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TEMPORAL AND SPATIAL PREDICTION OF RADIOCAESIUM TRANSFER TO FOOD PRODUCTS

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ABSTRACT

A recently developed semi-mechanistic temporal model to is used predict food product radiocaesium activity concentrations using soil characteristics available from spatial soil databases (exchangeable K, pH, % clay and % organic matter content). A raster database of soil characteristics, radiocaesium deposition, and crop production data has been developed for England and Wales and used to predict the spatial and temporal pattern of food product radiocaesium activity concentrations (Bq kg^{-1}). By combining these predictions with spatial data for agricultural production, an area's output of radiocaesium can also be estimated, we term this flux (Bq y^{-1} unit $area^{-1}$). Model predictions have been compared to observed data for radiocaesium contamination of cow milk in regions of England and Wales which received relatively high levels of fallout from the 1986 Chernobyl accident (Gwynedd and Cumbria). The model accounts for 56 and 80% of the observed variation in cow milk activity concentration for Gwynedd and Cumbria respectively. Illustrative spatial results are presented and suggest that in terms of food product contamination areas in the north and west of England and Wales are those most vulnerable to radiocaesium deposition. When vulnerability is assessed using flux the spatial pattern is more complex and depends upon food product.

INTRODUCTION

Radiocaesium is a persistent environmental contaminant which can be deposited from the atmosphere following nuclear accidents such as that at the Chernobyl nuclear power plant in April 1986.

Models have been developed that estimate the transfer of radiocaesium to food products, for example ECOSYS-87 [1] and PATHWAY [2]. Such models incorporate a range of processes, including interception, weathering, resuspension, fixation and leaching in soils, root uptake and transfer to animals. However, variation in plant uptake as a function of soil properties has either not been considered systematically, or has only been incorporated at a rather simplistic level using transfer values varying over broad soil categories (e.g. SPADE, [3]). It is well known that there is considerable variation in the soil to plant transfer of radiocaesium. This is due to differences in pH, potassium status, clay and organic matter content [4].

Persistent contamination of food products in some upland regions of the UK following the Chernobyl accident highlighted their vulnerability to radiocaesium deposition [5]. Vulnerable or, radioecologically sensitive, areas can be regarded as those areas of greatest concern after radionuclide contamination [6]. This may relate to high environmental transfer resulting in high food product activity concentrations, and therefore potentially high individual doses, or high total radionuclide output in foodstuffs. The latter depends on environmental transfer, and food production. Areas of high food product contamination may correspond with relatively low levels of agricultural production or harvesting, in which case the input of radiocaesium to the human food chain will be limited. In contrast, an area with relatively low food product contamination but high production of contaminated products may be a significant contributor of radiocaesium to the food chain.

This paper presents a model combining aspects of established models with a recently developed approach to predict the radiocaesium uptake from soil to plants using soil properties which can be derived from available spatial databases. This model is encapsulated within a flexible user-friendly system for the identification of areas which are most vulnerable to radiocaesium deposition. In principle, the model can be applied to any area if the required input data are available. The model described is freely available via www.nottingham.ac.uk/environmental-modelling.

As an example application of the model, spatial databases of the model inputs have been developed for England and Wales enabling spatial and temporal prediction of food product contamination for that region.

MODEL DESCRIPTION

Overview

The model is schematically represented in figure 1. Spatial databases have been derived for England and Wales which contain the required soil characteristics, agricultural production statistics, and crop and agricultural management parameters. The databases have a spatial resolution of 5 x 5 km and comprise 5648 raster cells. The soil characteristics are required inputs to the model which estimates the food product radiocaesium activity concentration for each cell. Agricultural production data are then used to calculate the 'flux' of radiocaesium in foodstuffs produced within each cell.

The model is intended to be applied to large geographical areas and therefore has to be run for the large number of cells within the spatial databases. Consequently computation time has to be considered. To avoid the need for numerically intensive solution of differential equations, analytic solutions to the model equations have been employed throughout. This has required some simplifying assumptions, in particular relating to the dynamics of radiocaesium transfer between environmental compartments. As a consequence of these assumptions the model is, as implemented, limited to a single deposition event.

Interception and Weathering

Crops are initially contaminated with radiocaesium by foliar interception during the deposition event. The approach used to estimate the fraction of deposition intercepted is that described by Chamberlain and Chadwick [7], which is based on plant biomass at the time of deposition; prediction of biomass is presented below. Radiocaesium deposited to soil is assumed to be initially labile within the soil pool. The bioavailability to grazing animals of radiocaesium freshly deposited on plant surfaces is reduced by a 0-1 factor to simulate potential differences in initial bioavailability as observed following the Chernobyl accident (e.g. [8]). A value of 0.3 is appropriate to the Chernobyl deposit in the UK [8].

The plant-intercepted radiocaesium undergoes 'weathering' which is assumed to be a first order process. A rate coefficient equivalent to a half-life of 14 days is used (from ECOSYS-87 [1]). The weathered radiocaesium is transferred to the soil and is assumed to be available for plant uptake (i.e. added to the soil labile pool of radiocaesium). Given the short weathering half life the predictions described below for 1 and 10 years are unaffected by external contamination of plant surfaces.

The contribution of resuspension to plant activity concentration is not considered in the model. This simplification is based on the work of Crout et al [9] who argued that soil adhesion to vegetation is unlikely to be a significant dietary source of bioavailable radiocaesium unless the soil concerned exhibits an unusually high radiocaesium bioavailability. In such cases a high plant uptake would be expected so that resuspended contamination would still be relatively small component of the total radiocaesium contamination of the vegetation.

