NRPB-R273

FARMLAND: A Dynamic Model for the Transfer of Radionuclides Through Terrestrial Foodchains

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Abstract

Models to simulate the transfer of radionuclides through terrestrial foods have been developed at NRPB and regularly used over the last 20 years. The foodchain model is named FARMLAND (Food Activity from Radionuclide Movement on LAND) and it contains a suite of submodels, each of which simulates radionuclide transfer through a different part of the foodchain. These models can be combined in various orders so that they can be used for different situations of radiological interest. The main foods considered are green vegetables, grain products, root vegetables, milk, meat and offal from cattle, and meat and offal from sheep. A large variety of elements can be considered, although the degree of complexity with which some are modelled is greater than that for others; isotopes of caesium, strontium and iodine are treated in greatest detail.

This report gives an overview of the FARMLAND model with the aim of consolidating all the information on the model available in past NRPB publications. In addition, recent model developments are described.

The use of FARMLAND for different applications is addressed. In particular, the generation of a set of parameter values and assumptions for use in general applications in countries in the European Union are discussed. Activity concentrations in foods are presented for a few important radionuclides for both routine and accidental release applications. The conclusions of verification and validation studies performed using FARMLAND are also outlined.

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Approval date:	**October 1994**
Publication date:	**July 1995**

HMSO, £10.00
ISBN 0 85951 380 7

NRPB-R273

Errata

Two entries in Tables 7 and 8 of NRPB-R273 appear incorrectly. These are:

Table 7: Line 3 from bottom – Polonium should read Plutonium

Table 8: Line 1 – Polonium should read Phosphorus

Replacement tables are attached.

TABLE 7 Equilibrium soil-to-plant concentration ratios (wet weight plant to dry weight soil)

	Crop				
Element	Green vegetables	Grain	Root vegetables	Potatoes	Pasture
Phosphorus	1	1	1	1	1
Sulphur	$6\ 10^{-1}$	$6\ 10^{-1}$	$6\ 10^{-1}$	$6\ 10^{-1}$	$6\ 10^{-1}$
Chlorine	5	5	5	5	5
Chromium	$3\ 10^{-4}$	$3\ 10^{-4}$	$3\ 10^{-4}$	$3\ 10^{-4}$	$3\ 10^{-4}$
Manganese	$1\ 10^{-1}$	$1\ 10^{-1}$	$1\ 10^{-1}$	$1\ 10^{-1}$	$1\ 10^{-1}$
Iron	$2\ 10^{-4}$	$4\ 10^{-4}$	$3\ 10^{-4}$	$3\ 10^{-4}$	$4\ 10^{-4}$
Cobalt	$1\ 10^{-2}$	$5\ 10^{-3}$	$1\ 10^{-2}$	$1\ 10^{-2}$	$1\ 10^{-2}$
Nickel	$1\ 10^{-2}$	$1\ 10^{-2}$	$1\ 10^{-2}$	$1\ 10^{-2}$	$1\ 10^{-2}$
Zinc	1	1	$5\ 10^{-1}$	$5\ 10^{-1}$	1
Bromine	$2\ 10^{-2}$	$2\ 10^{-2}$	$2\ 10^{-2}$	$2\ 10^{-2}$	$2\ 10^{-2}$
Selenium	1	1	1	1	1
Rubidium	$1\ 10^{-1}$	$1\ 10^{-1}$	$1\ 10^{-1}$	$1\ 10^{-1}$	$1\ 10^{-1}$
Strontium	$3\ 10^{-1}$	$2\ 10^{-1}$	$1\ 10^{-1}$	$5\ 10^{-2}$	$5\ 10^{-2}$ [a]
Yttrium	$1\ 10^{-2}$	$1\ 10^{-2}$	$1\ 10^{-2}$	$1\ 10^{-2}$	$1\ 10^{-2}$
Zirconium	$1\ 10^{-4}$	$1\ 10^{-4}$	$1\ 10^{-4}$	$1\ 10^{-4}$	$1\ 10^{-4}$
Niobium	$1\ 10^{-2}$	$1\ 10^{-2}$	$1\ 10^{-2}$	$1\ 10^{-2}$	$1\ 10^{-2}$
Molybdenum	$1\ 10^{-1}$	$1\ 10^{-1}$	$1\ 10^{-2}$	$1\ 10^{-2}$	$1\ 10^{-1}$
Technetium	5	5	5	5	5
Ruthenium	$1\ 10^{-2}$	$1\ 10^{-2}$	$1\ 10^{-2}$	$1\ 10^{-2}$	$1\ 10^{-2}$
Silver	$2\ 10^{-1}$	$2\ 10^{-1}$	$2\ 10^{-1}$	$2\ 10^{-1}$	$2\ 10^{-1}$
Tin	$1\ 10^{-1}$	$2\ 10^{-1}$	$6\ 10^{-2}$	$6\ 10^{-2}$	$2\ 10^{-1}$
Antimony	$1\ 10^{-2}$	$1\ 10^{-2}$	$1\ 10^{-2}$	$1\ 10^{-2}$	$1\ 10^{-2}$
Tellurium	$3\ 10^{-3}$	$3\ 10^{-3}$	$4\ 10^{-4}$	$1\ 10^{-3}$	$5\ 10^{-3}$
Iodine	$2\ 10^{-2}$	$2\ 10^{-2}$	$2\ 10^{-2}$	$2\ 10^{-2}$	$2\ 10^{-2}$
Caesium[b]	$7\ 10^{-3}$	$1\ 10^{-2}$	$5\ 10^{-3}$	$7\ 10^{-3}$	$3\ 10^{-2}$
Barium	$1\ 10^{-2}$	$1\ 10^{-2}$	$5\ 10^{-3}$	$5\ 10^{-3}$	$1\ 10^{-2}$
Lanthanum	$3\ 10^{-3}$	$3\ 10^{-3}$	$3\ 10^{-3}$	$3\ 10^{-3}$	$3\ 10^{-3}$
Cerium	$1\ 10^{-3}$	$1\ 10^{-3}$	$1\ 10^{-3}$	$1\ 10^{-3}$	$1\ 10^{-3}$
Promethium	$3\ 10^{-3}$	$3\ 10^{-3}$	$3\ 10^{-3}$	$3\ 10^{-3}$	$3\ 10^{-3}$
Europium	$3\ 10^{-3}$	$3\ 10^{-3}$	$3\ 10^{-3}$	$3\ 10^{-3}$	$3\ 10^{-3}$
Lead	$1\ 10^{-2}$	$1\ 10^{-2}$	$1\ 10^{-2}$	$1\ 10^{-2}$	$1\ 10^{-2}$
Polonium	$2\ 10^{-4}$	$2\ 10^{-4}$	$2\ 10^{-4}$	$2\ 10^{-4}$	$2\ 10^{-4}$
Radium	$1\ 10^{-2}$	$1\ 10^{-3}$	$1\ 10^{-3}$	$1\ 10^{-3}$	$1\ 10^{-2}$
Actinium	$1\ 10^{-3}$	$1\ 10^{-3}$	$1\ 10^{-3}$	$1\ 10^{-3}$	$1\ 10^{-3}$
Thorium	$5\ 10^{-4}$	$5\ 10^{-4}$	$5\ 10^{-4}$	$5\ 10^{-4}$	$5\ 10^{-4}$
Protactinium	$4\ 10^{-2}$	$4\ 10^{-2}$	$4\ 10^{-2}$	$4\ 10^{-2}$	$4\ 10^{-2}$
Uranium	$1\ 10^{-3}$	$1\ 10^{-3}$	$1\ 10^{-3}$	$1\ 10^{-3}$	$1\ 10^{-3}$
Neptunium	$2\ 10^{-3}$	$2\ 10^{-3}$	$1\ 10^{-3}$	$1\ 10^{-3}$	$1\ 10^{-2}$
Plutonium	$1\ 10^{-5}$	$2\ 10^{-5}$	$5\ 10^{-5}$	$5\ 10^{-5}$	$1\ 10^{-4}$
Americium	$5\ 10^{-5}$	$5\ 10^{-5}$	$8\ 10^{-5}$	$8\ 10^{-5}$	$1\ 10^{-3}$
Curium	$5\ 10^{-5}$	$2\ 10^{-5}$	$3\ 10^{-5}$	$3\ 10^{-5}$	$1\ 10^{-3}$

Notes

(a) This value applies to uptake from the lower layers of soil, for the top 1 cm a value of $2\ 10^{-1}$ is appropriate.

(b) For crops other than pasture, fixation of caesium is incorporated implicitly in the root uptake values.

Contents

1 Introduction

Following the deposition of radioactive material from the atmosphere on to the ground one of the principal routes of exposure is internal irradiation from the ingestion of contaminated food. This exposure route is therefore included in assessments of the radiological significance of accidental and routine releases of radioactive material to the terrestrial environment.

Models to simulate the transfer of radionuclides through terrestrial foods have been developed at NRPB and regularly used over the last 20 years. The NRPB foodchain model is a dynamic one and aspects of its early development have been described in a number of publications[1-4]. The foodchain model is named FARMLAND (Food Activity from Radionuclide Movement on LAND) and it contains a suite of submodels, each of which simulates radionuclide transfer through a different part of the foodchain. These submodels can be combined in various orders so that they can be used for different situations of radiological interest. The main foods considered are green vegetables, grain products, root vegetables, milk, meat and offal from cattle, and meat and offal from sheep. A large variety of elements can be considered, although the degree of complexity with which some are modelled is greater than that for others; isotopes of caesium, strontium and iodine are treated in greatest detail. FARMLAND is compartmental and, although originally intended for use in connection with continuous, routine releases of radionuclides, it has many time-dependent features and its use was extended to a single accidental release. The most recent version can be used to predict concentrations in food as a function of time after an accidental release of radionuclides at a number of different times of the year.

This report gives an overview of the FARMLAND model with the aim of consolidating all the information on the model available in past NRPB publications. In addition, recent model developments are described, eg a fruit model for routine release applications[5] and a model for root vegetables[6]. The report is supported by an NRPB memorandum[7] giving details of the compartmental models, the parameter values used, information on how to use the models for different applications and a selection of activity concentrations in foods for accidental and routine release applications. A database of the results of running the model for both routine and accidental release applications will also be available.

The use of FARMLAND for different applications is addressed. In particular, the generation of a set of parameter values and assumptions for use in general applications in the European Union are discussed. Activity concentrations are presented for a few important radionuclides for both routine and accidental release applications. The conclusions of verification and validation studies performed using FARMLAND are also outlined.

2 Methodology

2.1 General approach

FARMLAND is a general, dynamic model with a modular structure. Separate submodels have been developed for each of the major crop types and animals considered, and these can be linked to represent the situation of radiological interest. The movement of radionuclides within each module is represented by transfers between interconnected compartments and within each module it is assumed that first-order kinetics apply, ie the transfer of material between compartments is in linear proportion to the inventory in the source compartment. The main advantage of a compartmental approach is that it allows a flexible system which can accommodate large differences in the amount of detail included in various parts of the system. Radioactive decay is taken into account in the model by a loss term from each compartment. FARMLAND can also consider the ingrowth of radioactive progeny; this is accommodated by introducing a parallel and identical system of compartments together with those representing transfer of the parent. The compartmental models are solved using a matrix technique for solving coupled linear first-order differential equations[7].

FARMLAND has been developed as a series of modules, each representing a different part of the foodchain. Selections of these modules can be put together to evaluate the transfer of radionuclides through a particular part of the foodchain. For example, modules for undisturbed soil, pasture and cows can be put together to represent the transfer of radioactive material to cows' milk. For some parts of the foodchain several modules have been developed of differing levels of complexity. This enables the level of complexity of the models chosen to be consistent with the purpose of the assessment; this is discussed in further detail in Section 4.

Where data are available the models are dynamic in form with temporal changes in the system being modelled. In particular, element-specific modules have been developed for animals to take into account the important biological and metabolic processes for those elements whose transfer through terrestrial foodchains is significant. More details of these are given in Section 2.2.9.2. For some parts of the foodchain, however, few data exist on the short-term time dependence of transfer and for these parts of the model quasi-equilibrium is assumed, eg root uptake into plants.

2.2 Transfer mechanisms included in FARMLAND

The methodological approach taken to modelling the transfer mechanisms in the terrestrial foodchain in FARMLAND is outlined in this section and details of the experimental basis for the assumptions made are given. The main transfer mechanisms are: migration of radionuclides in soil, root absorption into plants from soil, surface contamination of plants and subsequent translocation, and transfer to an animal and metabolism in the animal.

2.2.1 Migration of radionuclides in soil

The principal mechanisms for the removal of activity from the root zone of vegetation following deposition on to land are radioactive decay and downwards migration in soil. For radionuclides with long half-lives the rate of downward migration is likely to have a large effect on the time dependence of transfer to plants and, subsequently, animal products. For some elements, notably caesium, the availability for uptake into the plant from the soil via the roots also varies with time owing to physical and biochemical processes in the soil. Many parameters influence the rate of migration, particularly the nature of the element and its chemical form, soil composition, climate and rainfall. Agricultural land can be categorised into one of two types for the purposes of modelling migration: undisturbed land (eg permanent pasture) or land where the soil is kept well mixed by frequent ploughing or cultivation. Models have been developed to represent migration in these two conditions and their main features are outlined.

Model for well-mixed soil

The model for well-mixed soil, shown in Figure 1, is intended to represent land which is ploughed or cultivated annually or more frequently. The radionuclides are assumed to be uniformly mixed and evenly available to a depth of 30 cm; this depth is chosen to encompass the variation in depth of the root zones of most plants (usually 20–30 cm). Implicit in this approach is the

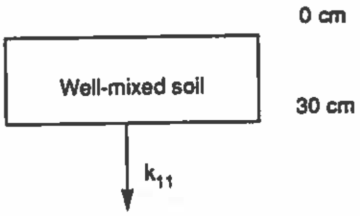

FIGURE 1 Schematic of well-mixed soil model

assumption that the uniform profile is not significantly altered by migration in the intervening period between ploughing or cultivation. Loss from the root zone occurs by downwards penetration processes, of which diffusion and transport along with general water movement are the most important; the migration out of this soil depth is represented by a single transfer.

Model for undisturbed land

The model for undisturbed land, shown in Figure 2, is intended to represent migration through undisturbed agricultural land, of which permanent pasture is an example. The movement of radionuclides through the soil column is represented by a series of transfers between compartments of varying depth; within each compartment the radionuclides are assumed to be uniformly mixed. The selection of compartments is a compromise between including all those relevant to an adequate representation of the migration processes and including only those that have physical significance for other parts of the terrestrial model. For example, resuspension of the contaminant on to plant surfaces is assumed to derive solely from the top 1 cm of soil, ie the surface

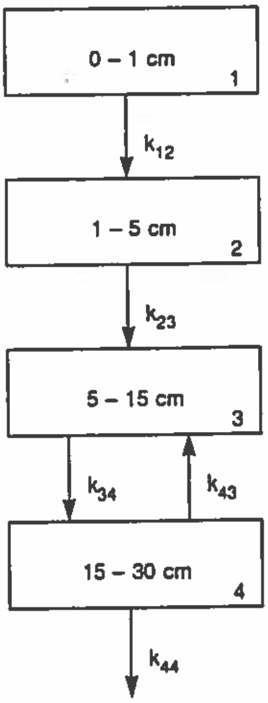

FIGURE 2 Schematic of the model for undisturbed land

compartment. Soil which is consumed inadvertently by animals is also assumed to be derived from the top 1 cm layer. The root zone of pasture grass is considered to extend to 15 cm in depth and the radionuclides present in each of the three compartments are available for root uptake.

Migration into soils has only been studied for a limited number of elements, mainly those long-lived radionuclides which are present in nuclear weapons fallout, in particular caesium, strontium and plutonium. In addition, there are some migration data available, particularly for plutonium, from single deposits on the ground following tests and accidents with nuclear devices[8,9] and leakage of radioactive material at a nuclear facility[10]. The rate of movement into the soil of these elements is slow, although there is significant variation between the results of the various observations owing to differences in soil composition and annual rainfall. None of the observations extends beyond 30 years after the deposition event. Studies on soil migration are also in progress using the deposition of caesium following the Chernobyl reactor accident in 1986[11,12]; the results of these studies have not been used in the current version of FARMLAND.

In view of the limited data on soil migration the transfer rates used in the model are based on the soil migration for plutonium, for which the majority of the data exist, and are assumed applicable to all other elements. This approach is considered realistic for elements such as caesium and strontium which appear to migrate at a similar rate to plutonium. It is recognised, however, that for more mobile elements, such as iodine, the model is conservative, ie the downwards migration assumed is slower than is probably the case. The transfer between soil compartments has been derived from experimental measurements of the migration of single deposits of plutonium in various soils[8-10]. The transfer rates were chosen to give the best fit to the experimental data and their derivation is described elsewhere[7]. These transfer rates are given in Table 1 and are for the migration of a stable isotope.

Foodchain model predictions are required beyond the 30 years following deposition for which observed data are available. Any estimate of migration beyond these times is, therefore, speculative. From a review and extrapolation of the migration data for plutonium, caesium and strontium a judgement has been made that a half-life of 100 years is representative for removal of activity from a 30 cm depth of well-mixed soil and 50 years for removal from the 15–30 cm depth layer of soil for undisturbed soil.

TABLE 1 Values of rate constants used in the models for migration in soil

Soil model	Pathway	Rate constants (d^{-1})
Well-mixed soil[a]	k_{11}	$1.90\ 10^{-5}$
Undisturbed land[b]	k_{12}	$6.65\ 10^{-4}$
	k_{23}	$1.72\ 10^{-4}$
	k_{34}	$1.07\ 10^{-4}$
	k_{43}	$4.03\ 10^{-6}$
	k_{44}	$3.80\ 10^{-5}$

Notes

(a) See Figure 1.

(b) See Figure 2.

The soil models for use with FARMLAND are currently under review at NRPB with a view to including element-dependent migration. Results from studies on soil migration carried out since the Chernobyl reactor accident in 1986 will be taken into account in this review.

2.2.2 Fixation of caesium in soils

For the majority of soil types a fraction of caesium in the soil is bound to the clay component of the soil and is unavailable for uptake into plants. This fraction will vary and for some soils is very small. However, for the majority of soils in the UK this fixation process progressively leads to most of the caesium in the soil becoming unavailable to plants in the course of a few years following deposition[13]. The presence of a surface soil layer which is rich in organic material and plant root matter initially limits the amount of fixation[14,15]. However, within a period of a few years the caesium migrates below this layer and progressively becomes less available for uptake to plants[16,17]. Based on studies on four UK soils[13] with a range of pH values, exchangeable calcium, clay and organic matter content, this process has been included in the model[18]. It is assumed that 90% of the caesium becomes fixed within the soil after 3 years; the process is assumed to have a half-life of 0.9 year. Studies on peat soils[19,20], which have a high organic content and are typically found in upland areas of the UK supporting poor quality pasture, have shown that the uptake of caesium into plants via the roots is much higher than that seen for clay based soils. The low clay content in these soils prevents the caesium becoming fixed within the soil lattice and therefore leaves it available for uptake. These upland pastures are typically used in the UK for grazing sheep. However, little of the UK lamb production comes directly from these pastures as the lambs bred in these areas are moved to lowland areas for fattening before slaughter. Soils typical of those found in upland areas are therefore not modelled in the generic FARMLAND model owing to their relative unimportance for UK food production. However, for site-specific studies involving these areas and soil types it would be more appropriate to take the lack of fixation of caesium into account. Soil fixation is not included for other elements. The caesium fixation model for pasture is described elsewhere[7]. For arable crops the effect of caesium fixation in soil is included in the root uptake and is described in Section 2.2.6.

2.2.3 Transfer of radionuclides to plants

The main features of the model developed to describe the transfer of nuclides to plants are illustrated in Figure 3. The compartment marked 'soil' represents the model for migration in soil appropriate to the plant species and agricultural conditions considered. All plants consumed directly by man are assumed to be derived from land that is frequently cultivated and the migration model for well-mixed soil is most appropriate in these circumstances. Grass, however, is assumed to be produced only on undisturbed pasture, in which case the migration model for undisturbed soil is applicable. Contamination of both the surface and internal parts of the plant is considered: transfer to the plant surface may occur by interception of depositing activity or by resuspension of activity from soil; transfer to the internal plant occurs via root uptake and by absorption from the surface of the plant and subsequent translocation. Each process is discussed in turn.

2.2.4 Interception, removal and translocation of deposited radionuclides

When radioactive material is deposited on to agricultural land from atmosphere, only part of the material is intercepted by the foliage of the plant with the rest landing on the surrounding soil. In general, radioactive material is removed from the surfaces of the plant by natural processes such

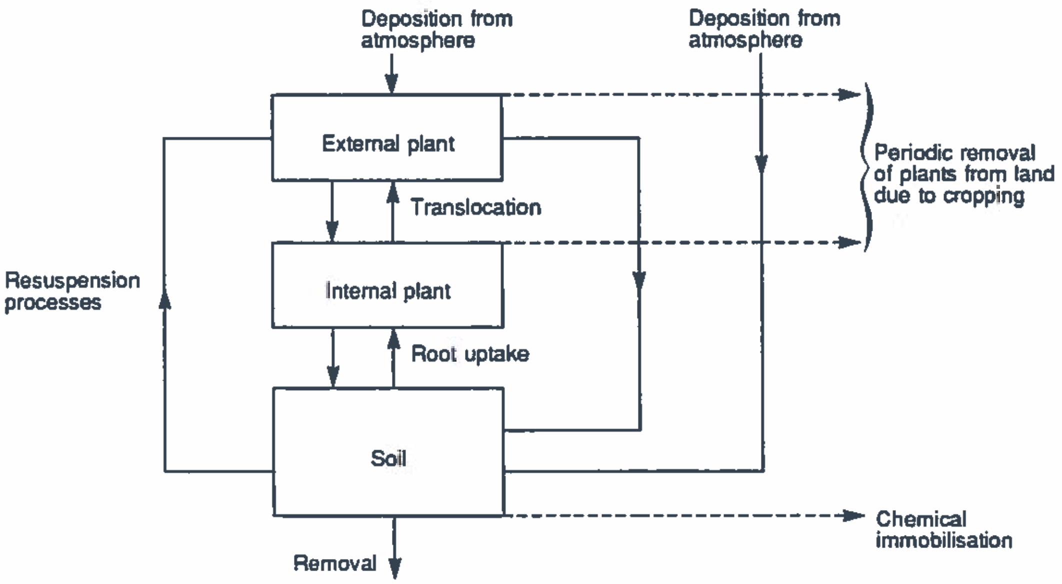

FIGURE 3 Schematic of the principal mechanisms for the transfer of radionuclides in plants

as dehiscence (bursting open) of fragments of wax from the leaf surface and weathering caused by wind and rain action on the plant. Some of the material deposited on plant surfaces may be absorbed and transferred to other parts of the plant; this process is known as translocation. The three processes, interception, retention and translocation, are interrelated and govern the contamination of plants from direct deposition on to the plant surface. Their inclusion in FARMLAND is described below.

2.2.4.1 Interception and retention

The interception and retention of radionuclides on plant surfaces will vary according to the physio-chemical form of the deposit, the meteorological conditions at the time of deposition, and the type of vegetation and the stage of its growth. Considerable variation has been observed in measured values of interception factors and removal rates of activity from plant surfaces[21-23]. The interception of particulate material by plants deposited under dry conditions depends on the particle size and the stage of development of the plant. Large particles, in excess of 45 μm, are seldom retained on plants while smaller particles in the range of a few micrometres, sizes typically seen in aged aerosols, are more readily intercepted by plants[16,23]. The dependence of the interception on the stage of development of the plant causes a pronounced seasonal effect, with the amount of material initially retained on the plant being much lower at times of the year when plants are at an early development stage[24]. In addition, the amount of wet deposition retained on the plant surface depends on the stage of development of the plant. However, it also depends on the amount of rainfall and the ability of the radioactive element to be fixed to the leaf[23,24]. If deposition occurs in rain which is sufficiently heavy to cause appreciable runoff from leaves, retention will be less than that after light showers[16,23,24]. Retention will also be greater when the deposit takes the form of finely dispersed fog[16,23]. A single value for an interception factor, ie the fraction of the deposit that is initially retained on the plant surface, will therefore not necessarily accurately represent the range of interception that may occur for all weather conditions and forms of deposit. However, for a generic foodchain model which will be used in situations where details of the deposit and weather conditions are not known, and for general assessments for both accidental and continuous releases to atmosphere, a single value representative of typical conditions is desirable.

The approach has been taken in FARMLAND to use the total deposition as an input to the system, ie there is no distinction between wet and dry deposited material, and to use interception factors that are applicable for annual average conditions. For routine release applications the annual deposition rate is used and is assumed constant and so the application of an interception factor appropriate for annual conditions is reasonable. This approach is also used in FARMLAND for accidental release applications and is appropriate for estimating representative doses from the ingestion of terrestrial foods over large areas. The approach is appropriate for use with probabilistic accident consequence codes which consider a range of meteorological conditions and estimate the consequences of postulated accidental release over large areas. It is also considered appropriate for use in the early phase after an accident before detailed meteorological data are available. The FARMLAND model could be used for specific situations where the meteorological conditions are known by adjusting the model parameters for interception and retention; however, this is not done with the generic FARMLAND model.

Other foodchain models developed primarily for use after accidental releases to atmosphere consider the interception of wet and dry deposited material separately; FARMLAND has been compared with one of these models, ECOSYS[25], for an accidental release situation[26]. The conclusion of the study was that for typical rainfall of a few millimetres the two approaches gave very similar results for interception factors; for high or low total rainfall there were differences of up to a factor of five between the two approaches.

Chamberlain[21] introduced a quantity, the Normalised Specific Activity (NSA), for use in assessing the contamination on vegetation during conditions of continuous deposition from atmosphere, which is defined as:

$$\text{NSA } (\text{m}^2 \text{ d kg}^{-1}) = \frac{\text{Activity per kg dry weight of crop}}{\text{Activity deposited per day per m}^2 \text{ of ground}}$$

For herbage, the NSA has been shown to be almost constant for a variety of contaminants during the growing season and to be related to the interception factor, P, and the retention half-life, T_w, by the following relationships:

$$1 - P = \exp(-\mu w)$$

$$\text{NSA} = \mu T_w / \ln 2$$

where μ is the uptake coefficient (m^2 kg^{-1}) and w is the herbage density (kg m^{-2}).

This method provides a simple means of estimating P and T_w values for use in assessing contamination levels on crops at harvest following continuous deposition. It implicitly takes into account the other processes which influence foliar contamination, namely, translocation and dilution due to plant growth[21,27].

From measured values of the uptake coefficient[21] and using a dry weight herbage density of 10^{-5} kg km^{-2}, which is the default yield used for pasture in the model (see Table 1), the interception factor for pasture is in the range 0.20–0.28 using the relationship given above. A value of 0.25 is used in FARMLAND. The concentration of radionuclides in hay and silage is predicted using a model similar to that for pasture except that the density of the grass, is assumed to be higher. The interception factor used is also higher than that for grazed grass, reflecting the relationship between pasture density and interception factor observed by Chamberlain[21].

For green vegetables, grain, root vegetables and fruit, interception factors have been determined from the literature; Chamberlain's relationship, which is applicable for continuous deposition and for contamination of the crop at harvest, has been used to estimate values of the interception factor for consolidation of the values chosen.

For green vegetables limited data on interception are available[27]. From the data available and with the assumption that Chamberlain's relationship holds for leafy vegetables a value for the interception factor of 0.3 can be estimated for a dry weight crop yield of $2\ 10^5$ kg km^{-2}.

Measurements are available on the interception of material by the grain seed[28,29] and a general interception factor of 0.012 is suggested. An interception factor for the cereal plant has been based on data for straw[28,29] and is compatible with that used for other plants.

