Modelling Approach for the Transfer of Radionuclides to Fruit Species of Importance in the UK

J Brown and J Sherwood

ABSTRACT

A compartment model has been developed to predict activity concentrations in fruit following deposition of radionuclides from both accidental and continuous releases of radioactivity to the atmosphere. This model considers the major fruit species grown in the UK.

The important routes of contamination for the major fruit species have been identified as a basis for determining the modelling approach following a review of experimental data and modelling approaches. A robust approach is adopted, reflecting the availability of information on radionuclide transfer to fruit. Where necessary, the modelling approaches adopted in foodchain models for other crops have been used to ensure that all potentially important transfer processes are taken into account.

This model replaces an earlier fruit model within the FARMLAND suite of foodchain models which was developed specifically for continuous release applications in 1995.

Centre for Radiation, Chemical and Environmental Hazards
Chilton, Didcot,
Oxfordshire OX11 0RQ

Approval: September 2012
Publication: September 2012
£21.00
ISBN 978-0-85951-722-5

This work was undertaken under the Environmental Assessment Department's Quality Management System, which has been approved by Lloyd's Register Quality Assurance to the Quality Management Standards ISO 9001:2000 and TickIT Guide Issue 5, certificate number 956546.

Report v1.0

EXECUTIVE SUMMARY

A compartment model has been developed to predict activity concentrations in fruit following deposition of radionuclides from both accidental and continuous discharges of radioactivity to the atmosphere. This model considers the major fruit species grown in the UK.

The important routes of contamination for the major fruit species have been identified following a review of experimental data and modelling approaches. A robust approach is adopted, reflecting the availability of information on radionuclide transfer to fruit. Where necessary, the modelling approaches adopted in foodchain models for other crops have been used to ensure that all potentially important transfer processes are taken into account.

The model is described and details are given on how to run the model following both accidental and continuous releases of radioactivity to the atmosphere. The activity concentrations predicted by the model are also given for some important radionuclides.

Limited verification and validation of the model has been carried out. This has been done mainly using the results of model intercomparison and validation exercises carried out by the Fruits Working Group of the International Atomic Energy Agency (IAEA) BIOMASS programme. The model developed agrees well, in general, with other models, with the predicted activity concentrations in fruit and other parts of the plant falling within the range of the other model predictions. Comparisons of the predicted activity concentrations with those observed in strawberries following an experimental study also show reasonable agreement. Activity concentrations in most cases are within a factor of 2 - 3 of the observed values, which is acceptable given that the developed model was run with its default parameter values and not tailored for the site specific situation of the experiment. The validation and verification carried out gives confidence that the model provides a robust prediction of activity concentrations that could be found in fruit in the UK following a release of radioactivity to the environment.

This model replaces an earlier fruit model within the FARMLAND suite of foodchain models which was developed specifically for continuous release applications in 1995.

CONTENTS

1 INTRODUCTION

Following the deposition of radioactive material from the atmosphere onto 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 continuous releases of radioactive material to the terrestrial environment. Models to simulate the transfer of radionuclides through terrestrial foods have been developed at the Centre for Radiation, Chemical and Environmental Hazards within the Health Protection Agency (HPA-CRCE) and are used regularly. The foodchain model is named FARMLAND and it contains a suite of sub-models, each of which simulates radionuclide transfer through a different part of the foodchain [Brown and Simmonds, 1995]. This report describes the modelling approach developed within the FARMLAND model for assessing radionuclide transfer to fruit species of importance in the UK. The model described here supersedes an earlier fruit sub-model developed specifically for continuous release applications [Mayall, 1995].

The body of data on the transfer of radionuclides to fruit has increased since the development of the earlier fruit sub-model due to an increase in experimental work in this area and the work of the Fruits Working Group of the International Atomic Energy Agency (IAEA) BIOMASS (BIOsphere Modelling and ASSessment) Programme [Carini et al, 2005]. This information provides a better understanding of the important transfer processes and, in conjunction with previous modelling experience, enables a model to be developed that best utilises the available information.

A review of available information has been carried out for the fruit species of importance in the UK. The available data on the transfer of radionuclides to these fruit species, other supporting information on the behaviour of radionuclides in the food chain and the agricultural practices involved in the cultivation of fruit have been reviewed. The modelling approaches currently adopted in key models in the European Union for fruit and other crops have also been reviewed to ensure that all potentially important transfer processes are considered [Linkov *et al*, 2006; Müller and Pröhl, 1993; Carini *et al*, 2005].

The important routes of contamination for the major fruit species for both continuous and accidental release applications have been identified as a basis for determining a modelling approach. A robust modelling approach has been recommended which utilises the available data, the understanding of the behaviour of radionuclides in the foodchain and the important features of radionuclide contamination. The approach takes the form of a compartment model for use for both continuous release and accident applications.

The report includes the activity concentrations predicted by the model for some important radionuclides following both a single deposition and continuous deposition over a year. Full details of how to implement the model are also provided. The verification and validation carried out on the models is also described.

The model is an extension of the fruit model published by Teale and Brown (2003) for actinide transfer to fruit and replaces the fruit model developed for continuous release applications published in 1995 [Mayall, 1995].

2 GENERAL APPROACH

Fruit can be classified into five different categories as shown in Table 1 [Carini, 2001]. In the UK, apples have accounted for approximately 60 - 70% of the commercial fruit production over the last decade with soft fruit (produced on both herbaceous plants and shrubs) accounting for about 20 - 30% [Defra, 2010]. Strawberries dominate the production of soft fruit in the UK and have contributed, on average, 16% to the overall UK fruit production over the last decade. Any modelling of transfer to fruit should therefore consider, at least, the fruit categories of woody trees and herbaceous plants, as listed in Table 1. To ensure that the HPA can be confident that any advice given covers all orchard and soft fruit produced in the UK by commercial or domestic growers, it is also appropriate to consider shrub fruit such as raspberries, currants and gooseberries. The areas of land utilised and quantities of fruit produced in the UK in 1999/2000 and averaged over 2000 - 2009 for these three categories of fruit are given in Table 2 [Defra, 2010]. Estimated yields of each fruit type are also given.

The consumption patterns for fruit produced in the UK also support this approach [MAFF, 2000]. Apples, bananas and citrus fruit dominate the net consumption of fruit in the UK. However, for radiological assessment purposes, it is important to differentiate between those fruit species that are grown in the UK and those that are imported. All bananas and citrus fruit are imported. In addition, about 65 - 75% of the apples that are consumed in the UK are imported, the corresponding range for soft fruit being 20 - 40% depending on the type of soft fruit [Defra, 2010]. However, consumption of soft fruit is small, approximately 3% of the total amount of fruit consumed. Consequently, the consumption of apples dominates the overall consumption of fruit grown in the UK. Soft fruit consumption is much more seasonal than that of orchard fruit and it should be recognised that consumption of soft fruit is likely to be a higher proportion of the overall consumption of fruit during the summer months.

Table 1 Classification of fruit

Category	Examples
Woody trees	Apple, pear, peach, apricot, damson
Citrus and olives	Orange, mandarin, grapefruit, lemon, olive
Herbaceous plants	Strawberry, melon, watermelon
Shrubs	Gooseberry, blackcurrant, red currant, raspberry
Tropical fruits	Banana, pineapple, mango, avocado

Table 2 UK production of fruit

Fruit	Area (hectares) 1999/2000[a]	Area (hectares) 2000-2009[b]	Fruit produced (10^3 tonnes) 1999/2000[a]	Fruit produced (10^3 tonnes) 2000-2009[b]	Yield[c,d] (kg m^{-2}) 1999/2000[a]	Yield[c,d] (kg m^{-2}) 2000-2009[b]
Apples	12817	9803	248	209	1.9	2.1
Pears	2325	1787	18	27	$7.7\ 10^{-1}$	1.5
Plums	1119	980	9	12	$8.3\ 10^{-1}$	1.2
Woody tree (apple/pear/plum)	16261	12570	275	248	1.7[c]	2.0
Herbaceous plants (strawberry)	3341	3957	44	56	1.3[c]	1.4
Shrub (other soft fruit)	4314	4823	24	33	$5.6\ 10^{-1}$	$6.8\ 10^{-1}$

a) Data taken from Defra, 2001.

b) Average of values for 200 – 2009. Data taken from Defra, 2010.

c) The values for the fruit yields of woody tree and herbaceous plants used in the model are those for 1999/2000 as these were the most recent data available at the time the model was developed [Defra, 2001]. A more recent review indicates that values averaged over 2000 - 2009 are consistent with the earlier data and a change in fruit yields is not justified in the model [Defra, 2010].

d) The yields given are for the whole fruits including non-edible parts such as cores and stones in woody tree fruit.