Crop Biomass

The interception approach described above requires an estimate of plant biomass. To achieve this the growth of arable crops (potato, leafy vegetables, root vegetables, wheat, fruit, maize, and stored grass(i.e. hay and silage)) is described by a logistic growth curve [10] and that of pasture is described by an exponential function [11]. The maximum biomass is defined by the yield and harvest index (ratio of yield to total standing crop dry weight at harvest). The shape of the growth curves are set by the timing of sowing and harvesting. The parameters used for the predictions presented in this paper are given in Table 1.

Soil to Plant Transfer

A recently developed approach is used to predict the soil to plant transfer of radiocaesium. It is based on the model presented by [12,13] which relate soil clay content, organic matter content, pH and exchangeable K to three key parameters describing radiocaesium bioavailability. The soil solution K concentration is determined from exchangeable K, and distributed between organic and inorganic cation exchange capacities, estimated from clay and organic matter contents and soil pH. The radiocaesium distribution coefficient (k_d) describes the partitioning between sorbed and solution phases of radiocaesium in the soil and is calculated from specific (clay) and non-specific (humus) K^+-competition coefficients and solution K concentration. The radiocaesium concentration factor (Bq kg^{-1} DW plant/ Bq dm^{-3} soil solution) represents the ratio of radiocaesium in vegetation to that in soil solution and may be derived as a function of soil solution K concentration [14].

The above approach is used to predict soil solution activity concentration at the time of deposition. Radiocaesium bioavailability in soil declines with time due to the processes of fixation by clay minerals and leaching from the root zone. To simulate these processes, the initial radiocaesium concentration in solution is reduced by a time dependent 0-1 factor calculated using a double exponential equation [13], which, in the absence of soil organic matter has half lives of 1 and 10 years [15]. Fixation is assumed to apply only to radiocaesium adsorbed on the clay fraction of the soil (i.e. not on organic matter) and therefore the rate of decline is adjusted to account for the partitioning of radiocaesium between sites on clay minerals and organic matter for a given soil.

The soil-plant transfer sub-model is able to calculate activity concentration in seven representative agricultural crops: pasture grass, winter wheat (representing cereals), leafy vegetables (generic), potato, root crops (generic), maize (silage) and fruit (generic). The activity concentration of radiocaesium in stored grass is estimated as a function of concentration in pasture and the number and timing of cuts.

To run the model, inputs are required for soil clay content, exchangeable K concentration, pH, and organic matter content. These soil characteristics are easily measured for a soil and are available in existing soil spatial databases for many areas. In principle soil illite content would be a more appropriate input than total clay content, however this type of detailed clay mineralogical information is rarely available within spatial data bases.

Plant-Animal Transfer

The activity concentration of an animal food product is predicted from the product of an equilibrium transfer coefficient, F_f or F_m (d kg^{-1} or d L^{-1}, respectively for meat and milk), an animal's daily dry matter intake (kg d^{-1}) and the activity concentration in the feed stuff (Bq kg^{-1}). This has the advantage of numerical simplicity, but the disadvantage that the biological turnover of radiocaesium within animal tissues and products is not effectively simulated, as would be the case with a fully dynamic model. However, the effect of this is limited as the model is principally used to simulate food product contamination in the medium to long term and biological half-lives for animal products are generally in the range 1-40 days [1]. The model considers eight animal products: beef, pork, chicken, lamb, goat meat, and cow, sheep and goat milk. The transfer coefficients are taken from Müller and Pröhl [1]and are presented in Table 2.

The daily dry matter intake of four types of feed (pasture, stored grass (i.e. grass silage and hay), maize silage and concentrate) for each animal species is defined over the course of a season within six bi-monthly intervals (January-February, March-April, etc.). In the model all feedstuffs are assumed to be derived from local sources and will therefore reflect predicted local contamination levels (i.e. within the 5x5 km cell). Values for total daily dry matter intakes (kg DM day^{-1}) are: 0.92 (sheep); 17 (dairy cow); 11 (cattle); 0.92 (goat); 2.55 (pig) and 0.08 (poultry) [16]. These have been distributed seasonally between the four feed types according to normal UK agricultural practice [17]. As with the crop biomass parameters, the animal feed intake values have been assumed to apply uniformly across England and Wales.

Calculation of Radiocaesium Flux

In the results presented below the radiocaesium flux is defined as the annual output of radiocaesium from a cell (i.e. the 5x5 km grid square) via a given food product (Bq cell^{-1} y^{-1}). In the case of crops which are harvested annually (e.g. cereals) this is calculated from the product of production (kg (FW) cell^{-1} y^{-1}) and the predicted food product contamination (Bq kg^{-1}) calculated at the time of harvest. In case of plant products (e.g. wheat) the predicted activity concentration is expressed on a per unit dry weight basis and standard dry:fresh weight ratios are used to account for this. In the milk which is continually produced the flux is calculated as the time integral (over a year) of the production rate and contamination. The estimation of agricultural production is described below.

As calculated, flux values are only a estimate of the potential radiocaesium contribution of an area to the human food chain, as not all agricultural production is directly consumed by humans (e.g. some cereals and milk products are used as animal feed. A more detailed analysis would needed to take this into account.

SPATIAL INPUTS

The spatial inputs for soil pH, exchangeable K and organic matter have been derived from the Geochemical Atlas of England and Wales [18] which is a database of experimentally measured values, taken at pre-determined grid reference points throughout a 5 x 5 km grid across England and Wales. Cores were taken to a depth of 15 cm (using a screw auger) at the intersections of a 4 m grid within a 20 x 20 m square centred on the site co-ordinate; the cores then combined to give a single sample.

