The application of the RESTORE-EDSS to Chile

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Abstract. In Chile unexpectedly high ^{137}Cs activity concentrations in soils and in food products due to the weapons fallout in the 60th have been detected. This is partly due to the prevailing climatic conditions (high precipitation rates) and the soil characteristics of the Chilean soils especially in the 10th administrative Region. Within an EC project of the 4th framework programme in Nuclear Fission Mastering Event of the Past (RESTORE 'restoration strategies for radioactive contaminated ecosystems') an EDSS (Environmental Decision Support System) has been developed which can be adapted to the ecological and site specific conditions of Chile by using information on soil properties, soil contamination and soil-plant transfer factors of ^{137}Cs for characteristic Chilean soil types and crops. These data can be used to identify areas which are potentially radioecological sensitive i.e. will result in elevated radiation doses to people living and using these areas, and further more where countermeasure actions might be implemented. The EDSS will use the modern tools such as GIS (geographical information systems) and geostatistical methods, recently developed dynamic soil-plant transfer models to determine fluxes of radiocaesium, and dose calculation models. The system will provide an analysis of the present contamination with radiocaesium of Chile. Later it can be modified and applied for other radionuclides such as radiostrontium. Examples for the implementation of the EDSS and first results are presented.

1. INTRODUCTION

Relevant dynamic radioecological models for the determination of the transfers of radiocaesium and radiostrontium from soils to vegetation have been developed which more reliably predict transfer through food chains to man and dose estimates. Spatial and temporal variations in its radioecological operative parameters which influence transfer to foodstuffs and man have been addressed [1, 2]. These are based on information of soil characteristics, soil contamination, land use, production and production rates, and consumption habits and behaviour of the population. Geographical information systems and geostatistical measures as a tool to determine fluxes in different ecosystems and to highlight *radioecological sensitive areas* [these proceedings] have been applied. These models have been developed and applied in the areas of Western Europe (SAVE=Spatial Analysis of Vulnerable Areas in Europe) and the NIS such as Russia, Ukraine, Belarus and Kasachstan (RESTORE=Restoration of Radioactive Contaminated Ecosystems) to create environmentally base decision support systems. The generic character of these EDSS for application in a different ecological environment (here Chile) is tested, and first results presented.

2. METHODS

2.1. Data from Chile

The influence of the latitudinal position and climatic factors on ^{137}Cs inventory in soils was studied in five Chilean natural and semi-natural environments located between latitudes 27 and 63°S: Easter Island, 9th and 10th Regions, 11th Region, West Patagonia and South Shetland Islands in the Antarctic territory. The measured ^{137}Cs inventories ranged up to 5400 Bq m^{-2}, being highest in the 10th Region, because of its mid-latitudinal position (around 40°S), and due to the high precipitation rates occurring in this zone (1150 to 4000 mm y^{-1}) [3,4,]. In both hemispheres, zones located at mid-latitudes are exposed to a higher global deposit of long-lived radioactive contaminants emitted to the stratosphere due to the predominant circulation direction of the air masses [5, 6] (Fig. 1). Otherwise, high precipitation rates contribute to an efficient atmospheric washout, originating a high deposit of anthropogenic radionuclides from the atmosphere [7, 8, 9]. The local annual precipitation rate was found to be the major influencing factor on the ^{137}Cs inventory measured within the latitudinal band of the studied Chilean territory. Therefore areas of Central-South Chile are zones of high radioactive fallout deposit in the Southern hemisphere, and consequently of higher potential risk in case of radioactive emissions to the atmosphere (Fig. 2; [8, 9]).

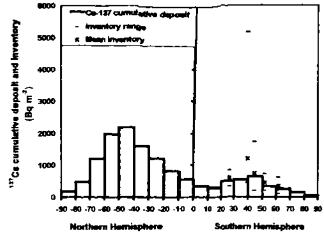

Fig.1 Latitudinal distribution of ^{137}Cs cumulative deposit estimated for 1998 (Ref. UNSCEAR, 1982), and measured ^{137}Cs inventories at different latitudes in Chile.

