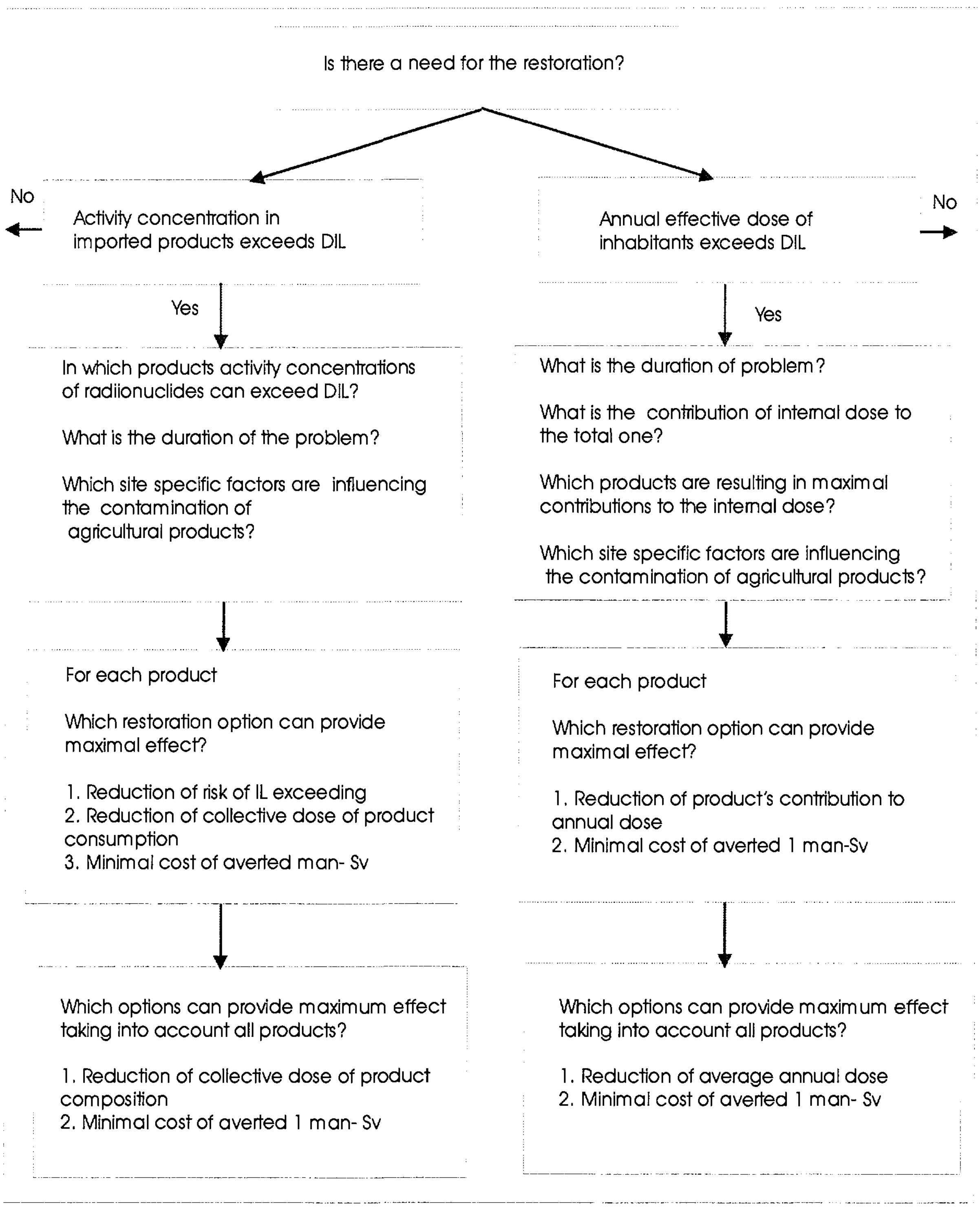

FIG. 1. The conceptual scheme of decision making on the application of restoration measures for agricultural land.

In the first instance the main criterion for determining the necessity for restoration is the exceeding of appropriate non-accidental Intervention Levels for radionuclides concentrations in agricultural products, which have been adopted for each product and each radionuclide. In the second instance, the criterion for determining the necessity for restoration is the average annual effective dose received by inhabitants of settlements located on the contaminated territory. The Federal law adopted in 1996 by the Russian Federation restricts the additional irradiation of the population by 1 mSv/y, which is now applied as Intervention Level [3]. The main difference between these criteria is that the first one limits the production of agricultural products in zones, which require the restoration, and the second one is aimed at lowering annual doses to the local population to less than 1 mSv/y.

Another point which should be considered when justifying the approach selected from the range of available restoration options, are the criteria for the selecting these options. It is clear that, at the stage of identifying optimal restoration strategies, using the criteria allows to make a reasonable choice. Among such criteria the following need to be considered:

- Reduction of risk from exceeding of Derived Intervention Levels (DIL_S);
- Reduction of collective dose from product consumption;
- Cost of averted dose of 1 man-Sv.

The first of the above criteria is the most important, when the concentrations of radionuclides in agricultural products are above DIL_S over a large territory.

It allows to evaluate the feasibility of obtaining foodstuffs that meet existing standards, as well as to determine the period of time for which restoration measures need to be applied to zones according to their level of contamination. The remaining criteria are of secondary importance and are used for selecting the most effective options. Thus comparable effects in terms of decreasing the radionuclide concentrations in products can be achieved by applying a wide range of different restoration measures. In order to select the most rational ones, additional criteria and data should be employed. In this case one should use more general criteria which take into account the dose reduction resulting from the application of these activities and their respective costs.

The cost of one man-Sievert being averted as a result of applying restoration measures application is often used as an integral indicator. The ICRP Publication no. 37 [4] considers measures justified, when the cost of reducing the collective dose by 1 man-Sv resulting from their application is within the range of 10–20 thousand US$. In this case the upper limit can be treated as a criterion for the most developed and the lower limit for the less developed countries.

3. SITE CHARACTERIZATION OF AGRICULTURAL LANDS FOLLOWING RADIOACTIVE CONTAMINATION

The importance of agricultural ecosystems as a source of irradiation for the population depends on site-specific features of the contamination, which directly highlights the need for adequate site characterisation. Among specific characteristics of agricultural land contamination determining the need for restoration measures the following can be considered:

- Degree of contamination of the agricultural lands by long lived radionuclides;
- Mobility of long lived radionuclides in soil;
- Land use.