Values of topsoil (top 15 cm) clay content values have been taken from the Soil Survey and Land Research Centre National Soil Inventory database. These data were partly direct measurements (58% of cells) and partly derived from qualitative texture classes (42% of cells). The clay content/texture observations were made using the same 5 x 5 km grid as that used for the England and Wales Geochemical Atlas.

In order to remove the small scale variation associated with such localised observations, the data were interpolated using block kriging to derive the mean and variance of soil properties for each 5 x 5 km raster cell, using the Gstat geostatistical package [19]. These data were combined to create a database of (i) initial plant transfer factors (Bq kg^{-1} plant dry weight per Bq kg^{-1} soil dry weight) predicted immediately after deposition and (ii) the proportion absorbed on clay sites [13]. This latter value is used to determine the rate of decline in radiocaesium bioavailability within each cell due to radiocaesium fixation. Radiocaesium deposition from the Chernobyl accident was derived for England and Wales from the Radiocaesium Atlas for Europe [20] and a correction made for nuclear weapons fallout.

In order to predict radiocaesium flux, estimates of annual production of three important food products (sheep meat, cow milk and cereals) were made for each cell. This was achieved by combining regional data on production [21] (regions as defined in Figure 2) with the proportion of a region's production attributed to a particular 5 x 5 km cell. This was calculated as the proportion of a region's agricultural land present within a given cell, derived from a land cover map [22] at a higher cell resolution size of 1 x 1 km. Production data were derived from statistics for 1996 and are assumed to be constant. The spatially attributed production statistics were biased by the arbitrary choice of geographical boundaries or regions. To overcome this difficulty the interpolation method of Tobler [23] was used, as described by Lam [24], using the 5 x 5 km grid and regional boundaries for each MAFF (Ministry of Agriculture, Fisheries and Food) region, to estimate production for each raster cell.

MODEL IMPLEMENTATION

Clearly, a large number of variables, some varying spatially and temporally, are required to generate realistic radiocaesium contamination scenarios. Similarly, a substantial volume of results will be generated when such a model is applied using large spatial databases. Therefore, the model described here has been incorporated into a user-friendly software system allowing the model to be readily applied to user-defined contamination scenarios. Results can be presented as maps, supported by graphs, tables and histograms as appropriate. The software allows a variety of important radioecological parameters in the model to be adjusted easily and these are summarised in Table 3.

MODEL VERIFICATION

The model has been tested by two parallel approaches. In the first, the underlying modelling approach has been tested by comparing predictions made by the soil-plant transfer model to data independent of the model parameterisation. This is a 'point model comparison'; all data in the model are related to a single coordinate with no consideration of the spatial aspects of prediction. This work has been reported by Absalom *et al* (11,12) and is summarised below. The second approach to model verification is to test the predictions of the model using the spatially interpolated inputs against food product contamination data collected for specified regions.

Soil-Plant Model Verification

The validation data used by Absalom, *et al*. (11,12) covered a range of agricultural crop types and, for example, in the case of wheat (the crop most commonly represented in the database) the soil-plant transfer model accounted for 89% of the observed variation in radiocaesium activity concentration (N=89; $p<0.001$). However, wheat is grown almost exclusively on mineral soils and therefore its results are not fully representative of the full range of soil properties in England and Wales. Of the crops contained in the database, barley had the largest number of observations made on soils with relatively high organic matter contents, although even in this case the data is not an ideal data-set for testing model performance on organic soils. Predicted radiocaesium transfer factors for barley accounted for 52% of the observed variation ($n=71$, $P<0.001$) [13]. In the absence of a more suitable data set, this provides some encouragement for the use of the model independently of the data set used to parameterise it. Furthermore, the barley results used for validation were derived from a variety of experimental designs (lysimeter and field), over a considerable range of time periods (1.2 to 10 years).

Spatial Verification and Uncertainty

Spatial predictions are probably best used to give a general picture, and the quantitative values may only be meaningful when averaged over a number of cells (for example at county level). Therefore, the most appropriate data sets to validate the model predictions would be food product contamination data for small regions as a function of time since deposition. Ideally, the data would be drawn from unbiased sampling across the region of interest.

Following the Chernobyl accident widespread monitoring of radiocaesium contamination of food products was undertaken in England and Wales, mainly by MAFF. The most heavily monitored food products were sheep meat and cow milk, and the monitoring programme focused on those areas where contamination was found to be greatest, principally in North West England and North Wales. These data are published as values for individual samples, with the date of observation, however the geographical location is only provided as a county or district [25-28]. From the point of view of model verification a major limitation of these data is that the sampling within each county/district may have been biased. Shortly after deposition the sampling was quite widespread, focusing mainly on areas where relatively high deposition was believed to have occurred. In the longer term the monitoring effort became more directed towards areas where contamination of food products remained high. This was particularly the case with sheep as some areas suffered high levels of contamination which required systematic monitoring, thereby introducing significant spatial bias into the data. Consequently the verification work presented below concentrates on comparisons with observed milk activity concentration. Of course milk is a key contributor to dose to the population and therefore an important model output which merits testing irrespective of the sampling considerations.

In order to compare these data to the model predictions, monthly mean cow milk activity concentrations were calculated from observations by county/district from all the individual reported values (per animal) taken within that county or district within a given month. The number of animals sampled on each individual monitoring date varied between 1 to 40. Whilst these data are not ideal for testing the model presented they are the most comprehensive data sets available for these regions.