For root vegetables the experimental data of Moorby and Squire[30] indicate an interception factor of 0.4 for the 'tops' of potatoes; with the relationship between interception and yield of Chamberlain this is consistent with reported yields of potato 'tops' and this value has been used for all elements. For fruit an interception factor of 0.01 is adopted for use in FARMLAND based on a review of the literature[5].

Values of interception factors for average meteorological conditions for use in FARMLAND are given in Table 2.

2.2.4.2 Weathering

The removal of activity from the external plant surface is modelled using a retention halflife. This halflife represents the loss due to weathering from rain and wind and that due to dehiscence from the leaf surface of fragments of wax, to which radioactivity has been attached. Experimental work has shown that the retention can be assumed to be element independent[16,21].

Few data are available on the retention of surface deposits on vegetables in field conditions. In one of the few relevant experimental studies a retention halflife of 9 days was observed[31]. Measured NSA values in green vegetables were used to determine a retention halflife for green vegetables[29] and a value of 14 days was found to be appropriate with an interception factor of 0.3. For root vegetables and fruit no data were available on the loss due to weathering, which is therefore assumed to be similar to that for other crops.

For grain the retention on the grain and that on the rest of the plant is considered. The value for the retention halflife on grain was based on experimental data by Aakrog for ruthenium and cerium[28,29] and a value of 14.4 days is used. For the whole plant a value of 14 days has been chosen based on data for straw[28,29] and to be compatible with other crops.

The retention halflife on grass is based on a review of the available data[21,32]. Measured values of the retention halflife have been found in the range 13 to 19 days in summer, with longer retention halflives observed in winter when little growth occurs or on ungrazed pasture. A value of 14 days which is in the middle of the range and is commonly used in modelling studies has been adopted for use in FARMLAND. For accidental release applications where the winter period is modelled explicitly a longer retention halflife of 28 days is used for the period when animals are not grazing pasture, consistent with the observed values in the literature[32].

Values for retention halflives used in FARMLAND are given in Table 2.

TABLE 2 Element-independent parameters for crops and pasture

	Value					
Parameter	Green vegetables	Grain	Pasture	Hay/silage	Root vegetables/ potatoes	Fruit[a]
Yield, fresh weight (kg km^{-2})	$1\ 10^6$	$4\ 10^5$	$5\ 10^5$	$1\ 10^{6\ b}$	$4\ 10^5/3\ 10^6$	$9\ 10^5$
Interception factor	0.3	0.3^c 0.012^d	0.25	0.62	0.4	0.08^e 0.02^f 0.01^g
Halflife on plant surface (d)	14	14^c 14.4^d	14^h 28^i	14	14	11
Soil on plant surface (% of dry plant weight)	0.1^j	0.01^j	28^i	–	0.1^j	–
Depth of soil (cm)	30^k	30^k	15^l	15^l	30^k	100
Dry weight, content (%)	20	90	20	–	20	20

Notes

(a) The model for fruit is based on apples.
(b) This is the yield from three harvests and is expressed as dry weight.
(c) Whole cereal plant.
(d) Grain seed.
(e) For caesium and similar elements.
(f) For strontium and similar elements.
(g) For plutonium and similar elements.
(h) Summer.
(i) Winter.
(j) Before preparation and processing.
(k) Depth of well-mixed soil from which root uptake occurs.
(l) Depth of undisturbed soil from which root uptake occurs.

2.2.4.3 *Translocation*

Part of the surface deposits to plants may be absorbed and transferred to other parts of the plant; this process is known as translocation and is significant for elements which are mobile within the plant such as caesium and is relatively unimportant for immobile elements such as the actinides. For root vegetables, translocation is the only mechanism by which radionuclides are transferred from the surface of the plant to the edible root underground. The translocation process is included in the models for green vegetables, cereals and root vegetables. For pasture, both grazed and grown for hay or silage, only interception and retention are modelled explicitly with translocation only being included implicitly through the choice of values for the other parameters. For fruit, which currently is only modelled for routine release applications, translocation is modelled implicitly through the choice of interception factor and retention half-time[5].

Experimental data on the transfer of radionuclides to the edible parts of crops following a single deposit are rather limited. Experimental studies carried out predominantly in the late 1950s and early 1960s for strontium and caesium in cabbages and cereal plants (straw, husks and grain) by Aarkrog[28,29] and Middleton[33] have been used in the model.

2.2.4.4 *Modelling of interception, retention and translocation in FARMLAND*

In FARMLAND, the interception factor, retention halflives on the plant surface and translocation are all chosen to fit available experimental and environmental measurement data. Data for both the time dependence of the transfer for a single deposit and the overall transfer following continuous deposition have been used[27-29,31,33]. Data for contamination of crops during continuous deposition can be expressed in the form of a normalised specific activity as defined above[21]. NSA values obtained from experimental measurements have been compared with those predicted by the models and are discussed below. The experimental data of Aakrog and Middleton have been used to develop models for grain, green vegetables and root vegetables[28,29,31,33] which are based on data for wheat, cabbages and potatoes, respectively. The model for grain includes interception and retention of the deposit by the grain seed as well as by the rest of the plant. The values for the fraction of the deposit intercepted by the plant or grain and the loss of material from the plant or grain surfaces were assumed to be element independent and are discussed above.

Figure 4 shows the experimental data and model predictions for strontium and caesium in wheat following a single deposit at various times before harvest. For both elements the experimental data show a considerable scatter but the model predictions follow the observed trends. For strontium the peak concentrations in grain at harvest occur for a deposit about 10 days

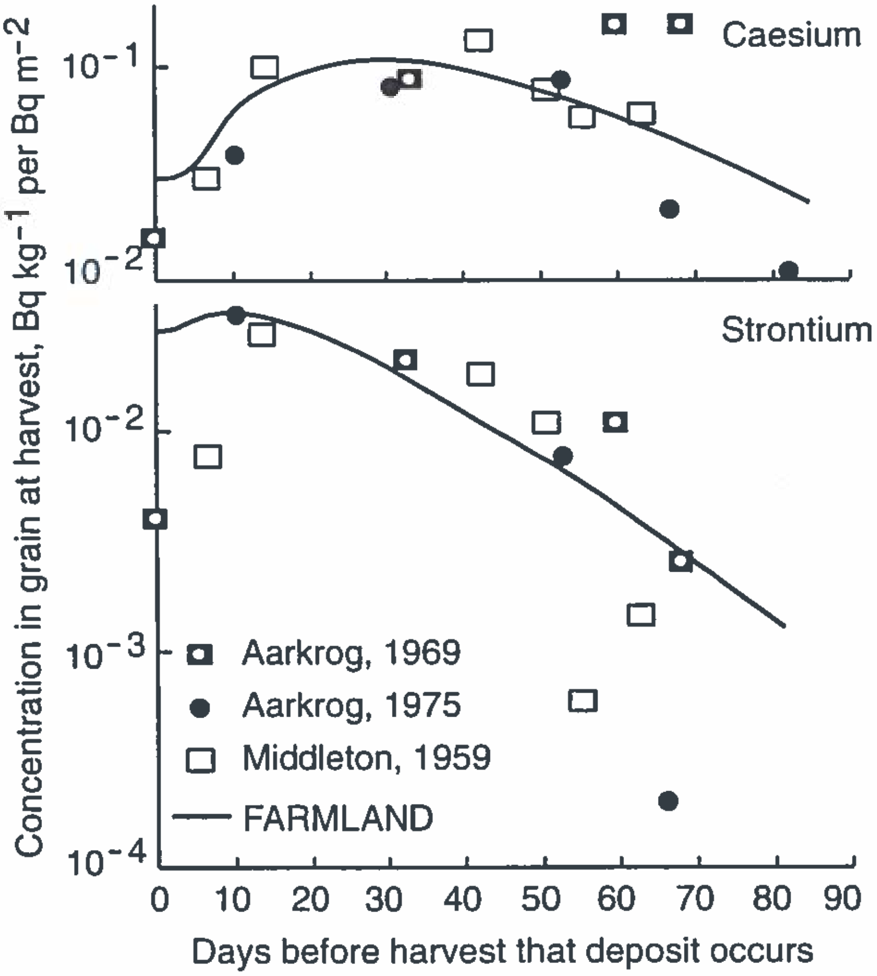

FIGURE 4 **Comparison of model and experimental results for single deposits of caesium and strontium on grain plants at various times before harvest**

beforehand, while for caesium the highest concentrations arise when the deposit is about 30 days before harvest.

For root vegetables the interception and retention parameters are related to the yield of the crop foliage and not the yield of the edible crop and the values used in FARMLAND are given in the previous sections. The transfers in the model representing absorption and translocation were obtained by fitting to experimental data[31,33].

A similar approach was adopted in modelling surface contamination and translocation in green vegetables. The interception on to and weathering off the plant surface were modelled using the parameter values given above. Absorption and translocation were modelled by fitting to experimental data[33] for caesium and strontium, on the assumption that the concentrations found in washed cabbage hearts were due to translocation from the external parts of the plant only.

The models can be applied to other elements by analogy with caesium and strontium or, if data are available for other elements, by determining the appropriate transfers. It is assumed that caesium is representative of elements which are mobile in plants while strontium is representative of elements which are less mobile and for which transfer within the plant is less important. In FARMLAND it has been assumed that iodine behaves similarly to caesium[34]. Based on the work by Aakrog[28,29] on ruthenium and cerium which showed that the concentrations at harvest in grain were due to the surface contamination of the plant, it has been assumed that for elements classified as immobile the translocation process is unimportant and this transfer process is ignored. The elements considered in FARMLAND have been classified as mobile, semi-mobile and immobile. For mobile elements the model for caesium is used, for semi-mobile elements the model for strontium is used, and for immobile elements a model excluding translocation is used. The classification has been based on information given by Prohl[34] and general knowledge on the mobility of elements in terrestrial systems. The translocation of strontium, caesium and iodine assumed in FARMLAND is given in Table 3. The data are expressed as the percentage of material deposited on the plant which is found in the crop at harvest as a function of the time deposition before harvest. The classification of elements into mobile, semi-mobile and immobile is given in Table 4.

TABLE 3 Translocation of strontium, caesium and iodine for wheat and potatoes

	Translocation[a] (%)		
	Winter and spring wheat		Potatoes
Time before harvest (d)	Strontium	Caesium and iodine	Caesium and iodine
0	~8	~3	0
30	1.5	10	10
60	0.3	6	7
90	0	2 (0.2[b])	3
120	0	0.6 (0[b])	0

Notes

(a) Translocation is expressed as the percentage of the total deposition that is found in 1 kg dry weight of the crop at harvest (Bq kg^{-1} per Bq m^{-2}).

(b) Values for spring wheat.

TABLE 4 Assumed mobility of elements in plants in FARMLAND

Element	Translocation
Phosphorus	m
Sulphur	m
Chlorine	m
Chromium	i
Manganese	s
Iron	s
Cobalt	s
Nickel	s
Zinc	s
Bromine	m
Selenium	m
Rubidium	m
Strontium	s
Yttrium	s
Zirconium	s
Niobium	s
Molybdenum	s
Technetium	m
Ruthenium	i
Silver	s
Tin	s
Antimony	s
Tellurium	m
Iodine	m
Caesium	m
Barium	s
Lanthanum	s
Cerium	i
Promethium	i
Europium	i
Lead	s
Polonium	m
Radium	s
Actinium	i
Thorium	i
Protactinium	i
Uranium	i
Neptunium	i
Plutonium	i
Americium	i
Curium	i

Note
Mobility of each radionuclide for translocation has been classified as mobile (m), semi-mobile and immobile (i).

The NSA values predicted by the models have been compared with those calculated from experimental data[27] for caesium, strontium and, where possible, plutonium, and are shown in Table 5. A distinction is made between grain and flour and between prepared and unprepared green vegetables. With the exception of plutonium in green vegetables, the models are in reasonable agreement with the measured data[27]. The few measured NSAs for plutonium are considerably lower than those for strontium and caesium. This is to be expected as plutonium is known to be very immobile in plants. For grain, on the assumption that only direct contamination of the grain seed occurs, the predicted NSAs for plutonium are in reasonable agreement with those based on measurements. However, for green vegetables, neglecting translocation still leads to a significant overestimation of the measured NSA for plutonium in prepared vegetables. This overestimation could be reduced by lowering the retention halflife for plutonium from 14 days to 5 days[27]. However, there is no other evidence to suggest that the weathering of plutonium is different to that for other elements.

TABLE 5 Comparison of measured and predicted normalised specific activities (NSAs) for crops

	NSA (m^2 d kg^{-1} dry weight)					
	Strontium		Caesium		Plutonium	
Crop/product	Measured	Predicted	Measured	Predicted	Measured	Predicted
Grain	2.7–4.5[a]	1.3[b]	4.7–6.9[a]	6.2[b]	0.52–0.80[a]	0.63
Flour	0.5–1.4[a]	0.8[b]	5.6–6.2[a]	5.7[b]	0.02–0.05[a]	0.06
Green vegetables						
Before processing	34–57[a]	30.5[b]	–	29.3[b]	–	3.60
After processing	3.5–16.8[a]	6.6[b]	3.0–10.7[a]	6.7[b]	0.27–0.78[a]	7.20
Root crops[c]	0.55–1.7	0.32	4.6–8.6	7.3	–	–
Fruit[d]	1.5–2.0	1.7	5.1–10.7	7.0	0.93	0.87

Notes
(a) See reference 27.
(b) See reference 35.
(c) See reference 6.
(d) See reference 5.

A model for fruit, based on apples, has been developed for routine release applications and has been fitted to measured NSAs using Chamberlain's relationship to determine interception factors and retention halflives on fruit[5]. Different values of interception factor have been obtained for caesium, strontium and plutonium with a retention halflife of 11 days for all elements. Other elements should be treated as either caesium, strontium or plutonium depending on their mobility (see Table 4).

The default values for interception factor, yield, retention halflife and translocation given in Tables 2 and 3 are interrelated as discussed above. They should not be changed independently of each other without considerable care. Details of the models for crops, pasture grass and hay and the rate constants used in the model are given in a supporting document[7].

2.2.5 Resuspension of activity from soil to external plant surfaces

The resuspension of activity from the soil surface to the external parts of crops will occur due to the action of wind and rain. Considerable variation might be expected in the importance of this route of contamination depending on the plant type, the conditions under which crops are grown and the method of their preparation before consumption. Grain seeds and leguminous vegetables are protected from external contamination processes by protective layers, whereas leafy green vegetables which grow closely to the ground are readily contaminated. Root vegetables are not affected directly by resuspension from the soil surface but contaminated soil is likely to be attached to the tuber surface. Few data are available in this area, however, and the same general approach is adopted for all surface crops.

The contamination of the plant surfaces by resuspension is considered in two stages. The first concerns the resuspension of the radioactive material in the period soon after deposition by wind driven processes. The second involves the resuspension, by a variety of processes, of soil particles with which the radioactivity becomes associated within a few months or years of deposition. The first process is governed by a time-dependent resuspension formula which has been determined by experimental observations and is the model suggested by Garland based on post-Chernobyl data[36]. In this model resuspension decreases according to the reciprocal of the time after deposit, using the expression given in Appendix A.

To use this resuspension model in FARMLAND a single mean resuspension factor is required. Various approximations have been made to facilitate the incorporation of this relationship into FARMLAND and these are described with the resuspension factors used in the model in Appendix A.

The transfer of radionuclides to external plant surfaces by the second process can be determined readily from the quantities of soil typically associated with the edible parts of crops when harvested. For crops other than grass the activity concentration in the soil adhering to the plant surface is assumed to be the same as that in the well-mixed top 30 cm soil layer; for grass which is assumed to grow on undisturbed soil the approach is different and is discussed in detail in Section 2.2.8. The quantities of soil contaminating various plant surfaces are uncertain and the values assumed are based on a review of data primarily in the UK and the USA[37,38]. Measurements in these countries have shown that a value of 0.01% is typical of the quantity of soil associated with the whole grain seed when expressed in terms of the dry weight of the latter; in exceptional circumstances it could be as much as 0.1%. For vegetables, including fruit, there is an even greater uncertainty in assigning a representative value to the amount of soil contamination on plant surfaces. The range of vegetable types is large and this will have a marked influence on the degree of surface contamination; for example, leguminous vegetables, such as peas, are protected by a pod, whereas leafy vegetables, such as lettuce, which are grown close to the ground may on occasion be subject to significant contamination by soil[39]. A value of 0.1% of the dry plant weight has been indicated as being representative for vegetables from the literature[37,39] and has been adopted in FARMLAND for all vegetables and fruit. For root vegetables and potatoes which are contaminated by soil due to immersion in soil, the component of the tuber contamination from soil is implicitly included in the absorption of radioactivity from soil by the tuber and is therefore not considered explicitly.

2.2.6 Root uptake

The absorption of elements from soil by plants varies considerably depending on a number of factors, notably soil type. There can also be significant variation due to the nature of the plants (eg root crops compared with grain crops) and the chemical and physical form of the element at the time of deposition may also influence uptake. However, with the exceptions of a few elements, such as strontium and caesium, and to a lesser extent the transuranium elements, these variations have not been investigated in detail. Data on root uptake tend to be in the form of concentration factors between plants and soil at the end of the growing period. Such data contain no information on the time dependence of the uptake mechanisms and as such cannot be rigorously applied in that context.

The International Union of Radioecologists (IUR) has compiled a database of root uptake concentration factors for a variety of radionuclides, plants and soil types[40]. This database has been used together with a database compiled by Ng *et al*[41] and other sources[42-49] to obtain root uptake transfer data for a number of elements. In some cases it has been possible to distinguish between the transfers between soil and different plant species. For many elements it has not been possible to make this distinction and the transfer has been assumed to be independent of plant type. In some cases the paucity of data is such that the transfers are chosen by analogy with other elements for which data are available.

The application of concentration factors to a model which is time dependent in character is valid only where the variation in the concentration of the radionuclide in the root zone is small during the growing period. For long-lived radionuclides this assumption is in general valid. Where it is invalid, the assumption is made in the model that the plant rapidly comes into equilibrium with the soil. Where the concentration of activity in soil varies rapidly with time the activity in plants will be determined largely by the concentration in soil just prior to harvesting.

The derivation of transfer rates for use in FARMLAND from concentration factors is described elsewhere[7]; although these rate constants represent the rate of transfer from soil to plant and vice versa the time dependence is an artefact. The coefficients are chosen solely to ensure that the concentration factor between plant and soil is attained rapidly.

In addition to the migration process which progressively removes elements from the rooting zone, some contaminants and notably caesium become increasingly unavailable for absorption by the plants' roots as a result of chemical immobilisation processes in the soil. The process is known as fixation. The concentration factors used in FARMLAND for crops other than pasture grass are assumed to include implicitly any effect of fixation on plant uptake as they are applicable for well-mixed soil of depth around 30 cm and because the concentration factors have been established for equilibrium conditions over a long time. For pasture grass where the soil depth profile is modelled in more detail the fixation process is modelled explicitly for caesium. The time dependence of the fixation process and the fraction of activity that has become fixed in the soil which is subsequently unavailable for uptake into the plants' roots were discussed earlier (see Section 2.2.2). In the present FARMLAND model fixation is considered only for caesium. The details of the model structure used is given elsewhere[7].

2.2.7 Transfer of radionuclides to animals

The transfer of radionuclides to animals can be considered in two stages: the intake of radionuclides into the animal by ingestion or inhalation and the subsequent metabolism of these radionuclides and in particular their transfer to animal tissues and animal products that are consumed by man. Models for cattle and sheep are included in FARMLAND. Dynamic models for pigs and chickens are not included in FARMLAND; they have, however, been considered and are discussed in Section 8. The same model for animal metabolism is used for both dairy and beef cattle and is based on the dairy cow. Although the diets of beef cattle can vary significantly compared to those of dairy cows, a substantial part of the diet is pasture grass either grazed or cut as silage and hay, and the use of a single cattle diet is appropriate for a generic foodchain model for use in the UK. The differences in cattle diets and the assumptions made in FARMLAND are discussed in more detail in Section 3.3. Owing to the modular structure of FARMLAND the animal models can be combined with modules for other crops, such as grain, to consider different diets.

2.2.8 Intake of radionuclides by grazing animals

The principal mechanisms involved in the transfer of radionuclides to grazing animals are illustrated in Figure 5. Ingestion is the most important route of intake by the animal; inhalation is, in general, not important, although it may be significant for those radionuclides whose transfer across the gut of the animal is small.

The major feedstuff considered in the animal models is pasture grass, the model for which is described above. The inadvertent consumption of soil associated with grass by grazing animals is also considered. For radionuclides which have a low transfer from soil to grass by root uptake the ingestion of soil may be the most important source of intake. Values used in FARMLAND for inadvertent consumption of soil are 4% and 20% of the dry matter intake for cattle and sheep, respectively[50-52]. Experimental studies in progress are showing that the availability of radionuclides associated with soil particles for absorption across the gut is significantly less than for those biologically incorporated into grass for some elements[53] and that the availability is element dependent. FARMLAND does not at present take this into account but could be extended to include this when robust conclusions from the experimental work can be drawn.

Two major routes of intake for inhalation are considered in the model: the inhalation of activity during deposition and the subsequent inhalation of resuspended activity. The intake of

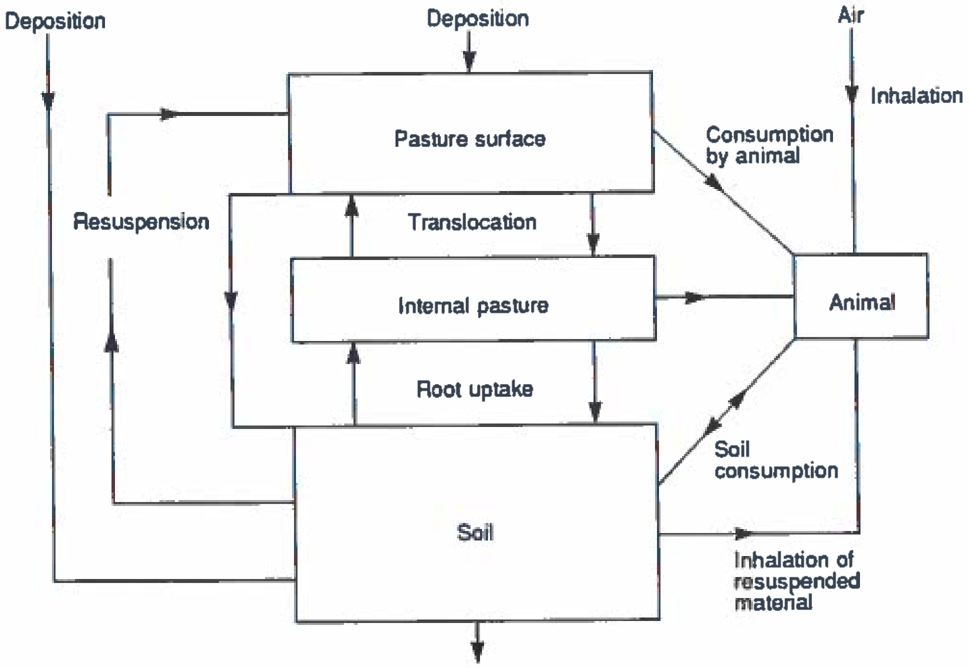

FIGURE 5 Schematic of the principal mechanisms for the transfer of radionuclides in grazing animals

activity by inhalation during deposition can be evaluated from the breathing rate of the animal and the activity concentrations in air. The inhalation of resuspended activity is estimated using a resuspension factor derived for undisturbed pasture based on the resuspension model discussed above (see Appendix A for details of simplifications made). The localised enhancement of resuspended air concentrations caused by the disturbance of soil during grazing is not taken into account in FARMLAND owing to an absence of data; it should be recognised that inhalation by grazing animals may, therefore, be underestimated in the model, although validation studies have showed that this pathway is probably insignificant[18,54].

The rates of intake for inhalation and ingestion are important parameters in the model as they govern the intake of activity into the animal. Ingestion rates depend on the grazing habits of the animal, which are difficult to assess, particularly for free grazing animals and for those animals which are selective eaters, eg sheep. Ingestion rates also depend on the body weight of the animal and the choice of values used in FARMLAND are for typical body weights. Details of ingestion rates and body weights are given in Section 3 and inhalation rates, based on a literature review, are discussed there.

2.2.9 Metabolism of inhaled or ingested radionuclides by animals

There are two approaches in FARMLAND to modelling the metabolism of ingested and inhaled radionuclides involving models of different levels of complexity. The level of complexity required depends on the radiological importance of the element of concern and the radiological application. The complexity of the model for a particular element is also often limited by sparcity of data and use may have to be made of data and models developed to represent human metabolism. Both simple and complex metabolic models are used for cattle and sheep and, in general use of FARMLAND, a single model type is used for a particular element: the two approaches are outlined below.

2.2.9.1 Simple metabolic model

The simpler metabolic model is used to determine the metabolism of all radionuclides other than those of strontium, caesium, iodine and the transuranium elements and is illustrated in Figure 6.

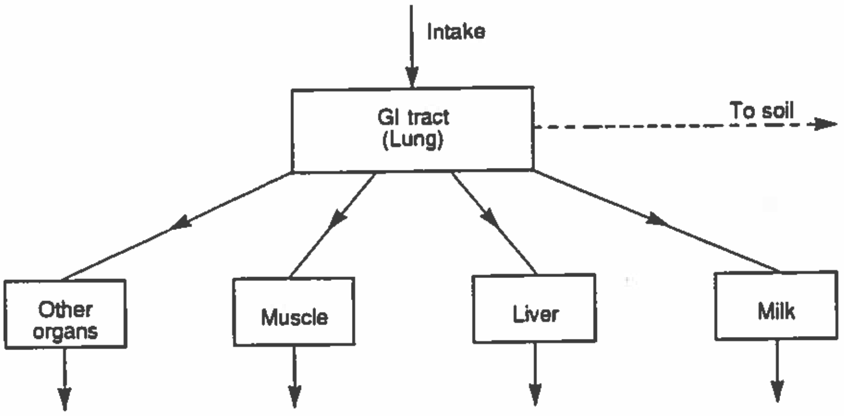

FIGURE 6 Schematic of the simpler metabolic model for animals

The approach taken is to model the fractional transfer of ingested or inhaled activity to particular organs and tissues of the animal and the halflives of activity in these tissues. The amount of activity that enters both meat and milk is usually expressed in terms of an equilibrium transfer factor. The available data are mainly for cattle and are in the form of the fraction of the daily intake that is transferred to a unit mass (1 kg) of the product at equilibrium which has the units d kg^{-1}. The model also uses biological halflives in the animal to enable activity concentrations as a function of time to be evaluated. The origin and reliability of the data are variable; some data are based on field experiments, whereas others are extrapolations from experiments with other animals or even derived by analogy with other elements. Data on the transfer to liver are sparse. Equilibrium transfer factors are derived from data recommended for man[55] on the assumption that the fractional transfer from body fluids to liver is the same in cattle as in man. For those elements where no data are available the transfer to liver and the biological halflives are assumed to be equal to those in meat.

Data for the transfer of elements to sheep are more sparse. For elements where data in the literature are not available the model for cattle is used with due account taken of the difference in body mass. The equilibrium transfer factors for meat and liver are derived from those of cattle using the following expression:

$$f_s = f_c \times \frac{M_c}{M_s}$$

where f_s and f_c are the equilibrium transfer factors for meat or liver for sheep and cattle, respectively, and M_s and M_c are the masses of meat or liver, in sheep and cattle, respectively.

Few data are available on the fractional transfer of inhaled activity to the body organs of grazing animals. The values used have been derived from metabolic data recommended for man. The fraction of the daily intake by inhalation appearing in a particular organ or milk, from a grazing animal, $F(inh)_c$, is obtained as

$$F(inh)_c = \frac{f(inh)_M}{f(ing)_M} F(ing)_c$$

where $f(inh)_M$ is the fraction of inhaled activity reaching body fluids in man, $f(ing)_M$ is the fraction of ingested activity reaching body fluids in man, and $F(ing)_c$ is the fraction of the ingested daily intake appearing in the organ or milk from cattle.