Data on the transfer of radionuclides in fruit plants are relatively sparse in the literature. However, given the range of fruit types produced in the UK, it is important to produce a modelling approach that distinguishes between orchard fruit (woody tree) and soft fruit (herbaceous plant and shrub), where appropriate. In choosing data for use in the model, emphasis has been placed on the fruit species dominating UK production in the two categories; these species are apples for orchard fruit and strawberries for soft fruit. Account has been taken of any differences between shrub fruit and herbaceous fruit where these may affect the mechanisms by which radionuclides are transferred to the fruit.

3 LITERATURE AND MODEL REVIEW

A review of available data on the processes by which radionuclides can contaminate fruit crops and, in particular, the edible fruit has been undertaken. Each of the processes that could contribute to or influence the contamination of fruit has been considered and the available literature has been reviewed. The modelling approaches currently adopted have also been reviewed. The current modelling approach adopted in the FARMLAND fruit model and for other crop models, where appropriate, is described for each process [Mayall, 1995; Brown and Simmonds, 1995]. The ECOSYS model was studied in detail as one of the key foodchain models used in Europe [Müller and Pröhl, 1993]. A brief description of the processes modelled for fruit in the ECOSYS model is given in Appendix A. Other models have been studied in general terms to identify what processes have been considered and the modelling approach that has been adopted, including the conceptual model developed by the Fruits Working Group of the IAEA BIOMASS Programme [Carini *et al*, 2005], which is shown in Figure 1. The objectives of developing the conceptual model were to provide guidance for future development of models to estimate the contamination in fruit following atmospheric deposition, to assess the state of knowledge for the dominant contamination pathways and to identify any gaps concerning key processes. During the BIOMASS programme, due to the lack of models specifically developed for fruit, new models were developed and some existing models for other agricultural crops were extended or adapted to describe the transfer of radionuclides in fruit systems. A summary of the modelling approaches adopted in these models can be found in Linkov *et al* (2006) and Ould-Dada *et al* (2006).

The processes included in the conceptual model developed by the BIOMASS Fruits Working Group are listed in Table 3 and the available experimental data for these processes are discussed below. The importance of the processes in determining the transfer of radionuclides to fruit and their inclusion in the model developmed for FARMLAND are discussed further in Section 4.

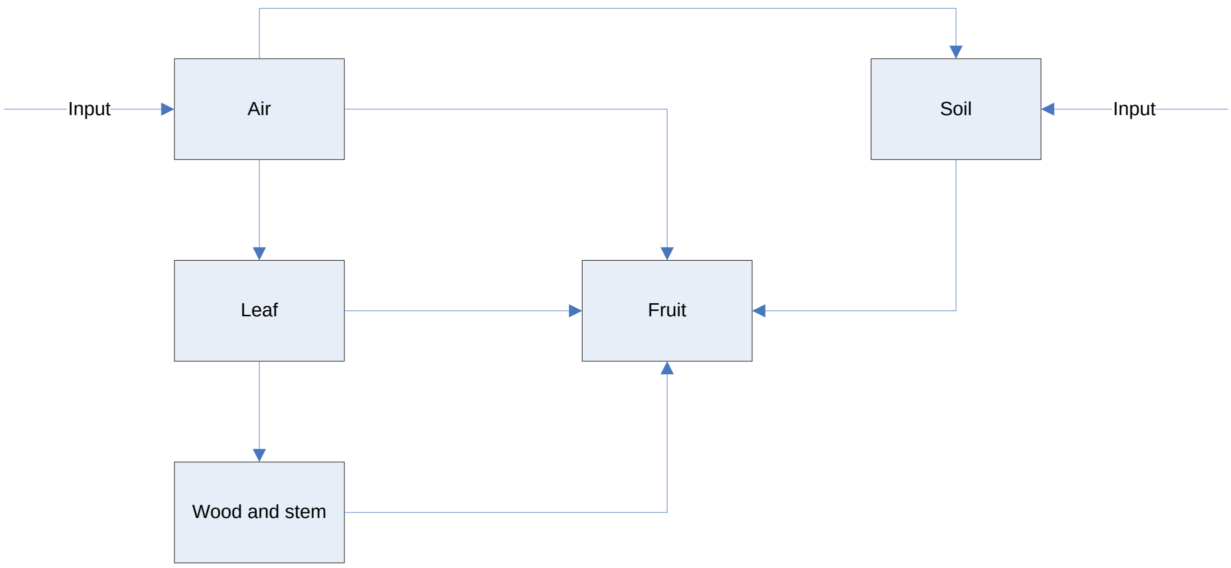


Figure 1: Conceptual fruit model developed by the Fruit Working Group of the IAEA BIOMASS programme

Table 3 Processes considered in review

Process	Section of report
Root uptake	3.1
Direct soil contamination	3.2
Soil migration	3.3
Resuspension (soil to fruit & plant)	3.4
Interception	3.5
Weathering (from plant & fruit)	3.6
Translocation (plant to fruit)	3.7
Agricultural practices[a]	3.8
Storage and processing[a]	3.9

a) not part of BIOMASS conceptual model

3.1 Root uptake

3.1.1 Literature

Most of the data in the literature on root uptake are concerned with determining soil-to-fruit Transfer Factors (TFs) for different combinations of radionuclides and fruit types. The TF is defined as the ratio of the activity concentration in the plant (Bq kg^{-1} fresh mass) to the concentration in the soil (Bq kg^{-1} dry mass), once equilibrium has been reached. The relevant fruit entries from an international database of soil-to-plant TFs, which are taken from many literature sources, are tabulated by Carini [Carini, 2001]. Although the main bulk of the TFs for fruit in this compilation are for radiocaesium and radiostrontium, there are also some data for plutonium and americium. The ranges of TFs for the different fruit types being considered in this study are shown in Table 4. Plutonium and americium appear to behave in a similar way in the soil/plant system [Carini, 2001; Green *et al*, 1997] and due to the similar values for plutonium and americium, their TF ranges have been combined in the table under the name 'actinides'.

Table 4 Soil-to-fruit transfer factors for caesium, strontium and actinides from Carini (2001)

Fruit type	Soil-to-fruit transfer factor, Bq kg^{-1} fresh mass fruit / Bq kg^{-1} dry mass soil		
	Caesium	Strontium	Actinides
Orchard fruit	$8.6\ 10^{-4}$ – $8.0\ 10^{-2}$	$1.2\ 10^{-3}$ – $7.0\ 10^{-2}$	$1.3\ 10^{-6}$ – $9.2\ 10^{-4}$
Soft fruit	$4.1\ 10^{-4}$ – $8.9\ 10^{-3}$	$5.4\ 10^{-3}$ – $2.1\ 10^{-1}$	$2.7\ 10^{-5}$ – $8.3\ 10^{-4}$

There are a few data in the compilation for other elements, notably iodine, but these do not form a sufficient basis for making any decisions on modelling.

A large proportion of the TFs reported in Carini [Carini, 2001] originated from Green *et al* (1997). These data comprise measurements made in the field on a plot of land reclaimed from the sea and in lysimeter experiments. A wide range of fruit species was studied on the experimental field plot, whereas only strawberries and apples were grown in the lysimeters. Studies for both the reclaimed land site and the lysimeters continued after the original 1995 study and TFs were measured over the period of 1996 to 2002 [Green *et* al, 2005]. The data from these studies are for UK conditions and have therefore been investigated in more detail. The mean TFs from the studies for fruit grown in lysimeters and the reclaimed land plot are given in Table 5 and Table 6, respectively.

3.1.2 Current modelling approach in the FARMLAND model

The FARMLAND model [Brown and Simmonds, 1995] adopts a modelling approach that uses the soil-to-fruit transfer factors directly. The model assumes that the radionuclides are well mixed within the entire rooting zone of the crop and uses the activity concentration in the soil and the soil-to-fruit TF to estimate activity concentrations in fruit from root uptake. This approach is described further in Section 5.1.5.