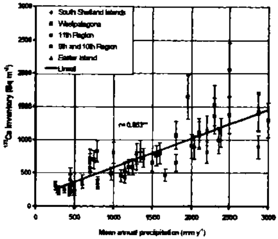

Fig. 2 ^{137}Cs inventory (ref. Jan: 1988) at different Chilean ecosystems as a function of the local mean annual precipitation.

Between 1982 and 1992 the ^{137}Cs soil-to-prairie plants transfer (TF_{sp}) was studied in different soil types of agricultural ecosystems of the 9th and 10th Regions. The TF_{sp} varied from 0.008 to 0.4 in Palehumult (Umbric Alisol), between 0.05 and 2.3 in Hapludand (Umbric Andosol) and from 0.52 to 5 in Placandepts (Umbric Andosol) [8, 9]. Soil-to-plant transfer was also studied in the other mentioned semi-natural environments varying between <0.06 and 1.8 in Easter Island, from 0.03 to 2.4 in the 11th Region, and from <0.04 to 0.26 in West Patagonia.

The time course of the ^{137}Cs concentration in the soil-prairie plant-milk pathway was followed from 1982 to 1997 in dairy farms of the 10th Region, without the transfer being affected by new radioactive fallout inputs. The ^{137}Cs concentration in the 10 cm upper soil layer decreased at a rate similar to that predicted by the physical decay of the radionuclide [4, 8]. Nevertheless, the ^{137}Cs concentration in prairie plants and milk showed a decrease much more rapid than the ^{137}Cs physical decay rate would predict: The effective half-life for ^{137}Cs concentration in prairie plants was found to be 5.6 during the first 1982-1990 observation period, and 12 years during 1991-1997. The feed-to-milk transfer factor was found to be constant at about 0.010 d kg^{-1} during the whole observation period [4, 8].

2.2. The RESTORE-EDSS

The core of the EDSS consists of various sub-models to calculate ^{137}Cs transfer through parts of the food chain. The first step in the EDSS is to simulate the transfer soil to food product based on maps of soil type, land use and soil contamination. Various models are available for modelling the soil to food product transfer depending on the scale and quality of the input data. The available models range from a simple steady state transfer factor model to a semi-mechanistic dynamic soil-plant transfer model. If soil contamination is only available at point locations, these contamination values can be interpolated using a geostatistical interpolation routine. Subsequently, the ^{137}Cs intake by humans is calculated using the previously calculated food product contamination and diet information and fluxes are calculated based on agricultural production data which is demonstrated in more detail in the following. In addition, external exposure is calculated based on soil contamination by ^{137}Cs and residence time in various environments.

To select the areas to run the models and to display input data a user-friendly interface has been developed based on HTML documents and model dialog boxes. The HTML documents allow the user to view the dialog boxes for adjusting model input parameters, run the model for selected data sets and display model results

2.2.1. Spatial soil-plant models

2.2.1.1. Steady state transfer factor model
The steady state ^{137}Cs transfer factor model calculates food product contamination by ^{137}Cs (Bq/kg) based on soil contamination by ^{137}Cs and soil texture class (peat - sand - loam - clay). Two steady state transfer factors have been implemented into the EDSS: a single food product model to calculate ^{137}Cs transfer to any food product and a multiple food product model to calculate ^{137}Cs transfer to milk, potatoes, grain, meat, mushrooms and berries.

The ^{137}Cs transfer from soil to food products is calculated using soil type and food product dependent aggregated transfer factors (Tag's) (m^2/kg). The soil contamination by ^{137}Cs is corrected for physical decay (half-life = 30 y). The time-dependency of the Tag values is simulated using a two-step first order kinetic relationship:

$$Tag_t = (A1 * \exp(-k1 * t) + A2 * \exp(-k2 * t)) * Tag_0 \qquad (1)$$

Where:			
	Tag_t	=	Aggregated transfer factor at time = t (m^2/kg)
	Tag_0	=	Aggregated transfer factor at time = 0 (1986) (m^2/kg)
	A1	=	Empirical parameter (fixed to 0.814)
	A2	=	Empirical parameter (1 - A1 = 0.186)
	k1	=	Empirical first order decay constant fast pool (0.6935 y^{-1})
	k2	=	Empirical first order decay constant slow pool (0.06935 y^{-1})

The model allows for input of Tag-values that apply to any contamination year. The model corrects these Tag-values to the year of prediction using equation (1). The contamination of the food products is only calculated for those areas where the food product is being produced or collected. These areas are selected from the appropriate classes from either the land use map or the crop type map. The model output consists of three maps for each food product considered: i) ^{137}Cs contamination of food product; spatial distribution over the areas where product is produced or collected; ii) ^{137}Cs contamination of food product; area averages for the selected areas (farms or entire modelling area); iii) Critical load maps i.e. exceeding of intervention limit.