The fractions of ingested or inhaled activity reaching body fluids depend on the physio-chemical form of the element considered. Each element is assumed to be in the oxide form and when inhaled to be in the form of a 1 μm AMAD aerosol. It is further assumed that the transfer of activity from the lung to body fluids occurs instantaneously; in reality, depending on the compound inhaled, the time constant for transfer may be days, weeks or years. This assumption will overestimate the transfer from the lung of cattle, particularly for radionuclides with radioactive half-lives short compared to the time constant for transfer from the lung. The assumption is, however, conservative and considered justified bearing in mind the many other uncertainties in the data used in the model.

The parameter values used in FARMLAND for cattle and sheep are discussed in Section 3. The derivation and values of rate constants for use with the models are described elsewhere[7].

2.2.9.2 *Complex metabolic models*

More complex metabolic models are used for strontium, caesium, iodine and the transuranic elements. These models take into account the important metabolic processes for each of the elements considered and they have been developed to enable a more accurate prediction to be made of the time dependence of the transfer to animal products, particularly milk. The main difference between the two types of model is that the more complex model considers organs other than muscle and liver where they have a significant effect on animal metabolism and influence the time dependence of the transfer to meat and milk; it also considers the recycling of activity between these organs and body fluids. Figure 7 shows the main features included in the more complex approach to modelling animal metabolism.

The metabolism of the animal can be represented by three physiological mechanisms: the absorption of the nuclide into the bloodstream and body fluids from the gastrointestinal tract, the distribution and recycling of the radionuclide between the circulating fluids and the body organs and tissues, and the excretion of the radionuclide from the body including the secretion into milk. The transfer of radionuclides from the lung to the gut and circulating fluids of the animal is based on models recommended for man[56]. The modifications and simplification of these models for application to the animal models are described elsewhere[7].

The models for strontium, caesium and iodine for cattle and sheep have been developed by studying the literature to determine the important metabolic processes for each element and appropriate parameter values. Using a proposed compartmental model structure the transfers between compartments have been determined by fitting the model predictions to measured activity concentrations in milk and meat, and in the case of iodine the thyroid, and obtaining the best fit to the data. Constraints are placed on the model parameters such that the equilibrium transfers to meat and milk agree with those in the literature and the values for transfer rates are not unreasonable, given knowledge of the metabolic processes. Details of the metabolic processes included in the models for cows and sheep and the development of the models are given in Appendix B. The rate constants and details of how to use the models for different applications are given elsewhere[7].

The model for the transuranium elements is described in detail elsewhere[4] and the model structure and rate constants used are given elsewhere[7]. The model includes bone as a single organ

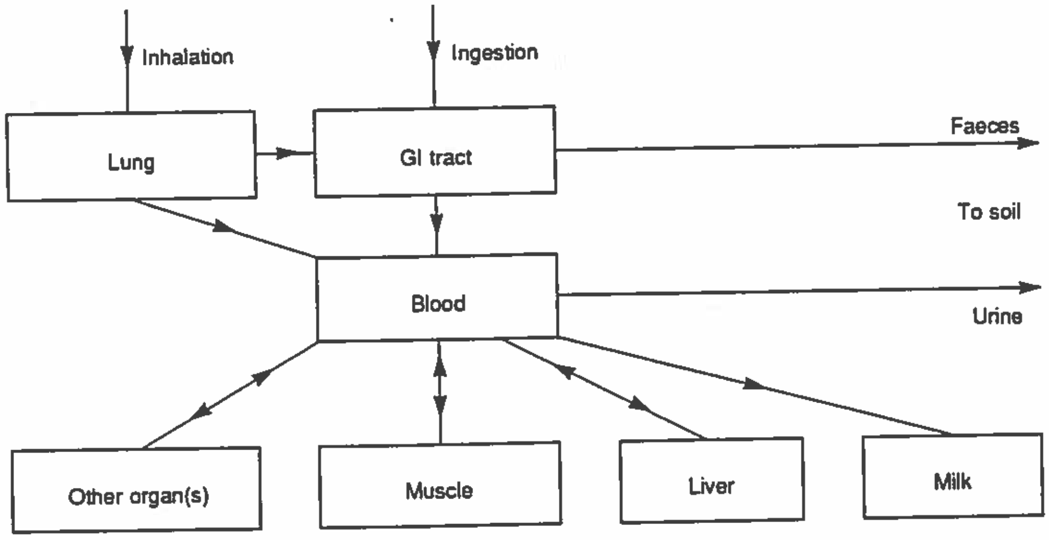

FIGURE 7 Schematic of the more complex metabolic model

and takes into account the recycling of activity between bone, meat and liver and the body fluids. The transfer from the gut to blood is based on experimentally determined gut transfer fractions for humans beings and a value of 5 10^{-4} is used for all the transuranium elements. The transfer from the lung to blood is calculated using the method described by Brown and Smith[7], on the assumption of lung class W for all actinides. The remaining transfers in the model have been chosen to give the best predicted fit to measured percentages of plutonium in bone, liver, muscle, blood and milk in cows from two experiments[4]. In the absence of other data the chosen transfers are assumed to be equally valid for americium, curium and neptunium. The model does not explicitly use equilibrium transfer factors; however, these can be predicted using the model. As it takes up to 100 years for equilibrium to be reached in the animal the transfer over the mean lifetime of the animal (discussed in Section 3) needs to be considered. The model predicts effective equilibrium transfer factors in meat and milk over the animal's lifetime consistent with the literature. The same model is used for cattle and sheep.

3 Default parameter values and assumptions

For most applications the FARMLAND model is used in its generic form and this requires that a set of default parameter values is chosen for use with the model. These parameter values have been chosen to be generally applicable for the UK and take into account average farming practices and, to some extent, average soil types and environmental conditions. FARMLAND is also used for general assessments in Europe. Work has been undertaken to agree parameter values for use with a dynamic foodchain model such as FARMLAND in the European Union[26]. This work and assumptions for use in European applications are described in more detail in Section 4. Default parameter values used as input to the FARMLAND model in the UK are described here.

The parameters form the basic input to the models and are used to determine the rate constants which describe the transfer between compartments in the models; the methods for determining these rate constants are given elsewhere[7].

3.1 Element-independent parameters

The element-independent parameters required for the FARMLAND plant and crop models are related to the interception and retention of radionuclides on the plant surface. In addition, the dry matter content of crops is used to determine activity concentrations on a dry weight or fresh weight basis and to convert some of the experimental data in the literature into the required form for the models. In all calculations fresh weight is used as the default.

Based on a review of information on the composition of foods[57], percentages of dry matter in the various crops modelled have been determined. The green vegetable category encompasses a large range of vegetables with varying moisture contents. As a default 20% dry matter content is assumed. Values for all crops are given in Table 2.

As discussed in Section 2.2 the interception, retention and yield of the crop in the model are all linked. The interception factors, retention halflives and yields for each crop are given in Table 2. The yields of crops obviously vary with crop variety, growing conditions etc, and the default values used in the model are taken from UK agricultural statistics[58] and are averaged over crop varieties and regions of the UK for each broad crop category modelled. Table 2 also gives the default values for soil contamination of plants as discussed in Section 2.2.

A number of parameters for the modelling of the transfer of radionuclides to animals are required by FARMLAND. These are: animal intake rates, milk production rate, animal weight, numbers of animal per square kilometre, and age at slaughter. Values for these parameters are summarised in Table 6 and their choice is described below.

Animal intake rates are important parameters in the modelling of transfer to animal products. There is a large uncertainty associated with ingestion rates for grazing animals, particularly sheep which are selective grazers and also often graze over large areas. In addition, the range of fodder crops used to feed cattle and sheep varies markedly across the UK and even within small regions depending on availability and farming practices. For the FARMLAND model assumptions have been made on dietary composition and intake rates that are robust for generic applications of the model. FARMLAND is flexible and can take into account specific animal husbandry practices and this is discussed in Section 3.3.

Ingestion rates are dependent to some degree on the body mass of the animal and it is therefore necessary to establish a default value for the body mass. FARMLAND includes a generic model for cattle and does not distinguish between dairy and beef cattle. A value of 500 kg is used as an average weight for cattle[59] which takes into account the types of animal used for beef production in the UK. Use of liveweight of 500 kg is consistent with required dry matter intakes around 10 kg d^{-1} and 13 kg d^{-1} for beef and dairy cattle, respectively[59]. From a review of the literature[16,60] and the estimation of dietary requirements for cows producing average milk yields, a dry matter intake of 13 kg d^{-1} has been adopted in FARMLAND.

Over the winter period cattle are fed a variety of feedstuffs, the main components being silage, hay and grain. Suggested diets are given in the literature[16,61,62] and diets have been estimated for cattle liveweights and milk yields consistent with the assumptions in FARMLAND. The diets have been converted to hay equivalents with due account taken of the dry matter content of the various components and, to some extent, the nutritional value of each feedstuff. From these data a hay equivalent of 15.5 kg d^{-1} has been adopted for use in the model.

TABLE 6 Element-independent parameter values for animals

Parameter	Cattle[a]	Cattle[b]	Sheep[a]	Sheep[b]
Mean life (y)	6	6	1	1
Weight of muscle (kg)	230[c]	360[d]	18[c]	30
Weight of liver (kg)	6	6	0.8	1
Milk production rate (l d^{-1})	10	10	–	–
Number of animals per km^2 [e]	400	400	500	500
Intakes (kg d^{-1} dry weight pasture)	13[f]	13[f]	1.5	1.5
Soil as % of dry matter intake	4	4	20	20
Inhalation rate (m^3 s^{-1})	1.5 10^{-3}	1.5 10^{-3}	1.0 10^{-4}	1.0 10^{-4}

Notes
(a) Simple model used for all elements other than strontium, caesium and iodine.
(b) Complex model used for strontium, caesium and iodine.
(c) This is the carcass weight, the weight of lean meat is 150 kg for cattle and 15 kg for sheep.
(d) This is the weight of all soft tissues, the weight of lean meat is 150 kg for cattle and 15 kg for sheep.
(e) Values appropriate for the UK. The applicability of these values for EU is under review.
(f) During winter months when animals fed stored feed, intake = 15.5 kg d^{-1} dry weight silage.

The liveweight used for sheep is 50 kg and this implies required dry matter intakes of 1.0 kg d^{-1} to 1.5 kg d^{-1} for sheep of varying ages[59]. Intakes in this range are confirmed in the literature[16]. A value of 1.5 kg d^{-1} is adopted in FARMLAND.

The inhalation intake rates used in FARMLAND for cattle and sheep are taken from the Handbook of Biological Data[63] and are given in Table 6.

For the modelling of the transfer of radionuclides to animal products FARMLAND models a herd of animals and determines the average activity concentrations in the herd at any particular time. The parameter values for milk yields, stocking densities and slaughter age are chosen to be representative of the herd and implicitly take into account the natural variation within the herd and the variation in husbandry practices across the UK.

The milk production rate is dependent on the calorific intake rate of the cow and the stage of lactation[59,60,62]. A milk production rate of 10 l d^{-1} is used in FARMLAND as representative of an average yield over the whole year given that each cow in a herd does not lactate throughout the whole year. Larger yields can be achieved under current farming practices. However, as the model is not very sensitive to small changes in milk yield the value of 10 l d^{-1} is used.

The numbers of animals that graze a unit area of pasture vary depending on the quality of the pasture and the climate. Marked differences are seen across the UK: it is necessary, however, for FARMLAND to use a generic value that is representative, as far as possible, of current UK farming practices. A review of agricultural practices in the UK in 1988[59,64,65] suggested values of four cows per hectare and five sheep per hectare and these values are adopted in FARMLAND. Previous versions of FARMLAND have used lower animal densities on pasture[2,3]. The implication of increasing the animal densities to be more appropriate for current farming practices is to decrease activity concentrations in animal products predicted by the model by 20% to 40%.

The slaughtering ages of cattle and sheep used in FARMLAND are 6 years for cattle and 1 year for sheep. The value for cattle is based on dairy cows; the slaughtering age for beef cattle is typically lower and around 18 months to 2 years. However, owing to the proportion of beef that is produced from dairy cows and the fact that equilibrium has been reached in the animal within the lifetime of both dairy and beef cattle for the majority of radionuclides of radiological significance, this assumption is considered reasonable.

The liveweights of cattle and sheep used for the estimation of intake rates are discussed above. The models also require the weights of meat and liver in order to determine the activity concentrations per unit mass of the tissue. The simple and complex models have been developed using slightly different definitions of the weight of soft tissue in the animal. The simple model uses the carcass weight of the animal and the complex model uses the weight of all soft tissue. In both cases the weight of lean meat is assumed to be 150 kg for cattle and 15 kg for sheep.

3.2 Element-dependent parameters

The transfer of radionuclides from soils to plants via the plant root system is generally expressed as a concentration factor, as discussed in Section 2.2.6. This concentration factor is the ratio of the activity concentration of any radionuclide in vegetation to that in soil and is element dependent. Values of the concentration factor are available from the literature for many elements and the default values used in FARMLAND are given in Table 7. The largest source of all soil–plant concentration factors is the International Union of Radioecologists (IUR) database[40] which contains data collected across Europe. Data for some elements, particularly plutonium

TABLE 7 Equilibrium soil-to-plant concentration ratios (wet weight plant to dry weight soil)

	Crop				
Element	Green vegetables	Grain	Root vegetables	Potatoes	Pasture
Phosphorus	1	1	1	1	1
Sulphur	$6\ 10^{-1}$	$6\ 10^{-1}$	$6\ 10^{-1}$	$6\ 10^{-1}$	$6\ 10^{-1}$
Chlorine	5	5	5	5	5
Chromium	$3\ 10^{-4}$	$3\ 10^{-4}$	$3\ 10^{-4}$	$3\ 10^{-4}$	$3\ 10^{-4}$
Manganese	$1\ 10^{-1}$	$1\ 10^{-1}$	$1\ 10^{-1}$	$1\ 10^{-1}$	$1\ 10^{-1}$
Iron	$2\ 10^{-4}$	$4\ 10^{-4}$	$3\ 10^{-4}$	$3\ 10^{-4}$	$4\ 10^{-4}$
Cobalt	$1\ 10^{-2}$	$5\ 10^{-3}$	$1\ 10^{-2}$	$1\ 10^{-2}$	$1\ 10^{-2}$
Nickel	$1\ 10^{-2}$	$1\ 10^{-2}$	$1\ 10^{-2}$	$1\ 10^{-2}$	$1\ 10^{-2}$
Zinc	1	1	$5\ 10^{-1}$	$5\ 10^{-1}$	1
Bromine	$2\ 10^{-2}$	$2\ 10^{-2}$	$2\ 10^{-2}$	$2\ 10^{-2}$	$2\ 10^{-2}$
Selenium	1	1	1	1	1
Rubidium	$1\ 10^{-1}$	$1\ 10^{-1}$	$1\ 10^{-1}$	$1\ 10^{-1}$	$1\ 10^{-1}$
Strontium	$3\ 10^{-1}$	$2\ 10^{-1}$	$1\ 10^{-1}$	$5\ 10^{-2}$	$5\ 10^{-2}$ [a]
Yttrium	$1\ 10^{-2}$	$1\ 10^{-2}$	$1\ 10^{-2}$	$1\ 10^{-2}$	$1\ 10^{-2}$
Zirconium	$1\ 10^{-4}$	$1\ 10^{-4}$	$1\ 10^{-4}$	$1\ 10^{-4}$	$1\ 10^{-4}$
Niobium	$1\ 10^{-2}$	$1\ 10^{-2}$	$1\ 10^{-2}$	$1\ 10^{-2}$	$1\ 10^{-2}$
Molybdenum	$1\ 10^{-1}$	$1\ 10^{-1}$	$1\ 10^{-2}$	$1\ 10^{-2}$	$1\ 10^{-1}$
Technetium	5	5	5	5	5
Ruthenium	$1\ 10^{-2}$	$1\ 10^{-2}$	$1\ 10^{-2}$	$1\ 10^{-2}$	$1\ 10^{-2}$
Silver	$2\ 10^{-1}$	$2\ 10^{-1}$	$2\ 10^{-1}$	$2\ 10^{-1}$	$2\ 10^{-1}$
Tin	$1\ 10^{-1}$	$2\ 10^{-1}$	$6\ 10^{-2}$	$6\ 10^{-2}$	$2\ 10^{-1}$
Antimony	$1\ 10^{-2}$	$1\ 10^{-2}$	$1\ 10^{-2}$	$1\ 10^{-2}$	$1\ 10^{-2}$
Tellurium	$3\ 10^{-3}$	$3\ 10^{-3}$	$4\ 10^{-4}$	$1\ 10^{-3}$	$5\ 10^{-3}$
Iodine	$2\ 10^{-2}$	$2\ 10^{-2}$	$2\ 10^{-2}$	$2\ 10^{-2}$	$2\ 10^{-2}$
Caesium[b]	$7\ 10^{-3}$	$1\ 10^{-2}$	$5\ 10^{-3}$	$7\ 10^{-3}$	$3\ 10^{-2}$
Barium	$1\ 10^{-2}$	$1\ 10^{-2}$	$5\ 10^{-3}$	$5\ 10^{-3}$	$1\ 10^{-2}$
Lanthanum	$3\ 10^{-3}$	$3\ 10^{-3}$	$3\ 10^{-3}$	$3\ 10^{-3}$	$3\ 10^{-3}$
Cerium	$1\ 10^{-3}$	$1\ 10^{-3}$	$1\ 10^{-3}$	$1\ 10^{-3}$	$1\ 10^{-3}$
Promethium	$3\ 10^{-3}$	$3\ 10^{-3}$	$3\ 10^{-3}$	$3\ 10^{-3}$	$3\ 10^{-3}$
Europium	$3\ 10^{-3}$	$3\ 10^{-3}$	$3\ 10^{-3}$	$3\ 10^{-3}$	$3\ 10^{-3}$
Lead	$1\ 10^{-2}$	$1\ 10^{-2}$	$1\ 10^{-2}$	$1\ 10^{-2}$	$1\ 10^{-2}$
Polonium	$2\ 10^{-4}$	$2\ 10^{-4}$	$2\ 10^{-4}$	$2\ 10^{-4}$	$2\ 10^{-4}$
Radium	$1\ 10^{-2}$	$1\ 10^{-3}$	$1\ 10^{-3}$	$1\ 10^{-3}$	$1\ 10^{-2}$
Actinium	$1\ 10^{-3}$	$1\ 10^{-3}$	$1\ 10^{-3}$	$1\ 10^{-3}$	$1\ 10^{-3}$
Thorium	$5\ 10^{-4}$	$5\ 10^{-4}$	$5\ 10^{-4}$	$5\ 10^{-4}$	$5\ 10^{-4}$
Protactinium	$4\ 10^{-2}$	$4\ 10^{-2}$	$4\ 10^{-2}$	$4\ 10^{-2}$	$4\ 10^{-2}$
Uranium	$1\ 10^{-3}$	$1\ 10^{-3}$	$1\ 10^{-3}$	$1\ 10^{-3}$	$1\ 10^{-3}$
Neptunium	$2\ 10^{-3}$	$2\ 10^{-3}$	$1\ 10^{-3}$	$1\ 10^{-3}$	$1\ 10^{-2}$
Plutonium	$1\ 10^{-5}$	$2\ 10^{-5}$	$5\ 10^{-5}$	$5\ 10^{-5}$	$1\ 10^{-4}$
Americium	$5\ 10^{-5}$	$5\ 10^{-5}$	$8\ 10^{-5}$	$8\ 10^{-5}$	$1\ 10^{-3}$
Curium	$5\ 10^{-5}$	$2\ 10^{-5}$	$3\ 10^{-5}$	$3\ 10^{-5}$	$1\ 10^{-3}$

Notes

(a) This value applies to uptake from the lower layers of soil, for the top 1 cm a value of $2\ 10^{-1}$ is appropriate.

(b) For crops other than pasture, fixation of caesium is incorporated implicitly in the root uptake values.

TABLE 8 Equilibrium transfer factors for cattle and sheep

	Cattle			Sheep		Biological half-time (y)	
Element	F_m[a]	F_f meat[b]	F_f liver[c]	F_f meat[b]	F_f liver[c]	Meat	Liver
Phosphorus	$2\ 10^{-2}$	$3\ 10^{-2}$	$3\ 10^{-2}$	$5\ 10^{-1}$	$2\ 10^{-1}$	$3\ 10^{-2}$	$3\ 10^{-2}$
Sulphur	$2\ 10^{-2}$	$3\ 10^{-1}$	$3\ 10^{-1}$	5	2	$3\ 10^{-1}$	$3\ 10^{-1}$
Chromium	$2\ 10^{-3}$	$5\ 10^{-3}$	$5\ 10^{-3}$	$5\ 10^{-2}$	$5\ 10^{-2}$	$9\ 10^{-2}$	$9\ 10^{-2}$
Manganese	$3\ 10^{-3}$	$5\ 10^{-3}$	$2\ 10^{-1}$	$5\ 10^{-2}$	2	$6\ 10^{-2}$	$7\ 10^{-2}$
Iron	$3\ 10^{-4}$	$1\ 10^{-3}$	4	$1\ 10^{-2}$	$3\ 10^{1}$	5	5
Cobalt	$2\ 10^{-3}$	$1\ 10^{-3}$	$1\ 10^{-1}$	$1\ 10^{-2}$	1	$5\ 10^{-1}$	$5\ 10^{-1}$
Zinc	$1\ 10^{-2}$	$2\ 10^{-3}$	$2\ 10^{-3}$	$2\ 10^{-2}$	$2\ 10^{-2}$	$8\ 10^{-1}$	$8\ 10^{-1}$
Selenium	$4\ 10^{-3}$	$4\ 10^{-2}$	1	$5\ 10^{-1}$	10	$7\ 10^{-2}$	$7\ 10^{-2}$
Rubidium	$1\ 10^{-2}$	$1\ 10^{-2}$	$1\ 10^{-2}$	$1\ 10^{-1}$	$1\ 10^{-1}$	$1\ 10^{-1}$	$1\ 10^{-1}$
Strontium	$2\ 10^{-3}$	$3\ 10^{-4}$	$3\ 10^{-4}$	$3\ 10^{-3}$	$3\ 10^{-3}$	–[d]	–[d]
Yttrium	$2\ 10^{-5}$	$1\ 10^{-3}$	$1\ 10^{-2}$	$1\ 10^{-2}$	$1\ 10^{-1}$	$4\ 10^{1}$	$4\ 10^{1}$
Zirconium	$1\ 10^{-5}$	$1\ 10^{-5}$	$1\ 10^{-5}$	$1\ 10^{-4}$	$1\ 10^{-4}$	$2\ 10^{-2}$	$2\ 10^{-2}$
Niobium	$1\ 10^{-5}$	$1\ 10^{-5}$	$1\ 10^{-5}$	$1\ 10^{-4}$	$1\ 10^{-4}$	$3\ 10^{-1}$	$3\ 10^{-1}$
Molybdenum	$1\ 10^{-3}$	$5\ 10^{-3}$	$1\ 10^{-1}$	$5\ 10^{-2}$	1	$1\ 10^{-1}$	$1\ 10^{-1}$
Technetium	$1\ 10^{-2}$	$1\ 10^{-2}$	$4\ 10^{-2}$	$1\ 10^{-1}$	$3\ 10^{-1}$	$8\ 10^{-3}$	$8\ 10^{-3}$
Ruthenium	$1\ 10^{-6}$	$1\ 10^{-3}$	$1\ 10^{-3}$	$1\ 10^{-2}$	$1\ 10^{-2}$	$1\ 10^{-1}$	$1\ 10^{-1}$
Silver	$3\ 10^{-2}$	$1\ 10^{-3}$	$4\ 10^{-1}$	$1\ 10^{-2}$	3	$1\ 10^{-1}$	$1\ 10^{-1}$
Tin	$1\ 10^{-4}$	$1\ 10^{-3}$	$1\ 10^{-1}$	$1\ 10^{-2}$	1	$5\ 10^{-2}$	$5\ 10^{-2}$
Tellurium	$5\ 10^{-4}$	$5\ 10^{-3}$	$5\ 10^{-3}$	$5\ 10^{-2}$	$5\ 10^{-2}$	$5\ 10^{-2}$	$5\ 10^{-2}$
Iodine	$5\ 10^{-3}$	$2\ 10^{-3}$	$2\ 10^{-3}$	$5\ 10^{-2}$	$5\ 10^{-2}$	–[d]	–[d]
Caesium	$5\ 10^{-3}$	$3\ 10^{-2}$	$3\ 10^{-2}$	$5\ 10^{-1}$	$5\ 10^{-1}$	–[d]	–[d]
Barium	$5\ 10^{-4}$	$5\ 10^{-4}$	$5\ 10^{-4}$	$5\ 10^{-3}$	$5\ 10^{-3}$	$9\ 10^{-2}$	$9\ 10^{-2}$
Lanthanum	$2\ 10^{-5}$	$5\ 10^{-3}$	$2\ 10^{-1}$	$5\ 10^{-2}$	2	$1\ 10^{1}$	$1\ 10^{1}$
Cerium	$2\ 10^{-5}$	$1\ 10^{-3}$	$2\ 10^{-1}$	$1\ 10^{-2}$	2	$1\ 10^{1}$	$1\ 10^{1}$
Promethium	$2\ 10^{-5}$	$5\ 10^{-3}$	$4\ 10^{-2}$	$5\ 10^{-2}$	$3\ 10^{-1}$	$1\ 10^{1}$	$1\ 10^{1}$
Europium	$2\ 10^{-5}$	$5\ 10^{-3}$	$4\ 10^{-2}$	$5\ 10^{-2}$	$3\ 10^{-1}$	$1\ 10^{1}$	$1\ 10^{1}$
Lead	$3\ 10^{-4}$	$1\ 10^{-3}$	$2\ 10^{-3}$	$1\ 10^{-2}$	$2\ 10^{-2}$	$7\ 10^{-1}$	$7\ 10^{-1}$
Polonium	$1\ 10^{-4}$	$3\ 10^{-3}$	$8\ 10^{-2}$	$5\ 10^{-2}$	$6\ 10^{-1}$	$1\ 10^{-1}$	$1\ 10^{-1}$
Radium	$4\ 10^{-4}$	$5\ 10^{-4}$	$5\ 10^{-4}$	$5\ 10^{-3}$	$5\ 10^{-3}$	$7\ 10^{-2}$	$7\ 10^{-2}$
Actinium	$3\ 10^{-6}$	$1\ 10^{-4}$	$2\ 10^{-2}$	$1\ 10^{-3}$	$2\ 10^{-1}$	$1\ 10^{1}$	$1\ 10^{1}$
Thorium	$5\ 10^{-6}$	$1\ 10^{-4}$	$1\ 10^{-3}$	$1\ 10^{-3}$	$1\ 10^{-2}$	2	2
Protactinium	$5\ 10^{-6}$	$1\ 10^{-3}$	$5\ 10^{-4}$	$1\ 10^{-2}$	$5\ 10^{-3}$	$7\ 10^{-2}$	$7\ 10^{-2}$
Uranium	$6\ 10^{-4}$	$2\ 10^{-4}$	$2\ 10^{-4}$	$2\ 10^{-3}$	$2\ 10^{-3}$	$3\ 10^{-2}$	$3\ 10^{-2}$
Neptunium	$1\ 10^{-6}$	$1\ 10^{-4}$	$2\ 10^{-2}$	$4\ 10^{-4}$	$3\ 10^{-2}$	–[d]	–[d]
Plutonium	$1\ 10^{-6}$	$1\ 10^{-4}$	$2\ 10^{-2}$	$4\ 10^{-4}$	$3\ 10^{-2}$	–[d]	–[d]
Americium	$1\ 10^{-6}$	$1\ 10^{-4}$	$2\ 10^{-2}$	$4\ 10^{-4}$	$3\ 10^{-2}$	–[d]	–[d]
Curium	$1\ 10^{-6}$	$1\ 10^{-4}$	$2\ 10^{-2}$	$4\ 10^{-4}$	$3\ 10^{-2}$	–[d]	–[d]

Notes

(a) F_m denotes the fraction of the daily intake by ingestion transferred to a litre of milk.