Table 5 Soil-plant transfer factors from UK lysimeter experiments, Bq kg^{-1} fresh mass fruit / Bq kg^{-1} dry mass soil [Green *et al*,1997; Green *et al*, 2005]

Fruit [a]	Soil type	^{137}Cs	^{90}Sr	^{239}Pu	^{241}Am
Apples	Loam	9.4 10^{-4}	1.2 10^{-2}	8.0 10^{-6}	8.0 10^{-6}
	Sand	1.9 10^{-3}	2.5 10^{-2}	1.5 10^{-5}	1.5 10^{-5}
	Peat	3.7 10^{-2}	1.2 10^{-3}	1.3 10^{-6}	1.3 10^{-6}
Strawberries	Loam	9.0 10^{-4}	1.0 10^{-1}	8.8 10^{-5}	7.3 10^{-5}
	Sand	4.2 10^{-3}	2.1 10^{-1}	1.6 10^{-4}	1.7 10^{-4}
	Peat	6.4 10^{-3}	1.2 10^{-2}	7.3 10^{-5}	6.8 10^{-5}

a) Data are for washed fruit. Apples are also cored.

Table 6 Soil-plant transfer factors from UK field experiments, Bq kg^{-1} fresh mass fruit / Bq kg^{-1} dry mass soil [Green *et al*,1997; Green *et al*, 2005]

Fruit[a]	^{137}Cs	^{90}Sr	^{239}Pu	^{241}Am
Melon	4.1 10^{-4}	2.0 10^{-2}	8.3 10^{-4}	7.2 10^{-4}
Rhubarb	5.3 10^{-4}	2.0 10^{-2}	3.6 10^{-5}	5.5 10^{-5}
Gooseberry	1.0 10^{-3}	5.9 10^{-2}	4.4 10^{-5}	5.1 10^{-5}
Strawberry	1.8 10^{-3}	4.4 10^{-2}	4.1 10^{-4}	3.6 10^{-4}
Blackcurrant	3.3 10^{-3}	1.2 10^{-1}	1.9 10^{-4}	1.8 10^{-4}
Apple	1.2 10^{-3}	2.3 10^{-2}	2.7 10^{-5}	2.2 10^{-5}

a) Data are for washed fruit. Apples are also cored.

3.2 Direct soil contamination

3.2.1 Literature

Wilkins *et al* (1996) reported that olive trees were not contaminated by soil splash due to the height of the tree. However, for some fruits, especially those that grow close to the ground, e.g. strawberries, contamination from soil splash may be an important contamination pathway, particularly for radionuclides that are immobile and which have low uptake to fruit via the roots and low translocation to the fruit from foliar contamination. There are no data in the literature on the level of soil contamination that could be expected for such fruits.

3.2.2 Current modelling approach in the FARMLAND model

In the FARMLAND model for vegetables, it is assumed that 0.1% of the dry plant mass is present as soil on the crop at harvest [Brown and Simmonds, 1995]. Direct soil contamination was not included explicitly in the earlier fruit model in FARMLAND [Mayall, 1995].

3.3 Soil migration

3.3.1 Literature

Data on the migration of radionuclides in soil are available in the literature. These data are largely for undisturbed soil, such as that underlying permanent pasture, and have been analysed and used in the development and validation of soil models for undisturbed and arable mixed soils. Details of some of the important data sources are given in Simmonds (1979) and Busby (1999). The use of these data for development and validation of the soil models in the FARMLAND model is described below.

3.3.2 Current modelling approach in the FARMLAND model

The FARMLAND model [Brown and Simmonds, 1995] contains two different soil models, one for undisturbed pasture soil and one for arable soil. The two models were based on a review and extrapolation of migration data for plutonium, caesium and strontium [Simmonds *et al*, 1979]. The arable soil model uses a soil migration half-life of 100 years for the loss of material from the top 30cm of well-mixed soil. This is consistent with the migration from the same depth that is implied from the more complex, undisturbed pasture soil model.

A study was carried out [Busby, 1999] to validate the FARMLAND pasture soil model for undisturbed soil against measurement data from locations around the world. It was found that the model predictions matched closely with measurements made.

3.4 Resuspension

3.4.1 Literature

Whereas direct soil contamination accounts for mechanisms such as rain splash onto fruit surfaces, radioactive particles in the soil may also contaminate the fruit via resuspension into the air and subsequent deposition onto the plant and fruit surfaces. The resuspension pathway is often quantified in terms of a resuspension factor and a deposition velocity. The resuspension factor is the ratio between the activity concentration in the air (Bq m^{-3}) and the initial surface deposition (Bq m^{-2}) onto the soil. The deposition velocity is the rate at which the resuspended material returns to the ground surface, some of which will be intercepted by the plant, tree or fruit.

Pinder III *et al* (1987) found that resuspension onto fruit and leaves of orange trees was negligible following deposition measured over spring and summer sampling periods. The authors suggest that resuspension is not significant at heights greater than 1m above the ground and fruits of mature trees are unlikely to be significantly contaminated by resuspension.

Wilkins *et al* (1996) reported that olives (typically up to several metres from the ground) were found to be contaminated by dust, which accounted for 0.003% of the mass of the olive fruit and 0.15% of the mass of the leaves.

3.4.2 Current modelling approach in the FARMLAND model

The FARMLAND model [Brown and Simmonds, 1995] adopts a method to incorporate the resuspension pathway that uses a time-dependent resuspension factor following deposition [Garland *et al*, 1992], where:

resuspension factor $= \dfrac{1.210^{-6}}{t}$, where $t \geq 1$ is the time in days after deposition.

The FARMLAND model uses this formula with the assumption that the time-dependent factor is averaged over the growing period of the crop and is constant over that period. The resuspension factor used for crops, averaged over a 120 day growing period, is $8\ 10^{-8}\ m^{-1}$. The average resuspension factor gives the same integrated concentration in air as a time-dependent factor over the growing period of the crop. This approach is conservative for deposition occurring before the growing season, but will underestimate resuspension if deposition occurs at a short time before harvest. However, given that the contribution to the overall activity concentrations in a crop from resuspension is very small compared with that from direct deposition on to the fruit, this underestimation is not important. The FARMLAND model uses a value of $10^{-3}\ ms^{-1}$ for the deposition velocity of resupended particles onto the crop surface.

Resuspension factors are lower when the mean particle size is larger, for example, after a nuclear weapons accident [Wilkins *et al*, 1996]. However, in such cases, the general resuspension factors quoted above could still be applied, recognising that they may give a conservative estimate of resuspension onto crops.

3.5 Interception

3.5.1 Literature

Interception of contaminants is often quantified using an interception fraction, that is, the proportion of the total deposited material that is intercepted by the plant canopy. Interception during dry deposition is often considered to be element independent, whereas during wet deposition, the chemical properties of the particular radionuclide can have a significant effect [Kinnersley and Scott, 2001].

For generic field crops including fruit canopies, a generic interception fraction of 0.74 is the best estimate given in Kinnersley and Scott (2001) for dry deposition, i.e. 74% of the deposited activity is intercepted by the leaves and fruit, the remaining 26% being deposited on the soil. Alternatively, the interception fraction can be calculated using a relationship derived by Chamberlain (1970), where the interception coefficient, μ, is an empirical measure of the ability of the canopy to filter out deposited material.

Kinnersley and Scott (2001) do not give specific values for the parameters used, but suggest the same approach for estimating the interception fraction. The interception fraction given by Chamberlain [Chamberlain, 1970] is:

$$\rho = 1 - \exp(-\mu W)$$

where:

ρ is the proportion of deposited activity that is intercepted by the plant
W is the mass of the plant (kg m^{-2})
μ is a plant-dependent interception coefficient (m^2 kg^{-1})

Vandecasteele *et al* (2001) suggest a variant on this relationship, where the interception fraction is scaled by a number, M (less than 1), to represent the maximum interception fraction for a particular type of vegetation. The interception fraction then tends to M rather than 1 as the mass increases.

For wet deposition, the proportion of deposited activity retained by the plant can also be estimated using the approach of Kinnersley and Scott (2001). They also give the following formula for calculating interception during wet deposition based on properties on the plant. Again, no plant specific values are recommended in the review.

$$F_i = \frac{LAI.S_i}{R}\left(1 - \exp\left(\frac{-\ln 2}{3.S_i}R\right)\right)$$

where:

F_i is the average interception fraction for crop i
S_i is the retention coefficient for crop i and particular radionuclide (mm)
R is the amount of rainfall (mm)
LAI_i is the leaf area index for crop i

These formulae have traditionally been used to estimate interception on to the whole crop.

The transfer of ^{134}Cs to strawberries following wet deposition was investigated in Hungary [Oncsik *et al*, 2002]. The interception on to strawberry plants, including the fruit, at various stages of development ranged from 23% - 40%, with the highest interception being at anthesis, i.e. when flowers are present and green fruits are starting to form.