As was noted earlier the goal of such characterisation is to provide the information needed for decision making on the restoration of contaminated lands. The parameters listed above are considered as the most important for this type of site characterisation. Owing to this fact three monitoring programs in agriculture were carried out in the Russian Federation after the heavy radiation accidents.

The objective of the first monitoring programme was to provide a characterisation of agricultural lands at the scale of individual fields in production. Identification of such site-specific characteristics as a degree of contamination by long lived radionuclides, soil properties and land use were included into this programme. Three surveys were performed between 1986 and 1996.

The second programme carried out on an annual basis at the level of each collective farm or settlement and concentrated on the estimation of current levels of radionuclide concentrations in agricultural products.

The aim of the third program was to estimate mobility of radionuclide in agroecosystems as a function of soil properties, type of land use and other factors. Estimations of the decrease in the contamination of typical plants and soils for each type of land use were also included. These more comprehensive studies were organised on stationary plots, where observations were carried out on a regular basis.

A system of distributed data bases was created for the collation of all these data in order to allow the implementation of a decision support systems for the selection of appropriate restoration strategies as is described below. On the whole, this approach allowed to establish clear links between site characterisation and optimisation of restoration policies.

3.1. Levels of contamination of agricultural lands by long lived radionuclides

The levels of contamination by long lived radionuclides are one of the most important criterion for different restrictions on agricultural activities on contaminated lands.

In the case of the Kyshtym accident, the reference radionuclide was ^{90}Sr, determining the long term hazard of contamination of the environment. The agricultural lands with a contamination level above 74 kBq m^{-2} were excluded from economic use [5].

^{137}Cs is the basic dose-forming radionuclide in the zone of the Chernobyl NPP accident (except for the period during and immediately after the accident when short lived and intermediate term lived radionuclides played an important role). Only in the part of the 30-km zone around the Chernobyl NPP, where economic activities had to be discontinued, and in a small zone beyond it, ^{90}Sr is of some importance. Therefore, the evaluation of the radiological consequences of the accidental releases from the Chernobyl NPP, as well as the planning and implementation of restoration measures, are based on information on the ^{137}Cs levels in the environment and the trends of its concentration changes in agricultural products [6].

In the first period after the accident at the ChNPP, the decisions concerning the organisation of agricultural production on contaminated territories were mainly based on the level of contamination of agricultural lands by ^{137}Cs. Thus, agricultural land with a level of contamination above 1480 kBq m^{-2} were excluded from the economic use [7]. However, at the next stage, different restrictions and recommendations for the organisation of agricultural production, taking into account the mobility of radionuclides in the soil and the land use, were introduced for agricultural lands with contamination above 185 kBq m^{-2}.

3.2. Mobility of radionuclides along the agricultural food chain

The mobility of radionuclides along the agricultural food chain, and initially through the soil, is another important factor determining consequences of radioactive contamination and the need for the application of restoration measures. The mobility of radionuclides in agroecosystems depends mainly on two factors, i.e. on the soil properties and on the physical and chemical properties of the fallout itself.

3.2.1. Soil properties

The relevance of internal irradiation is particularly high in regions where low fertility soils are widespread (soils poor in nutrients and humus, with acidic pH, and of light sand or sandy loam composition). In such regions radionuclides bio-availability is high, and in consequence, transfer rates through the soil-plant system are higher than in heavier, more fertile soils, resulting in increased levels of radionuclides in agricultural products [8]. Such are the characteristic bio-geochemical conditions of the main zone with the highest contamination levels after the accident at the Chernobyl NPP. The zone includes the Polesyes area, straddling Belarus, Russia and Ukraine, where light sandy and sandy loamy soddy-podzolic and hydromorphous peat soils are widespread. In this region an increased mobility of ^{137}Cs (as well as that of ^{90}Sr) in the soil-plant system was noted as early as the 1960's following global fallout after atmospheric nuclear weapon tests [8]. According to the data in Balonov [9], on soddy-podzolic soils in the Polesye region, the contribution from internal irradiation to the effective equivalent dose after the Chernobyl NPP accident amounted to 90%, whereas on fertile heavy chernozem soils in the same region it did not exceed 10%.

Therefore, considerable effort was applied to ranking of the soils according to the mobility of radionuclides. The technique, which was applied for characterisation of soils, is based on the estimation of aggregated transfer factors (TFs) calculated as the concentration (Bq kg^{-1}) in plant per deposition density (kBq m^{-2}).

There are approximately 2,000 permanent measurement stations in Russia, where samples of soils and agricultural produce have been collected for radioactivity measurement since the mid-1970's. Of these, just over 200 are located in the Bryansk, Kaluga, Orel and Tula regions, which were subject to the most intense radioactive contamination following the Chernobyl accident. The main results from this monitoring programme are already available [10] [11]. For the purposes of soil characterisation, only those sites, which were subject to deposition following the Chernobyl accident, and to which no restoration measures were applied, have been included in the evaluation.

The Chernobyl accident resulted in the contamination of soils with widely varying soil characteristics. The main soil types in the contaminated zone are soddy-podzolic, soddy-gleyed and soddy soils of different mechanical composition, grey forest soils and chernozems of different subtypes (leached, podzolized etc.), peaty soils and flooded meadows. For the purpose of this study, soils have been divided into four groups according to their ability to retain ^{137}Cs. One group consists of peaty soils for which the highest ^{137}Cs transfer coefficients are normally observed. Mineral soils were divided into three groups according to their mechanical composition using the N.A. Kachinsky-classification routinely applied in Russia [12]. The main characteristics of the different soil types are presented in Table I.

The results show a clear difference between the transfer of ^{137}Cs to different crops and between soils respectively. As reported elsewhere [13] [14] [15] [16], the highest transfer rates are observed on peaty soils and on mineral soils. The rate of uptake decreases with increasing clay content. In terms of crops, the highest ^{137}Cs transfer is to annual grasses, followed by perennial grasses, maize and finally fodder beet. The data for all crops studied have been merged in order to derive a relationship between the uptake of ^{137}Cs from the different soil groups (Table II). Ratios have been calculated separately for each year and each crop and the geometric mean was subsequently calculated. The observed ratios show good agreement with those recently reported by the International Atomic Energy Agency for temperate climates [17].

3.2.2. Land use

Taking into account specific features of technologies four types of land use (natural, cultivated pastures, and arable lands used for silage, and cereal or potato production) can be considered. Annual grasses, perennial grasses, maize and cereal crops are typical plants for these types of the land use.