(b) F_f denotes the fraction of the daily intake by ingestion transferred to a kilogram of muscle.

(c) F_f denotes the fraction of the daily intake by ingestion transferred to a kilogram of liver.

(d) Not required in the FARMLAND model used for this element.

and americium, have been supplemented by experimental data from NRPB[42]. Soil–plant concentration factors for elements not considered in the IUR database have been taken from other literature sources[41-49].

The translocation of radioactive material from the outside of the plant to the inside is also element dependent and is discussed in detail in Section 2.2. The rate constants used in the models to represent this process are given elsewhere[7].

The animal models use equilibrium transfer factors and biological retention half-times as discussed in Section 2.2. Values for these parameters have been taken from a large number of literature sources[26,46-49,56,66,67]. Table 8 gives the values for these parameters for cattle and sheep that are used in FARMLAND. Where data for a particular element are not available for sheep, values have been determined by scaling to the values for cattle, as described in Section 2.2.9.

3.3 Agricultural practices

The FARMLAND model takes into account agricultural practices in the modelling of transfer of radioactivity to food. This is of particular importance for accidental releases when the time of year at which a release to atmosphere occurs has a marked influence on the subsequent transfer through the foodchains. The extremes are a release in winter, when relatively few crops are grown and many livestock are housed indoors, and a release in summer at the height of the growing season and when cattle and sheep are grazing pasture. The influence of the time of year of the release depends on the agricultural practice adopted. The FARMLAND model contains assumptions on agricultural practice that are appropriate for the UK. There are large variations in agricultural practice within the UK and also between countries[26]. The default assumptions made for the UK are based on a review of information on UK agricultural practices[3,5,6,26] and regional variations have also been taken into account. The default agricultural practices for the UK are listed in Table 9. Although recommendations are made for the generic use of FARMLAND the model is flexible enough that specific agricultural practices, eg harvesting dates, can be used. A review of agricultural practices appropriate for general use in the European Union and the variation across countries in the European Union has also been made and is discussed in Section 4.3.

TABLE 9 Assumed agricultural practices for default UK FARMLAND (crops for human consumption)

Product	Agricultural practice
Green vegetables	Continuous harvesting throughout the year
Spring wheat*	Sown: 1 May Harvested: 1 September
Root vegetables and potatoes*	Planted: 1 February Harvested for consumption: 15 June – 1 August Harvested for consumption and storage: 1 August – 15 November
Cows – milk and beef	Graze pasture: 15 April – 31 October Eat silage/hay: 1 November – 15 April
Sheep – meat	Graze pasture all year

* Single harvests are modelled for 2 years following deposition. After the second year harvesting is assumed to be continuous.

In the UK, varieties of green vegetables are grown throughout the year and, as the variation in the production of green vegetables marketed fresh is not large, the assumption is made that the production and consumption of green vegetables is uniform throughout the year[3]. For grain products the sowing and harvesting times assumed are for spring varieties of wheat which are the most commonly used for human consumption. Winter varieties are becoming more popular and are also used for animal fodder and the harvesting times tend to be earlier than seen for spring varieties. The difference in predicted activity concentrations for the two varieties are, in general, small and as a default only spring varieties are considered. The model is flexible enough, however, to model winter varieties of cereals and the different sowing and harvesting times. Following a discrete harvest it is assumed that the grain is consumed over the rest of the year during which time radioactive decay occurs.

The consumption of potatoes dominates the total consumption of root vegetables[26] and, although the agricultural practices for different root vegetables vary, it is assumed that the agricultural practices for potatoes are appropriate for all root vegetables. A single sowing time is used for all root vegetables[6] and two periods of cropping are taken into account, one representing the production for immediate consumption, eg new potatoes, and the other representing production for consumption and storage. It is assumed that the stored crop is consumed over the rest of the year, during which time radioactive decay occurs. The harvesting periods are based on a review of current UK practices[6].

There is a large variation across the UK in feeding practices for cattle and sheep. Generally dairy cattle are outdoors on pasture for about 6 months and are fed additional feedstuffs, such as hay; however, grass provides the bulk of the feed requirements. Beef cattle are also grazed outdoors but the variation in time spent outdoors is greater. The extremes are cattle outdoors on pasture permanently and cattle that are intensively reared indoors on a diet of cereals, silage and other products. Beef production in the UK is obtained from both dairy and beef herds, and therefore the majority of cattle for meat production graze pasture for part of the year. In the winter when they are housed indoors cattle are fed a variety of feeds, with hay and silage being the most common. The default practices in FARMLAND are that both dairy and beef cattle graze pasture for the summer months and during the rest of the year are fed locally grown hay or silage harvested over the summer using a typical three-cut system[59].

It is assumed in the model that sheep remain outdoors grazing pasture throughout the year. The intake of supplementary feeds through the winter is ignored. In parts of the UK it is common to house the sheep indoors through part of the winter prior to lambing[65]. However, for use of FARMLAND in its generic form the assumption that sheep remain outdoors throughout the year is taken as representative of typical practices. The effect of housing sheep indoors throughout the winter on the activity concentrations predicted by FARMLAND has been considered and is discussed in Section 6.

3.4 Preparation losses

FARMLAND includes losses due to culinary preparation and the processing of grain into flour. Much of the external contamination on crops at the time of harvest will be removed before consumption of the edible parts by man. Washing and removal of outer leaves of green vegetables and the removal of outer layers of grain in the production of flour lead to a reduction in contamination levels in the edible crop. Data on losses through preparation and processing have been widely studied, especially in the context of possible reductions following accidental

TABLE 10 Fractions of activity retained in crops following preparation

Food	Fraction*
Green vegetables	0.2
Grain	0.1
Root vegetables/potatoes	1.0
Fruit	0.6

* Applies to surface contamination of the plant only.

releases[26,68]. The losses assumed are given in Table 10 and are only applied to the surface contamination of the plant. For root vegetables and potatoes surface contamination of the peel is not modelled explicitly and contamination is assumed to be uniform throughout the tuber or root, including the peel. This is explained in more detail elsewhere[6]. For consistency with the modelling approach no losses due to culinary preparation are assumed. For some elements, particularly the actinides which concentrate in the skin, this may lead to an overestimation of the activity concentration in the tuber if it is peeled before consumption. Radioactive material which is incorporated into plants or animal products is less readily removed by preparation or food processing and any losses are ignored.

4 Applications of FARMLAND

The FARMLAND model described in the previous sections is the full model which can be used for a number of applications. It is primarily used to study the transfer of radionuclides to the foodchain following accidental or routine releases of radioactivity to atmosphere. The way in which the model is used and the assumptions made depend on the application and these are described in more detail elsewhere[7]. For the consideration of routine releases simplifying assumptions can be made as the releases are assumed to be continuous and constant throughout each year and the temporal accuracy of calculations required is not less than 1 year. It is therefore unnecessary to model the time dependence of the transfer to the food in detail for routine release applications. In general, the model structure and the processes considered for routine release applications are the same as those for accidental release applications; however, assumptions concerning agricultural practices are simplified as described below.

The full complexity of FARMLAND is used for accidental release applications where prediction of the time dependence of the transfer of radionuclides to food is required as an important input to post-accident management and also to the development of emergency plans.

For the application of FARMLAND to the assessment of the effect of routine releases to atmosphere on the foodchain the assumptions made on agricultural practices can be simplified from those given in Table 8. The assumption is made that the releases are continuous and constant throughout each year but possibly varying from one year to the next. It is therefore unnecessary to model explicitly the details of agricultural practices, eg sowing and harvesting times, and their relation to the time of deposition. The agricultural practice assumptions used for routine release assumptions are given in Table 11.

For all crops a single crop is modelled in the first year for a typical growing period of 4 months followed by a fallow period for the rest of the year. This enables the activity

TABLE 11 Assumed agricultural practices for routine releases (for human consumption)

Product	Agricultural practice
Green vegetables	Year 1: single harvest after 120 days Year 2 onwards: continuous cropping
Cereals	Year 1: single harvest after 120 days Year 2 onwards: continuous cropping
Root vegetables and potatoes	Year 1: single harvest after 120 days Year 2 onwards: continuous cropping
Cows – milk and beef	Graze pasture continuously throughout the year
Sheep – meat	

concentration in the harvested crop from a whole growing period to be evaluated regardless of when in the year it was planted. Following the first year the harvesting of the crop is modelled as a continuous removal of activity from the system. This approximation is appropriate even for crops which are discretely harvested as, for routine release assessments, the temporal accuracy of calculations required is not less than 1 year and so it is unnecessary to model the sowing and harvesting of crops each year.

For cattle and sheep the assumption is made that they remain out of doors throughout the year. For cattle the activity concentrations in locally produced hay or silage will not be significantly different to those in the pasture grass consumed and it is therefore unnecessary to model explicitly the cattle indoors during the winter.

4.1 Use of FARMLAND in the European Union

FARMLAND has been used in the development of a default model for application in the European Union (EU) which is intended for use where site-specific data are not available. This work was undertaken as part of a Commission of the European Communities project to compile underlying data for derived emergency reference levels[26]. The default foodchain model is based on two dynamic foodchain models, ECOSYS[25], developed at Gesellschaft für Strahlen-und Umweltforschung mbH (GSF), Germany, and FARMLAND. Various studies were carried out to validate the two models by comparing their predictions with sets of environmental measurements. Validation studies carried out with FARMLAND are described in Section 5 and elsewhere[54]. The predictions of the two models were then compared for a number of different situations for the following foods: green vegetables, root vegetables, potatoes, wheat, cows' milk, beef and lamb. Details of these studies are given elsewhere[26].

Based on these studies default parameter values have been suggested for use with either model or any other similar model for application in the EU when site-specific information is not available. Data are provided for the most important element-independent parameters, the translocation of strontium, caesium and iodine to wheat and potatoes, soil–plant transfer factors, feed–animal product transfer factors, and agricultural practices for use in the default model for the EU. The default parameter values for use in the model are the same as those recommended for use in FARMLAND for UK applications except for agricultural practices.

Default data for agricultural practices have also been suggested for the whole of the EU[26] and are given in Table 12. The agricultural practices recommended for use as a default for the EU are, in general, very similar to those assumed in FARMLAND for use in the UK. The major difference is that it is assumed that sheep are housed indoors during the winter months during which time they are fed on locally produced hay or silage. In addition, a more detailed analysis of agricultural practices in the EU was carried out in which the EU was divided into four regions. The use of regional agricultural practices can lead to significant differences in the predicted concentrations in particular foods for releases at different times of the year. However, often what appear to be large variations in concentrations as a function of time have very little effect on the total integrated concentrations and hence intakes. More details of this study are given elsewhere[26].

A further more detailed study of the variation in the types of food grown and regional agricultural practices has been carried out for southern Europe[69]. In addition, differences in the transfer of radioactivity in the foodchain between northern and southern France have been considered[36]. Large differences are found in the types of food produced and consumed. For example, there are few cattle in the south and little butter and cheese from cows' milk are produced or eaten. However, cheese from goats' milk and oils, such as olive oil, are widely produced and consumed. There are also large differences in the times at which crops are planted and harvested and in the feeding regimes for animals. These differences in agricultural practice would be significant for accidental releases where there is a single deposit at a particular time of year[26]. For routine releases such differences in agricultural practice are insignificant in estimating concentrations in terrestrial foods.

In any study where FARMLAND is used for specific regions of Europe it could be important in accidental release applications for local agricultural practices to be considered if they are significantly different from those recommended as a default. For both routine and accidental release studies it is also important that the appropriate foods for the region concerned are considered.

Any differences in transfer parameters for regions of southern Europe appear to be small compared with variation due to other factors such as soil type. The use of the default parameter

TABLE 12 Assumed agricultural practices for the EU default foodchain model

Product	Agricultural practice
Green vegetables	Continuous harvesting throughout the year
Winter wheat	Sown: 1 October Harvested: 5 August
Spring wheat	Sown: 15 April Harvested: 15 August
Root vegetables	Planted: 1 May Harvested: 1 August – 31 October
Potatoes	Planted: 15 May Harvested: 1 August – 25 September
Cows – milk and beef	Graze pasture: 15 April – 31 October Eat silage/hay: 1 November – 15 April
Sheep – meat	Graze pasture: 15 April – 31 October Eat silage/hay: 1 November – 15 April
Pigs	Eat winter wheat grown under conditions described above

values recommended for use with FARMLAND for the UK and the EU are considered equally appropriate for southern European conditions[26].

4.2 Use of FARMLAND when the source of radioactivity is irrigation

Freshwater into which radionuclides are discharged may be used to irrigate agricultural land and provide a source of radioactivity for terrestrial foods. Various types of irrigation are widely used in the EU, notably in the drier southern areas. The types of irrigation methods adopted and their extent are discussed in detail elsewhere[69]. The type of irrigation which has potentially the greatest radiological significance is spray irrigation. In this case large quantities of water are sprayed over crops leading to radionuclides depositing on both the crops and the soil. Other types of irrigation, eg via channels, lead to radionuclides entering the soil only initially and then subsequently transferring to plants by root uptake and resuspension.

It is possible to use FARMLAND to estimate the concentrations of radionuclides in terrestrial foods when the input is via irrigation. Spray irrigation may be treated as an atmospheric source with deposition on to plants and soil and the default parameter values may be used in the absence of other data. However, if the spray irrigation is carried out at a high rate, it is similar in effect to heavy rain and there will be reduced interception by plants[24,35]. It may then be appropriate to use a reduced interception factor. For other types of irrigation it is again possible to use models as described but with input only into the appropriate soil compartment and not directly on to plants.

5 Verification and validation studies carried out with FARMLAND

A number of verification and validation studies have been carried out on FARMLAND during its development and since its implementation. In these studies the model predictions have been compared with those of similar models for given conditions (verification) and with a variety of sets of environmental measurement data (validation). The performance of FARMLAND in these studies is summarised here. In addition, areas where testing of FARMLAND is ideally still required are outlined. Full details and results of the studies are described elsewhere[54].

5.1 Verification studies

Throughout the development of FARMLAND the predicted activity concentrations in foods have been checked against hand calculations, and have been compared with the results given by relatively simple, multiplicative foodchain transfer models.

FARMLAND has also been used in four extensive model intercomparison studies at various stages of its development. The results of FARMLAND and the model ECOSYS, developed at Gesellschaft für Strahlen-und Umweltforschung (GSF), Germany, have been compared in two studies partially funded by the Commission of the European Communities over the last 8 years[54]. Both these models contain many similar features; in particular, both models include the possibility of considering deposition at various times of the year. Other dynamic foodchain models developed in the UK by Associated Nuclear Services (ANS), for the Ministry of Agriculture, Fisheries and Food (MAFF), and the Berkeley Laboratories of Nuclear Electric (NE) have also been compared with FARMLAND[54]. FARMLAND has been used in an international cooperative effort to test biosphere models, BIOMOVS. A scenario (B1) was designed to compare the predictions of a number of foodchain models given an average long-term concentration of iodine-131 and caesium-137 in air and known precipitation[54].

In the model comparison studies the concentrations in food predicted by the models were generally in reasonable agreement and the same pattern of time dependence was seen. Where agricultural practices were not fixed as input these led to the largest differences between model prediction. Agreement was generally closest for strontium, caesium and iodine, elements which have been extensively studied, and the largest differences were between parameter values used for plutonium and ruthenium, for which data are relatively poor. Differences due to the structure of the models were usually smaller than those due to agricultural practices and the choice of parameter values. In the BIOMOVS model intercomparison the predictions of FARMLAND were similar to those of the other models. The studies that have been made on FARMLAND and other foodchain models have shown that FARMLAND compares favourably with other major foodchain models in Europe. Its performance gives confidence in the implementation of the model as differences between models are largely due to choice of parameter values and assumptions on agricultural practice.

5.2 Validation studies

The FARMLAND model has been tested against several different types of data. These are data from field studies in Cumbria, activity concentrations in milk from fallout due to atmospheric weapons testing over the last 30 years, and, more recently, measurements made in various foods after the Chernobyl reactor accident, both from monitoring programmes and site-specific measurements[54]. FARMLAND has also been used in the BIOMOVS international model validation study in two scenarios. The first one, Scenario B1, is a verification exercise (see Section 5.1). In the second study FARMLAND has been tested for various locations in the northern hemisphere where data were collected after the Chernobyl accident. In this study the predictions of 22 models from 16 groups were collated for comparison and analysis.

In general, detailed data for validation studies are only available for the pasture–cow–milk pathway; more limited data for green vegetables, grain, beef and sheep meat are available, mainly in the form of environmental monitoring data following the Chernobyl accident.

Details of the FARMLAND model have been available in the literature for many years and the model has been subjected to validation studies by other organisations that have wanted to test its applicability for specific situations[70].

The comparison of FARMLAND predictions with measurement data and especially post-Chernobyl measurements has strengthened confidence in the validity of the model for use in general radiological assessments, which was the use for which it was intended.

In general, FARMLAND provided good predictions for the time dependence of the transfer of radionuclides to the foods considered. Some discrepancies between measurements and model predictions in the magnitude of the transfer were found at particular sites. These are often due to differences between general assumptions made in the default FARMLAND model and the actual conditions. There were also differences in some cases where deposition occurred in rainfall as FARMLAND does not distinguish between wet and dry deposition. These findings are to be expected owing to the general nature of the FARMLAND model.

The aim of the validation studies carried out on FARMLAND is to test the model's suitability and reliability to represent the general conditions for which it was developed. As part of this process inadequacies of the model have been identified and changes to the model and parameter values have been made. The results from some of the earlier studies carried out during the development of the pasture and cow models of FARMLAND have been used for further development and improvement of the models. The validation of FARMLAND using measurement data for the Chernobyl accident led to a change in the value of the equilibrium transfer factor for iodine in milk, which has been altered downwards by a factor of two in common with data used in other international foodchain models, eg ECOSYS[25].

5.3 Areas of FARMLAND not tested

FARMLAND predicted the time variation in concentration following the Chernobyl accident well in general as was shown in the studies outlined above. The release, however, occurred at one time of the year and it has not been possible to test the model for deposition at times of the year when the stages of plant growth are very different. Data were also very sparse for other countries in the EU, especially the Mediterranean countries, where land types, climate and agriculture could be very different from those in northern Europe.

Data have been limited to only a few foods. Activity concentrations in foods other than milk and beef, and to a limited extent grain, have generally only been measured in environmental monitoring programmes. These measurements are unsuitable for rigorous model validation because often the deposition is unknown at the site where food concentrations are measured; also measurements in many foods do not start soon enough after deposition to test the adequacy of the model in predicting variations with time. The testing of the models to predict concentrations in vegetables, grain and root crops, and to a lesser extent lamb and beef, has not been as thorough as it would ideally be because of this lack of data.

The testing of FARMLAND has also been limited to a few radionuclides, namely iodine-131, caesium-134 and caesium-137 and, for continuous releases, strontium-90.

6 FARMLAND results for accident and routine release applications

FARMLAND is used for calculating activity concentration and integrals of concentrations in terrestrial foods following accidental and routine releases of radioactivity to atmosphere. In this section some example results are given for reference and the effects of the transfer processes included in the models on the results are discussed. In addition, examples of the importance of individual foods and radionuclides in contributing to individual ingestion doses for accidental releases at different times of the year are given.

6.1 Selected results for accidental releases to atmosphere

The predicted activity concentrations and time-integrated concentrations of strontium-90, ruthenium-106, iodine-131, caesium-137 and plutonium-239 in green vegetables, grain, cows' milk and lamb for a single deposit on 1 January and 1 July are given in Tables 13 and 14, respectively. The results are presented for a series of times to show the variation of concentration as a function of time and the period over which most of the total integrated concentration is expressed. The activity concentrations (Bq kg^{-1}) could be used, for example, to determine if and for how long concentrations in a food exceed a criterion set for restricting the consumption of food based on activity concentrations. The time-integrated concentrations (Bq y kg^{-1}) are typically used for estimating ingestion doses, both individual and collective, where the intake of a particular radionuclide in a particular food in a given period is calculated using the time-integrated concentration and a consumption rate.

For green vegetables the assumption is made that they are grown and harvested all year and so the time of year of the deposit has no effect on the concentrations. From the tables it can be seen that, with the exception of strontium, the majority of the total integrated concentration found in green vegetables is from the first year following deposition. For strontium-90 where about 50% is from the first year, this is due to the importance of root uptake for this element.

The concentrations in grain following an accidental release will vary significantly depending on the time of the year when deposition occurs. Until the time of harvest the concentrations in grain consumed will be zero. For deposition during the summer when the cereal crop is growing, the concentration in the first year's harvest following deposition will be the highest. Concentrations in subsequent harvests will be lower, will be hardly affected by the original timing of the deposit and will be mainly due to uptake from the soil via the roots. The effect of the time of deposit is more marked for some radionuclides than for others. It is particularly noticeable for iodine-131 for which there is almost no contamination of grain if the release occurs in winter. Even during the growing season the time of deposition has a significant effect on the contamination of grain at harvest with iodine-131. For strontium-90, however, the overall variation in the time integral of concentration for deposition at various times of the year is small compared with that for other radionuclides; this is due to the importance of root uptake in the years following the deposit. The small concentrations predicted for ruthenium-106 and plutonium-239 reflect their relative immobility within plants, leading to the assumption that there is no transfer from the surface of the plant to internal tissue. The highest concentrations for deposition during the growing season (Table 14) are seen for caesium-137 and are at their highest 1 month before harvest. These results reflect the greater mobility of caesium within the plant.

For milk and meat the time of the deposit affects both the time integral of concentration and the variation in the concentration as a function of time following the release. This is illustrated in Figure 8 which shows the concentration of caesium-137 in milk following a unit deposit at two times of the year, January and May. When the deposit occurs in January no activity is predicted to appear in milk until mid-April when the cows are assumed to be moved on to pasture for grazing. For a deposit in May, the peak concentration occurs a few days after the deposit and the concentrations then decline owing to the loss of surface contamination on pasture. In FARMLAND cows are assumed to leave the pasture at the end of October and the concentration in milk then increases again for the time they are fed contaminated hay or silage. This increase occurs because the grass for winter feed is harvested throughout the summer including the times when levels of caesium in grass are higher. The influence of winter feed is more marked when the deposit occurs during the summer. Finally, as the cows return to pasture in the following spring the concentration in milk returns to the levels of the previous autumn and slowly declines.

Similar patterns of concentration as a function of time are predicted for deposits at other times of the year and for other relatively long-lived radionuclides. For beef similar features are seen.

The total integrated concentrations in meat and milk from cattle also vary depending on the time of year of release. Tables 13 and 14 show that the variation between winter and summer is more than an order of magnitude for milk and similar results are seen for beef. For iodine-131 the differences between winter and summer are even greater and there is almost no activity predicted in milk and meat when the deposit occurs between November and the end of February.

(text continues on page 38)

TABLE 13 Activity concentrations and time-integrated concentrations for a number of foods following deposition of 1 Bq m^{-2} on 1 January

	Nuclide									
	^{90}Sr		^{106}Ru		^{131}I		^{137}Cs		^{239}Pu	
Time	Concentration (Bq kg^{-1})	Integral of concentration (Bq y kg^{-1})	Concentration (Bq kg^{-1})	Integral of concentration (Bq y kg^{-1})	Concentration (Bq kg^{-1})	Integral of concentration (Bq y kg^{-1})	Concentration (Bq kg^{-1})	Integral of concentration (Bq y kg^{-1})	Concentration (Bq kg^{-1})	Integral of concentration (Bq y kg^{-1})
Green vegetables										
7 days	$2.05\ 10^{-1}$	$4.79\ 10^{-3}$	$1.81\ 10^{-1}$	$4.51\ 10^{-3}$	$1.12\ 10^{-1}$	$3.66\ 10^{-3}$	$2.04\ 10^{-1}$	$4.78\ 10^{-3}$	$2.04\ 10^{-1}$	$4.78\ 10^{-3}$
30 days	$5.85\ 10^{-2}$	$1.21\ 10^{-2}$	$3.40\ 10^{-2}$	$1.00\ 10^{-2}$	$4.41\ 10^{-3}$	$5.74\ 10^{-3}$	$5.86\ 10^{-2}$	$1.21\ 10^{-2}$	$5.77\ 10^{-2}$	$1.21\ 10^{-2}$
1 year	$6.64\ 10^{-4}$	$1.57\ 10^{-2}$	0.00	$1.13\ 10^{-2}$	0.00	$5.83\ 10^{-3}$	$5.08\ 10^{-5}$	$1.52\ 10^{-2}$	$3.65\ 10^{-5}$	$1.50\ 10^{-2}$
2 years	$6.06\ 10^{-4}$	$1.63\ 10^{-2}$	0.00	$1.13\ 10^{-2}$	0.00	$5.83\ 10^{-3}$	$1.44\ 10^{-5}$	$1.52\ 10^{-2}$	0.00	$1.50\ 10^{-2}$
10 years	$4.69\ 10^{-4}$	$2.06\ 10^{-2}$	0.00	$1.13\ 10^{-2}$	0.00	$5.83\ 10^{-3}$	$1.13\ 10^{-5}$	$1.53\ 10^{-2}$	0.00	$1.50\ 10^{-2}$
50 years	$1.30\ 10^{-4}$	$3.12\ 10^{-2}$	0.00	$1.13\ 10^{-2}$	0.00	$5.83\ 10^{-3}$	$3.39\ 10^{-6}$	$1.56\ 10^{-2}$	0.00	$1.50\ 10^{-2}$
Grain										
7 days	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
30 days	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1 year	$4.33\ 10^{-4}$	$1.44\ 10^{-4}$	$1.12\ 10^{-5}$	$4.18\ 10^{-6}$	$9.31\ 10^{-19}$	$1.01\ 10^{-15}$	$2.18\ 10^{-5}$	$7.26\ 10^{-6}$	$2.43\ 10^{-7}$	$8.07\ 10^{-8}$
2 years	$4.20\ 10^{-4}$	$5.71\ 10^{-4}$	$5.62\ 10^{-6}$	$1.23\ 10^{-5}$	0.00	$1.01\ 10^{-15}$	$2.12\ 10^{-5}$	$2.88\ 10^{-6}$	$2.42\ 10^{-7}$	$3.23\ 10^{-7}$
10 years	$3.27\ 10^{-4}$	$3.82\ 10^{-3}$	$2.19\ 10^{-8}$	$2.34\ 10^{-5}$	0.00	$1.01\ 10^{-15}$	$1.66\ 10^{-5}$	$1.93\ 10^{-4}$	$2.28\ 10^{-7}$	$2.36\ 10^{-6}$
50 years	$9.49\ 10^{-5}$	$1.13\ 10^{-2}$	0.00	$2.34\ 10^{-5}$	0.00	$1.01\ 10^{-15}$	$4.99\ 10^{-6}$	$5.80\ 10^{-4}$	$1.73\ 10^{-7}$	$1.03\ 10^{-5}$

TABLE 13 (continued)