Carini *et al* (2003) measured interception of ^{134}Cs and ^{85}Sr on to the leaves of strawberry plants following wet aerial deposition. Interception depended on the growing stage of the plant at the time of deposition and ranged from 17% - 39% for ^{134}Cs and from 30% - 46% for ^{85}Sr. No positive correlation was found between interception and leaf area or the biomass of the leaf (expressed on a dry mass basis). From this study it appeared that interception is more affected by variables such as the physical orientation of the leaves than by leaf area or biomass.

Following the Chernobyl accident, measurements made of ^{137}Cs on the leaves of apple, pear and cherry trees showed that interception varied according to the species, with the amount absorbed depending on the shape and characteristics of the leaves and canopy [Anguissola Scotti and Silva, 1992]. The leaves of pear trees were found to contain levels of ^{137}Cs about 4 times higher than apple trees grown at the same site.

Radioactive material can also be intercepted by the fruit itself as opposed to the rest of the above-ground parts of the plant or tree. Pinder III *et al* (1987) conducted a study into the interception of ^{238}Pu by orange trees, particularly looking at the proportion of the deposition that was intercepted by the oranges themselves. It was shown that 0.11% of the deposited plutonium was intercepted by the oranges. However, the experiments were carried out on small trees and the authors estimated that an interception fraction of 0.8% would be a more suitable value for mature orange trees.

Carini *et al* (2003) found that interception by strawberries is lower than that of plant leaves due to their ovoid shape and their orientation toward the base of the plant. Interception values ranged from 0.2% to 1.2% of the sprayed activity for both ^{134}Cs and ^{85}Sr depending on the stage of development of the plant at the time of deposition. Interception was found to be broadly correlated with the dry biomass of the fruit.

One day after spraying an apple branch with soluble ^{134}Cs and ^{85}Sr, about 5% of the applied activity was found to be present in the fruit [Bengtsson, 1992]. It is thought that this fraction is unusually high, however, due to a smaller fruit to leaf area at the time of deposition [Carini and Bengtsson, 2001].

3.5.2 Current modelling approach in the FARMLAND model

The FARMLAND fruit model for continuous releases uses an effective interception fraction for the fruit, this being the fraction of the total deposition that is intercepted by the fruit. The estimated values were based on the mobility of the element, and were 0.01 for actinides, 0.02 for semi-mobile elements and 0.08 for mobile elements [Mayall, 1995]. This ‘effective’ value has been fitted in conjunction with a weathering rate to ensure that the predicted activity concentrations in fruit agree with measured values following continuous deposition onto fruit crops over the growing period. On its own, the effective interception fraction does not necessarily reflect the actual interception of material onto the fruit surface.

3.6 Weathering

3.6.1 Literature

Once material has been deposited onto the fruit plant and fruit, it will begin to weather off the surface due to the action of wind, rain, abrasion between leaves and shedding of cuticular wax. The rate at which this occurs is usually given by the retention or weathering half-life, that is, the time that it takes for the contamination on the surface to reduce by half.

The loss from fruit tree leaves was found to be dependent on the type of plant and is not significantly different for strontium and caesium [Carini *et al*, 1999]. Losses from leaves of apple trees over a 50 day period following wet deposition were 91% and 87% for caesium and strontium, respectively. The corresponding value for pear trees was 91% for both strontium and caesium. Losses from grapevine leaves were higher.

Miller and Hoffman (1983) (cited in Carini *et al*, 2003) reported a mean retention half-times on herbaceous vegetation of 11 days for crops grown under field conditions, with a range of 4.5 - 34 days.

Carini *et al* (2003) also measured retention on leaves of strawberry plants grown in a polytunnel following aerial wet deposition. For strawberry plants contaminated at predormancy, the residual fraction of the intercepted activity on the leaves was 66% for caesium and 87% for strontium after 128 days. After this time the leaves are lost and a complete renewal of the aboveground part of the plant takes place prior to flowers and fruit forming. These values give an indication of a weathering half-life of 186 days and 481 days for caesium and strontium, respectively. Weathering half-lives after deposition at antheis* were found to be between 46 - 74 days for strontium and caesium over the 56 days prior to harvest and values for the whole period after deposition including the dormant and growing periods were 114 days and 109 days for caesium and strontium, respectively. The authors recognise that these values are significantly higher than those reported in the literature for crops grown under field conditions. Other studies have also shown lower losses of radionuclides from fruit plants grown in greenhouses compared with those grown under field conditions [Carini *et al*, 1999].

In the study on orange trees carried out by Pinder III *et al* (1987), the analysis over a 28-day period of the retention on the oranges with time indicated that there was no significant reduction in ^{238}Pu activity concentrations. The authors did not know the reason for this high retention.

Carini and Bengtsson (2001) note that the retention of intercepted contamination on fruit is dependent on the surface properties of the fruit. Losses from fruit over a 50 day period following wet deposition were measured for grapes and apples [Carini *et al*, 1999]. In percentage terms, the amount of activity lost compared with that initially applied to the fruit were 73 for strontium and 39 for caesium. The higher loss of strontium from the fruit surface was thought to be due to differences in absorption by the fruit skin, strontium being lower than caesium. No significant difference was seen between fruit species. Assuming that strontium is not absorbed through the skin [Bengtsson, 1992], the loss given for strontium can be expressed as a weathering half-life of 26 days.

3.6.2 Current modelling approach in the FARMLAND model

Weathering is reported as an element independent process in the literature and is treated as such in the FARMLAND model [Brown and Simmonds, 1995]. The FARMLAND fruit model uses an effective half-life of 11 days [Mayall, 1995] for

* Antheis is defined as the stage of plant development when flowers are present and green fruits are starting to form.

weathering from the fruit surface. This ‘effective’ value has been fitted in conjunction with an interception factor on to apples and therefore may not explicitly reflect the actual loss of material from the fruit due to weathering. The FARMLAND model uses a weathering half-life from the plant surface of 14 days for all other crops [Brown and Simmonds, 1995].

3.7 Translocation

3.7.1 Literature

Once material has been deposited on to the above-ground parts of the plant or tree, it can transfer to the edible fruit part by translocation. Published data on translocation are not always comparable as some authors relate the activity in fruit to that applied to external surfaces of the above-ground part (initially retained activity), while others relate the activity to that recovered in the plant at harvest. Carini *et al* (2001) have reviewed literature on translocation for fruit and expressed the experimental results in terms of the fraction of activity applied or intercepted that was found in the fruit at harvest. The relevant experimental data are reviewed below.

Katana *et al* (1988) measured the amount of ^{134}Cs that was transferred by translocation from the leaves and branches to the fruit of apple trees following simulated deposition using a leaf droplet method, which simulated interception on to the top surface of the leaves. The trees were contaminated at the beginning of fruit development and fruit was harvest at maturity 10 weeks later. The percentage of the deposited activity that was measured in the fruit pulp of the apples located near to the initial deposit ranged from 19% to 42%. Similar results were found when leaves close to developing fruit were dipped into a solution containing ^{134}Cs. Translocation from the external bark to the apples was also investigated as part of this study. This process is far less significant than translocation from leaves, with only 0.2% - 1.8% of the applied activity reaching the fruit.

Bengtsson (1992) applied soluble ^{134}Cs and ^{85}Sr to apple tree branches during a period in which the trees were protected from precipitation. Translocation to the fruit was only detected for ^{134}Cs, where 5%, 21% and 34% of the applied ^{134}Cs was found in the fruit harvested after 1, 41 and 84 days following deposition, respectively. About 5% of this activity was attributed to direct deposition onto the fruit although this value was believed to be high due to the high fruit to leaf area at the time of deposition. Carini *et al* (1999) measured a leaf-fruit transfer of 6% for apples.

Leaf to fruit transfer for strontium is much lower than that observed for caesium. Kopp et al (1990) studied the foliar uptake of radionuclides in various soft fruits. Radionuclides were deposited onto the leaves of the fruit plants, before the fruit had started to develop, and the activity in the fruit part was measured at later growth stages. The results show a general trend for the contamination due to translocation to increase during growth, with caesium being far more mobile than strontium. The translocation to strawberries was greater than for any of the shrub fruit in the study and the authors suggest that this is due to the difference in leaf structure. For ripe fruit, strawberries contained about 22% of the applied ^{134}Cs and 0.6% of the applied ^{85}Sr. Transfer of caesium and strontium to gooseberries was 4% and 1.9%, respectively and for redcurrants, 3.8% of caesium was transferred and only traces of strontium were transferred. For blueberries, about 1.5% of the initial caesium deposit was transferred and 0.02% of strontium was transferred. Carini *et al* (1999) measured a leaf-fruit transfer of 0.8% for strontium translocation to apples.