In making such comparisons it is useful to estimate the uncertainty associated with the model predictions. The true overall model uncertainty arises from a combination of uncertainty in the sampled spatial data, interpolation method and the model itself in terms of the formulation of the model relations and parameter uncertainty. The uncertainty in the spatial attributes was taken as the estimation (or kriging) variance for each spatial attribute. It is recognised that this does not represent the true variation in spatial attributes within each cell (e.g. the estimated variances will be less than those obtained by point kriging [29]) but is the best estimate available. The model was rerun for small changes in input spatial attributes and the results were combined with the estimated kriging variances to estimate the uncertainty in model predictions due to uncertainty in the spatial data. Similarly, the effect of model parameter uncertainty was investigated by multiple runs of the model with incremental changes in the model parameters. It was found that the spatial uncertainty was the largest component in the overall model uncertainty.

Results are presented for cow milk in figure 3 for the counties of Gwynedd and Cumbria which are the most contaminated counties in England and Wales. For both counties the model is able to predict the time course of mean monthly cow milk activity concentration effectively, accounting for 56 and 80% of the observed variation for Gwynedd and Cumbria, respectively. Generally, observations fall outside one standard deviation (kriging error) of the predicted monthly mean. However across each county the spatial attributes vary significantly and this gives rise to large variation in predicted milk activity. Given the potential spatial bias in sampling, this variation needs to be considered when interpreting these results. Nearly all the observations lie within the lower and upper quartile of predictions made for the individual cells of each region.

An important aspect of the comparison presented in figure 3 is that the predicted data has been summarised by giving all the cells in the region equal weighting. Given the unknown pattern of spatial sampling this is probably the only reasonable approach, however it limits the interpretation of the comparisons presented.

PREDICTION OF VULNERABLE AREAS

To illustrate the application of the model it has been used to identify areas which are expected to be vulnerable to radiocaesium under two deposition scenarios, the Chernobyl pattern of deposition and a uniform deposition of 1535 Bq m^{-2} (occurring at the same time of year). The latter scenario represents the same total radiocaesium deposition for England and Wales as the Chernobyl scenario (as estimated from the deposition database) but distributed uniformly over all raster cells allowing for comparisons to be made between the vulnerability of different geographical areas. In each case vulnerability is judged in terms of food product activity concentration and radiocaesium flux.

Figure 4 shows maps of the predicted radiocaesium contamination of cow milk (activity concentration Bq L^{-1}) for the two scenarios one year after the deposition event. Under the uniform scenario the activity concentration of milk has declined to < 5 Bq L^{-1} suggesting a low vulnerability 1 year following the initial fallout. For the Chernobyl scenario the most vulnerable areas in terms of highest concentration activity are identified as North Wales, Cumbria, the Pennines and some parts of SW England. In a few cases the activity concentration of milk is > 5 Bq L^{-1} although the levels are low compared to the threshold for intervention (1000 Bq kg^{-1}). These correspond to areas where relatively high deposition is coincident with soils of relatively low pH, clay content and exchangeable K and relatively large soil organic matter content. The relatively high values in areas of SW England are surprising as there was little Chernobyl deposition data in this region. However the deposition data used does show some relatively high levels and further analysis suggests these may be attributable to a single, anomalously, high value in the Radiocaesium Atlas for Europe [20]. The results for this region should therefore be treated with caution. In the case of uniform deposition the pattern of activity concentration is different in the extent of food contamination and areas affected, with only the Pennines and North Wales standing out as areas of relatively high transfer.

The predicted radiocaesium flux via cow milk (Bq $cell^{-1}$ y^{-1}) for the first year following the deposition event, under the two deposition scenarios, is shown in figure 5. Whilst the general pattern of 'vulnerability' is similar to that shown in the maps of predicted radiocaesium activity concentration in cow milk, it is evident that areas of relatively high flux are more widely distributed than areas of relatively high activity concentration. In general, the soils with the greatest soil-to-plant transfer are in areas of low agricultural productivity. Conversely soils with low soil-to-plant transfer often support high agricultural production. Therefore, a relatively large flux can be achieved despite low predicted radiocaesium activity concentrations in agricultural produce. However, the variation in cow milk contamination between cells is greater than that of cow milk production, therefore the spatial distribution of flux map is strongly determined by the distribution of predicted radiocaesium activity concentration, especially for the Chernobyl scenario. For a uniform pattern of deposition, the effect of high milk production in the west of England is apparent with a more smoothly varying pattern.

The cumulative regional flux (GBq y^{-1}) for England and Wales via sheep meat, cow milk and cereals is summarised in Table 4 for both the 'short' and 'long'term. Short term is defined as the first year after the deposition event (i.e. May 1986 to April 1987), with the long term defined as the year between May 1995 to April 1996. The proportion of the total flux attributed to each of the 9 MAFF regions (Figure 2) within England and Wales is also presented.

In general, flux is ranked cow milk > cereals > sheep meat. In terms of the input to the human food chain a large proportion of UK cereal production is used as animal feed and for industrial purposes (approximately 60% [30]) greatly reducing the exposure of the population to this source. Similarly some milk products are used for non-human consumption. The relative contributions of the different regions to the total flux for a food product remains approximately constant between the two time periods, suggesting that there are no major regional differences in the rate at which radiocaesium bioavailability declines with time for the specified agricultural products. Whilst there are differences in the rate of decline of bioavailability between in individual raster cells (due to relative differences in the absorption of radiocaesium on clay minerals and organic matter), these differences disappear once averaged over regions. For sheep meat the regions of Wales and the North account for over 70% of the total flux under both scenarios, whilst for cow milk the flux contributions are more evenly spread between South West, North West, North and Wales. Sheep and milk production are biased towards the western regions of England and Wales, whereas the central and eastern regions dominate cereal production. Chernobyl fallout occurred mainly in the north and west and the interaction of these patterns of production and deposition is reflected in the relative magnitude of the total flux for each product between the two deposition scenarios. For the case of cereals there is a marked change in the spatial pattern of flux under a uniform deposition scenario, with the East Midlands and South East contributing more significantly to the total flux.