As was already noted, there are clear differences in accumulation of radionuclides between these plants. Data on the uptake of ^{137}Cs by plants show that the respective differences can be as great as a factor of 100 dependent on soil properties. With respect to selected groups of plants and within the period of 1991–1994 the highest TFs for ^{137}Cs occured to natural grasses (the geometric mean of TFs amounts to 15.6 10^{-3} m^2 kg^{-1}), followed by perennial grasses (6.1·10^{-3}), maize (1.7·10^{-3}) and finally cereals, potatoes and fodder beet (0.1·10^{-3}). This shows that the contamination of agricultural produce and, hence, the restoration requirements, depend on the specific combination of soil type and plant grown, i.e. they depend on the type of land use. On the other hand, the DILs for different agricultural products can also be different and, therefore, can influence the restrictions on agricultural land use.

The data from the monitoring programme mentioned earlier were used for estimating the differences in the levels of soil contamination, which would result in exceeding DILs in various products for different types of land use (Figure 2). These levels of soil contamination calculated as a ratio of DILs to TFs for reference plants are considered as the levels determining the need of restoration and can be easily applied in practice.

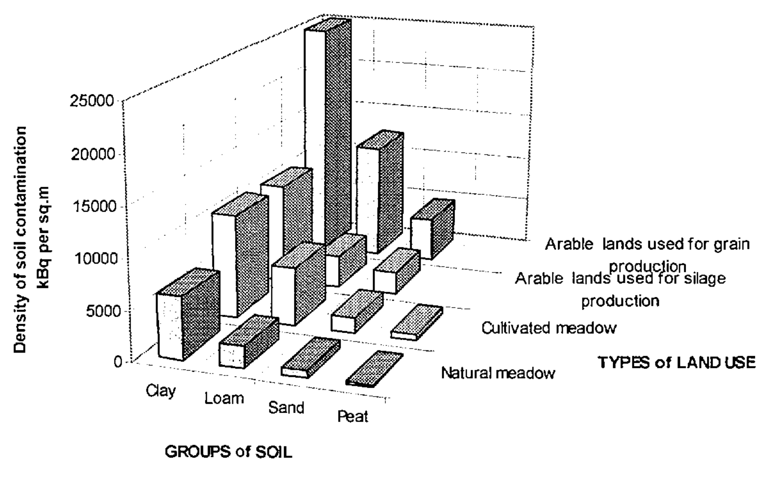

FIG. 2. Levels of soil contamination by ^{137}cs which would result in exceeding dils in the various products at different types of land use and soil groups.

The data presented show that differences between ^{137}Cs accumulation in plants typical for each type of land use result in different levels of residual contamination still restricting the use of agricultural produce. The influence of soil properties on the need for restoration can be also seen from the data given in Figure 2. It is thus possible to decide whether an area with a defined land use and soil type requires restoration, or whether a change in land use might be more appropriate. Such options might include the conversion of arable land into pasture, or handing over agricultural land to forestry.

3.2.3. Fallout properties

One of the peculiarities of the Chernobyl NPP accident was the duration of the radionuclide release into the environment [18] resulting in overlapping of radioactive trails and formation of zones with different physico-chemical compositions of the fallout [19] [20]. The major part of ^{137}Cs was deposited in the form of easily soluble finely dispersed aerosols, and some of it was included in coarsely dispersed particles and in fuel particles.

The fact that the ^{90}Sr and ^{137}Cs deposition after the Chernobyl NPP accident occured in two main forms — fuel particles from the destroyed reactor core, and condensed ones — resulted in two radionuclide fluxes into the agro-ecosystems, which were rather dynamic in the course of time after the accident and depended on the distance from the ChNPP. In the area where the condensed form of ^{90}Sr and ^{137}Cs dominated, the contaminants were characterised by high mobility and consequently elevated availability for plant uptake. To the contrary, ^{90}Sr and ^{137}Cs released into the environment as fuel particles were less available for root uptake at least during first few years after the accident. This fact did not correspond to the common behaviour of ^{137}Cs and ^{90}Sr of global origin, as well as to the data from experimental investigations in the accident area in the South Urals (Kyshtym, 1957).

The presence of ^{137}Cs in form of particles in the soils results in the development of two simultaneous, but opposing processes, i.e. an increase with time of the plant "available" amount due to the destruction of fuel particles, and a decrease in its "mobility" due to the fixation of ^{137}Cs by the organic and clay-mineral soil fractions.

Results derived from studies carried out in the vicinity of the ChNPP [21] show that the mechanism of plant uptake of fuel particle-derived radionuclides is of a complicated nature. For instance, in 1986 the ^{137}Cs plant uptake decreases with increasing fuel component in the fallout, due to a high proportion of it in fallout being bound in fuel particles during this period and, thus, not available for plant uptake. Subsequently, as a result of destruction of fuel particles and leaching of ^{137}Cs, the character of this dependence changes, and in the 3rd year after the fallout, plant uptake of radionuclides is an inverse function of the fraction of the fuel component, i.e. an increase of ^{137}Cs availability in the zones with high concentration of fuel particles in the soil can be observed (Figure 3).

Five to 7 years after the deposition, the ^{137}Cs plant availability in zones with different fallout characteristics equal out, which is due to the decreasing amount of radionuclides present in the form of fuel particles, and to caesium fixation in soil. It should also be noted that the degree of influence of fallout properties on the dynamics of ^{137}Cs-TFs to meadow vegetation depends also on soil characteristics. In the case of hydromorphic soils, the influence of fuel particles is more pronounced than on automorphic ones because of the higher mobility of ^{137}Cs in hydromorphic soils [21].