	Nuclide									
	^{90}Sr		^{106}Ru		^{131}I		^{137}Cs		^{239}Pu	
Time	Concentration (Bg kg^{-1})	Integral of concentration (Bq y kg^{-1})	Concentration (Bq kg^{-1})	Integral of concentration (Bq y kg^{-1})	Concentration (Bq kg^{-1})	Integral of concentration (Bq y kg^{-1})	Concentration (Bq kg^{-1})	Integral of concentration (Bq y kg^{-1})	Concentration (Bq kg^{-1})	Integral of concentration (Bq y kg^{-1})
Cows' milk										
7 days	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
30 days	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1 year	7.67 10^{-4}	4.52 10^{-4}	1.12 10^{-7}	9.83 10^{-8}	0.00	1.73 10^{-8}	1.12 10^{-3}	7.66 10^{-4}	6.81 10^{-8}	3.58 10^{-8}
2 years	4.98 10^{-4}	1.07 10^{-3}	1.34 10^{-8}	1.41 10^{-7}	0.00	1.73 10^{-8}	2.05 10^{-4}	1.32 10^{-3}	8.70 10^{-8}	1.21 10^{-7}
10 years	6.38 10^{-5}	2.50 10^{-3}	1.57 10^{-11}	1.56 10^{-7}	0.00	1.73 10^{-8}	1.27 10^{-5}	1.77 10^{-3}	2.18 10^{-8}	4.18 10^{-7}
50 years	4.77 10^{-6}	3.30 10^{-3}	0.00	1.56 10^{-7}	0.00	1.73 10^{-8}	0.00	1.82 10^{-3}	6.62 10^{-11}	5.46 10^{-7}
Sheep meat										
7 days	1.59 10^{-3}	1.86 10^{-5}	5.08 10^{-4}	4.63 10^{-6}	1.99 10^{-2}	2.61 10^{-4}	1.67 10^{-1}	1.85 10^{-3}	9.04 10^{-5}	9.61 10^{-7}
30 days	1.61 10^{-3}	1.35 10^{-4}	1.25 10^{-3}	6.6 10^{-5}	3.44 10^{-3}	9.13 10^{-4}	2.33 10^{-1}	1.64 10^{-2}	9.71 10^{-5}	7.45 10^{-6}
1 year	1.11 10^{-4}	3.63 10^{4}	1.82 10^{-4}	6.33 10^{-4}	0.00	9.13 10^{-4}	4.90 10^{-3}	4.60 10^{-2}	3.34 10^{-5}	5.56 10^{-5}
2 years	7.03 10^{-5}	4.52 10^{-4}	3.12 10^{-5}	7.14 10^{-4}	0.00	9.13 10^{-4}	3.22 10^{-3}	5.00 10^{-2}	1.57 10^{-5}	7.87 10^{-5}
10 years	6.54 10^{-6}	6.31 10^{-4}	1.78 10^{-8}	7.42 10^{-4}	0.00	9.13 10^{-4}	3.23 10^{-4}	5.95 10^{-2}	1.01 10^{-6}	1.12 10^{-4}
50 years	4.58 10^{-7}	7.12 10^{-4}	0.00	7.42 10^{-4}	0.00	9.13 10^{-4}	0.00	5.95 10^{-2}	1.10 10^{-9}	1.16 10^{-4}

TABLE 14 Activity concentrations and time-integrated concentrations for a number of foods following deposition of 1 Bq m^{-2} on 1 July

Time	Nuclide									
	^{90}Sr		^{106}Ru		^{131}I		^{137}Cs		^{239}Pu	
	Concentration (Bq kg^{-1})	Integral of concentration (Bq y kg^{-1})	Concentration (Bq kg^{-1})	Integral of concentration (Bq y kg^{-1})	Concentration (Bq kg^{-1})	Integral of concentration (Bq y kg^{-1})	Concentration (Bq kg^{-1})	Integral of concentration (Bq y kg^{-1})	Concentration (Bq kg^{-1})	Integral of concentration (Bq y kg^{-1})
Green vegetables										
7 days	$2.05\ 10^{-1}$	$4.79\ 10^{-3}$	$1.81\ 10^{-1}$	$4.51\ 10^{-3}$	$1.12\ 10^{-1}$	$3.66\ 10^{-3}$	$2.04\ 10^{-1}$	$4.78\ 10^{-3}$	$2.04\ 10^{-1}$	$4.78\ 10^{-3}$
30 days	$5.85\ 10^{-2}$	$1.21\ 10^{-2}$	$3.40\ 10^{-2}$	$1.00\ 10^{-2}$	$4.41\ 10^{-3}$	$5.74\ 10^{-3}$	$5.86\ 10^{-2}$	$1.21\ 10^{-2}$	$5.77\ 10^{-2}$	$1.21\ 10^{-2}$
1 year	$6.64\ 10^{-4}$	$1.57\ 10^{-2}$	0.00	$1.13\ 10^{-2}$	0.00	$5.83\ 10^{-3}$	$5.08\ 10^{-5}$	$1.52\ 10^{-2}$	$3.65\ 10^{-5}$	$1.50\ 10^{-2}$
2 years	$6.06\ 10^{-4}$	$1.63\ 10^{-2}$	0.00	$1.13\ 10^{-2}$	0.00	$5.83\ 10^{-3}$	$1.44\ 10^{-5}$	$1.52\ 10^{-2}$	0.00	$1.50\ 10^{-2}$
10 years	$4.69\ 10^{-4}$	$2.06\ 10^{-2}$	0.00	$1.13\ 10^{-2}$	0.00	$5.83\ 10^{-3}$	$1.13\ 10^{-5}$	$1.53\ 10^{-2}$	0.00	$1.50\ 10^{-2}$
50 years	$1.30\ 10^{-4}$	$3.12\ 10^{-2}$	0.00	$1.13\ 10^{-2}$	0.00	$5.83\ 10^{-3}$	$3.39\ 10^{-6}$	$1.56\ 10^{-2}$	0.00	$1.50\ 10^{-2}$
Grain										
7 days	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
30 days	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1 year	$3.03\ 10^{-3}$	$2.53\ 10^{-3}$	$7.43\ 10^{-4}$	$8.27\ 10^{-4}$	0.00	$7.77\ 10^{-6}$	$5.49\ 10^{-2}$	$4.59\ 10^{-2}$	$1.45\ 10^{-3}$	$1.20\ 10^{-3}$
2 years	$4.19\ 10^{-4}$	$3.40\ 10^{-3}$	$5.64\ 10^{-6}$	$9.54\ 10^{-4}$	0.00	$7.77\ 10^{-6}$	$2.06\ 10^{-5}$	$5.36\ 10^{-2}$	$2.42\ 10^{-7}$	$1.45\ 10^{-3}$
10 years	$3.25\ 10^{-4}$	$6.42\ 10^{-3}$	$2.19\ 10^{-8}$	$9.63\ 10^{-4}$	0.00	$7.77\ 10^{-6}$	$1.61\ 10^{-5}$	$5.55\ 10^{-2}$	$2.28\ 10^{-7}$	$1.46\ 10^{-3}$
50 years	$9.43\ 10^{-5}$	$1.39\ 10^{-2}$	0.00	$9.63\ 10^{-4}$	0.00	$7.77\ 10^{-6}$	$4.85\ 10^{-6}$	$5.59\ 10^{-2}$	$1.73\ 10^{-7}$	$1.46\ 10^{-3}$

TABLE 14 (continued)

Time	Nuclide									
	^{90}Sr		^{106}Ru		^{131}I		^{137}Cs		^{239}Pu	
	Concentration (Bq kg^{-1})	Integral of concentration (Bq y kg^{-1})	Concentration (Bq kg^{-1})	Integral of concentration (Bq y kg^{-1})	Concentration (Bq kg^{-1})	Integral of concentration (Bq y kg^{-1})	Concentration (Bq kg^{-1})	Integral of concentration (Bq y kg^{-1})	Concentration (Bq kg^{-1})	Integral of concentration (Bq y kg^{-1})
Cows' milk										
7 days	$1.16\ 10^{-2}$	$1.74\ 10^{-4}$	$1.75\ 10^{-5}$	$4.03\ 10^{-7}$	$5.06\ 10^{-2}$	$1.04\ 10^{-3}$	$7.08\ 10^{-2}$	$1.01\ 10^{-3}$	$1.04\ 10^{-6}$	$1.54\ 10^{-8}$
30 days	$2.65\ 10^{-3}$	$5.62\ 10^{-4}$	$1.69\ 10^{-7}$	$8.26\ 10^{-7}$	$9.42\ 10^{-4}$	$1.83\ 10^{-3}$	$1.55\ 10^{-2}$	$3.41\ 10^{-3}$	$6.81\ 10^{-7}$	$6.93\ 10^{-8}$
1 year	$1.11\ 10^{-3}$	$2.28\ 10^{-3}$	$3.22\ 10^{-8}$	$1.78\ 10^{-6}$	0.00	$1.84\ 10^{-3}$	$1.09\ 10^{-3}$	$1.11\ 10^{-2}$	$1.16\ 10^{-6}$	$9.02\ 10^{-7}$
2 years	$5.03\ 10^{-3}$	$3.15\ 10^{-3}$	$1.33\ 10^{-8}$	$1.81\ 10^{-6}$	0.00	$1.84\ 10^{-3}$	$2.01\ 10^{-4}$	$1.14\ 10^{-2}$	$3.46\ 10^{-7}$	$1.86\ 10^{-6}$
10 years	$6.39\ 10^{-5}$	$4.69\ 10^{-3}$	0.00	$1.82\ 10^{-6}$	0.00	$1.84\ 10^{-3}$	$1.26\ 10^{-5}$	$1.19\ 10^{-2}$	$6.65\ 10^{-8}$	$3.22\ 10^{-6}$
50 years	$4.75\ 10^{-6}$	$5.49\ 10^{-3}$	0.00	$1.82\ 10^{-6}$	0.00	$1.84\ 10^{-3}$	0.00	$1.19\ 10^{-2}$	$6.92\ 10^{11}$	$3.53\ 10^{-6}$
Sheep meat										
7 days	$1.59\ 10^{-3}$	$1.86\ 10^{-5}$	$5.08\ 10^{-4}$	$4.63\ 10^{-6}$	$1.99\ 10^{-2}$	$2.61\ 10^{-4}$	$1.67\ 10^{-1}$	$1.85\ 10^{-3}$	$9.04\ 10^{-5}$	$9.61\ 10^{-7}$
30 days	$1.61\ 10^{-3}$	$1.35\ 10^{-4}$	$1.25\ 10^{-3}$	$6.66\ 10^{-5}$	$3.44\ 10^{-3}$	$9.13\ 10^{-4}$	$2.33\ 10^{-1}$	$1.64\ 10^{-2}$	$9.71\ 10^{-5}$	$7.45\ 10^{-6}$
1 year	$1.11\ 10^{-4}$	$3.63\ 10^{-4}$	$1.82\ 10^{-4}$	$6.33\ 10^{-4}$	0.00	$9.13\ 10^{-4}$	$4.90\ 10^{-3}$	$4.60\ 10^{-2}$	$3.34\ 10^{-5}$	$5.56\ 10^{-5}$
2 years	$7.03\ 10^{-5}$	$4.52\ 10^{-4}$	$3.12\ 10^{-5}$	$7.14\ 10^{-4}$	0.00	$9.13\ 10^{-4}$	$3.22\ 10^{-3}$	$5.00\ 10^{-2}$	$1.57\ 10^{-5}$	$7.87\ 10^{-5}$
10 years	$6.54\ 10^{-6}$	$6.31\ 10^{-4}$	$1.78\ 10^{-8}$	$7.42\ 10^{-4}$	0.00	$9.13\ 10^{-4}$	$3.23\ 10^{-4}$	$5.95\ 10^{-2}$	$1.01\ 10^{-6}$	$1.12\ 10^{-4}$
50 years	$4.58\ 10^{-7}$	$7.12\ 10^{-4}$	0.00	$7.42\ 10^{-4}$	0.00	$9.13\ 10^{-4}$	0.00	$5.95\ 10^{-2}$	$1.10\ 10^{-9}$	$1.16\ 10^{-4}$

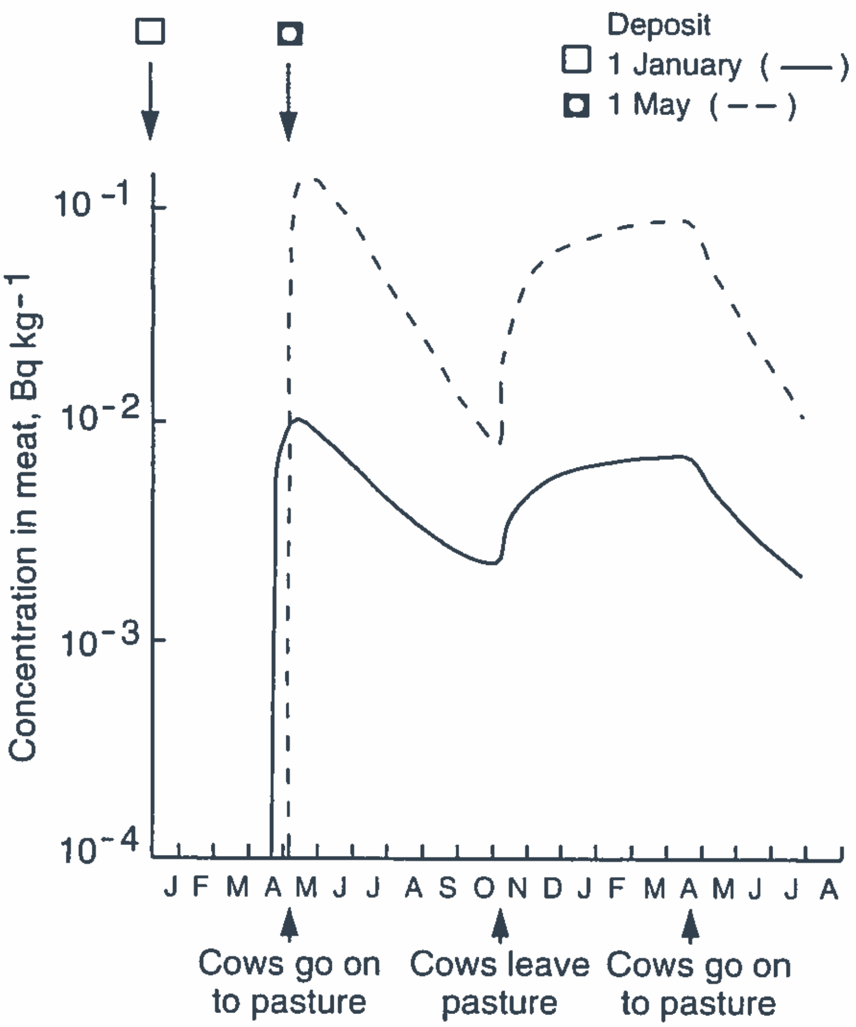

FIGURE 8 Concentration of caesium-137 in meat as a function of time following an accidental release at two different times of the year

The same general pattern is seen for other radionuclides. However, for strontium-90 the variation between winter and summer is predicted to be only about a factor of two because of the importance of uptake from the soil in the years following the deposit for this radionuclide.

In FARMLAND the assumption is made that in the UK sheep remain outdoors grazing pasture all year and the predicted concentrations are independent of the time of the year that deposition occurs. For the relatively long-lived radionuclides given in Tables 13 and 14 the majority of the time integral of concentrations is from the first 10 years. For short-lived radionuclides, such as iodine-131 the majority of the time integral of concentration arises in the first few months following deposition. The concentrations of caesium-137 in lamb are significantly higher than those seen for the other radionuclides; this reflects the importance of caesium transfer within the pasture–animal pathway.

The influence of the season of the year in which an accident occurs has been examined for three hypothetical releases representing a range of accident postulated for pressurised water reactors (PWRs)[71]. In this study agricultural consequences of these releases, expressed as the amount of produce affected by restrictions on food supplies and collective dose from ingestion, were estimated on the assumption that no countermeasures were implemented. Some results of the study are given in Table 15 which shows the extent of predicted restrictions on supplies of milk, livestock and crops following a small degraded core accident at different times of the year. The agricultural consequences were predicted in this study using a dose of 5 mSv from a year's intake of food as the criterion for restricting food consumption. The results are, however, also illustrative of the variations in consequences with time of the year that would be seen if a criterion of activity concentration in food was used, although the absolute results would be slightly higher. The results were calculated for a single set of meteorological conditions and it can be seen that for milk and crops there is more than an order of magnitude between results obtained for winter and summer releases. The effect is less marked for livestock because of the significance of sheep in the UK diet, which are assumed to graze outside throughout the year.

TABLE 15 Variation in amount of food production affected by restrictions following an accidental release at different times of the year[*]

	Amount of agricultural product restricted		
Month of release	Milk (l)	Crops (km^2 y)	Livestock (livestock y)
February	1.5 10^6	1.3 10^1	1.9 10^4
April	9.1 10^6	1.3 10^1	2.9 10^4
June	2.7 10^7	1.0 10^2	5.3 10^4
August	2.6 10^7	9.9 10^2	4.7 10^4

[*] For details of the release and other aspects of the analysis see reference 71.

In general, the results of the study showed that there is considerable variation in agricultural consequences with the season in which the release occurs. This seasonal variation seems to be more marked for a single set of meteorological conditions than for a full probabilistic analysis which considered a wide range of weather sequences. When the results of accidents occurring at different times of the year were combined in a probabilistic analysis it was shown that the yearly averaged results could be adequately determined by a single, representative time of the year for the release. For the types of release considered in the assessment and for UK agricultural practices, the results for a release in June were consistent with the combined consequences of a rigorous seasonal analysis. For other types of releases and for different agricultural practices it is likely that a representative time of the year could be found, but it would not necessarily be June[71].

6.2 Selected results for routine releases to atmosphere

FARMLAND has been applied to evaluate the time dependence of the transfer of activity to foodstuffs following the continuous deposition of activity on land for a year at a rate of 1 Bq m^{-2} s^{-1}. Results have been generated of the time integral of strontium-90, ruthenium-106, iodine-131, caesium-137 and plutonium-239, per unit mass of food (Bq y kg^{-1}) derived from such land for green vegetables, grain, potatoes, cows' milk and lamb and are given in Tables 16 and 17. These integrals, when combined with intake rates or the spatial distribution of agricultural production yields and deposition rates of radionuclides, can be used to estimate the transfer of activity to man via terrestrial foods following continuous releases of activity to atmosphere. If the annual deposition rate is constant the integral to time t years is equivalent to the concentration in the food at t years for continuous deposition over t years.

TABLE 16 Time-integrated concentrations in crops following continuous deposition of 1 Bq m^{-2} for 1 year

	Time integrated activity concentrations (Bq y kg^{-1})				
	Times (years)				
Nuclide	1	50	100	500	100 000
Green vegetables					
^{90}Sr	$1.17\ 10^{5}$	$6.20\ 10^{5}$	$7.25\ 10^{5}$	$7.52\ 10^{5}$	$7.52\ 10^{5}$
^{106}Ru	$1.01\ 10^{5}$	$1.02\ 10^{5}$	$1.02\ 10^{5}$	$1.02\ 10^{5}$	$1.02\ 10^{5}$
^{131}I	$4.12\ 10^{4}$	$4.12\ 10^{4}$	$4.12\ 10^{4}$	$4.12\ 10^{4}$	$4.12\ 10^{4}$
^{137}Cs	$1.32\ 10^{5}$	$1.45\ 10^{5}$	$1.47\ 10^{5}$	$1.48\ 10^{5}$	$1.48\ 10^{5}$
^{239}Pu	$1.05\ 10^{5}$	$1.05\ 10^{5}$	$1.05\ 10^{5}$	$1.05\ 10^{5}$	$1.05\ 10^{5}$
Grain					
^{90}Sr	$7.10\ 10^{4}$	$4.18\ 10^{5}$	$4.95\ 10^{5}$	$5.16\ 10^{5}$	$5.16\ 10^{5}$
^{106}Ru	$5.37\ 10^{3}$	$6.10\ 10^{3}$	$6.10\ 10^{3}$	$6.10\ 10^{3}$	$6.10\ 10^{3}$
^{131}I	$4.21\ 10^{4}$	$4.21\ 10^{4}$	$4.21\ 10^{4}$	$4.21\ 10^{4}$	$4.21\ 10^{4}$
^{137}Cs	$5.02\ 10^{5}$	$5.20\ 10^{5}$	$5.24\ 10^{5}$	$5.25\ 10^{5}$	$5.25\ 10^{5}$
^{239}Pu	$5.38\ 10^{3}$	$5.46\ 10^{3}$	$5.52\ 10^{3}$	$5.66\ 10^{3}$	$5.67\ 10^{3}$
Potatoes					
^{90}Sr	$1.24\ 10^{3}$	$8.82\ 10^{4}$	$1.07\ 10^{5}$	$1.12\ 10^{5}$	$1.12\ 10^{5}$
^{106}Ru	$1.91\ 10^{2}$	$9.51\ 10^{2}$	$9.51\ 10^{2}$	$9.51\ 10^{2}$	$9.51\ 10^{2}$
^{131}I	$8.58\ 10^{3}$	$1.09\ 10^{4}$	$1.09\ 10^{4}$	$1.09\ 10^{4}$	$1.09\ 10^{4}$
^{137}Cs	$1.22\ 10^{5}$	$1.59\ 10^{5}$	$1.62\ 10^{5}$	$1.63\ 10^{5}$	$1.63\ 10^{5}$
^{239}Pu	$1.07\ 10^{0}$	$1.46\ 10^{2}$	$2.51\ 10^{2}$	$4.87\ 10^{2}$	$5.02\ 10^{2}$

Table 16 shows the time integrals of activity per unit mass of plant to 1, 50, 100 and 500 years after the deposition commenced and to 100,000 years (assumed to be infinity) for green vegetables, potatoes and grain. For surface plants (green vegetables and grain) a large fraction of the integrated activity is accumulated in the first year primarily as a result of depositions on to plant surfaces. Only in the case of strontium-90 does the time integral of activity increase significantly in subsequent years; this is due to the relatively high rate of root uptake of strontium from soils. This is illustrated in Figure 9(a) which shows the relative importance of each transfer mechanism in contributing to the time integral of activity as a function of time for grain. The uptake from soil by the plant's roots becomes an increasingly important transfer with time. The time integral of activity by root uptake exceeds that due to direct deposition within a few years of ceasation of deposition. The time integral continues to increase for over 100 years, at which time the contribution exceeds that due to direct deposition by about an order of magnitude. The eventual decline of root uptake of strontium-90 is predominantly due to its radioactive decay.

Plutonium-239 has relatively low absorption from soil to plant roots and the direct deposition of activity makes by far the most important contribution to the time integrals of activity

TABLE 17 Time-integrated concentrations in animal products following continuous deposition of 1 Bq m^{-2} for 1 year

	Time integrated activity concentrations (Bq y kg^{-1})				
	Times (years)				
Nuclide	1	50	100	500	100 000
Cows' milk					
^{90}Sr	4.33 10^4	1.39 10^5	1.42 10^5	1.42 10^5	1.45 10^5
^{106}Ru	2.90 10^1	3.01 10^1	3.01 10^1	3.01 10^1	3.01 10^1
^{131}I	5.82 10^4	5.82 10^4	5.82 10^4	5.82 10^4	5.82 10^4
^{137}Cs	1.54 10^5	1.79 10^5	1.79 10^5	1.79 10^5	1.79 10^5
^{239}Pu	1.61 10^1	8.22 10^1	8.22 10^1	8.22 10^1	8.22 10^1
Sheep meat					
^{90}Sr	1.14 10^4	2.24 10^4	2.27 10^4	2.27 10^4	2.27 10^4
^{106}Ru	2.00 10^4	2.34 10^4	2.34 10^4	2.34 10^4	2.34 10^4
^{131}I	3.17 10^4	3.17 10^4	3.17 10^4	3.17 10^4	3.17 10^4
^{137}Cs	1.45 10^6	1.91 10^6	1.91 10^6	1.91 10^6	1.91 10^6
^{239}Pu	1.75 10^3	3.66 10^3	3.66 10^3	3.66 10^3	3.66 10^3

in grain and green vegetables. This is shown in Figure 9(b) for green vegetables. For caesium, iodine and ruthenium the major contribution to the time integral is also direct deposition on the plant surfaces. The direct deposition component is greatest for caesium and iodine, reflecting the importance of translocation from the plants surface to the edible part of the crop.

In root crops the time integrals of activity continue to increase while activity remains in the root zone. After the first year the only mechanism of importance for transfer of activity to root crops is absorption from the soil. This continues until activity is removed by migration out of the root zone or by radioactive decay. For plutonium-239 and ruthenium-106 the time integral of activity in root crops is significantly lower than that in the surface crops. This reflects the negligible translocation of these radionuclides from the plant surface to the edible crop. In contrast, for iodine and caesium where translocation is significant, concentrations in root vegetables are of the same order or greater than those in surface crops.

Table 17 shows the time integrals of activity per unit mass of milk and lamb for 1, 50, 100 and 500 years after the deposition commenced and to 100,000 years (assumed to be infinity). The results for beef show similar characteristics to lamb, although the absolute values differ. The most notable feature is that by far the majority of activity is transferred to the various animal food products within about 50 years of the initial deposition with little transfer later.

The relative importance of the intake of pasture grass (contaminated by direct deposition, resuspension and root uptake), inadvertent ingestion of soil and inhalation of resuspended activity on concentrations in milk and meat can be evaluated and is presented in detail elsewhere[69]. For strontium, direct deposition on to pasture and root uptake make the greatest contributions to the transfer to animal products; the contribution from inadvertent ingestion of soil is small and that from the inhalation of resuspended material is negligible. After about 3 years the main contribution is

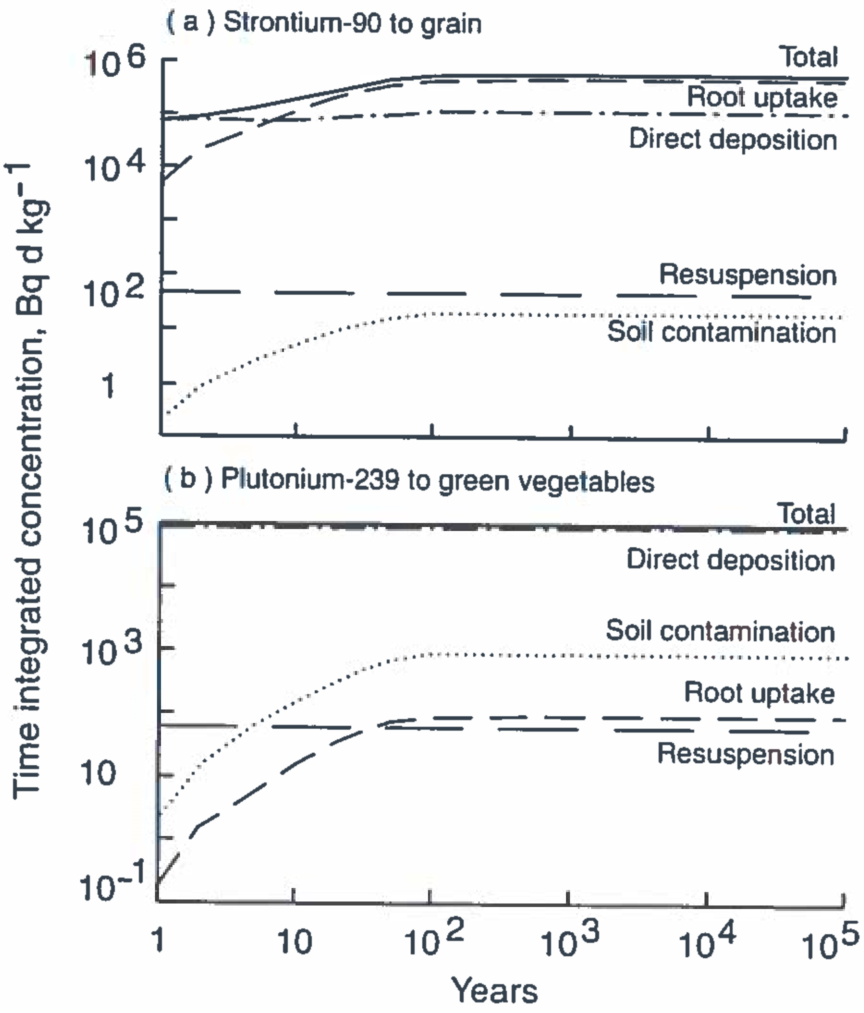

FIGURE 9 Relative importance and time dependence of the important mechanisms for the transfer of (a) strontium-90 to grain and (b) plutonium-239 to green vegetables

from root uptake of strontium. For caesium the total transfer to animal products is dominated by direct deposition on to pasture at all times. The inadvertent ingestion of soil and root uptake make similar contributions to the total transfer particularly at long times when fixation has reduced the amount of caesium available for root uptake. Similarly to caesium, direct deposition on to pasture dominates the total transfer for plutonium. However, the contribution from root uptake is much smaller for plutonium than for caesium and inadvertent soil ingestion is significantly more important than root uptake.