CONCLUSIONS

The model described links the prediction of radiocaesium transfer to agricultural food chains with spatially distributed data for soils and production. Such models have the potential to identify the regions where food products may be most contaminated, or areas where the combination of production and contamination level combine to maximise the overall input of radiocaesium into the food chain. Spatial models may therefore be useful for identifying regions where monitoring may be necessary and, potentially to give an estimate of the likely effectiveness of any remedial management.

The model verification presented here is rather limited due to the inherent difficulties in using point monitoring data as a comparison to the predictions of a spatial model. The model works reasonably well in predicting transfer to cow milk (Figure 3), however, for future potential uses it would be desirable to develop improved data sets which could be used for more effective model validation across a range of food products.

Whilst the results presented here have been limited to sheep, cow milk and cereals the model can be readily extended to consider other food products if additional agricultural production data are provided. Similarly the system is capable of making predictions for other geographical areas, providing the necessary spatial databases are available.

Although we have identified a number of limitations to the model presented it is nonetheless a useful first attempt to predict the spatial and temporal variation in vulnerability to radiocaesium deposition over large geographical areas. It would be a useful decision making tool in the event of a major nuclear emergency.

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Table 1. Crop biomass parameters for England and Wales used in the model.

Table 2. Animal transfer coefficients used in the model (Müller and Pröhl, 1993).

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Figure 4. Predicted radiocaesium activity concentration in cow milk (Bq L^{-1}) 1 year after: (a) Chernobyl; (b) Uniform (1535 Bq m^{-2}) deposition.

Figure 5. Predicted radiocaesium flux of radiocaesium via cow milk (Bq $cell^{-1}$ y^{-1}) for the first year after: (a) Chernobyl; (b) Uniform (1535 Bq m^{-2}) deposition.

Table 1.

	Start of Growing Season (DOY[1])	**Harvest Date (DOY)**	**Minimum Biomass (kg FW m^{-2})**	**Yield (kg FW m^{-2})**	**Harvest Index**
Wheat	274	217	0.013	0.67	0.43
Maize	91	248	0.015	0.75	0.50
Potato	105	288	0.087	4.34	0.55
Leafy Vegetables	91	274	0.045	2.27	0.9
Root Vegetables	91	288	0.085	4.23	0.55
Fruit	60	213	0.015	0.73	0.50
	Date of Peak Biomass (DOY)	**End of Growing Season (DOY)**	**Minimum Biomass (kg FW m^{-2})**	**Maximum Biomass (kg FW m^{-2})**	
Pasture	181	304	0.216	4.32	

[1]DOY = day of year

Table 2.

Beef (d kg^{-1})	Sheep (d kg^{-1})	Goat (d kg^{-1})	Pork (d kg^{-1})	Poultry (d kg^{-1})	Cow Milk (d L^{-1})	Sheep Milk (d L^{-1})	Goat Milk (d L^{-1})	Eggs (d kg^{-1})
0.010	0.500	0.300	0.400	4.500	0.003	0.060	0.060	0.400

Table 3.