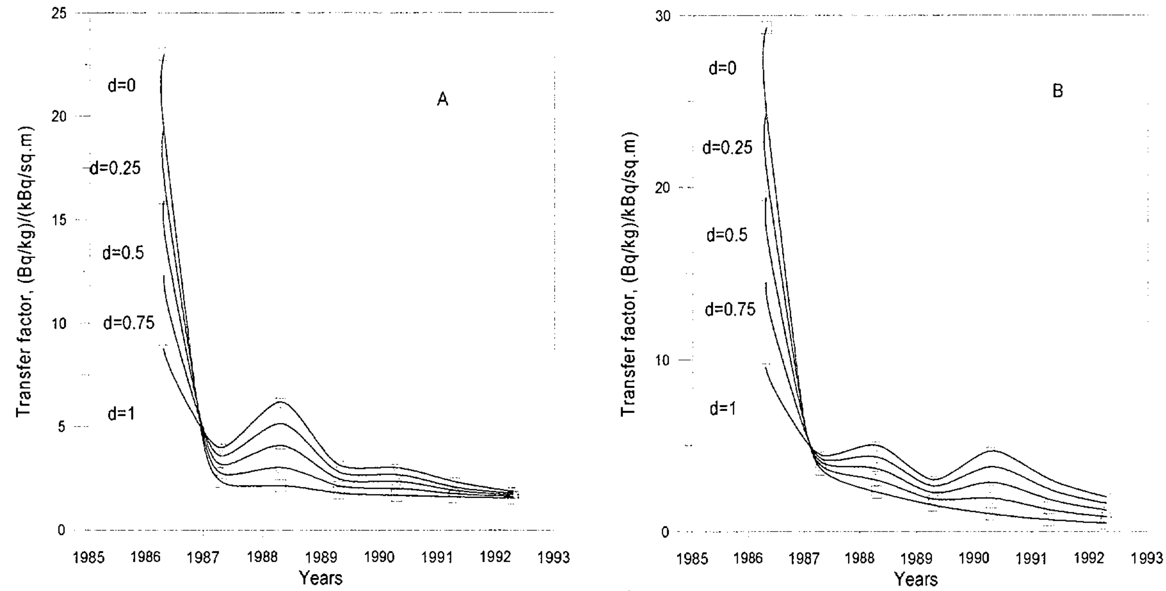

FIG. 3. Variation with time in the dynamics of ^{137}cs transfer factors (tfs) to meadow plants for different proportions (d) of fuel component in the fallout [21]; (a) automorphic soils; (b) hydromorphic soils.

4. FACTORS GOVERNING THE DECREASE OF ^{137}CS CONCENTRATIONS IN PLANTS

Assessment of the dynamics of internal doses during the post-accident period for the purpose of implementing restoration measures should include the estimation of decreases of radionuclide concentrations in agricultural produce with time elapsed after a single (accidental) release into the environment. This decrease is due to the fact that radionuclides transferred to the environment are gradually fixed by natural sorbents (soils, bottom sediments in water ecosystems, etc.) and become less biologically available for inclusion into the migration chain, in particular, into the soil-plant system. Therefore, effective half lives of ^{137}Cs in plants and residence times of ^{137}Cs in soil are among the most important parameters used for assessing the need for making adjustments to the restoration measures in the course of time after the contamination event.

4.1. Effective half lives of ^{137}Cs in plants

For comparative analysis of radionuclide bioavailability in food chains it is reasonable to use the half-life of the decrease of radionuclide levels in the various compartments of agricultural or natural ecosystems. Since radionuclide transfer is governed to a considerable extent by ecological factors, such parameters are usually defined as ecological half-life (T_{ec}).

According to the definition, ecological half-lives are equal to the period of time when content of radionuclides in some definite compartment of the trophic chain is decreased by half, due to all other factors, but except for radioactive decay. Effective half-lives (T_{eff}) have a similar definition, however in this case radioactive decay is taken into account.

Effective half-lives of ^{137}Cs TFs to plants are calculated on the basis of information derived from the monitoring programmes for the periods 1987 to 1990 and 1990–1994 mentioned earlier, and are given in Table III. For the initial years after the accident, the calculated values generally lie between one and four years, with most of the values ($R^2 > 0.9$) being less than two years.

The effective half-lives calculated for the period 1987 to 1994 are generally longer than those for the period up to 1990, thereby indicating that from 1990 onwards the rate of reduction in the uptake of ^{137}Cs by vegetation and fodder crops is reduced.

The databank of the International Union of Radioecologists has been used to estimate an effective half-life for ^{137}Cs uptake by agricultural crops, which was between four and eight years, although the inclusion of some early data from the former Soviet Union may have biased these calculations towards the lower end of the true values [22]. A different estimate is provided by the studies following the nuclear weapons testing, which suggest a half-life of eight to 15 years [15], although this value may not be directly comparable with the Chernobyl situation due to the different periods of deposition of the fallout. Clearly, a longer period of observation is required before the effective half-live can be applied to the current situation.

4.2. Mean residence times of ^{137}Cs in soil

This parameter requires the study of vertical distributions of radionuclides in soil profiles for different periods after the contamination event, as a basis for the validation and parametrization of the model used for the evaluation. Standard techniques of soil sampling and measurements are used at the first stage [8], allowing the determination of radionuclides concentrations in soil as a function of time and depth.

Validation of the model used for the residence-times calculations is a more complicated procedure. It has been shown elsewhere [23] that mean residence times calculated on the basis of simple compartimental or convection-diffusion models can not be used for the long term prediction of radionuclide transfer in soil, as they do not take into account the changing the mobility of radionuclides with time.

Therefore, to estimate the half-times of radionuclides in the top layer the more complicated model describing the variety of mobile ^{137}Cs fraction in soil as a result of sorption of radionuclides by soil and leaching the radionuclides from the fuel matrix as well as their vertical transfer was used [24].

The mean residence times in undisturbed soils of meadow of different types are shown in Table IV as an example of the results derived from this study.

The results presented indicate that the role of self-clearance for mineral soil is negligible. On the contrary, for wet meadows or peat land it can be an important factor, which effects a decrease in the intensity of ^{137}Cs transfer into food chains.

5. EFFECTIVENESS OF THE RESTORATION MEASURES

Restoration measure in agriculture can be classed into two groups: the restoration measures of the first group are based on the mechanical, physical or chemical treatment of soils, effecting either the removal of radionuclides from the soil or their fixation in some stable form, thus restricting their mobility in the environment. Normally they include [24]:

(1) Methods, which are based on the removal with or without replacement of the most contaminated top layer of the surface soil, with subsequent disposal of it at specially allocated places (excavating, planing, scraping, etc.);

(2) Methods for stabilization *in situ* without relocation of contaminated material, e.g. by cement stabilization, freeze crystallization or vitrification by thermal treatment, or the relocation of contaminants into deeper strata on site, e.g. by plowing-under, turning of flagstones, resurfacing roads,

(3) Methods for removal of contamination from soil *ex situ* or on site, e.g. physical separation techniques (screening, gravity and magnetic separation, vacuum swiping etc.), soil washing techniques (solvent extraction using water or solutions containing surfactants, chelating agents, acids or bases), or electrokinetic techniques.