6.3 Importance of individual foods and radionuclides in contributing to ingestion doses for accidental releases

Tables 18 and 19 give the percentage contribution the foods considered in FARMLAND make to the intake of radionuclides via ingestion by an adult in the first year following deposition on 1 January and 1 July, respectively. Mean consumption rates for adults in the UK have been used. The percentage contributions are given for a unit deposit of 1 Bq m^{-2} of strontium-90, ruthenium-106, iodine-131, caesium-137 and plutonium-239, each considered separately. In addition, the total intake of each radionuclide is given.

TABLE 18 Contributions of foods to total adult intake for deposition on 1 January as a function of nuclide

	Food					
	% contribution to annual intake in first year					
Nuclide	Milk	Grain	Green vegetables	Potatoes/ root vegetables	Lamb	Beef
^{90}Sr	38	6	50	2	3	1
^{106}Ru	–*	–*	88	–*	10	–*
^{131}I	–*	–*	72	–*	28	–*
^{137}Cs	13	–*	10	–*	67	10
^{239}Pu	–*	–*	99	–*	1	–*

* Contribution is negligible.

TABLE 19 Contributions of foods to total adult intake for deposition on 1 July as a function of nuclide

	Food					
	% contribution to annual intake in first year					
Nuclide	Milk	Grain	Green vegetables	Potatoes/ root vegetables	Lamb	Beef
^{90}Sr	57	22	17	1	1	2
^{106}Ru	–*	7	70	1	8	14
^{131}I	80	–*	8	4	3	5
^{137}Cs	20	50	1	5	8	16
^{239}Pu	–*	12	86	–*	1	1

* Contribution is negligible.

For deposition on 1 January, green vegetables dominate the intakes received for all radionuclides, other than for caesium-137 where lamb contributes the most. This reflects the assumptions made in FARMLAND on agricultural practices where both green vegetables and lamb are produced throughout the winter. For strontium-90 milk is also important, and for caesium-137 milk and beef also contribute to the intake. These results reflect the behaviour of the radionuclides in terms of their transfer to various foods.

For deposition on 1 July the pattern is significantly different and the importance of any individual food is not so marked as seen for deposition in the winter. For strontium-90 milk, grain and green vegetables are important, for caesium-137 milk, grain and beef are important, while for iodine-131 milk dominates the contributions to the total intake. If delays between production and consumption of milk were included the intakes from iodine-131 would be lower and hence less significant than seen in Table 19. For ruthenium-106 and plutonium-239 green vegetables are the most important with smaller contributions from grain and, for ruthenium-106, from lamb and beef.

These results show that the importance of individual foods and radionuclides following an accidental release of activity to atmosphere is largely dependent on the radionuclides released and the time of the year when the release occurs.

The total intake of each radionuclide reflects the relative importance of transfer of the radionuclide in the foodchain. In the first year following deposition on 1 July intakes from caesium-137 are the highest with intakes from ruthenium-106 and plutonium-239 approximately two orders of magnitude lower, given a unit deposition of each radionuclide. This reflects the mobility of the elements in the terrestrial environment. The intakes following deposition on 1 January are lower than those seen for 1 July, most significantly for caesium-137 and iodine-131, where the difference is an order of magnitude. This reflects the importance of translocation of material deposited on the plant surface to the edible crop when deposition occurs during the growing season in contributing to the activity concentrations in grain and root vegetables and the consumption of newly contaminated grass by cows in contributing to the activity concentrations in milk. For ruthenium-106 and plutonium-239 the intakes are very similar for deposition at both times of year, reflecting the relative immobility of these elements and the importance of green vegetables in contributing to the total intake at both times of the year.

7 Use of FARMLAND in uncertainty studies

It is important to estimate the uncertainty associated with the predictions made by a model such as FARMLAND. There are three principal sources of uncertainty which are referred to as modelling uncertainties, data uncertainties and 'completeness' uncertainties.

Modelling uncertainties have been reduced and quantified by verification and validation of the FARMLAND model. However, it has not been possible to validate all parts of FARMLAND owing to a lack of data. In these cases the models have been subjected to peer review to ensure that no important processes have been omitted.

The effects of data uncertainties can be quantified by carrying out an uncertainty analysis where the uncertainties in the assessment or model results are quantified following the assignment of realistic probability distributions to model input parameters and propagating these through the model to its output. The uncertainties on the activity concentrations predicted by FARMLAND have not yet been quantified explicitly. FARMLAND has been developed to provide best estimates of activity concentrations in food with a bias to conservatism where there is a lack of data and knowledge of parameter values is poor. It is expected that FARMLAND will predict activity concentrations in food to within a factor of five with a bias to overestimation. FARMLAND has, however, been used in such studies to determine the uncertainties in endpoints relating to ingestion doses and countermeasures placed on food in accident consequence assessments using the probabilistic risk assessment code, MARC[72,73]. In addition, the parameters whose uncertainty contributes most to the uncertainty in the endpoints considered were also identified. These studies are described in detail elsewhere[72,73].

The parameters whose uncertainty contribute significantly to the overall uncertainty in food-related endpoints in accident consequence assessments depend on the nature and size of the release and the countermeasures employed. In the earlier study[72] where a large reference accident for a pressurised water reactor in the UK was considered, the important parameters were identified as the concentration in flour in the first harvest following deposition, the root uptake concentration factor, the transfer of caesium to meat and the initial resuspension factor. In the later study[73] where smaller accidents were also considered, similar results were found and, in addition, uncertainty in the parameter values relating to animals' winter feeding were also found to be significant.

The study assessing the overall uncertainty of accident consequence assessments[73] suggests that the uncertainties on the parameters describing foodchain transfer do not make major contributions to the overall uncertainty. The uncertainty on risk coefficients, particularly for late health effects, is the most important contributor to the overall uncertainty in the assessment of risks from accidental releases.

8 Limitations of FARMLAND and future developments

FARMLAND is a generic model which has been developed for use in general assessments in the UK and has found wide application. The model is flexible and can be adapted to be more appropriate for specific applications as has been described in the text. The model has also been tested against data for specific sites in a number of validation studies to test its robustness for performing over a range of conditions (see Section 5). When used in its generic form there are some limitations to the model if it is used in certain situations and there are areas where future development has been identified to improve the model and to include a wider range of foods; these are outlined below.

FARMLAND uses the total deposition to ground as input into the system and there is no distinction between wet and dry deposited material. An interception factor for plants is used that is applicable for annual average conditions. For general assessment this approach is appropriate as discussed in Section 2.2.4.1. For typical rainfall events of a few millimetres of rain the approach adopted in FARMLAND agrees well with models that take wet and dry deposition into account separately[25]. However, for situations where there is very high rainfall FARMLAND tends to overestimate the interception on to plants by up to a factor of about two. For very low rainfall the model tends to underestimate interception on plants by up to a factor of five.

The model for soil migration in FARMLAND is element independent except for the inclusion of the fixation of caesium in soil as discussed in Section 2.2. A future development of FARMLAND is to include a model which takes into account element-dependent migration.

A fruit model has been developed for routine release applications[5]. This model is based on apples and is assumed relevant for other related fruits, such as pear and plums. For use for citrus fruits the appropriateness of the model parameter values needs to be reviewed. The model has been partially fitted to measurement data in fruit following periods of continuous deposition and it is not therefore necessarily adequate for use for accidental releases. In addition, the time dependence of transfer is not modelled. A future development of FARMLAND is to look at the applicability of this model for accidental release applications and to develop an appropriate model.

In FARMLAND all vegetables grown above ground are considered as one category, green vegetables. The data available for the model are biased towards brassica varieties such as cabbage and also lettuce. Legumes form a large part of the consumption of vegetables and in recent years more data have become available on the behaviour of radionuclides in these vegetables. Furthermore, the agricultural practices in the UK for legumes are different to other vegetables. Work is in progress to develop a separate module within FARMLAND to model the transfer of radionuclides to legume vegetables.

FARMLAND contains models for the grazing animals cattle and sheep. These animals are important in the transfer of activity to man because of the large surface areas of pasture from which they obtain food and the quantities of their products that are consumed. However, products derived from pigs and chickens are also important contributors to man's diet. The majority of pigs and chickens in the UK are reared indoors and are largely fed on processed and imported feeds whose type and origin vary. In addition, the rearing practices and the composition of the diet of pigs and chickens is subject to large regional variation. For general assessments FARMLAND does not include pigs and chickens, as it is assumed that only a very small part of their diet would be contaminated and hence the consumption of pork, chicken and eggs will not contribute significantly to ingestion doses. For specific situations where a significant fraction of the diet is locally derived or where animals are reared outdoors consideration should be given to these foods. Work is in progress at NRPB to look at the importance of including pigs and chickens for a variety of applications and types of assessment and a model consistent with the level of complexity required will be developed.

A personal computer (PC) version of the FARMLAND model is being developed. This will be included in a PC version of a code for assessing the radiological impact of routine releases to the atmospheric and aquatic environments.

9 Conclusions

The NRPB dynamic model for the transfer of radionuclides through terrestrial foodchains, FARMLAND, has been described. FARMLAND comprises a suite of models, each of which simulates radionuclide transfer through a different part of the foodchain. The models have been developed for generic use in the UK but their appropriateness for use in general assessment in the European Union has also been addressed and parameter values recommended where they differ from those used in the default FARMLAND model. FARMLAND may be used to asses the impact of deposition on to land from both accidental and routine releases of radionuclides to atmosphere.

FARMLAND has been used in a series of verification and validation studies to test its reliability and robustness in predicting activity concentrations in food over a range of conditions. The use of FARMLAND in model intercomparisons has given confidence in the implementation of the model as differences between models have been shown to be largely due to the choice of parameter values and assumptions about agricultural practice. The comparison of FARMLAND predictions with measurement data and especially post-Chernobyl measurements has strengthened confidence in the validity of the model for use in general radiological assessments, which is its intended use.

The report contains selected illustrative results of activity concentrations in food produced using FARMLAND. Additional results are presented elsewhere[7].

Areas of future development have been identified which include the addition of foods which could be of significance for specific applications. These extensions and improvements to the model will be published in due course.

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APPENDIX A

Estimation of Resuspension of Activity on to Plant Surfaces

The initial resuspension of a fresh deposit of radioactivity on to plants is governed by Garlands's time-dependent resuspension factor k(T) where

$$k(T) = \frac{1.2\ 10^{-6}}{T}$$

where T is the time after deposit (≥ 1 day) in days and k(T) is in m^{-1}.

This model was in good agreement with the measurements made following the Chernobyl nuclear accident. It is based on a series of wind tunnel experiments carried out by Garland[1-3] and has since been supported by further measurements carried out by Nicholson[4]. The time at which the relationship starts to become applicable is not clear, but for use in this study it is assumed that the maximum value of k(T) is $1.2\ 10^{-6}\ m^{-1}$ and that the relationship applies at times greater than 1 day.

To use this in FARMLAND a single mean resuspension factor is required, k_m. The value of k_m is chosen so that the integrated air concentration using k_m is equal to that using the time-dependent resuspension factor k(T).

Therefore, for a *single deposit* D on day 1

$$D \int_1^{t_1} k_m\, dt = D \int_1^{t_1} k(T)\, dT$$

$$Dk_m[t]_1^{t_1} = 1.2\ 10^{-6}\ D[\ln T\ ]_1^{t_1}$$

$$k_m = \frac{1.2\ 10^{-6}}{(t_1 - 1)} \ln t_1$$

For crops the time t_1 is the cropping life which is assumed to be 120 days for the crops considered in FARMLAND. Therefore

$$k_m = 1.2\ \frac{10^{-6}}{119} \ln 120 = 4.83\ 10^{-8}\ m^{-1}$$

For pasture the time, t_1, is the mean residence time in the surface layer of soil in the soil model for undisturbed land and is 3.5 years. Therefore

$$k_m = 1.2\ \frac{10^{-6}}{1277} \ln 1278 = 6.72\ 10^{-9}\ m^{-1}$$

For a *continuous deposition rate*, D, from day 1 to t_1 the mean resuspension factor, k_n, is given by

$$\int_1^{t_1} k_n DT\, dt = \int_1^{t_1} k(t)D\, dt = \int_1^{t_1 -1} k(t)D\, dt + \ldots + \int_1^{2} k(t)D\, dt$$

$$Dk_n\left[\frac{T^2}{2}\right]_1^{t_1} = D\ 1.2\ 10^{-6}[\ln T]_1^{t_1} + D\ 1.2\ 10^{-6}[\ln T]_1^{t_1 -1} + \ldots + D\ 1.2\ 10^{-6}[\ln T]_1^{2}$$

$$k_n\left(\frac{t_1^2}{2} - \frac{1}{2}\right) = 1.2\ 10^{-6}\ t = \sum_{t=1}^{t_1} \ln T$$

From this it can be calculated that:

for crops $t_1 = 120$ days $k_n = 7.63\ 10^{-8}\ m^{-1}$
for pasture $t_1 = 1278$ days $k_n = 1.12\ 10^{-8}\ m^{-1}$

The estimations of resuspension factors for use with crops and pasture grass for a single deposit and for continuous deposition are not the same, although they are numerically close. Given the uncertainties inherent in the whole approach, the use of different values for accident and continuous release applications cannot be justified. For crops the higher continuous release value of $8\ 10^{-8}\ m^{-1}$ has been chosen for use in FARMLAND for all applications. For pasture a value of $10^{-8}\ m^{-1}$ has been chosen from the two calculated values.

The relationship derived by Garland is appropriate for undisturbed surfaces in a rural environment in northern Europe. Values of resuspension factors have also been obtained in a semi-arid region in Southern Europe (Palomares)[5]. The observed time dependence is roughly in agreement with the Garland model and values are compatible with those based on fallout measurements. Therefore, the Garland model seems also to be applicable to the dryer conditions which are frequent in southern Europe. However, when using the Garland model in these conditions the predicted values should be considered as a rough estimate, due to the observed variability in time and space[6].

For the calculation of a rate constant from soil to plant surfaces for use in the foodchain model a deposition velocity is required. A deposition velocity of $10^{-3}\ m\ s^{-1}$ is used consistent with the deposition velocity for particulate material[6]. The rate constant for initial resuspension is given by

k_{12} = mean resuspension factor (m^{-1})
× deposition velocity ($m\ s^{-1}$)
× interception factor for crop/grass

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APPENDIX B

Development of Dynamic Models for Transfer of Strontium, Caesium and Iodine in Cattle and Sheep

This appendix summarises the development of compartmental models which represent the time dependence of the transfer of strontium, caesium and iodine isotopes from the intake by cattle and sheep to food products, such as milk and meat. Emphasis has been placed on describing the time dependence at short times after intake, particularly for milk, but long-term processes (such as the recycling of strontium in bone) have been incorporated where necessary. Consideration is also given to the applicability of these more complex models to different situations, by comparing their predictions with those of more simplistic models.

1 Approach adopted for model development

Particularly useful in developing models are those experiments where a radionuclide is administered to the animal, either orally or intravenously, and the transfer to its milk, meat and important body tissues and fluids is measured as a function of time. The experiments fall into two main types, single intake or chronic intake. Single intake experiments are those where an animal is fed a known quantity of activity, and then is maintained on uncontaminated feed. Chronic intake studies involve maintaining the animal on contaminated feed, usually of constant, known activity.

The values for the equilibrium inventories of tissues and animal products following chronic intake of radioisotopes are also important parameters for developing the models. The transfer factors to meat and to milk are especially important, and are defined as the concentration of an isotope at equilibrium in Bq kg^{-1} (for meat) or Bq l^{-1} (for milk) following a chronic intake of 1 Bq d^{-1} by the animal. These parameters are commonly given the symbols F_f and F_m for the transfer to meat and milk of the stable isotope, and have units of d kg^{-1} and d l^{-1}, respectively. Values for these parameters can be estimated directly from experiments involving the chronic intake of an isotope whose physical halflife is long compared with the time it takes for equilibrium to be reached, or indirectly from experiments involving the single intake of an isotope.

Milk, meat and offal are animal food products that are important contributors to the radiation dose to man from ingestion. All models must be able to predict the concentrations of radionuclides in these products accurately. However, it is unnecessary for the model to simulate accurately the concentrations in other parts of the animal, eg blood, urine, faeces and bone, as these tissues and fluids are of no direct radiological significance. Therefore, these organs are only modelled to the extent necessary to predict accurately the transfer of radionuclides to meat, offal and milk. Data for young animals have been discounted to a certain extent. To model the metabolism of young animals it would be necessary to have rate constants and tissue masses that vary with age. It has been decided that the added complexity is not worthwhile for the purposes of radiological protection.

2 Data used for model development

The data used in the development of the models for cattle and sheep are summarised below.

2.1 Cattle

Data describing the time dependence of the transfer of strontium, caesium and iodine to milk are well reported in the literature[1-7]. From a review of the experimental data the curves of concentration in milk as a function of time after a single oral intake predicted by Lengemann *et al*[1] were based on the largest sample of animals, and probably have the least uncertainty associated with them. These data therefore formed the basis for the model described here.

Estimates of the F_m values for strontium, caesium and iodine can be made from these curves by calculating their time integrals. F_m values may also be derived from the results of other experiments, and reviews of such values have been published by Ng *et al*[8-10]. Their best estimate and ranges for the values of F_m for strontium, caesium and iodine are presented in Table B1, and these data can be compared with those derived purely from integrating the results of Lengemann *et al*[1], shown in Table B2.

TABLE B1 Best estimates and ranges of the values for animal product transfer factors[a]

Element	Milk transfer factors, F_m (d l^{-1})	Beef transfer factors, F_f (d kg^{-1})
Strontium	$1.4\ 10^{-3}$ ($4.5\ 10^{-4}$ to $3.8\ 10^{-3}$)	$3.0\ 10^{-4}$ ($6.4\ 10^{-5}$ to $5.7\ 10^{-4}$)
Caesium	$7.1\ 10^{-3}$ ($2.5\ 10^{-3}$ to $1.6\ 10^{-2}$)	$2.6\ 10^{-2}$
Iodine	$9.9\ 10^{-3}$ ($2.7\ 10^{-3}$ to $3.5\ 10^{-2}$)	$3.6\ 10^{-3}$ [b]

Notes
(a) Taken from references 8–10.
(b) This is the value for iodine-131 and so includes radioactive decay; the value for stable iodine would be higher.

TABLE B2 Comparison of the integral of the Lengemann *et al* single dose curve with the Ng *et al* best estimate for the milk transfer factor, F_m

	Milk transfer factors, F_m (d l^{-1})	
Element	Ng *et al* best estimate[a]	Integral of Lengemann *et al* single dose curve[b]
Strontium	$1.4\ 10^{-3}$	$7.4\ 10^{-4}$
Caesium	$7.1\ 10^{-3}$	$1.8\ 10^{-2}$
Iodine	$9.9\ 10^{-3}$	$1.2\ 10^{-2}$

Notes
(a) Taken from references 8–10.
(b) Taken from reference 1.

The value for strontium derived from the Lengemann *et al* curve is about one-half that of the Ng *et al* best estimate. Indeed, Ng *et al* note that values for strontium of F_m derived from single intake data are about one-half of those derived from equilibrium values during continuous intake. The explanation is probably that there is a small, but long-term, component to the single intake curves which is not easily measurable in single intake experiments such as that of Lengemann *et al*. It is likely that this long-term component is due to the retention of strontium in the skeleton of the cow. The data used in the development of the model for strontium are therefore from the Lengemann *et al* single intake curve integrated to about 50 days after intake and the Ng *et al* value of F_m at long times.

For caesium, the Ng *et al* best estimate of F_m is approximately 0.4 of the integral of the single intake curve of Lengemann *et al*, which is reported to represent 100% absorption of the radiocaesium by the animal. There is evidence that caesium when found in the environment is fixed to soil particles, etc, and is then in a form that may not be readily available for uptake to the cow. Lengemann *et al* mention this and state that the shape of the milk concentration versus time curve following single intake is independent of the form in which the caesium is fed. This suggests that for the purposes of developing a model it is not unreasonable to normalise the Lengemann *et al* curve to the Ng *et al* value for F_m in order to represent the transfer of 'environmental' caesium to milk.

The difference between the Ng *et al* best estimate of F_m for iodine and the F_m derived from the Lengemann *et al* curve is less than 20%. For the purposes of model development the Lengemann *et al* curve was again normalised to the Ng *et al* best estimate of F_m for iodine.

The data for time-dependent transfer to meat and offal derived from the cow are much fewer than the data for milk. Experimental measurement of the time dependence of the activity concentrations in animal tissue would involve slaughtering many animals, a costly procedure. Some experiments have been performed with caesium-137 where the whole body retention of the nuclide is measured *in vivo*. This gives some information on the likely time distribution of activity in the soft tissues, but it is difficult to correlate this with an absolute value for the concentration in meat and offal. The few measurements available on the transfer to meat as a function of time are insufficient to support any rigorous data-fitting procedures in model development; they may be used, however, to compare the predictions of the developed model.

Data do exist, however, on the equilibrium transfer factors to meat, F_f, which are of better quality than the data on time-dependent transfer to meat. Ng *et al* have reviewed the experimental data for F_f and their best estimates and ranges for its value for strontium, caesium and iodine are presented in Table B1[9]. In the model, values of F_f for adult animals have been used as milk and most meat is from these animals. The evidence shows that the metabolism of young animals may be significantly different to that of adult cattle. Modelling the metabolism of young animals requires transfer rates and tissue masses which vary with age. The added model complexity is not considered worthwhile for radiological protection purposes and so the selected F_f values have been based on adult animals.

In summary, the final data to be employed for model development are the Lengemann *et al* curves for time-dependent transfer to milk, normalised where appropriate, together with the F_m and F_f values derived by Ng *et al*, and these data are presented in Tables B1 and B2.

2.2 Sheep

The available data on the time dependence of the activity concentrations of strontium, caesium and iodine in sheep meat are sparse. However, although these data are insufficient to develop a detailed metabolic process model they are adequate for developing a model for radiological protection purposes where modelling on a detailed process level is not required. The data reviewed and those chosen for model development are identified below.

The majority of the strontium taken into the sheep accumulates in the skeleton and this appears to be independent of the method of administration of the radioisotope. The content of strontium in the skeleton a few months after the start of repeated administration is, in general, between 300 and 1000 times higher than that in muscle tissue[11], although this does vary with the age of the sheep at the time of administration. Following a review of the literature, measurements of concentration of strontium in bone and meat as a function of time from an experiment where adult ewes were fed orally over 845 days were used for model development[11].

Data from several continuous feeding experiments are available[12-14] for caesium and additional information on an experiment where retention in the body of sheep was measured for 30 days after injecting caesium-137 intravenously[15]. Following a review of these data the results of two of the experiments, where caesium was measured in muscle over a period of 105 days continuous intake[12] and where the retention in muscle over a 30 day period following a single oral intake was measured[15], were chosen for model development.

Few data are available on the transfer of iodine to muscle and soft tissues, and the consequent concentrations in these tissues[16,17]. Data obtained by Daburon[16] are available on the retention in soft tissues, thyroid and blood after a single oral intake of iodine-131 to adult sheep and have been used for the model development. The data on the retention in the thyroid can be used in modelling the metabolic processes involved in the transfer of radioiodine to muscle.

3 Model development

In developing a model for radiological protection and applications, it is unnecessary to include all physical, chemical and biological processes, and the degree of complexity should be consistent with the desired applications and with the data available.

The metabolism of cows and sheep can be represented by three physiological mechanisms, namely: the absorption of the nuclide into the bloodstream and body fluids from the gastrointestinal tract, the distribution and recycling of the nuclide between the circulating fluids and the body organs and tissues, and the excretion of the nuclide from the body including the secretion into milk.

3.1 Gastrointestinal absorption

Ingested substances are absorbed into the body from the gastrointestinal tract. The tract varies in its complexity between different species, and in ruminants (such as cows, goats and sheep) the stomach is complex and consists of four compartments, which hold collectively a large volume of matter compared with the rest of the gastrointestinal tract. Based on a review of the literature 23 hours was used as the retention half-time in the stomach for cows and sheep in developing the models[18-20]. The rest of the gastrointestinal tract is of much narrower radius and mixing is not well achieved along its length. Retention half-times in the small intestine of 4.8 hours and 4 hours are used in the models for cows and sheep, respectively[18-20].

The location of the site of absorption and the extent of absorption varies between elements, and their chemical form. A general idea of the site of absorption can be gained from observations of the peak concentrations in blood following ingestion. There is a lag of at least 20 hours in the peak concentration in blood of both strontium and caesium; this implies that these elements are primarily absorbed from the lower part of the gastrointestinal tract, probably from the small intestine, and the absorption from the rumen is negligible. Radioiodine, however, shows a peak in concentration within a few hours of intake, indicating absorption from the upper part of the digestive tract[21]. Experiments comparing the relative concentration of radioiodine with other nuclides that are not absorbed in the cattle gastrointestinal tract, have confirmed that the rumen, as well as the small intestine, is a major site of absorption of iodine[22]. Whereas, in general, only a fraction of the strontium and caesium intake is absorbed into the body, iodine is almost completely absorbed from the gastrointestinal tract. Complete absorption of radioiodine is suggested by the observation that the levels of iodine in cows' milk were similar after an oral intake and an intravenous injection of the same activity. Best estimates of the fraction of each element absorbed across the gut have been chosen from the literature and are given in Table B3.

TABLE B3 Parameters for the model of the cattle and sheep gastrointestinal tracts

	Cattle		Sheep	
Nuclide-independent	Value (hours)	Range (hours)	Value (hours)	Range (hours)
Mean residence time in stomach	33	28–40	24	19–26
Mean residence time in intestine	4.8	2–10	–	–
Nuclide-dependent	f_1 (fraction of total intake absorbed by the gastrointestinal tract)			
Element	Value	Range	Value	Range
Iodine	0.98	0.85–1.00	0.87	0.60–1.00
Strontium	0.10	0.05–0.30	0.22	0.05–0.30
Caesium	0.40*	0.20–1.00	0.79	0.50–0.80

*This value was changed to 0.70 by the data-fitting procedure, in order to best fit the equilibrium transfer to meat for caesium.

3.2 Distribution and recycling of the nuclides between the circulating fluids and the body organs and tissues

Nuclides absorbed from the gastrointestinal tract enter the general circulation by the lymph and the blood, and are rapidly mixed. The circulating fluids permeate the animal's body and the nuclides diffuse into the tissues. In addition, some nuclides are preferentially taken up by specific organs and are metabolised differently owing to their particular chemical nature.

It is important in building a model to represent the important organs of storage in the body and also the mass of soft tissues into which nuclides diffuse from the general circulation. Following a review of the literature the important metabolic processes for each element have been taken into account in the development of the models.

Strontium, being an alkaline earth element, behaves in a similar manner to calcium, and is stored therefore in bones, teeth and other calcified tissues. It is also found in the circulating fluids and soft tissues, but only in relatively small amounts. After ingestion and absorption radiostrontium is deposited in both the bone surface and bone volume. An exchange with calcium on the surface of bone crystals occurs rapidly and this fraction reflects the strontium content in the circulating fluids, milk and soft tissues. Radiostrontium is also incorporated into new bone being formed. Such deposits may persist for a long time in the main volume of the bone and therefore tend to reflect the levels of strontium in the past. Caesium is an alkaline metal and behaves in a similar manner to potassium in the body. Apart from the rapid diffusion of the element into the soft tissues from the circulating fluids, there is also a considerable concentrating mechanism of caesium in the cells of the body[1]. The thyroid is the organ of importance for iodine within the body of the animal, its function being the production of iodine-containing hormones. The amount of radioiodine taken up by the thyroid depends on dietary iodine levels and physiological changes produced by factors such as lactation and seasonal temperatures[23]. Iodine is converted in the thyroid to an organic form which is then distributed among the organs and tissues of the body other than the thyroid. It remains in this form for some time before being broken down into inorganic iodine[24].