Measured leaf to fruit translocation in strawberries covers a range of 6.5% - 36% of the applied or intercepted activity for caesium and 0.3% to 2.2% for strontium, depending on the time of contamination and harvest [Carini *et al*, 2001]. Zehender *et al* (1993) ascertained that while 20-36% of applied ^{134}Cs was translocated from leaf to strawberries, no ^{85}Sr was found in the fruit. When comparing the effects of deposition at different stages of plant development, Carini *et al* (2003) found that the maximum contamination of fruit arises from leaf-to-fruit translocation when deposition occurs at anthesis. Values found of 15% for ^{134}Cs and 1.6% for ^{85}Sr confirm the higher mobility of caesium compared with strontium. When deposition occurs at predormancy, in autumn, translocation is still seen to fruit (harvested about 200 days after deposition) even though the old leaves are lost and new ones formed. This is thought to be due to a small percentage of the intercepted activity being translocated to storage organs before dormancy. Activity concentrations in repeated harvests were seen to decrease rapidly; a decrease of a factor of 4 was observed for caesium in harvests 14 days apart and a decrease of an order of magnitude was observed for strontium. The authors suggest that the re-translocaton from storage organs post dormancy at the resumption of growth probably leads to a higher concentration in those fruits developed from the first buds in the spring.

In the study of ^{238}Pu in orange trees, Pinder III *et al* (1987) found that relatively little of the plutonium was transferred from leaves to the fruit over a 56 day period. The minimum detectable transfer rate was approximately 0.0009 d^{-1}, so less than 0.09% of the activity in the leaves was transferred to the fruit each day. For oranges, 0.1% of applied caesium and 0.004% of applied strontium were found to be translocated to the edible part of the fruit [Delmas *et al*, 1971]. These data indicate a very low leaf to fruit translocation for evergreen orange trees compared with orchard fruit.

There is other experimental evidence that can be used to support the very low transfer of strontium from plant to fruit compared to caesium. Delmas *et al* (1969) found that 17% of ^{134}Cs recovered in above ground apple trees was in the apples following foliar irrigation with contaminated water; for strontium, the value was 2.2%. A study undertaken on behalf of the Food Standards Agency in the UK [Ould-Dada, 2003] looked at the transfer of caesium, strontium and lead to apples following wet deposition. After 56 days, between 5% and 17% of the caesium in the above ground tree was found in the apples; for strontium and lead the range was 0.05% to 0.2%. Similarly, the percentage of the total initial deposition found in the apples after 56 days was 12% - 43% for caesium and 0.3% - 0.7% for strontium. Data for lead were broadly comparable with strontium.

Following the contamination of strawberry plants at ripening with caesium and strontium, consecutive harvests of berries showed that the process of loss was dominant for strontium, whilst that of translocation dominated for caesium. The caesium content of fruit was on average three times higher than for strontium, the values being 6.5% and 2.2%, respectively. This trend held true for one month until the end of the harvest period [Carini and Bengtsson, 2001].

Following contamination of apple trees, almost all of ^{85}Sr activity in the apples was in the peel, irrespective of the time after spraying the branches [Bengtsson, 1992]. In contrast, the high faction of ^{134}Cs in the peel of apples 1 day after spraying (83%) had decreased considerably by 41 days after spraying to 33% of the total activity in the apple. The large accumulation of ^{134}Cs in the edible part of the fruit is consistent with a high rate of translocation from the foliage for caesium.

Baldini *et al* (1987), reported fruit:leaf activity ratios for apples, pears and peaches harvested after the Chernobyl accident in 1986. Ratios of 0.11 - 1.33 were observed for ^{137}Cs and ratios of 0.01 - 0.11 for ^{103}Ru, indicating that ruthenium is about an order of magnitude less mobile than caesium.

The factors that influence translocation are discussed in Carini and Bengtsson (2001). These can be summarised as follows.

a Rainfall rate. Lower translocation has been observed to apples when leaves are subject to heavy rainfall compared with light rainfall.

b Age of contaminated plant. Experiments with apples show that the translocation of ^{134}Cs from leaves to fruit is higher by at least a factor of 2 in one-year-old branches compared with 7-year-old branches.

c Different species. A comparison across different soft fruit species showed that strawberries and gooseberries had the highest translocation while blueberry and redcurrants had the lowest [Kopp, 1990].

d Different cultivars. Different apple cultivars have shown different levels of translocation although the differences are not very significant.

e Physiological properties of different species. Anguissola Scotti and Silva (1992) reported that activity concentration of ^{137}Cs in fruit harvested after the Chernobyl accident showed less variability than that seen in the leaves of the fruit trees and the activity concentrations did not depend on the amount intercepted by the leaves but on the plant species. The lowest values were observed in apples and pears, which were very similar, and higher values were observed in cherries and peaches.

Many of the above studies were based on short term deposition following the nuclear accident at Chernobyl or single short applications of radionuclides. Normalised Specific Activities (NSAs) can be determined for situations where continuous deposition occurs at an approximately uniform rate. For example, fallout data measured in Denmark in the early 1960s were used [Mayall, 1995]. Chamberlain [Chamberlain, 1970] defined the NSA as

$$\text{NSA (m}^2\text{ d kg}^{-1}\text{)} = \frac{\text{Activity concentration (Bq kg}^{-1}\text{ dry mass of crop)}}{\text{Activity deposition rate (Bq m}^{-2}\text{ d}^{-1}\text{)}}$$

Mayall (1995) reports measured NSA values for strontium, caesium and plutonium for the fruit part of apple trees; values are given in Table 7.

Table 7 NSA Values for Fruit (m^2 d kg^{-1} dry mass)		
Strontium	Caesium	Plutonium
1.5 – 2.0	5.1 – 10.7	0.93

3.7.2 Current modelling approach in the FARMLAND model

In FARMLAND [Brown and Simmonds, 1995], the interception factor, retention half-lives on the plant surface and translocation are all chosen to fit available experimental measurement data. The effective translocation of strontium, caesium and iodine predicted by FARMLAND for wheat and potatoes is given in Table 8. The data are presented as the percentage of the total deposit that is found in the crop at harvest as a function of the time deposition occurs before harvest. It is assumed that caesium is representative of elements that are mobile in plants while strontium is representative of elements which are less mobile and for which transfer within the plant is less important. For elements classed as immobile, it is assumed, based on experimental evidence, that the translocation process is not important and this transfer process is ignored [Brown and Simmonds, 1995]. The details of this classification are given in Table 9.

The earlier FARMLAND fruit model, based on apples, developed for continuous release applications was fitted to measured NSAs using Chamberlain's relationship to determine interception factors and retention half-lives on fruit [Mayall, 1995]. The interception factors and retention half-life used are discussed in Sections 3.5.2 and 3.6.2, respectively. The predicted NSAs from the model can be compared with those obtained from experimental data in Table 7 and are: 1.7 m^2 d kg^{-1} for strontium, 7.0 m^2 d kg^{-1} for caesium and 0.87 m^2 d kg^{-1} for plutonium.

Table 8 Predicted translocation of strontium, caesium and iodine for wheat and potatoes in the FARMLAND model

Time before harvest, d	Translocation (%)		
	Winter and spring wheat		Potatoes
	Strontium	Caesium & iodine	Caesium & iodine
0	~8	~3	0
30	1.5	1	10
60	0.3	6	7
90	0	2 (0.2[a])	3
120	0	0.6 (0[a])	0

a) values for spring wheat

Table 9 Mobility of elements in FARMLAND

Mobile*	Semi-Mobile†	Immobile‡
Phosphorus	Manganese	Chromium
Sulphur	Iron	Ruthenium
Chlorine	Cobalt	Cerium
Bromine	Nickel	Promethium
Selenium	Zinc	Europium
Rubidium	Strontium	Actinium
Technetium	Yttrium	Thorium
Tellurium	Zirconium	Protactinium
Iodine	Niobium	Uranium
Caesium	Molybdenum	Neptunium
	Silver	Plutonium
	Tin	Americium
	Antimony	Curium
	Barium	Lead
	Lanthanum	Polonium
	Radium	

* Mobile elements are assumed to be like caesium

† Semi-mobile elements are assumed to be like strontium

‡ Immobile elements are assumed to be like plutonium (actinides)

3.8 Agricultural practices

3.8.1 Literature

Growth stages of fruit crops and practices adopted for the growing and harvesting of fruit in the UK are required to determine which transfer processes govern the contamination of fruit at different times of the year. This is particularly important for situations involving accidental releases of radionuclides to atmosphere, when the presence or absence of the fruit or plant/tree at the time of deposition might have a significant effect on activity concentrations found in the fruit at the time of harvest. The agricultural practices adopted in the UK are given in Table 10 for some fruit species that are representative of the two categories of fruit being considered in this study [Outsider's Guides, 1995]. There is a clear difference between the harvesting practices for orchard fruit, e.g. apples, and those for soft fruit (herbaceous plant and shrub fruit). The majority of apples are picked within a very short period of time and then stored for consumption over the rest of the year [Jones and Sherwood, 2008]. Soft fruit is harvested both for immediate consumption and to be frozen or made into jam. In particular, raspberries, blackcurrants and gooseberries are often frozen or made into jam, both in the home and industrially [Jones and Sherwood, 2008].