The respective advantages and disadvantages of these methods are discussed elsewhere [24]. It is obvious that many of these techniques can only be applied to limited areas, owing to high unit costs, a general disturbance of the environment, and adverse impacts on important soil properties. Therefore, they had only limited application after large scale radiation accidents.

In general restoration measures in agriculture can be classed into three groups: organisational, agrotechnical, and agrochemical restoration methods.

Organisational methods in principal concern changes in land use. This may include increasing the area of land allocated to crops having a low accumulation rate for radionuclides. Other changes in land use are the conversion of arable land into pasture, or handing over agricultural land to forestry.

Agrotechnical restoration methods include deep ploughing with turning under the upper layer (on high fertility soils), and deep or superficial improvement of pastures. Many studies have been carried out on the effectiveness of root uptake reduction by meadow grass stands as a function of the various amelioration techniques. The techniques can be placed into two categories: deep and surface improvements. In addition, many combinations with ameliorants (lime, organic fertilizers and mineral fertilizers) which are potentially useful have been evaluated experimentally. Some restoration methods, however, have limited applicability; deep ploughing, for instance, is not applicable to soils with a thin humus layer. The advantage of these restoration methods is that they can be easily implemented as part of the normal agricultural practice.

Agrochemical options include liming of acid soils, application of increased doses of mineral fertilisers, addition of natural sorbents (different kinds of clay minerals) and use of organic fertilisers. The objective of applying mineral fertilisers to contaminated soils is to modify the ratio of the main plant nutrients. Liming is also one of the most important restoration methods that have been used to reduce caesium contamination levels in plants.

In the case of the Kyshtym accident, for the first time in the world experience with large scale restoration operations was gathered. Introduction of a complex of restoration programme for agricultural land in the area of the Eastern Urals Radioactive Trail (EURT) was iniated in spring, 1958. In the head part of EURT, the most contaminated zone, the soil cover consists of fertile soils, leached chernozems [8]. By a special soil treatment with burial of the upper layer containing radionuclides to the depths of 60 and 80 cm [8] [25]. In the EURT area, a radical amelioration of meadows and pastures was carried out, with the objective of providing a safe feeding basis for farm animals, that resulted in a 2- to 5-fold decrease of ^{90}Sr contents in plants used for fodder (Table V). Costly methods such as the removal and disposal of the contaminated upper 5–10 cm of the soil (scrapping) made it possible to achieve a 5- to 15-fold decrease of ^{90}Sr-transfer to the crops; however, this method was not applied widely [5] [8]

[25]. In essence an area of only 6200 hectares was subject to decontamination, using mainly the method of deep ploughing, thus bringing the upper radionuclide-containing layer to a depth of 50 cm.

In the of Kyshtym accident zone, the effect of mineral and organic fertilisers was tested, as well as that of liming the acid soils, with the objective of lowering the ^{90}Sr uptake by plants. On the average, liming resulted in a 10–30% decrease of ^{90}Sr-transfer to plants on the soils of the EURT, which belong to light acid type. Other options for lowering ^{90}Sr content in plant products were considered, such as cultivating crop varieties characterised by low accumulation of this radionuclide.

The Chernobyl accident provided a new example for a large scale application of such restoration actions. The experience from the previous accident was applied, taking into account the specific characteristics of the contaminated regions. A summary of the data on effectiveness of respective restoration measures based on information from both the Kyshtym and Chernobyl NPP accidents is given in Table V.

6. SITE CHARACTERISATION AND DECISION MAKING ON RESTORATION OF AGRICULTURAL LAND

Following the large scale radioactive contamination of agricultural land, the two main questions of importance in decisions making concerning restoration are:

— Which is the proportion of agricultural land requiring the restoration?
— When will the restoration measures need to be implemented?

As was discussed earlier, the answers to both of these questions are directly based on the site characterisation. The decisions on restoration of contaminated agricultural lands depend on several factors, which are to be defined on the basis of site characterisation activity. Among the factors which were distinguished were the levels of contamination by reference radionuclides, and their respective mobility in soil.

It is also obvious that the need for restoration, as well as the effectiveness of the methods applied, judging on the basis of criteria such as averted doses (for instance the cost of 1 man-Sv averted), is decreasing with the time elapsed after the contamination event.. Therefore, the amount of agricultural land where restoration is needed is also decreasing in time. The rates of this decrease depends on type of land use and respective soil properties. The phenomenon of change in the amount of in agricultural land in need of restoration is an important element in the long term policy for the organisation of agricultural production on the contaminated territories.

The criteria and classification of factors controlling the accumulation of ^{137}Cs in plants described earlier simplify the estimation of threshold contamination levels for each type of land use above which a specific restoration method can be considered as justified. It should be noted that due to the progressive decrease of radionuclides concentrations in soil and plants these levels are shifting towards higher values. This is illustrated in Figure 4 by the respective contamination levels calculated on the basis of different criteria for natural pastures on sandy soils as a function of time lapsed after the contamination event. The following criteria were considered in these calculations:

— The DIL for milk in regions the most affected after the Ch NPP accident is 370 Bq l^{-1};
— The cost of 1 man-Sv averted by radical improvement of natural meadows (the cost of implementing this measure is 150 USD per ha), calculated for the levels recommended by ICRP [4], are between 10,000 and 20,000 USD).

Figure 4 plots the initial concentration of ^{137}Cs-contamination versus the time elapsed before restoration and is parametrized by the dose criterion. Concentrations above the respective thresholds would justify restoration measures. It can be seen that with the increase in time elapsed since the concentration event, the initial concentration for which restoration would be justified increases. In other words, waiting for prolonged periods reduces the need and justification for restoration.