For the purposes of developing the model, experimental data[5,16] were used to determine the time dependence of iodine transfer within the thyroid.

3.3 Elimination from the body

It is unnecessary to model the activity concentrations of radionuclides in urine or faeces as a function of time, as the model is concerned only with the amount transferred to, and retained in, edible tissues. However, the rate of excretion is important in that the loss from circulating body fluids affects the amount of activity transferred to the meat. The other major elimination of activity from the body is via the secretion to milk. It is, obviously, necessary to model this transfer in cattle but for sheep the model can be simplified to exclude this transfer if sheep's milk and sheep's milk products are not of concern.

3.4 Model structure

Representations of the proposed compartment models to simulate the transfer of strontium, caesium and iodine for cows and sheep are presented in Figures B1, B2 and B3, respectively, and the main features are described below.

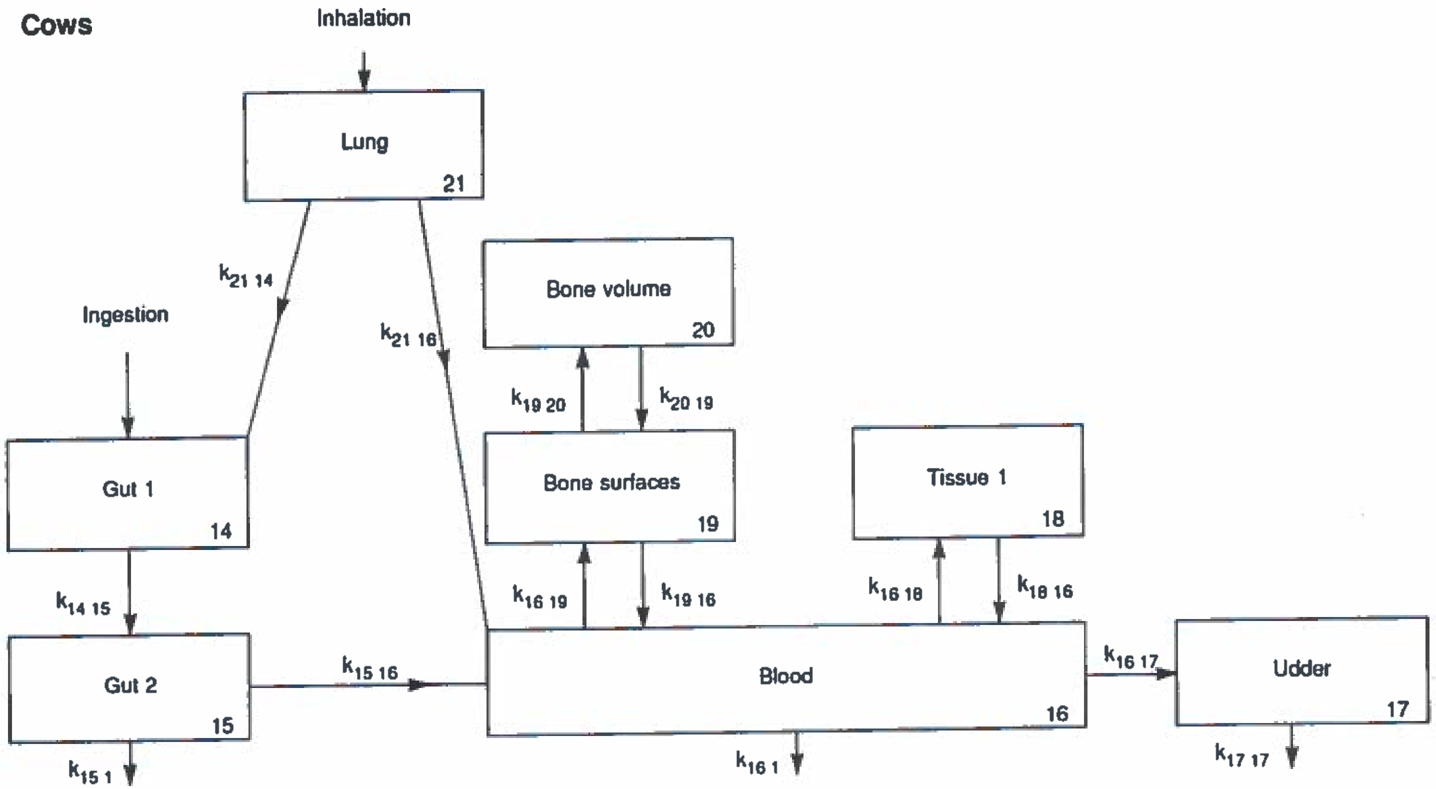
3.4.1 Cows

The stomach and intestine compartments, which represent the gastrointestinal tract, are common to all three models. Absorption takes place from the intestine into the circulating fluids of the animal; however, in the iodine model an extra transfer is allowed between the stomach and the circulating fluids to account for the rapid absorption of this element. The transfer to milk is similarly modelled for each element. In each case there is a transfer from the circulating fluids into milk with a slight delay in an udder compartment. As iodine in milk is derived from the inorganic iodine fraction of the blood, the circulating fluids compartment in the iodine model represents only the inorganic fraction.

The strontium metabolism model has two compartments that represent 'bone surface' and 'bone volume' (Figure B1). The former accounts for the rapid exchange between strontium in the circulating fluids and the calcium on the surface of the bone crystals; the latter represents the longer-term retention of strontium in the volume of the bone. In addition, the 'soft tissues' compartment represents the rest of the body and at equilibrium would have a concentration corresponding to the F_f value in Table B1.

(text continues on page 66)

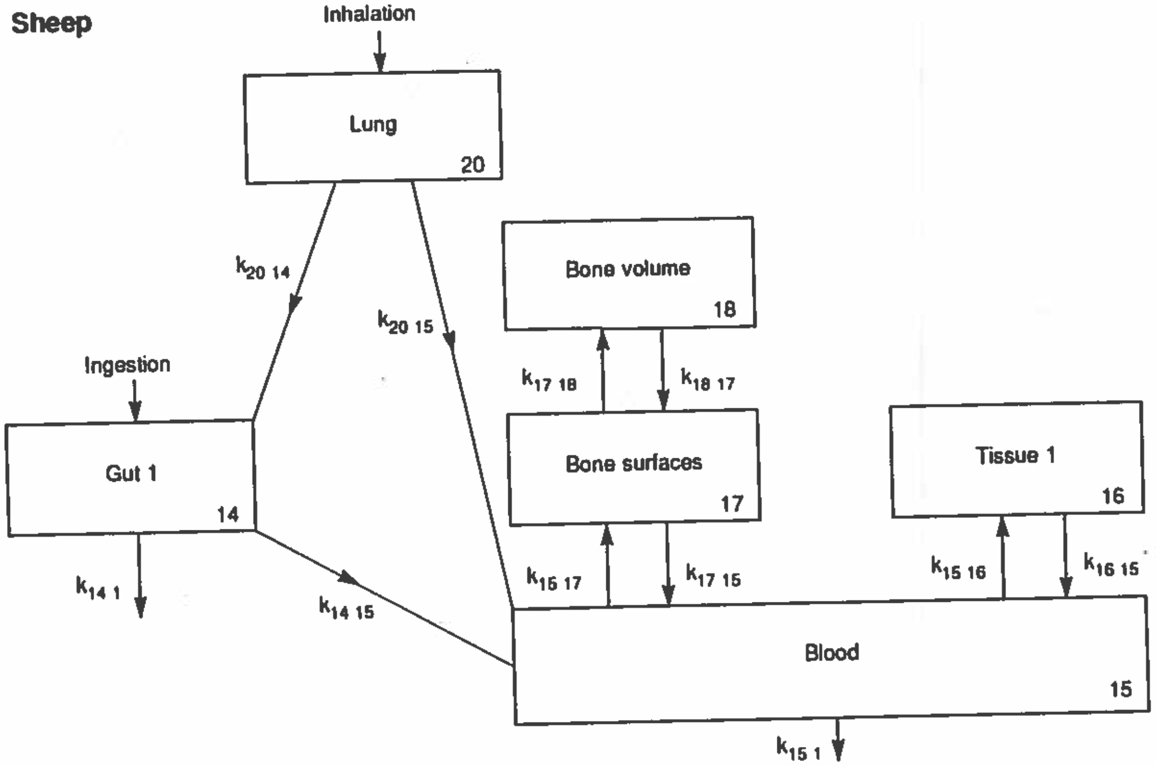
Cows



Notes

(a) $k_{16\ 1}$ and $k_{15\ 1}$ represent return to the soil (compartment 1) due to excretion processes.
(b) There is an additional loss from all compartments to represent the periodic slaughter of cows; the value of this rate constant is 4.56 10^{-4} d^{-1}.
(c) Compartment 18 (tissue 1) represents the rest of the body that is not modelled explicitly.

Sheep



Notes

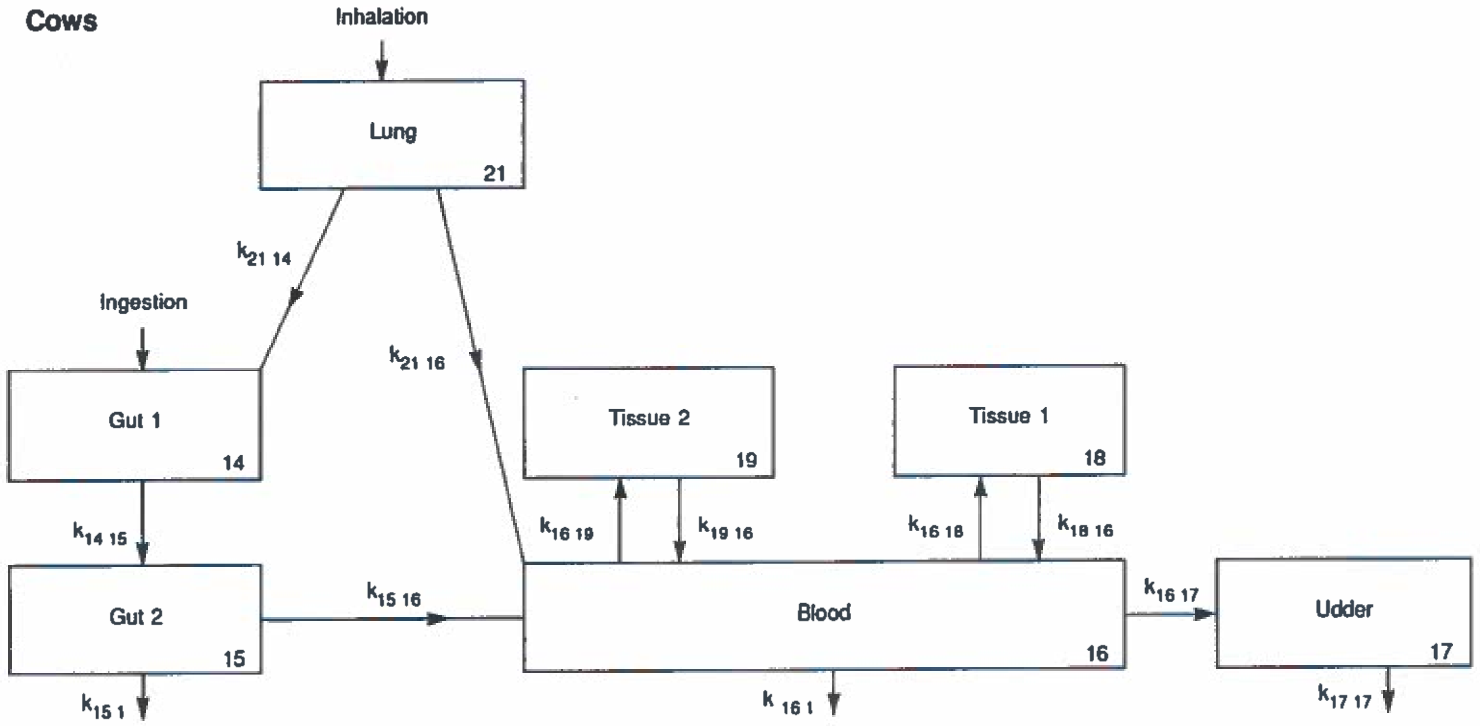
(a) $k_{14\ 1}$ and $k_{15\ 1}$ represent return to the soil (compartment 1) due to excretion processes.

(b) There is an additional loss from all compartments to represent the periodic slaughter of sheep; the value of this rate constant is 2.74 10^{-3} d^{-1}.

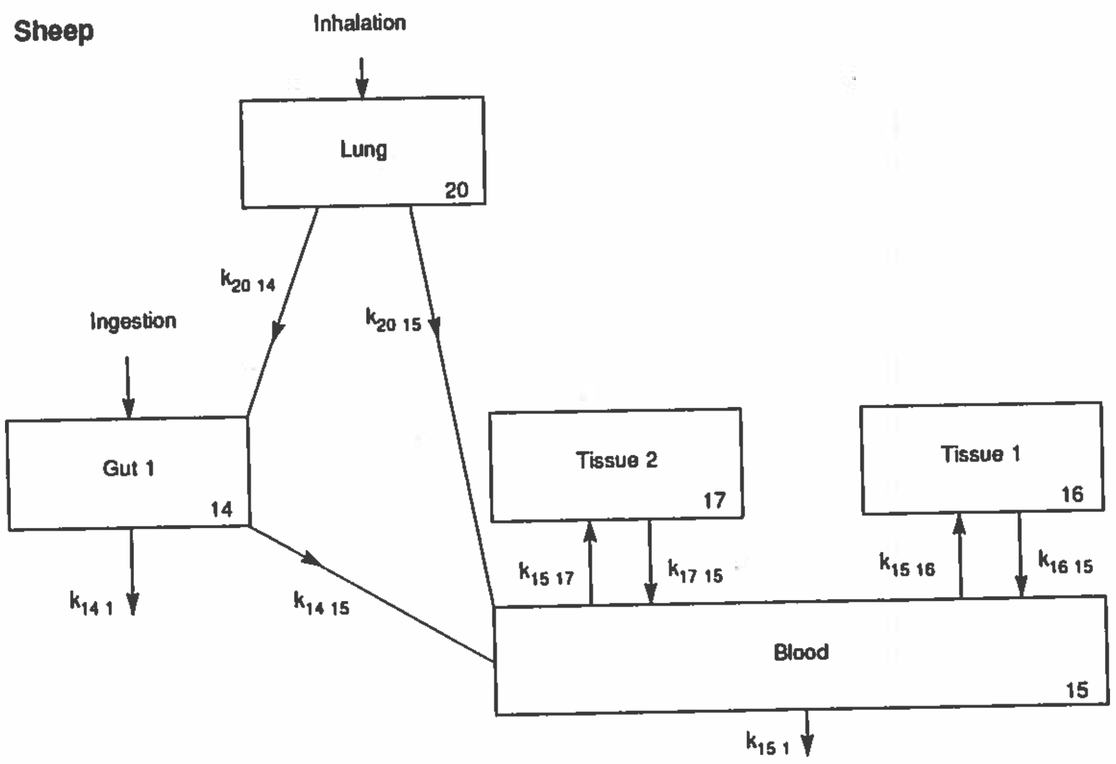
(c) Compartment 16 (tissue 1) represents the rest of the body that is not modelled explicitly.

FIGURE B1 Model structure for isotopes of strontium

Cows



Notes
(a) Tissue 1 (compartment 18) represents the diffusion of caesium from the blood to the rest of the body.
(b) Tissue 2 represents a slower concentrating mechanism of caesium in the soft tissues.
(c) Periodic slaughter is represented by losses from all compartments, the value of the rate constant is $4.56\ 10^{-4}\ d^{-1}$.



Notes

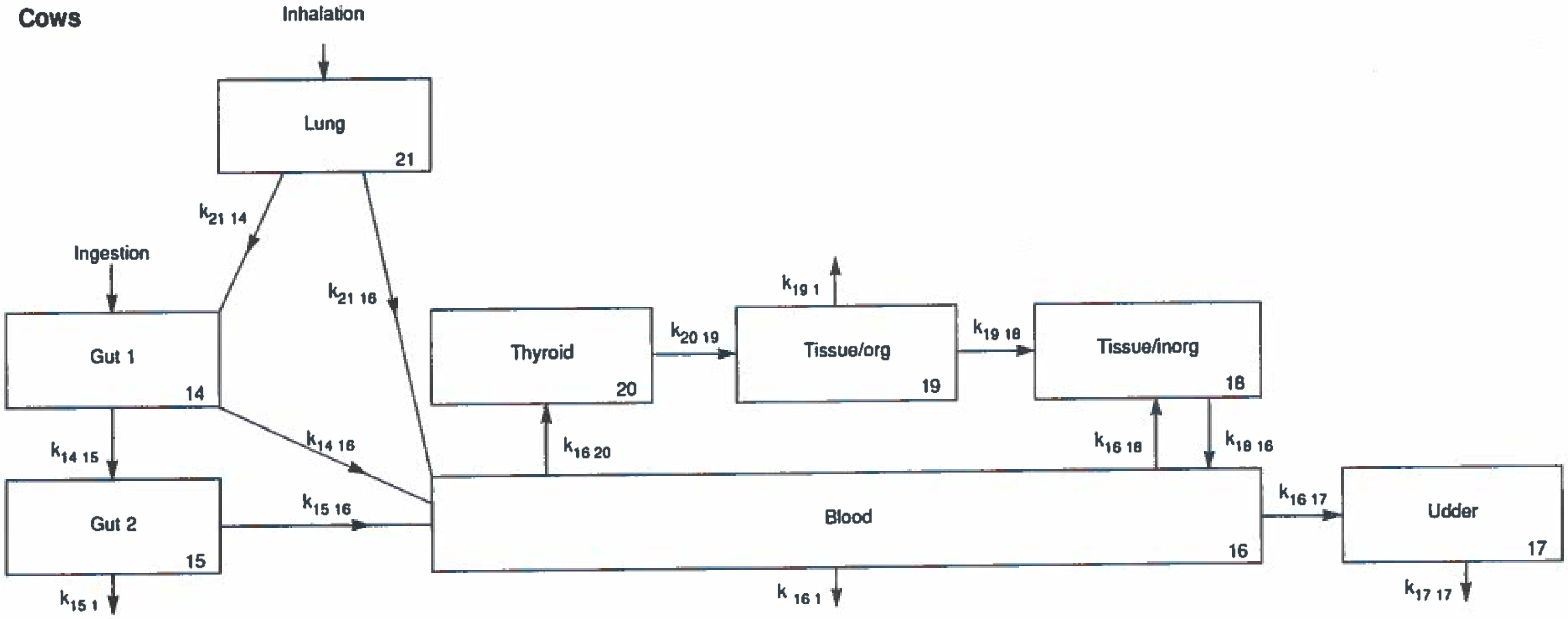
(a) Tissue 1 (compartment 16) represents the diffusion of caesium from the blood to the rest of the body.

(b) Tissue 2 represents a slower concentrating mechanism of caesium in the soft tissues.

(c) Periodic slaughter is represented by losses from all compartments, the value of the rate constant is $2.74\ 10^{-3}\ d^{-1}$.

FIGURE B2 Model structure for isotopes of caesium

Cows



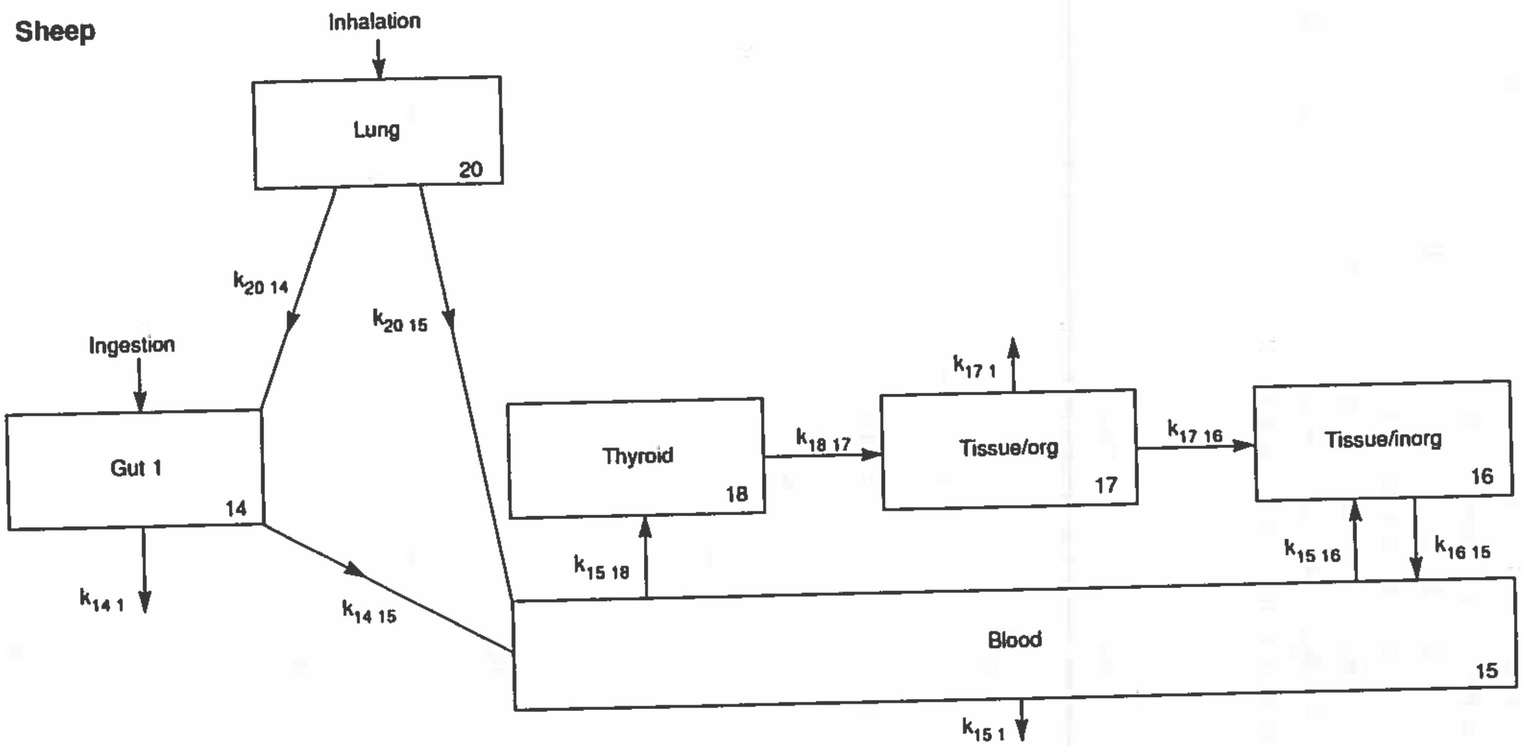
Notes

(a) $k_{14\,16}$ represents the early absorption of iodine from the rumen of the cow.

(b) The storage of iodine in the soft tissues is represented by two compartments (18 and 19). The organic iodine produced in the thyroid is re-distributed throughout the soft tissues and organs of the body where it remains for some time before being broken down into inorganic iodine.

(c) $k_{19\,1}$ represents the excretion of the organic fraction of iodine in the circulating fluids.

(d) Periodic slaughter is represented by losses from all compartments, the value of the rate constant is $4.56\ 10^{-4}\ d^{-1}$.



Notes

(a) The storage of iodine in the soft tissues is represented by two compartments (16 and 17). The organic iodine produced in the thyroid is re-distributed throughout the soft tissues and organs of the body where it remains for some time before being broken down into inorganic iodine.

(b) $k_{17\,1}$ represents the excretion of the organic fraction of iodine in the circulating fluids.

(c) Periodic slaughter is represented by losses from all compartments, the value of the rate constant is 2.74 10^{-3} d^{-1}.

FIGURE B3 Model structure for Isotopes of Iodine

The model chosen to represent the metabolism of caesium has two compartments representing soft tissues (Figure B2). The first is similar to the soft tissue compartment in the strontium model in that it simulates the diffusion of the nuclide into the rest of the body. The second compartment represents the slower concentrating mechanism mentioned in Section 3.2 above. The retention halflife of this compartment needed to fit the data is close to 32 days[7,11,25,26].

As a consequence of the different storage properties of inorganic and organic forms of iodine in soft tissue, two compartments are chosen to represent them. The structure of the model is of the form given in Figure B3, and shows the diffusion of inorganic iodine into tissues as well as conversion to the organic form via a compartment representing the thyroid gland. A loss term is allowed from the organic soft tissue compartment to represent excretion of organic iodine from the animal, without it being converted back to the inorganic form and available for transfer into milk.

3.4.2 Sheep

The models for sheep are similar in structure to those developed for cattle; however, there are two notable differences. In the UK, sheep's milk is not produced on a commercial scale, nor is it used on a large scale to manufacture other dairy products. For most radiological protection purposes, therefore, it is unnecessary to include the milk produced by sheep, and in developing the sheep model the loss from the general circulation by secretion into milk has not been distinguished from the loss by excretion from the circulating fluids. The second difference lies in the complexity in which the gastrointestinal tract is modelled. For sheep, the gastrointestinal tract has been simplified to one compartment, as the transfer to sheep's milk is not being considered. The delay before strontium and caesium are absorbed in the gastrointestinal tract is therefore not explicitly modelled, and the uptake of these elements at short times may be slightly overestimated. This overestimation is, however, negligible when the uncertainty from other sources is considered.

3.5 Derivation of transfer coefficients

The rate constants (k_{12}, k_{35}, etc) shown in Figures B1–B3 represent the fraction of the inventory of the compartment from which they originate that is transferred between compartments in unit time. In addition to these rate constants, radioactive decay for different isotopes may be represented by a loss term from each compartment, corresponding to the radioactive decay rate.

Methods for deriving estimates of the rate constants from the basic data have been discussed in a previous report[27]. However, it is usually not possible to determine explicitly all the rate constants. In order to estimate values for the 'unknown' parameters a data-fitting technique is employed. Initial estimates of the 'unknown' rate constants were made, and the model was run to predict the inventories in each of the compartments as a function of time after a single oral intake. The predictions were compared with experimental data on the time dependence of activity concentration in milk, meat and bone (and for iodine, in the thyroid) depending on the available data as described above; the 'unknown' parameters were varied in such a way as to improve the fit to these data and the procedure was repeated until the best fit to the data was achieved. Restrictions were placed – the equilibrium transfers to meat and milk must be predicted correctly and the values chosen for the 'unknown' rate constants must not be unreasonable.

4 Comparison of model predictions with experimental results

The structure of the three models for the transfer of strontium, caesium and iodine in cattle was chosen from considerations of the metabolic behaviour of the respective elements. Predictions of the concentration of the nuclides in milk and meat were fitted to the experimental data described in Section 2. For the cow model the equilibrium transfers to meat, F_f, and to milk, F_m, that are given in Table B1 were also used in the fitting process.

However, there are additional data available that can be used to validate the models developed in the sections above. These data include information on the concentration of the elements in meat and other organs at a few times following a single oral intake. Some examples of the performance of the models against these data are described here.