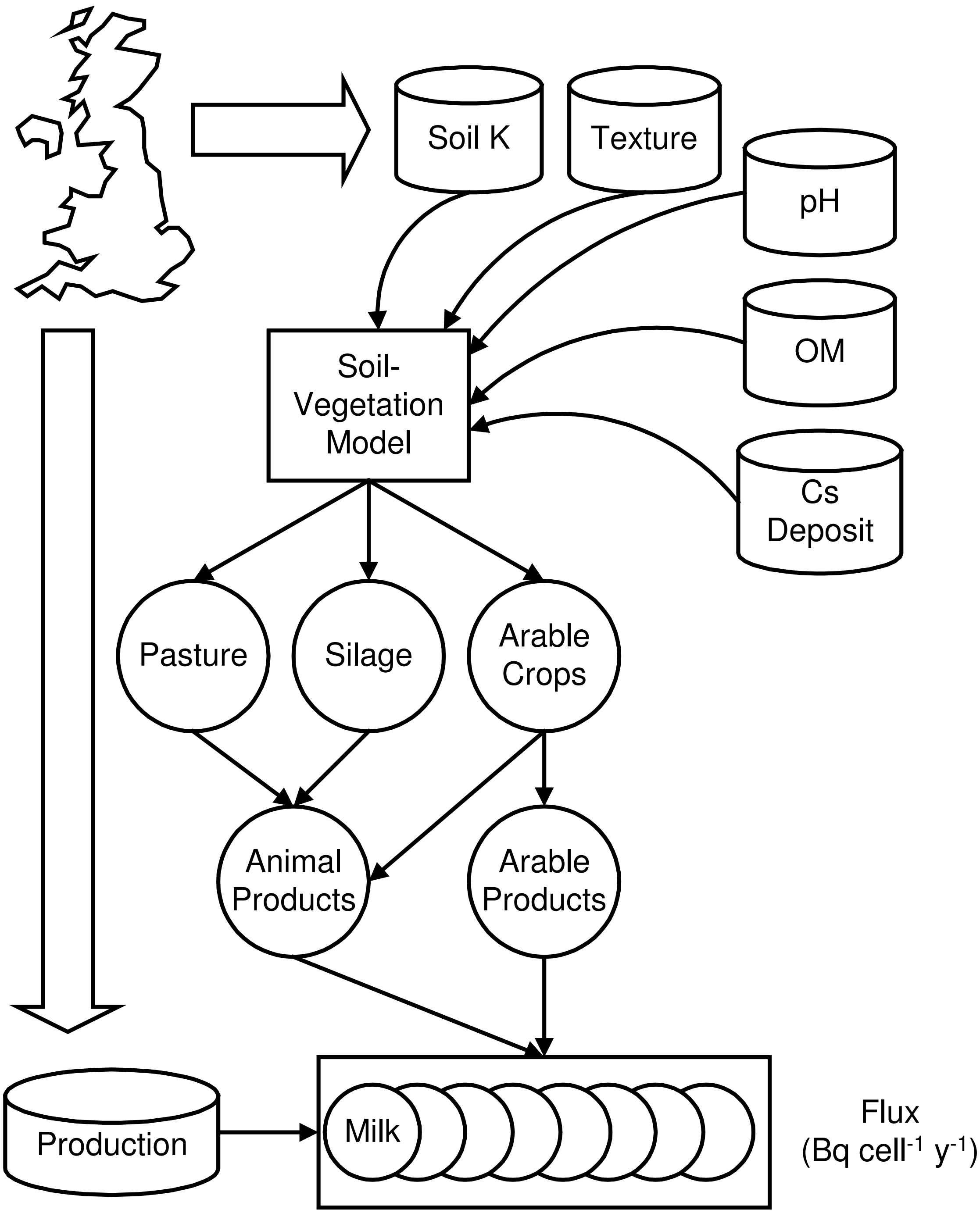
Dialog box	**Model Components Controlled**	**User defined parameters**	**Units**	**Temporal**	**Spatial**
Deposition		Uniform deposition Chernobyl deposition Deposit bioavailability Spatial distribution of deposition can be altered but requires input from a GIS	Bq m^{-2} Bq m^{-2} dimensionless Bq m^{-2}	N N N N	N Y N Y
Animal Management	Animal dry matter intake	Bi-monthly dry matter intake of pasture, silage, stored grass and concentrate)	kg DW d^{-1}	Y	Y
Transfers	Plant to Animal Soil to Plant	Animal transfer factor (meat or milk) Crop relative transfer ratios	d kg^{-1}, d L^{-1} dimensionless	N N	N N
	Crop biomass	Sowing/harvest date Yield Harvest index Residual biomass Number of cuts per year (stored grass only) Cut interval (stored grass only)	DOY kg FW m^{-2} dimensionless kg FW m^{-2} dimensionless d	N N N N N N	Y Y Y Y Y Y
Crop Production	Radiocaesium Flux	Crop or animal product production[1]	kg $cell^{-1}$	N	Y

Note : FW = fresh weight; DW = dry weight; DOY = day of year.
[1] total production can be altered per region for each product and combined with a land cover mask to give the estimated production per cell

Table 4.

MAFF Region / Product	Chernobyl Deposition Scenario		Uniform Deposition Scenario	
	Year 1	Year 10	Year 1	Year 10
Sheep Meat	% of Total Flux			
Wales	49	60	47	43
North	23	23	25	30
North West	11	7	11	3
South West	10	4	9	6
Yorks & Humberside	4	6	6	11
West Midlands	2	0	1	3
East Midlands	1	0	1	2
East Anglia	0	0	0	0
South East	0	0	0	2
Total Flux (GBq y^{-1})	**18**	**0.06**	**32**	**0.02**
Cereals	% of Total Flux			
South West	20	10	11	8
North West	17	13	2	3
Yorks & Humberside	17	34	14	27
North	15	29	6	27
East Anglia	15	2	17	8
Wales	7	8	2	3
East Midlands	5	3	18	9
West Midlands	4	1	9	5
South East	0	0	21	10
Total Flux (GBq y^{-1})	**40**	**0.23**	**100**	**0.24**
Cow Milk	% of Total Flux			
North West	33	25	30	10
South West	23	13	20	18
North	19	26	22	22
Wales	18	24	18	18
Yorks & Humberside	4	9	7	15
West Midlands	2	1	1	7
East Midlands	1	2	2	5
East Anglia	0	0	0	1
South East	0	0	0	4
Total Flux (GBq y^{-1})	**110**	**0.13**	**120**	**0.06**

Figure 1.

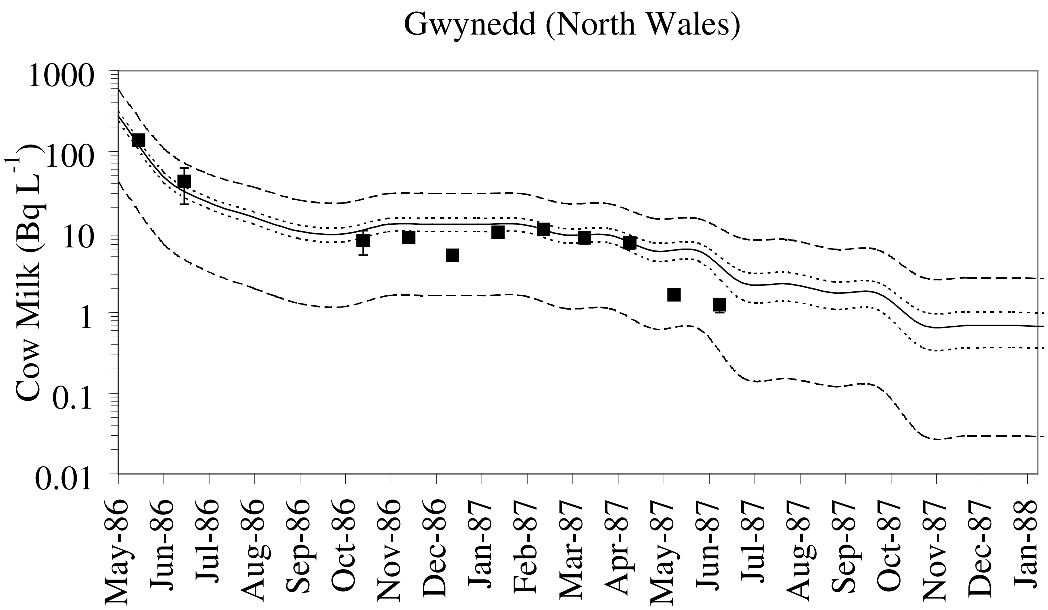


Soil K
Texture
pH
OM
Cs
Deposit
Soil-
Vegetation
Model
Pasture
Silage
Arable
Crops
Animal
Products
Arable
Products
Production
Milk
Flux
(Bq cell-1 y-1)