2.2.1.2. The Semi-mechanistic dynamic transfer model

Soil-to-Plant transfer. The SAVE-IT soil-plant transfer model to predict vegetation activity concentration as a function of radiocaesium deposition and soil characteristics has been applied in the RESTORE-EDSS for mineral and organic soils [10, 11]. The mineral model needs inputs of soil exchangeable K, clay and radiocaesium inventory. Plant activity concentration (Cs_{plant}, Bq kg^{-1}) is calculated from the product of a concentration factor (CF, dm^3 kg^{-1}) and the radiocaesium activity concentration in soil solution. CF is related to soil solution K concentration (m_K moles dm^{-3}) as observed experimentally by [12] Smolders *et al*. (1997). Data presented by [12, 13] indicated a relationship between RIP and clay content, so that m_K and RIP (radiocaesium interception potential) can be used to estimate a soil K_d value; K_d may then be used to estimate soil solution radiocaesium concentration in conjunction with CF in order to predict plant radiocaesium activity. As the value of m_K for a soil is unlikely to be recorded in spatial data sets, it is necessary to estimate this soil property within the model

As the bioavailability of radiocaesium decreases with time [14] the initial rate of decline in radiocaesium uptake may be described by an effective ecological half-life of around 1 year [15] while, concurrently, long term reduction rates may be modelled using a 10 year half-life [16]. Thus the model implements a double exponential equation using these half lives to predict the decline in solution radiocaesium with time.

In soil, the main competitor for K sorption on organic matter is likely to be Ca. The Gapon exchange coefficient (k_G) describes the relative selectivity of a sorbing surface for a pair of cations. As Ca and Mg dominate the sorbed fraction of cations, the sorbed concentrations of these ions may be approximated to the difference between the effective cation exchange capacity (CEC, $cmol_c\ kg^{-1}$) and soil exchangeable K. It may be reasonable to assume that there are just two types of exchange surfaces: humus and clay. Thus m_K ($mol\ dm^{-3}$) may be expressed in terms of an equilibrium between K sorbed on humus *or* on clay, as a function of organic and inorganic cation exchange capacity (CEC), Gapon exchange coefficients for K/Ca sorption on clay and humus, and relative quantities of clay and humus in the soil. CEC values for humus and clay are estimated from pH and clay content respectively.

Due to high radiocaesium sorption on organic material it was necessary to calculate k_d values for radiocaesium sorption on both clay and humic fractions. The clay associated k_d was estimated from RIP as described above (a function of clay content), modified to include the effect of soil solution ammonium (m_{NH4}, $mol\ dm^{-3}$), as high values of m_{NH4} were observed in these organic soils during plant growth.

Radiocaesium sorption by humic fractions is non-specific and so the humus associated k_d for radiocaesium is assumed to equal that of K (i.e. K sorbed on humus + m_K). Thus sorbed radiocaesium is partitioned between fixing (clay k_d) and non-fixing (humus k_d) sites. This allows the double exponential equation that describes fixation (see above) to be applied only to the radiocaesium which is sorbed at fixing (clay) sites. The result is that bioavailability of radiocaesium declines more slowly with increasing soil organic matter content. This revised model is therefore applicable to a wide range of soil types.

To run this model inputs are required for soil clay content, exchangeable K, pH, and organic matter content. These soil characteristics are easily measured for a soil and are available either directly, or can be derived from existing soil spatial databases for many areas.

2.2.2. Plant-Animal-Transfer

To predict activity concentration of animal products a conventional equilibrium transfer factor approach is used thus activity concentration of an animal food product is the product of the animals daily dry matter intake and the daily radiocaesium intake [17].