4.1 Cow models

The cow models were compared with experimental data from a number of experiments, many of which were individual measurements. These included: measurements of strontium in meat, bone and offal following single oral administration[6], concentrations of caesium in milk following a single oral intake[7,28,29], concentrations of iodine in meat and offal following

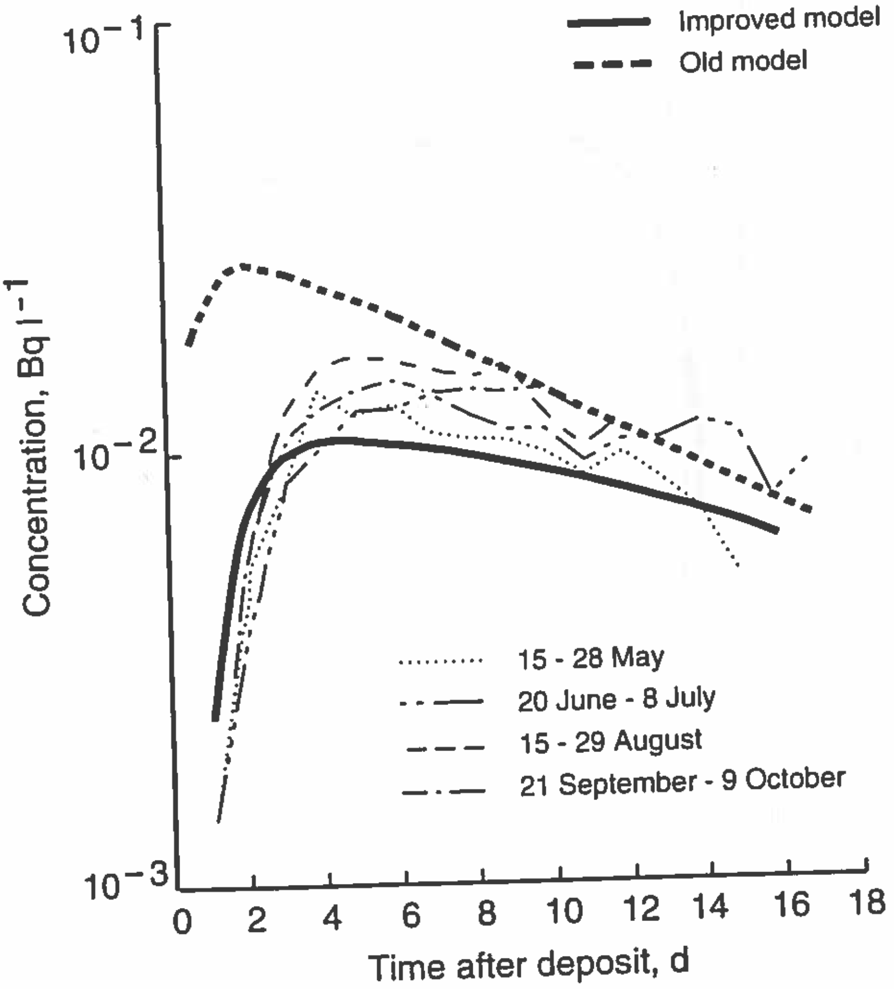


FIGURE B4 Concentration of strontium-85 in milk following a deposit of 1 Bq m^{-2} on pasture single oral intakes[23], and concentrations of iodine in milk, thyroid and whole body following repeated oral administration[23]. In general, the agreement between the model and the experimental data was reasonable given the uncertainties associated with the data and the variability seen between measurements.

An additional set of data was available which reflected a more realistic situation against which to test the performance of the models. These measurements were for a single deposit on to pasture and the subsequent transfer to milk via the grazing animal. Van den Hoek *et al*[30] published data on the measured strontium-85 and caesium-137 concentrations in the milk of herds of cows grazing on pasture after an initial contamination. The transfer as a function of the grazing regime and time of year was investigated. Two versions of the NRPB foodchain model have been used to predict the concentrations in milk following a single deposit on pasture for comparison with the experimental data. The first model[31] comprises the FARMLAND pasture module and a previous, simpler animal module; the second model uses the same pasture model but the strontium metabolism module discussed here. The predictions of the two models with the measured concentrations are presented in Figures B4 and B5 for strontium and caesium, respectively. For strontium, the previous model overestimated the concentration in milk, in general, and the peak concentration was calculated to occur earlier than the data suggest. This may be due to the very quick transfer from the

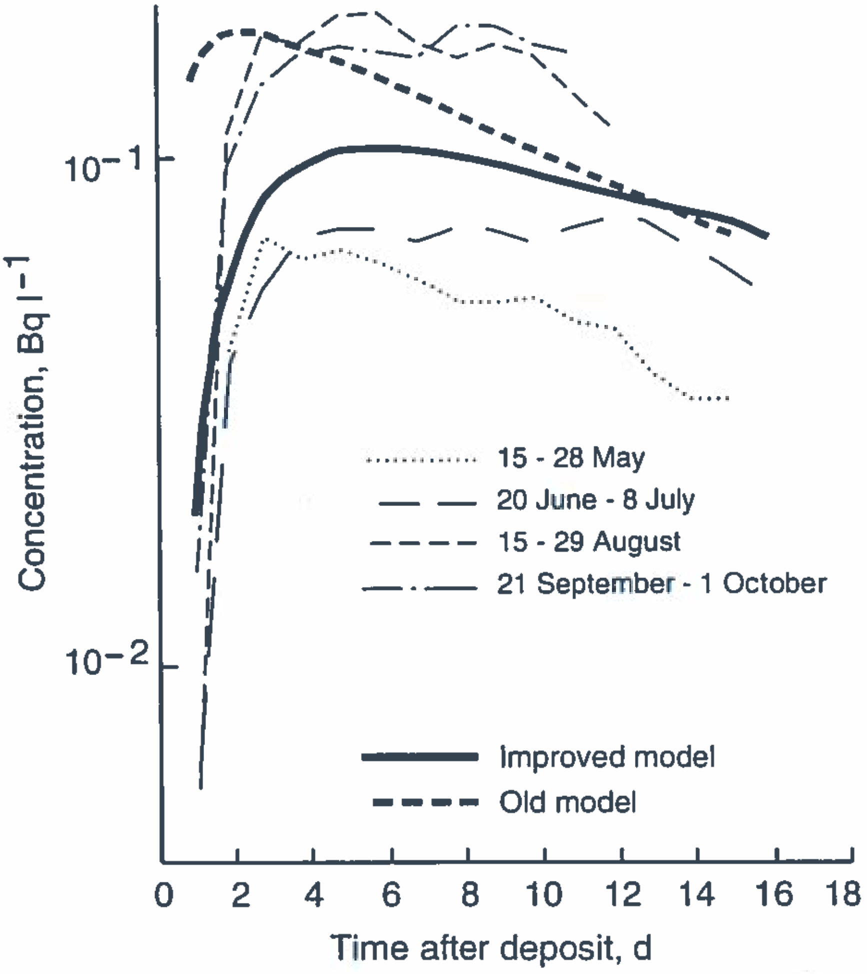


FIGURE B5 **Concentration of caesium-134 in milk following a deposit of 1 Bq m^{-2} on pasture**

gastrointestinal tract to milk assumed in this model. The prediction of the new model is considerably better; although the new model underestimates slightly the peak concentration, the predicted occurrence of the peak is close to that seen in the measurements. These data validate the use of the newer model for short times after a deposit. For caesium, the previous model peaks higher and earlier than the improved model. The improved model is in better accord with the experimental data of Van den Hoek *et al*[30].

4.2 Sheep models

Model predictions of the equilibrium transfer factor to meat, F_f, have been made by evaluating the equilibrium concentration in meat following a simulated, continuous oral intake of activity. The values predicted for F_f are presented in Table B4, together with the average values derived by Ng *et al*[9] from the literature for sheep of approximately 6 months. F_f values were not used in the development of the model other than to check that following the fitting of the model to experimental data the predicted F_f values were in reasonable agreement with those in the literature.

TABLE B4 Equilibrium transfer factors to sheep meat: a comparison between the model and literature

	Equilibrium transfer factors (d kg^{-1})		
	Element		
	Strontium	Caesium	Iodine
Model	1.6 10^{-3}	1.9 10^{-1}	2.5 10^{-1}
Ng *et al*[a]	2.2 10^{-3}	2.9 10^{-1}	3.0 10^{-2} [b]
	Range (1.1 10^{-3} to 3.7 10^{-3})	(7.8 10^{-2} to 5.0 10^{-1})	–

Notes

(a) Taken from reference 9.

(b) This is the value for iodine-131 and so includes radioactive decay; the value for stable iodine would be higher.

The F_f values predicted by the models compare favourably with the values from Ng *et al* for strontium and caesium. For iodine, however, there was a large difference between the predicted value and that obtained by Ng *et al*. On closer inspection of the data and the experimental data used in the model development it was concluded that the discrepancy was due to the value given by Ng *et al* not being decay corrected for iodine-131.

Other data used to give support to the model predictions include results from experiments where concentrations have been measured in the liver, kidney and soft tissues other than meat, following intakes of activity[11-13]. These data were not sufficiently complete to use in the development of the model. In general, the model predictions were in reasonable agreement with the experimental data given the uncertainties associated with the data. The model for strontium was compared against some data on retention in meat and bone following a single intake in contrast to the data used for development which were for a continuous intake[11]. For the two sets of data the model prediction for bone agrees reasonably well at all times, although the prediction and data do diverge slightly after 100 days. The model prediction for transfer of strontium to meat is in excellent agreement for the first 30 days after intake, but at longer times a difference of a factor of 10 becomes apparent. The reasons for this are not clear, but factors such as age at intake or diet may, in part, explain the discrepancy.

5 Comparison between the predictions of the previous NRPB model and the improved metabolic models

A comparison has been made of the results of the previous NRPB models for cows and sheep[31] and the improved metabolic models for four relevant nuclides and for four different situations of contamination. The nuclides considered are strontium-89, strontium-90, iodine-131 and caesium-137, with radioactive halflives of 50.5 days, 28.5 years, 8.04 days and 30.1 years, respectively. These radionuclides have been shown to be of particular importance in radiological protection applications.

Figures B6 and B7 show the concentration in milk and meat, respectively, of these nuclides in cows following a single oral intake. The diagrams show clearly the difference between the two models in predicting the time dependence of transfer to milk, particularly for strontium. For meat the difference between the two sets of models is not so great, but two points are of interest. Firstly, for strontium-90 the effect of including recycling of the nuclide from bone at about 100 days is

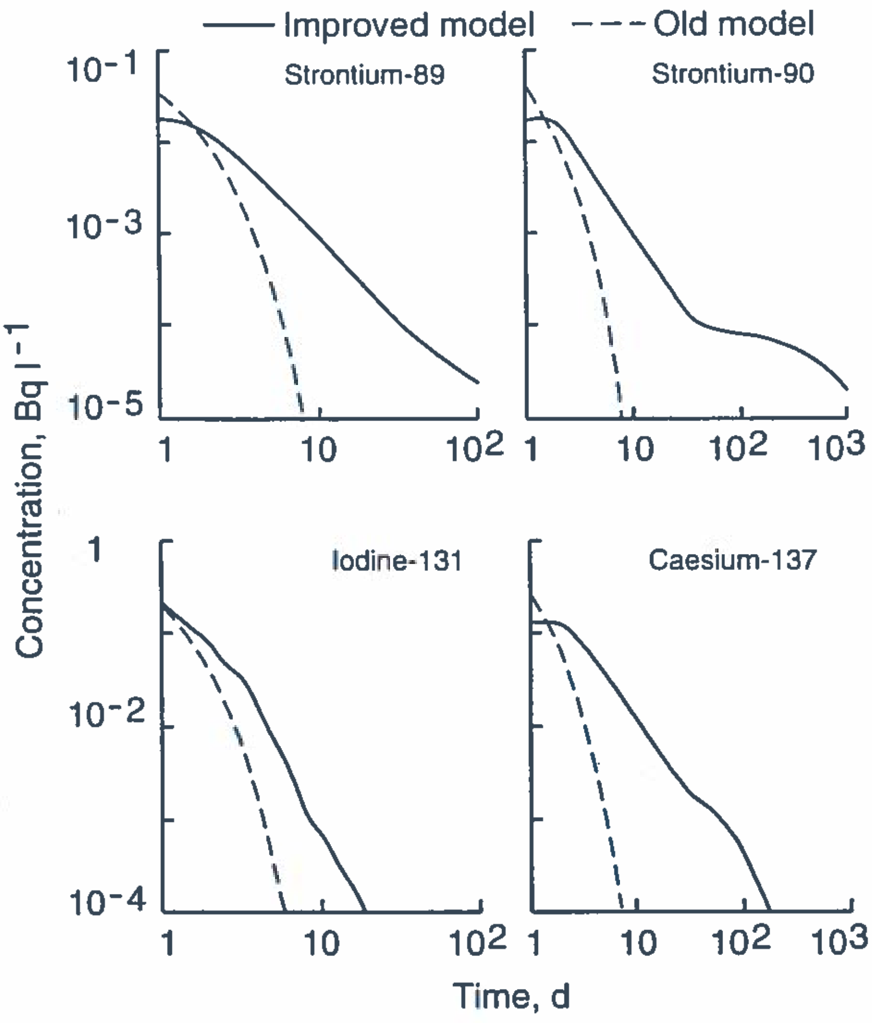


FIGURE B6 Concentration in milk after a single oral intake

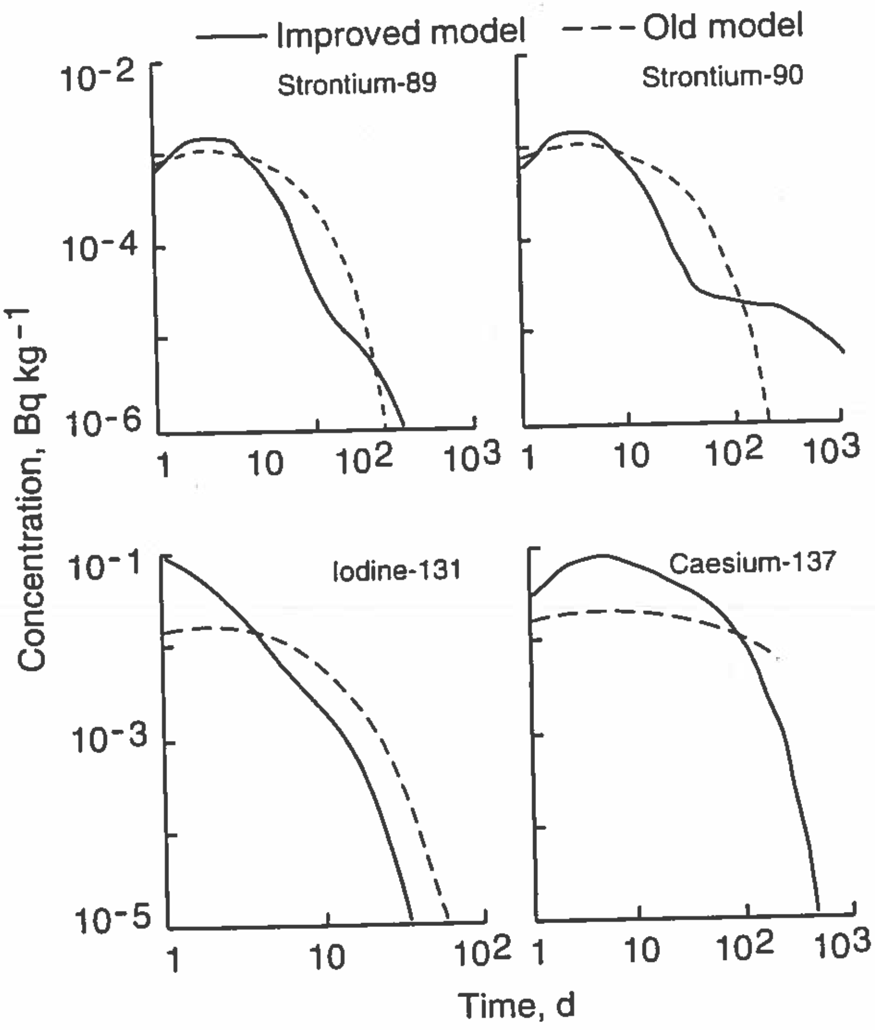


FIGURE B7 Concentration in meat after a single oral intake

apparent and, secondly, for iodine-131 there is a quite significance difference at a day after intake. The improved model predicts an increase of a factor of four in the concentration in meat, due presumably to the rapid absorption from the rumen. The same differences are seen between the old and new sheep models.

A more practical situation is where the animal is fed stored contaminated feed, ie the concentration of the nuclide in the feed decreases with time owing to radioactive decay. Again, because the new metabolic models considerably improve the predictions of the time dependence of the transfer to milk, the largest differences between the two sets of models occur for milk. The new model predicts consistently lower concentrations for all four nuclides considered at short times. For strontium and caesium the differences are a factor of eight at 1 day falling to less than a factor of two at 10 days. For iodine-131 the differences between the two models is not so noticeable, the new model predicting concentrations less than a factor of two smaller than the old at 1 day; the two agree by 10 days. For the long-lived strontium-90 the concentration in milk plateaus at a lower level than previously, but after about a year rises again as the nuclide begins to be recycled from bone. The predictions for the concentrations in the meat of cows and sheep are again relatively closer than the ones for milk and are shown in Figures B8 and B9 for sheep meat. For the strontium and caesium radionuclides the results agree to within a factor of about two at all times.

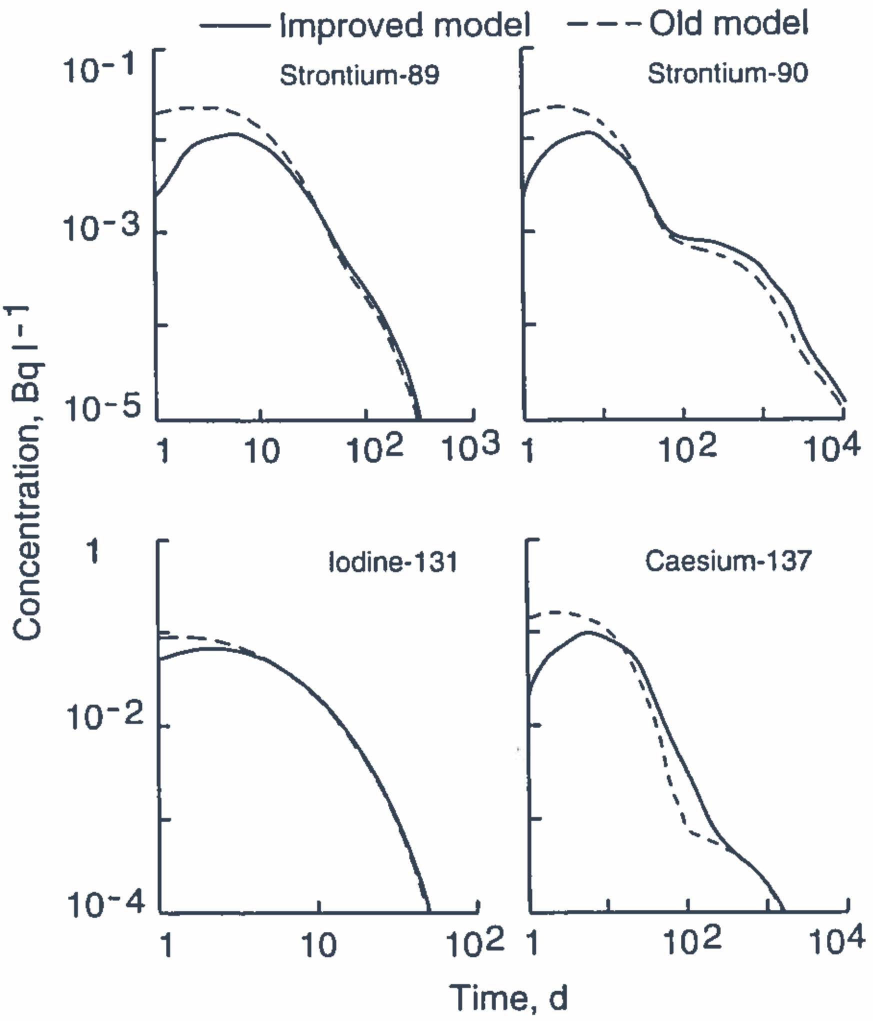


FIGURE B8 Concentration in milk after a single deposit of 1 Bq m^{-2}

The models for iodine-131 transfer to meat show a significant difference in the first few days. As the new model predicts much faster absorption and transfer from the gastrointestinal tract than the old model, the concentrations in meat in the first few days are higher by a factor of six or more using the new model. By 10 days the difference has fallen to a factor of two.

Figures B6–B9 are both applications of the model where the feeding regime and input to the model is simple. Two further situations of importance in practice when the cow is grazing contaminated pasture are where either the pasture is contaminated by an accidental release or the pasture is contaminated continuously by routine releases. The pasture model described in Section 2 of the main report has been used together with the two animal models to compare results for these two important applications.

Figure B10 represents the first of the two situations; the concentrations in milk and meat for cows are shown as a function of time after a single deposit of 1 Bq m^{-2} of the relevant nuclides on to pasture which the cows are grazing. In general, the differences between the two models in this situation are much smaller than between the results for the previous cases considered; this is because in this situation the results are dependent on both the pasture model, which is common to both, and the animal models. Significant differences between the two sets of results are seen for milk at short times; the new model predicts concentrations a factor of three or more lower than the

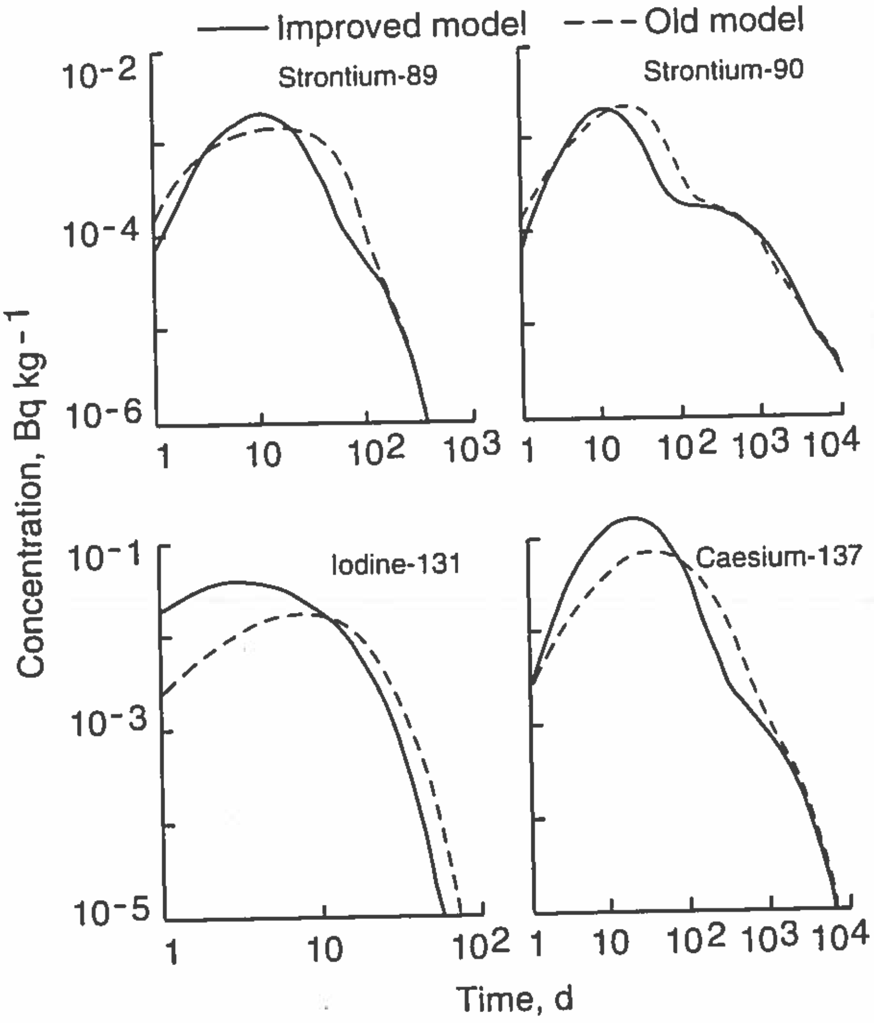


FIGURE B9 **Concentration in meat after a single deposit of 1 Bq m^{-2}**

old for the first few days for strontium and caesium. For iodine-131 the agreement is much better. However, by 10 days after the deposit the differences between the models are on the whole small. However, worthy of note are the results for iodine-131. The predicted transfer to meat is up to a factor of six higher in the first few days falling to a factor of two higher at 5 days for the new model than the old. This reflects again the rapid absorption of iodine from the rumen and its distribution in soft tissue. Similar observations can be made for sheep.

The differences between the model predictions for a continuous deposition of 1 Bq m^{-1} s^{-1} of each radionuclide on to pasture that is being grazed are also small. For milk the differences between the two models are only significant out to the first 20 days or so after the commencement of the deposit. Normally only long times are usually of interest when considering the concentration build-up after the start of a continuous release. At these long times, only strontium-89 shows any real change in the equilibrium value, owing to the radioactive decay of the radionuclide while it is stored in the cow's bones; the transfer to milk is reduced by some 70% according to the new model. This is not a large difference and compared with the many uncertainties is not at all significant. For meat the observations are similar. At short times the difference between the models is significant, but at the longer times of interest for the continuous release situation, the agreement is within a factor of two for all four radionuclides.

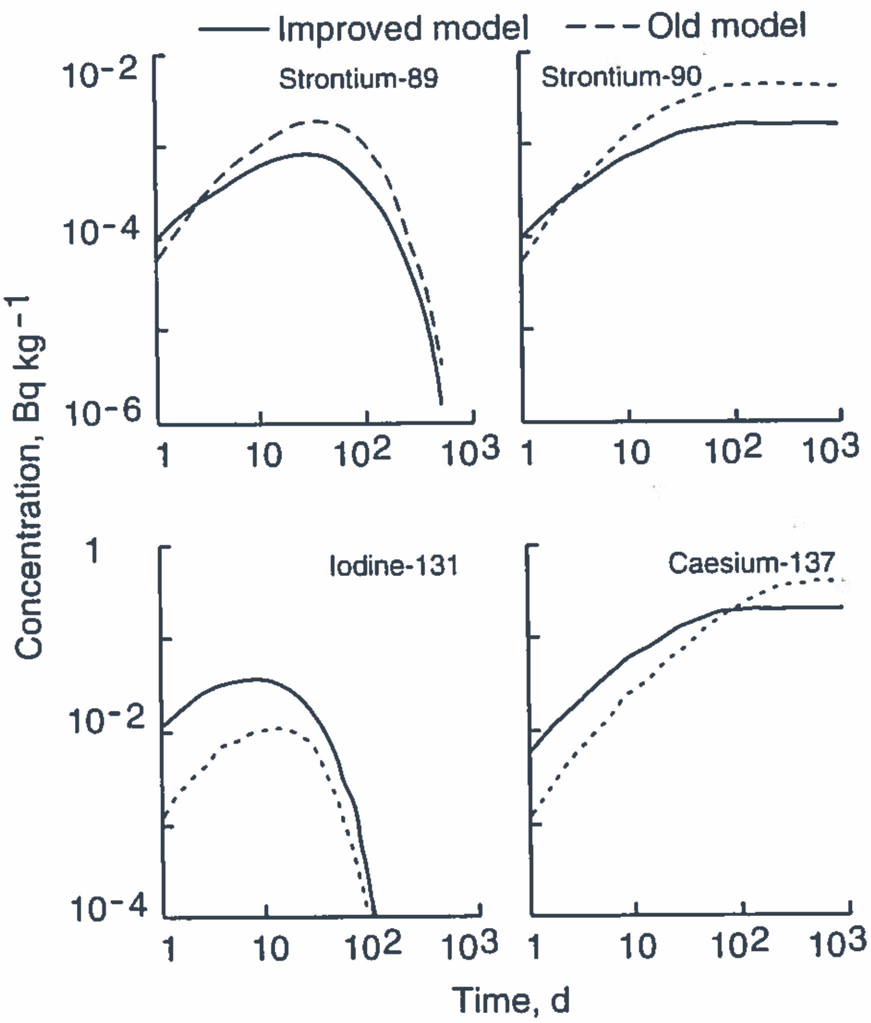


FIGURE B10 Concentration in meat during a continuous decaying oral intake (initial intake 1 Bq d^{-1})

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