Table 10 Agricultural practices in UK

Fruit	Planting	Fruit growing	Harvesting	Fruition life (years)	Availability for consumption from UK production
Apples (orchard)	Nov – Mar	Apr – Aug	Aug – Oct	12 – 15	Aug – Jun*
Strawberries (soft)	Mar	Apr – Jun	Jun – Jul	2 – 3	Jun – Oct
Everbearer strawberries (soft)	Apr	Apr – Jun	Aug – Oct	2 – 3	
Raspberries (soft)	Oct – Dec	Mar – Jul	Jun – Oct	10^	Jun – Oct

* Stored following harvest

^ 2 years to establish plant

3.8.2 Current modelling approach in the FARMLAND model

The FARMLAND fruit model [Mayall, 1995] has been developed for continuous release applications, where the objective is to calculate average annual activity concentrations. It assumes a growing period of 150 days with deposition starting at the beginning of the growing period. Agricultural practices for other crops in FARMLAND are taken into account [Brown and Simmonds, 1995] and are crop specific.

3.9 Fruit storage

3.9.1 Literature

Contamination of fruit can be reduced after harvesting by processing, e.g. peeling, and by storage in either a fresh or processed form. Storage losses are those due to radioactive decay between the time of harvesting and consumption. Carini (2000) and Jones and Sherwood (2008) recommend that, for conservative estimates, it should be assumed that there are no storage losses, i.e. the fruit is assumed to be consumed fresh immediately after harvesting.

The typical delay between harvesting and consumption for fresh apples and pears in the UK is between 1 day and 6 months, with a minimum delay before consumption of 0 days and an overall average of 3 months [Jones and Sherwood, 2008]. For soft fruit (strawberries, raspberries and blackberries), the average delay between harvest and consumption in the UK is about 4 days, with a minimum of 0 days with a typical range of 1 – 8 days. Fresh gooseberries and currants are less perishable due to their thicker skins with an average delay between harvest and consumption of 6 days with a typical range of 1 – 14 days [Jones and Sherwood, 2008].

Raspberries, blackcurrants and gooseberries are often frozen or made into jam, both in the home and industrially as discussed in Section 3.8. Frozen fruit is estimated to have a typical storage life of 2 weeks to 1 year with an average of 6 months [Jones and Sherwood, 2008]. This is probably also a reasonable assumption for jam.

3.9.2 Current modelling approach in the FARMLAND model

The FARMLAND model does not include any losses due to storage, although these may be taken into account in subsequent ingestion dose calculations.

3.10 Processing of fruit

3.10.1 Literature

Processing losses are observed as a result of preparing the food for consumption or storage, e.g. peeling the outer skin or washing. Carini (2000) also recommends that for a conservative estimate, it should be assumed that there are no losses due to processing. IAEA (1994) give an average food processing retention factor for apples, expressed as the ratio of total activity in processed food to total activity in raw food, of 0.76 for ^{134}Cs and 0.64 for ^{85}Sr. This parameter reflects the fraction of radionuclides retained on the skin, easily removable and not absorbed in the pulp of the fruit.

Bengtsson (1992) found that 1 day after spraying apple trees with an aerosol of ^{85}Sr and ^{134}Cs, 60% of the activity in the peel could be rinsed off the fruits for both radionuclides. Two further rinsings released much smaller fractions. At longer times following contamination (41 days and 84 days) the pattern differed between the two radionuclides with similar amounts of strontium being removed by rinsing and significantly lower amounts of caesium being washed off (7% at 41 days and 0.4% at 84 days). The author concluded that the fruit skin was a barrier to direct uptake of strontium and that some penetration of caesium cannot be excluded. However, the main factor influencing the results was the translocation of caesium from foliar contamination to the pulp of the fruit, some of which was incorporated into the pith-like layer under the skin which comprised part of the peelings measured (a 3mm layer).

Delmas *et al* (1969) reported a 73% removal of ^{90}Sr and a 39% removal of ^{137}Cs from apples following a 30 minute rinsing with water. Carini *et al* (1999) measured the impact of rinsing apples and fruit at harvest following aerial deposition 50 days earlier. Rinsing was found to remove 14% of ^{134}Cs and 10% of ^{85}Sr. Other data reviewed by Carini *et al* (1999) on the effectiveness of rinsing of fruit following the Chernobyl accident confirm, in general, the results from specific research studies. Rinsing removed 10 - 20% from berries, 25 - 30% from strawberries and soaking berries in water for 30 - 35 hours removed 30 - 60%.

Green and Wilkins (1995) studied processing losses for different combinations of foods and radionuclides. The processing losses are quantified as a processing factor, which is the fraction of the original activity concentration that remains after processing. Some of the results from this study for fruit are given in Table 11, for information.

There are no fruit processing factors measured specifically for actinides. For actinides, which are immobile, relatively small amounts of activity are likely to be found in the fruit flesh, the majority of activity remaining on the skin. Preparation techniques that remove or clean the skin are, therefore, likely to lead to larger reductions in overall activity concentrations in the fruit for actinides, i.e. lower processing factors, than those given in Table 11 for more mobile elements.

Table 11 Processing factors for fruit[+]

Type	Radionuclide	Preparation of fruit	Processing factors[*,$]
Blackcurrant	^{137}Cs	Wash	0.90
	^{103}Ru	Wash	0.7
Blueberry	^{137}Cs	Puree	0.72 – 0.85
Cherry	^{137}Cs	Stoned	0.78
	^{134}Cs	Stoned	0.71
	^{137}Cs	Can in syrup	0.85
	^{90}Sr	Can in syrup	0.54
	^{131}I	Stoned	0.7
	^{103}Ru	Stoned	0.35
	^{60}Co	Can in syrup	0.44
Peach	^{90}Sr	Mechanical peel	0.5
	^{90}Sr	Can	0.5
Pear	^{137}Cs	Can in syrup	0.73
	^{90}Sr	Can in syrup	0.63
	^{60}Co	Can in syrup	0.67
Redcurrant	^{137}Cs	Wash	0.79
Strawberry	^{137}Cs	Wash	0.6 – 0.88
	^{90}Sr	Wash	0.7 – 0.88

$The processing factor is defined as the fraction of the original activity concentrations that remains after processing

*Ignoring juice extraction

+ Taken from Green and Wilkins (1995)

3.10.2 Current modelling approach in the FARMLAND model

The FARMLAND fruit model [Mayall, 1995] applies a processing factor of 0.6 to the activity concentration on the external surface of the fruit; this represents basic washing and peeling of the fruit. No processing losses are applied to the contamination in the internal fruit pulp. The FARMLAND model does not include any losses due to storage, although these may be taken into account in subsequent ingestion dose calculations.

4 MODELLING APPROACH

The different contamination processes of importance have been combined in a compartment model to predict the transfer of radionuclides through the fruit plant/tree and the surrounding soil. Due to the lack of data for many of the processes, a simple approach has been adopted, commensurate with the data available.

The processes included in the model are listed in Table 12 and are discussed in detail below. The default agricultural practices that should be taken into account when using the model are presented in Section 4.7. All the contamination pathways included in the conceptual model for fruit (see Figure 1) suggested by the Fruits Working Group of the IAEA BIOMASS programme have been included [Carini *et al*, 2005].