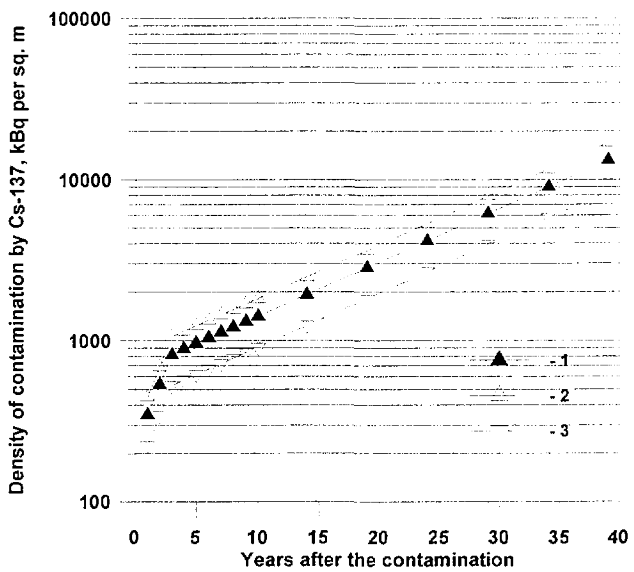

FIG. 4. Threshold levels of ^{137}Cs contamination in natural pastures as a function of time for which restoration measures are justified [27]. 1 and 2 threshold based on exceeding given permissible levels of ^{137}Cs in milk (370 Bq l^{-1}); 2 and 3 threshold based on the cost of averting 1 man-Sv (10 and 20 thousand USD, respectively)

A comparison of two criteria, lowering of the contamination levels of ^{137}Cs in milk below DIL_S, and lowering the collective dose by 1 man-Sv, shows that the contamination levels at which restoration is justified are 2–2.5 times higher for the second criterion than for the first. This indicates that the application of restoration measures can be considered justified for several years even after permissible levels of ^{137}Cs content in milk have been achieved, i.e. until both criteria have been met.

Figure 5 shows that inherent differences between soils concerning the decrease of mobility of radionuclides and its transfer outside of root containing layer should also influence the priority setting for large scale restoration policies of agricultural lands. In this example ^{137}Cs concentrations in milk were used as the criterion.

The data presented in this figure can be treated as threshold-levels of soil contamination for intervention after radioactive fallout. In the first year after the accident, the application of restoration measures on meadows with peaty soils is expedient for ^{137}Cs contamination above 110 kBq m^{-2} in the collective farms.

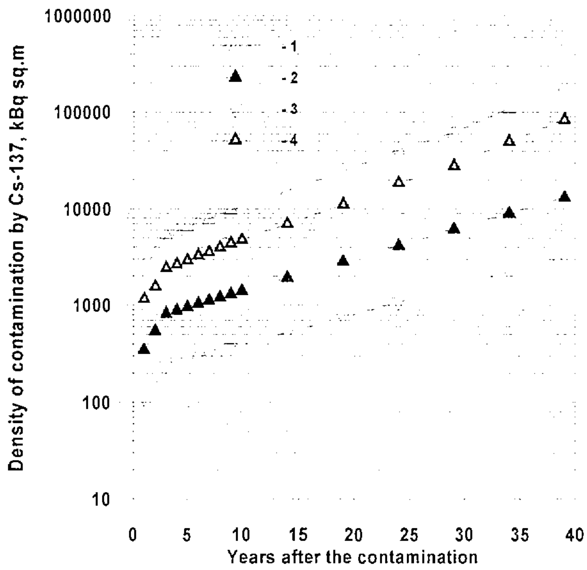

FIG. 5. Threshold levels of ^{137}cs contamination in natural pastures as a function of time for which restoration measures are justified. (1), (2), (3) and (4) refer to clay, sand, peat and loam soils respectively [27].

For sandy and heavy loamy soils these values are 350, 1150 and 2500 kBq m^{-2}, respectively. It can be seen from these data that restoration measures are only justified within 30 years following the contamination of natural meadows on peaty soils, within 20 years for sandy soils, and within the first five years on loam. Analogous results were derived for other types of land use.

Data on contamination levels, land use, and soil properties became available in electronic format from 1987 on. Using this information allowed to assess which areas of agricultural lands required long term restoration measures, and to set priorities for their implementation taking into account site specific characteristics.

7. APPLICATION OF DECISION SUPPORT SYSTEMS FOR THE SELECTION OF OPTIMAL RESTORATION STRATEGIES

It is clear from the discussion above that many site specific factors could influence the need for restoration of agricultural lands. Spatial and temporal variability of these factors make the analysis of options which could be applied a rather complicated task. This shows the need for using a flexible decision support system (DSS), capable of providing practical advice on restoration strategies, and taking into account site specific features of the contaminated agricultural lands. The general objectives of using a DSS in restoration planning are first to provide a link between site characterisation and the decision making on restoration options, and secondly to provide the means for a comparative analysis of the effectiveness of different restoration options, taking into account site specific characteristics of the contaminated land.

The decision support system FORCON (Figure 6) was specially designed to simplify the selection of restoration options.

This computer-based system is intended for widespread use by agricultural specialists, who are required to give advice, taking into account the local features of contaminated agricultural lands.