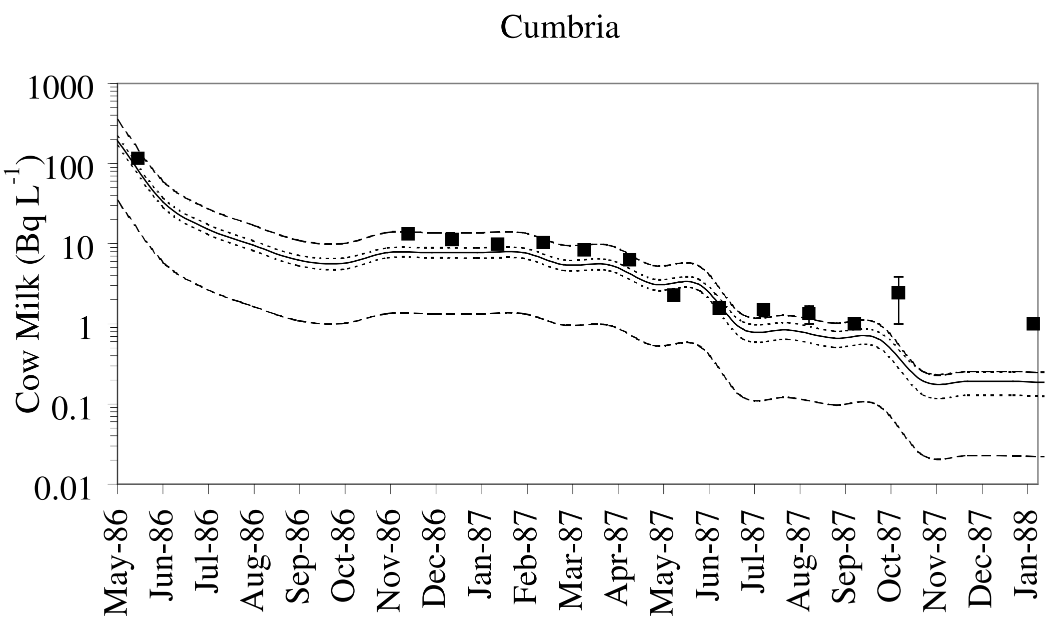
Figure 2

North
Yorkshire & Humberside
North West
East Midlands
West Midlands
Wales
East Anglia
South East
South West