Table 12 Transfer processes included in model

Process	Included	Discussion (Section)	Description of available data (Section)
Interception	Yes	4.1	3.5
Translocation	Yes (element dependent)	4.2	3.7
Weathering	Yes	4.3	3.6
Resuspension	Yes (first growing season only)	4.4	3.4
Root uptake	Yes	4.5	3.1
Direct soil contamination	Yes	4.6	3.2
Soil migration	Yes	4.5	3.3
Processing losses	Yes	4.8	3.10

4.1 Interception

Interception by the vegetative part of the plant and the fruit are considered separately. Interception is not included consistently in the available fruit models. Some consider interception to the fruit and leaves separately, while others only include either interception to the leaves or to the fruit.

4.1.1 Interception by the plant

Some data are available on the interception of caesium and strontium by strawberry plants. Interception factors range from about 20 - 45% with the highest interception being at anthesis, i.e. when flowers are present and green fruits are starting to form. Given the lack of data on the interception of material by other fruit plants and trees, the interception fraction, 74%, suggested by Kinnersley and Scott (2001) as being applicable regardless of crop type or conditions, has been used in the model.

4.1.2 Interception by the fruit

As discussed in Section 3.5, there are very few data on interception by fruit in the literature. Pinder III *et al* (1987) estimated an interception fraction for oranges on mature trees of 0.8%. Carini *et al* (2003) measured interception of strontium and caesium on strawberries of 0.2 - 1.2%. The interception factor depends on the stage of development of the fruit at the time of deposition and the biomass of the fruit at that time. The Chamberlain equation can be used to relate the interception by crops to the mass via an interception coefficient (see Section 3.5.1). Although this equation was developed based on the mass of entire crops rather than specific parts, it is deemed appropriate to use it to calculate the interception fractions for each of the fruit categories considered in the model, based on an interception coefficient deduced from the experimental data. The data from Pinder III *et al* (1987) were used and Appendix B provides details of this calculation. The data from Carini *et al* (2003) were not available at the time of the initial development of the model. However, it can be seen that the calculated interception factor for soft fruit of 0.3% (see Table B3) is in the range of values reported for strawberries, although it is an underestimate of what could be intercepted by fruit in the latter stage of ripening.

The available fruit models vary in that some consider interception to the fruit and leaves but some only include interception to either the leaves or the fruit.

4.2 Translocation

Results of studies on the ability of radionucldies to penetrate the fruit skin are inconclusive with most studies providing evidence that the fruit skin is an effective barrier to absorption of radionuclides [Carini and Bengtsson, 2001]. Even if some of the activity intercepted by the fruit surface is translocated to the fruit pulp, mobile elements also transfer from the plant surface to the internal fruit and, for caesium, a high rate of translocation from the foliage is observed [Bengtsson, 1992; Carini *et al*, 1999]. As the fruit itself intercepts far less deposited activity than the plant and the process of translocation from plant to the fruit dominates the overall translocation process, translocation through the fruit surface will not be an important contributor to activity concentrations in fruit at harvest and has not been considered in the model.

There is an apparent conflict betwen the available experimental data on the fractions of translocated activity that are found in fruit after a single deposition and the NSA values reported in Mayall (1995) for continuous deposition. For caesium, the fractions of intercepted activity onto the foliage that reaches the fruit following a single deposition are typically in the range of 20 - 40% for apples, although one value of 6% has also been observed. For strawberries, the corresponding range was 5 - 35%. Values of a few percent being translocated were observed in other berries, lower than those for apples and strawberries. The reported NSA values, 5.1-10.7 m^2 d kg^{-1} dry mass, are however much lower than these translocation fractions would suggest but the reported NSA values do indicate that there is a higher translocation of caesium compared to strontium.

To fit to both types of data an empirical modelling method has been used that transfers activity through the fruit plant and into the fruit. The individual transfer processes in the model that have been used to fit to the data are not representative of any particular physical processes and have been used merely to obtain satisfactory activity concentrations in the fruit at harvest from translocation. In particular, the model includes the transfer of activity from the internal fruit to the soil. There is no physical process causing such a transfer, but it is used within the model to prevent the activity concentration in the internal fruit from building up excessively.

The translocation transfer rates derived for use in the model for mobile elements, i.e. based on caesium, give a peak of about 15% of the activity transferred from the external plant surfaces to the fruit, which occurs around 30 days following deposition. This is within the range of values observed for fruit, although the value is lower than values observed for ripening and developed fruit. The calculated NSA for the model is approximately 25 m^2 d kg^{-1} dry mass which is higher than the range of reported NSA values. The model is, therefore, a balance between the different types of available data.

The transfer rates in the model for the translocation of semi-mobile elements, represented by strontium, are scaled from the translocation of mobile elements to give a satisfactory peak and NSA. The peak activity concentrations occur at about 20 - 30 days following deposition, similar to caesium. The calculated NSA for the model is approximately 1.7 m^2 d kg^{-1} dry mass, which is in the middle of the range of reported NSA values (see Table 7).

Translocation of immobile elements, represented by plutonium, is not included in the model as there is no evidence that any significant activity is translocated to fruit from foliar contamination [Pinder III *et al*, 1987]. This assumption is consistent with that assumed for other crops in the FARMLAND model [Brown and Simmonds, 1995].

Only some of the available fruit models include translocation from external plant surfaces to the fruit either directly or via the internal part of the plant. The ECOSYS model [Müller and Pröhl, 1993], for example, uses translocation factors expressed as the proportion of the deposition onto the plant that is transferred to the fruit at harvest for deposition occurring at different times before harvest (see Appendix A). The translocation factor used for mobile elements of 10% for deposition occurring between 14 days and 6 months is reasonably consistent with the peak value of 15% for deposition occurring 30 days before harvest chosen for the FARMLAND model.

4.3 Weathering

The rate at which the activity on the fruit and the plant/tree is weathered off on to the soil has been calculated using a weathering half-life. Only limited data are available on losses from fruit plants and fruit from natural weathering for plants grown under field conditions. For fruit trees and plants, a value that is consistent with other crops in FARMLAND [Brown and Simmonds, 1995] has therefore been assumed as a default. This value is 14 days. For fruit, there is a small amount of evidence in the literature (see Section 3.6.1) that the weathering half-life may be longer than that for the plant. However, there are not enough data to support a different value to that used for plants and a value of 14 days has also been used as a weathering half-life for the categories of fruit considered in the model.

The sensitivity of the predicted activity concentrations in fruit to the choice of weathering half-life chosen was investigated as part of the earlier fruit model development for actinides [Teale and Brown, 2003]. The results showed that the activity concentrations for immobile elements are only sensitive to the weathering half-life chosen for the first harvest when direct deposition to the plant and fruit occur. The predicted activity concentrations are most sensitive to the choice of weathering half-life when deposition occurs a few months before harvest; differences of 2-3 orders of magnitude are observed between weathering half-lives of 14 days and 90 days. The closer deposition occurs to the harvest, the less sensitive the activity concentrations in fruit become to this parameter. For mobile elements, the differences will be much smaller due to the significant contribution of contamination in the fruit from translocation from the foliage, which is not present for immobile elements. Due to the paucity of the available data, the use of 14 days is justified to be consistent with the weathering half-lives reported for other crops. It has also been shown that, based on limited validation of the model (see Section 7), the model predictions agree reasonably well with measured values in fruit.

All of the available fruit models include weathering from external plant surfaces but it is not clear whether they also include weathering from the fruit external surfaces in most cases. The SPADE fruit model [Mouchel Consultancy, 1999], for example, uses a 'washoff' transfer from the external leaf of the plant to the soil that also includes a contribution from leaf fall and is equivalent to a half-life of approximately 9 days. There are no weathering losses from the fruit itself in the SPADE model.

4.4 Resuspension

Resuspension is modelled as a transfer from the soil to the fruit surface or external plant surface, based on the resuspension rate, deposition velocity and interception fraction for the fruit category or the plant. Garland's formula for the resuspension factor [Garland *et al*, 1992] has been used and resuspension has been modelled using a resuspension factor that has been averaged over the first growing season. The formula used is:

resuspension factor $= \dfrac{1.210^{-6}}{t}$, where $t \geq 1$ is the time in days after deposition

The resuspension rate according to this formula is small for long times after deposition. Therefore, it is assumed that there is no resuspension in subsequent years.

Continuously varying parameters are not always compatible with compartment models. Therefore a single mean resuspension factor, k_m, for the growing and harvesting period is required. Various approximations have been made to facilitate the incorporation of this relationship into the FARMLAND model and these are described in Brown and Simmonds (1995). It was decided in Brown and Simmonds (1995) that due to the uncertainties inherent with the approach and the similarities between the resuspension factors calculated for the different crops for continuous and routine release applications, the use of a single default resuspension factor was justified. In order to maintain consistency with the existing FARMLAND crop models it was decided that this resuspension factor should also be used for the fruit model. The value for the resuspension factor used is $8\ 10^{-8}\ m^{-1}$.