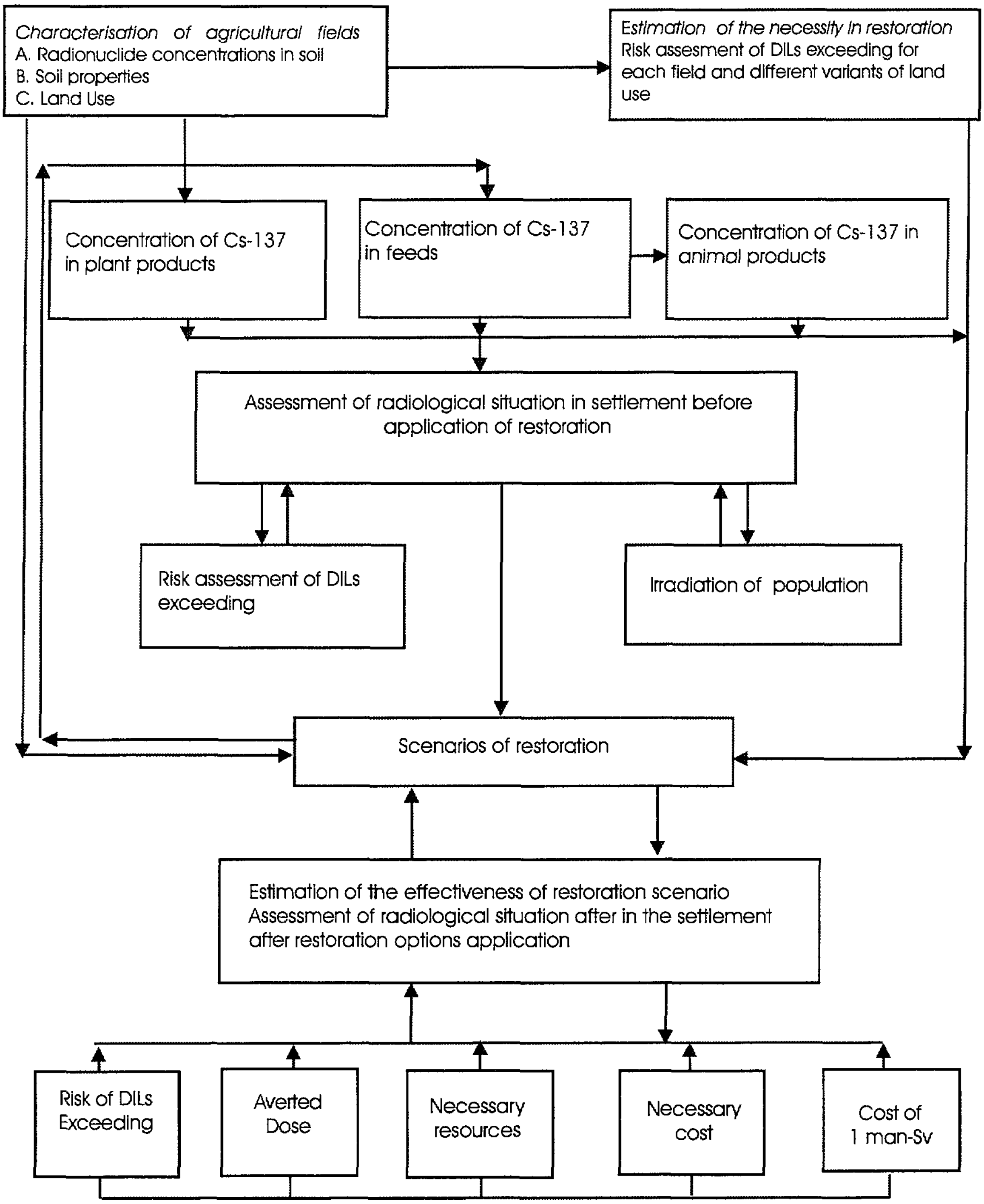

FIG. 6. Schematic representation of the 'FORCON' decision support system design.

The basic steps performed by the system are:

(1) Analysis of the existing radio-ecological situation on the basis of site characterisations of agricultural lands and the identification of those agricultural products that require some form of intervention;

(2) Assessment of the likely effectiveness of various restoration options taking into account prevailing conditions;

(3) Identification of the most appropriate restoration strategy.

The need for intervention and the development of a restoration strategy is based on either comparisons with Derived Intervention Levels (DILs), evaluation of the dose averted, or economic and other ancillary factors.

For an evaluation of the existing situation (without application of restoration measures) and the identification of the most appropriate strategy, the following information in the framework of the system is used: information on contamination levels on agricultural lands, type of land use, and soil characteristics. Within the FORCON, this information is represented on a map.

An analysis of this information constitutes the first stage in the selection of potential restoration options that are applicable. The second stage consists of an evaluation of contamination levels in crops on each field, and of the radionuclide contents in all types of other agricultural products from the settlement. Data on the quantities of each product are given in the form of tables, which include the proportion of each product in which DILs are exceeded.

To enable the user to select the most appropriate restoration strategy, the system provides the following information:

— maps which outline the possibilities for growing alternative products that would be below the relevant DIL for each year after the contamination. This analysis takes into account both, the contamination levels in individual fields. and soil characteristics;
— estimates for the radio-ecological effectiveness of different measures applied to each separate field in terms of lowering the activity concentrations in the product;
— the probability that a proportion of each product will exceed the DIL in the form of tables and graphics.

For each scenario of restoration chosen by the user, the following values are calculated: radionuclide concentrations in all of the foodstuffs produced; for animal products, data are presented separately for the periods spent on pasture and indoors; yields of each product; resources required (materials, transport, labour etc.) for the implementation of a given restoration option and the associated costs; the probability of the DIL being exceeded in each type of foodstuff after the restoration measures have been applied; averted dose; and averted dose per unit of costs. The user, therefore, has a comprehensive data sets on which to base his decisions, where radiological considerations may be constrained by other factors, such as finance or the availability of resources.

The restoration measures considered within the FORCON system are classified into four groups: organisational, agrotechnical, agrochemical, and restoration measures in animal husbandry.

Organisational restoration measures in principal concern changes in land use. This includes increasing the area of land allocated to crops characterized by a low accumulation of radionuclides, and in the case of areas of high contamination the abandoning of land from agricultural production. Within the current FORCON system, other changes in land use that can be considered are the substitution of current crops by hay, grain, potatoes, or pasture.

Agrotechnical restoration measures considered include deep ploughing with turning under of the upper layer (on high fertility soils), and deep or superficial amelioration of pastures.

Agrochemical restoration measures include liming of acidic soils, application of increased doses of K and P-K fertilizers, addition of natural sorbents (different kinds of clay minerals), and the use of organic fertilizers.

Decisions on the application of restoration measures in contaminated areas are based on predictions of the radionuclide content of foodstuffs. Many existing approaches are based on site specific data, with single values being allocated to each parameter. However, many parameters have an inherent variability, for instance because of non-uniform contaminant deposition, differences between animals in a single herd, or variations in soil properties. The approach taken within the FORCON system enables the radiological situation to be assessed in probabilistic terms, by taking into account information about observed variations in contaminant deposition and inherent variability in parameters that describe the radionuclide migration through the food chain. More detailed descriptions of the models and the approaches for dose calculations are given elsewhere [28].

To assess uncertainties in predicted values Monte-Carlo simulations are usually employed in radio-ecological models. However, this method is time consuming from the computational point of view, thus making it unsuitable for the interactive approach stipulated for systems such as FORCON. The procedure used in the FORCON combines deterministic and probabilistic simulations, the latter being based on observed distributions of parameter values whenever possible. The characteristics of these observed distributions are assumed to remain constant over time. Thus, for each year under consideration the best-estimate values for each parameter are calculated using dynamic models; the same probabilistic distribution is then applied to each individual value.

A model to estimate the cost which is associated with each restoration scenario is also included. It takes into account any changes in productivity which may result from the imposition of any given restoration option.

All the parameters required for the calculation, analysis and presentation of information are contained in the database. The database also includes supporting data for the cartographical representation of information. The database of the FORCON system consists of four groups of data needed for the assessment of the efficiency of restoration options, including parameters for the transfer and accumulation of radionuclides in various food chains, data on restoration efficiency by method, associated costs, and resources required to implement the method, and inquire into radiological information that have been derived from the assessment of data within JSP1 [29]. To date the system's database contains information on the efficiency of more than 300 variants of agricultural restoration methods. However, the use of FORCON is confined at present to radio-caesium, since most of the information used in the development of the system has come from areas affected by the Chernobyl accident. In the future the system should be enlarged with corresponding information for other potentially important radionuclides, such as ^{90}Sr.