2.2.3. Dietary Data

The ^{137}Cs intake model including diet and origin of food product calculates daily ^{137}Cs intake through foodstuffs (Bq/d) and the resulting individual internal dose (mSv/y) on the basis of the diet of an individual person living in a settlement. The following food products are considered in the multiple food products model: milk, potatoes, grain, meat, mushrooms and berries. The daily ^{137}Cs -intake via these food products is calculated separately. In the single food product model any product can be considered provided that the food product contamination by ^{137}Cs is known. The spatial distribution of the ^{137}Cs contamination of the considered food products is either calculated by the steady state ^{137}Cs transfer factor model (all food products) or the dynamic semi-mechanistic ^{137}Cs transfer model (milk, potatoes, grain, and/or meat).

2.3. Adaptation of models and EDSS to Chile

The models described above have been developed for the NIS (New Independent States) countries and are now adapted to Chilean conditions. For this purpose existing data as outlined in section 2.1. in addition to field work in selected sites (Fig. 3) on contamination of soils, deposition, land use, land cover, production and production rates are collated to fulfil the following objectives:

1. Creation of a data base on Chilean transfer factors soil-plant (pasture grass and crops) in dependence of soil properties (model parameters such as exchangeable K, % clay, texture, pH, bulk density etc.), performing of additional field work to complete information.
2. Identification of major pathways affecting radionuclide fluxes in contaminated areas in respect to a variety of contamination scenarios and ecosystems specific for Chile.
3. Application of data on local geophysical characteristics, production and consumption habits to derive an overview and identify vulnerable areas. This information will be incorporated into a Geographical Information System (GIS).
4. Comparison of predicted values of food stuff (grass, crops, milk) used for human consumption with measured values.
5. Application of this knowledge to develop an environmental management package and a decision support system providing an information system.

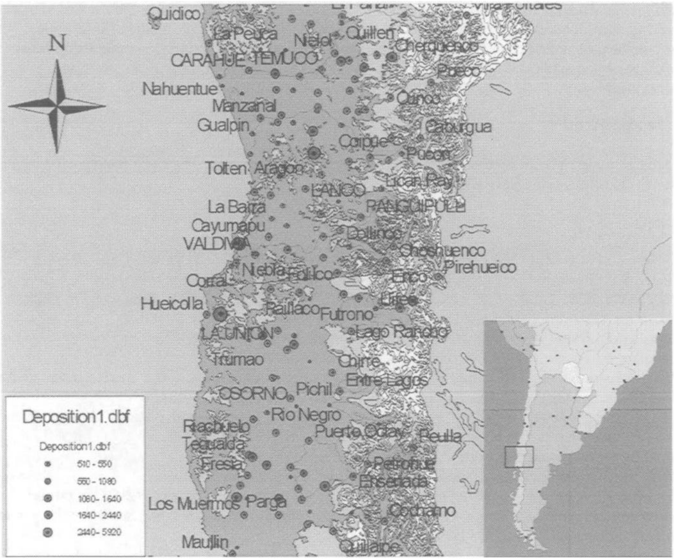

Fig. 3. Sampling sites in the 9[th] and 10[th] regions of Chile (^{137}Cs inventories given in Bq/m^2).

For the first generic approach existing maps are digitised, and the steady state model with adapted Tag values is used to estimate activity concentrations in the different major food products. The semi-mechanistic models will be further combined with detailed site specific geographical information to be tested on their robustness and precision.

3. CONCLUSIONS

The developed Chile-EDSS will allow the user to identify areas which are vulnerable or radioecological sensitive due to either high production rates or consumption habits of 'critical' population groups. As has been outlined previously areas in Chile with the highest soil contamination represent high production sites of Chile. Food product contamination and fluxes of radiocaesium therefore might be higher than generally expected, and appropriate measures to reduce contamination levels in food products of doses to humans might be required or advised. The results of the implementation of an EDSS (provision of maps and software to predict radiocaesium levels in soils and food products and dose distributions) will enable authorities and decision makers to i) assess the present radioecological situation in Chile and ii) direct countermeasures if necessary and iii) provide information on the radiological situation to the public. Therefore the potential of the RESTORE-EDSS, originally developed for the NIS countries, to be of generic nature and applicability to any situation of radioactive and conventional contamination is tested and demonstrated.

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