Figure 3

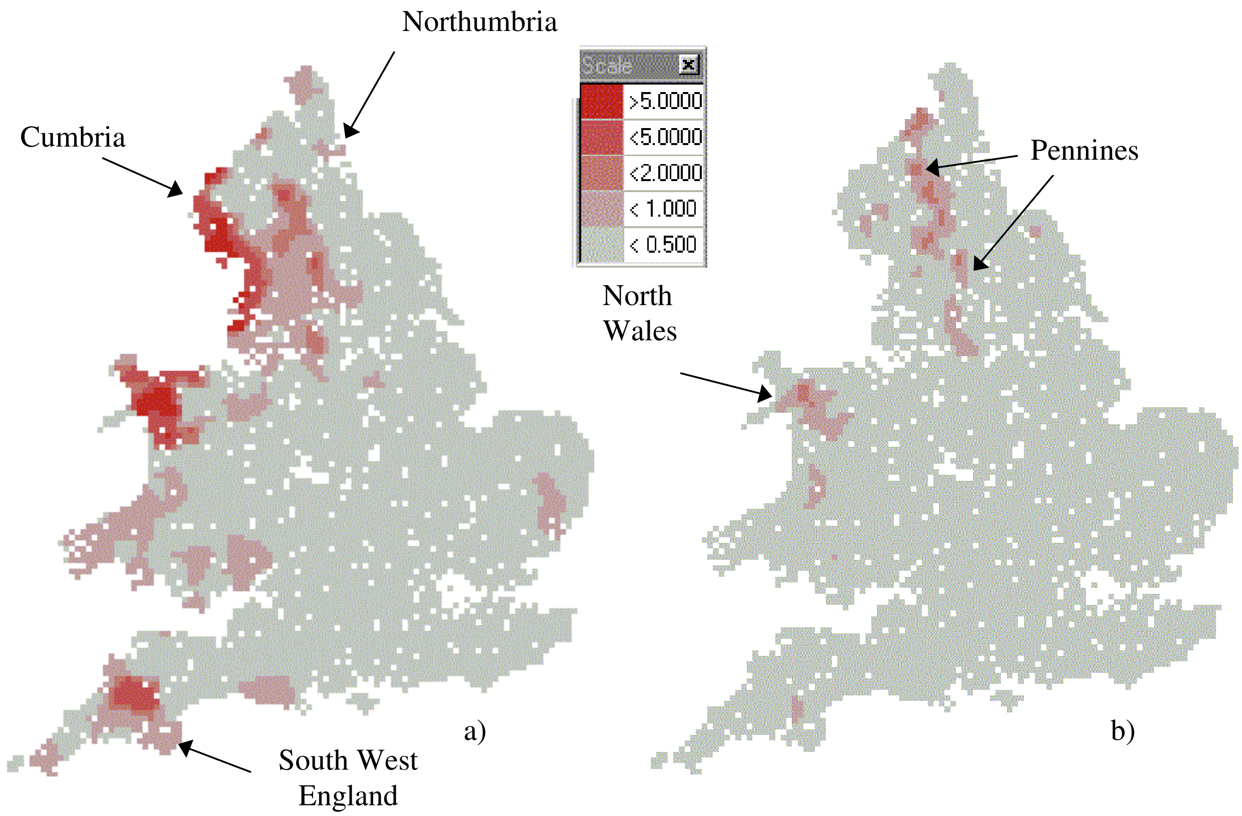


Gwynedd (North Wales)
1000
100
10
1
0.1
0.01
Cow Milk (Bq L^{-1})
May-86
Jun-86
Jul-86
Aug-86
Sep-86
Oct-86
Nov-86
Dec-86
Jan-87
Feb-87
Mar-87
Apr-87
May-87
Jun-87
Jul-87
Aug-87
Sep-87
Oct-87
Nov-87
Dec-87
Jan-88



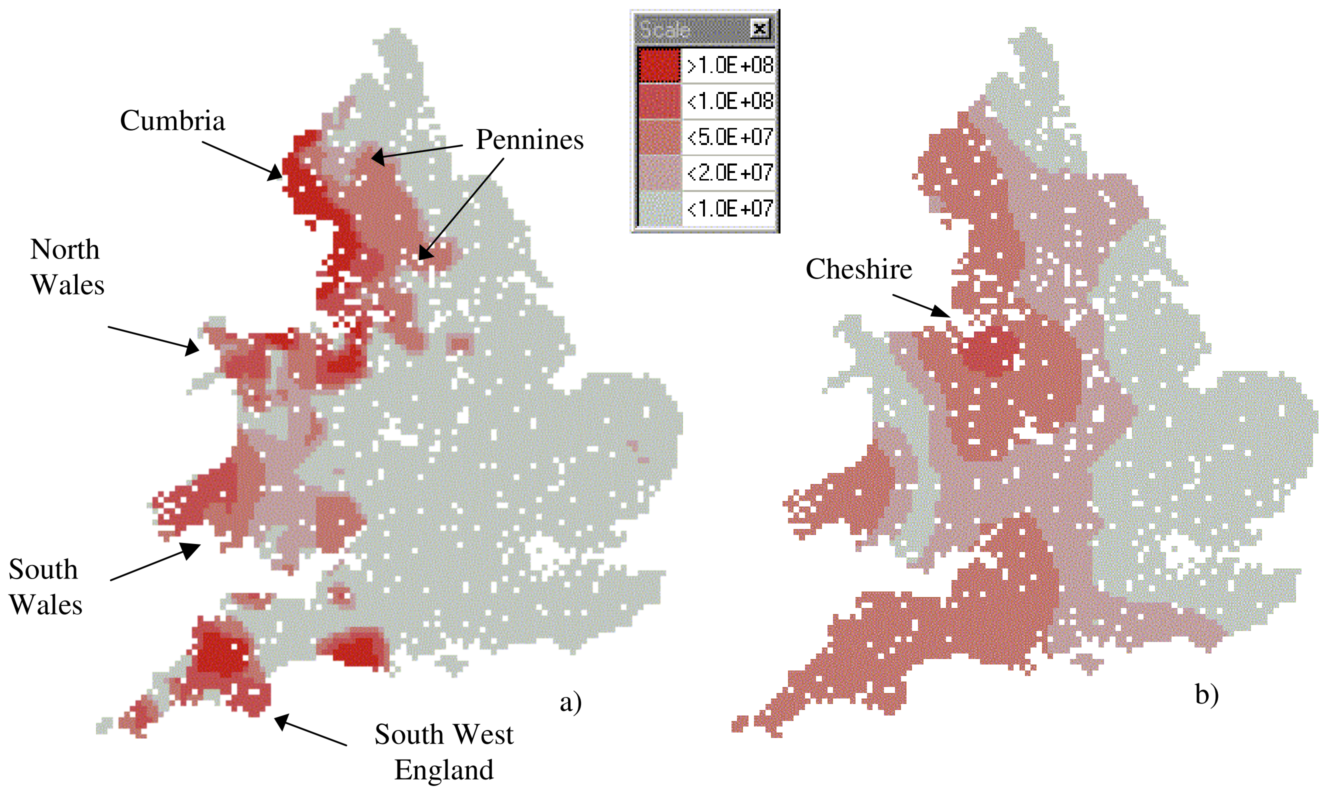
Cumbria
1000
100
10
1
0.1
0.01
Cow Milk (Bq L^{-1})
May-86
Jun-86
Jul-86
Aug-86
Sep-86
Oct-86
Nov-86
Dec-86
Jan-87
Feb-87
Mar-87
Apr-87
May-87
Jun-87
Jul-87
Aug-87
Sep-87
Oct-87
Nov-87
Dec-87
Jan-88

Figure 4



Northumbria
Cumbria
South West
England
a)
Scale
>5.0000
<5.0000
<2.0000
< 1.000
< 0.500
North
Wales
Pennines
b)

Figure 5


Scale
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<1.0E+08
<5.0E+07
<2.0E+07
<1.0E+07
Cumbria
Pennines
North Wales
South Wales
South West England
a)
Cheshire
b)