8. CONCLUSIONS

Following a number of serious radiation accidents a wide range of different restoration options have been developed and adopted for use in the case of radioactive contamination of agricultural land. In the ten years since the accident, various measures have been implemented and a vast amount of data on their effectiveness has been generated, together with information on ancillary factors, such as the required resources and costs. These measures vary considerably by their effectiveness, cost and practicability in actual situations. Their effectiveness depends on many factors, including soil and climatic conditions, or specific features of the agricultural production management. Owing to this the implementation of these restoration measures on the basis of general expert estimations often results in inadequate decisions. The results presented in this paper underlined the importance of the role of site characterisation in the selection of restoration strategies and demonstrated the need for implementing a flexible decision support system, which is capable to organise a comprehensive set of site specific information, and which provides a practical tool for advising on agricultural land restoration.

TABLE I. MAIN CHARACTERISTICS OF SOIL ACCORDING TO THE CLASSIFICATION USED IN THE STUDY.

Soil groups	**Soil types, as classified in Russia [12]**	**pH_{KCl}**	**% Humus**	**Cation exchange capacity[a]**	**Clay content[b]**
Sandy, Loamy sand	Soddy-podzolic; Soddy-gleyed; Soddy; light grey forest	3.5–6.5	0.5–3.0	3.0–15.0	<20%
Light loam, Medium loam	Soddy-podzolic; Soddy, grey and dark grey forest; Leached chernozem; podzolized chernozem	4.0–6.0	2.0–6.5	5.0–25.0	20–40%
Heavy loam, Clay	Dark grey forest; leached chernozem; podzolized chernozem; typical chernozem; usual chernozem	5.0–8.0	3.5–10.0	20.0–70.0	>40%
Peat	Peaty; peaty-bogged; peaty-gleyed	3.0–5.0	5.0–30.0	20.0–200.0	

[a] measured as meq per 100 g soil; [b] particle sizes <0.001mm

TABLE II. RATIO OF TRANSFER FACTORS OF ^{137}Cs FOR DIFFERENT SOIL GROUPS

	Ratio	**95% confidence interval.**	**Range**
PEAT : SAND	3.6	3.0–4.4	2.0–8.0
PEAT : LOAM	10.5	7.5–14.7	3.3–37.5
PEAT : CLAY	27.0	20.5–35.5	8.3–48.7
SAND : LOAM	2.4	1.9–2.9	0.8–6.0
SAND : CLAY	5.2	4.1–6.6	1.6–14.3
LOAM : CLAY	2.2	1.8–2.6	0.4–4.4

TABLE III. ENVIRONMENTAL HALF-LIVES FOR THE UPTAKE OF ^{137}Cs BY AGRICULTURAL PLANTS IN 1987–1990 AND 1990–1994.

	1987–1990			1990–1994		
Soil type	T_e	$Tf_1(0)$	R^2	T_e	$Tf_2(0)$	R^2
			Barley			
Sand	1.3	0.43	0.99	6.2	0.14	0.65
Loam	1.9	0.21	0.98	6.7	0.09	0.71
Clay	1.4	0.17	0.98	3.8	0.07	0.87
			Maize			
Sand	2.4	6.3	0.99	7.5	2.9	0.86
Loam	1.5	2.1	0.76	16.1	1.1	(0.21)*
Clay	1.9	1.3	0.98	17.3	0.53	(0.47)
			Potatoes			
Sand	1.2	0.57	0.88	7.5	0.12	0.99
Loam	2.4	0.14	0.98	8.5	0.1	(0.20)
Clay	2.9	0.07	0.95	5.0	0.04	0.64
			Beet-roots			
Sand	2.9	0.32	0.92	5.2	0.29	0.83
Loam	2.6	0.25	0.82	5.9	0.12	0.98
Clay	2.9	0.18	0.72	7.2	0.15	0.96
			Annual grasses			
Sand	1.6	29.0	0.99	15.4	18.3	0.87
Loam	1.3	7.0	0.99	4.7	2.3	(0.37)
Clay	1.3	3.6	0.99	4.9	1.4	0.56
Peat	1.8	83.4	0.84	10.9	29.6	0.72
			Perennial grasses			
Sand	2.3	11.8	0.99	4.8	3.5	0.91
Loam	2.5	11.7	0.95	4.6	0.6	0.60
Clay	2.5	1.9	0.95	10.2	0.65	0.66
Peat	2.6	23.4	0.99	21.0	9.9	(0.21)

TABLE IV. HALF-LIVES OF RADIONUCLIDES IN VARIOUS TYPES OF MEADOW SOIL [24]

		T_{ec} [years]		T_{eff}
Meadow type	**Soil type**	**Mode**	**95% CI**	**[years]**
Dry meadow	Sand	1870	1380– 2515	29.5
Dry meadow	Loamy sand	2030	1690–2400	29.6
Dry meadow	Heavy loam	1970	1260–3070	29.5
Lowland (wet) meadow	Light loam	530	403–692	28.4
Lowland (wet) meadow	Peat	280	200–387	27.1
Flood plain meadow	Loamy sand	440	220–890	28.1
Flood plain meadow	Peat	60	49–73	20.0
Transient peat land	Peat	17.4	14.2–21.3	11.0
Low peat land	Peat	26	19–35	13.9

TABLE V. EFFECTIVENESS OF THE MOST WIDESPREAD AGRICULTURAL RESTORATION MEASURES [8]

Restoration options	Soil type	Reduction factor in plants (times)	
		^{90}Sr	^{137}Cs
Ploughing	Mineral Organic	1.6–4.0	1.8–2.5 2.0–3.2
Ploughing with turning over upper layer	Mineral Organic	3.7–4.0	2.8–5.6 3.3–6.9
Liming	Mineral Organic	1.5–3.4 3.0–3.2	1.6–2.5 1.5–5.0
Application of organic fertilisers	Mineral	1.8–4.6	1.1–3.1
Application of mineral fertilisers	Mineral Organic	1.1–2.8 1.2–2.8	0.7–2.2 1.1–2.5
Radical improvement, including ploughing, standard dose of fertiliser, re-seed	Mineral Organic	1.6–3.5 2.5–5.5	1.8–3.3 3.1–3.9
Surface improvement, including rotary cultivation, standard dose of fertiliser, re-seed	Mineral Organic	1.1–2.5 1.5–4.1	1.3–1.9 1.4–2.2

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