For most of the other fruit models studied, it is not clear whether they consider resuspension from soil to fruit and plant surfaces explicitly. The SPADE model [Mouchel Consultancy, 1999], for example, uses a transfer from the soil to the external plant to represent resuspension for actinides only. The ECOSYS model (see Appendix A) [Müller and Pröhl, 1993], uses an average resuspension factor of $2.5\ 10^{-8}\ m^{-1}$, which is within the range of values calculated for use in the FARMLAND model (see Section 5.1.2). The deposition velocity of resuspended particles onto the crop surface used by ECOSYS ($10^{-3}\ ms^{-1}$) is also the same as that used in FARMLAND.

4.5 Root uptake and soil migration

Soil-to-plant transfer factors (TF) give the ratio of the activity concentration in the plant compared with the soil, assuming that the soil has been contaminated for the duration of the growing period. Many of the models use parameter values for soil-to-plant transfer that are derived from equilibrium models in the absence of detailed dynamic data, although some do attempt to model time-dependent transfer [Ould-Dad *et al*, 2006]. The ECOSYS model (see Appendix A) [Müller and Pröhl, 1993] assumes that the contamination due to root uptake is directly proportional to the fraction of the growing season for which the soil has been contaminated. The FARMLAND model approach [Brown and Simmonds, 1995] assumes that the soil and plant reach equilibrium very quickly and hence the TF is attained at harvest regardless of when deposition occurs.

For deposition during the growing season, the activity concentrations in fruit at the first harvest will be dominated by contamination due to direct deposition. The differences in the two approaches adopted in FARMLAND and ECOSYS will, therefore, not have a significant effect on the predicted overall activity concentrations in fruit. At subsequent harvests, when the soil has been contaminated for the whole of the growing season, the FARMLAND and ECOSYS modelling approaches are essentially the same. On this basis, the FARMLAND approach has been used, as it is easier to incorporate it into a compartment model. This approach is also consistent with that adopted in most of the other fruit models that have been developed.

For immobile elements, any soil contamination of plant samples used to obtain soil–to-plant transfer factors can have a very marked effect on the activity concentration in plants that are observed. Hence, it is very important to choose transfer factors where experimental conditions are known. The default transfer factors in the model are biased towards data for the UK and where experimental methods are known in detail. In the study by Green *et al* (1997), the fruit was thoroughly washed before the transfer factors were measured. It is therefore reasonable to assume that the measured transfer factors do not contain a contribution due to soil contamination. The values from the study by Green *et al* (1997) have therefore been used for the fruit model, with the assumption that soil contamination is not included in these values (see Table 5 and Table 6).

The study by Green *et al* (1997) provides data on root uptake transfer factors for caesium, strontium, plutonium and americium, but not for other elements. There are also very few data on any of the other elements in Carini (2001). In the absence of specific information, one approach that has been adopted for assessment purposes in the past has been to assume that root uptake by fruit is similar to that for green vegetables; this was deemed to not be unduly cautious by Green *et* al [Green *et al*, 1997]. For the purposes of this model, the root uptake transfer factors for fruit have been assumed to be the same as those in the FARMLAND cereal model [Brown and Simmonds, 1995]. In reality, the choice of adopting root uptake transfer factors for green vegetables or cereals is effectively the same, as for the majority of elements the same value is used for both food categories due to the scarcity of data.

The transfer factors found in the literature are calculated using the activity concentration in the top 30cm of the soil [Green *et al*, 1997]. This is also consistent with the approaches adopted in the FARMLAND and ECOSYS models. The soil depth in the model is assumed to be 30cm deep to make it consistent with the measurement data without making any assumptions about the depth to which fruit plants/trees can extract radionuclides from the soil. The use of root uptake factors calculated assuming that the activity concentration in the top 30 cm is uniformly mixed may lead to activity concentrations from root uptake being overestimated in the first few years following a single deposition, as the tree root system may be below the contaminated surface layers of soil. However, this is unlikely to be significant, particularly in the first year when activity concentrations in fruit will be at their highest and direct deposition processes dominate the overall activity concentrations.

A slow loss from the system due to radionuclides migrating down the soil profile, out of the range of the roots, has also been included. This is the approach adopted for all crops grown on cultivated land in FARMLAND [Brown and Simmonds, 1995]. Orchards may contain soil that has remained undisturbed for a number of years. However, for consistency with the root uptake data used, it has been assumed that the soil is well mixed as discussed above and soil migration as a function of depth is not modelled. It is not thought that this assumption will have any significant impact on the predictions of the model.

4.6 Direct soil contamination

Direct soil contamination has been modelled separately from root uptake. There are no data on the contamination of fruit by soil in the literature, as discussed in Section 3.2.1. In the FARMLAND model this process is described for other crops using a parameter that represents the amount of soil on the crop as a percentage of its dry mass at harvest. Given the height at which orchard fruit grow, it has been assumed that they are not susceptible to soil contamination. Soft fruit (herbaceous plant and shrub fruit) grow much closer to the ground and it is therefore likely that levels of soil contamination on the surface of the fruit are similar to those observed on other farm crops. A default value has been chosen to be the same as that for green vegetables in the FARMLAND model [Brown and Simmonds, 1995], i.e. 0.1% of the dry mass of the fruit is present as soil at harvest. This level of soil contamination is likely to be representative for domestically produced herbaceous fruit but, for commercially grown herbaceous fruit, such as strawberries, which are often grown on straw-covered soil to prevent such contamination, it is likely to give a cautious estimate. For shrub fruit, the assumption is likely to overestimate soil contamination. It is suggested that a value greater than 0.1% should only be used if information is available to suggest soil contamination of the fruit is significantly higher. For accidental releases occurring during the growing or harvesting periods, the contribution from direct deposition will always dominate the activity concentrations and therefore the default value of 0.1% is appropriate. For continuous release applications, the integrated activity concentrations are not very sensitive to the level of soil contamination chosen. It is therefore appropriate to use the default value of 0.1%.

There is no information to suggest that the other available fruit models consider direct soil contamination of fruit explicitly although it is recognised as a contamination pathway in the BIOMASS conceptual fruit model [Carini *et al*, 2005].

4.7 Agricultural practices

The year has been split up into periods during which the model is set up differently to reflect, for example, growing periods, including periods when the fruit is not present and harvesting periods. As the model is centred on the fruit part of the plant, it is important for the growing period to relate to the time when fruit has developed sufficiently for the transfer processes to begin. The actual growth stage at which a fruit is recognised as present, from the point of view of modelling the various processes, is not clear. For example, material that is deposited on the blossom from which an apple develops should certainly not be ignored in the modelling process. This is further complicated because the start of the growing season is also dependent on the weather conditions, which can vary significantly from region to region and year to year. To maintain a simple approach, a date, 15th April, was chosen to be representative of the start of the growing season that is applicable for all fruits based on the review in Section 3.8. This time represents when the plant/tree is in blossom and contamination of the 'fruit part' could start.

Orchard fruit, in particular apples, are harvested over a very short period and stored for consumption over the whole year. This has been modelled by an instantaneous harvest, when it is assumed that all of the fruit is removed from the trees. This instantaneous harvest is therefore equivalent to removing all of the activity from the fruit system, leaving only the contamination in the soil and plant. Activity from the plant is assumed to be returned to the soil at leaf fall in the autumn and no activity is left on the branches and trunks of bushes and trees. This assumption is reasonable as there is no evidence that significant activity is transferred from trunks and branches to fruit (see Section 3.7.1).

Table 13 Agricultural practices for fruit in the UK

	No fruit	No fruit	Fruit growing	Harvesting
	No plant	Plant present	Plant present	Plant present
Orchard fruit	15th Sept – 1st Apr	1st Apr – 15th Apr	15th Apr – 15th Sept	15th Sept
Soft fruit	31st Oct – 1st Apr	1st Apr – 15th Apr	15th Apr – 15th Jun	15th Jun – 31st Oct

Soft fruit are typically harvested over a period and consumed within a few days of harvesting. This has been modelled by taking a harvesting period over which the fruit is consumed directly from the field. The dates assumed are given in Table 13. Although there is a loss of activity from the whole system during the regular harvesting periods, the harvesting itself does affect the activity concentration in the fruit left in the field. To calculate the activity concentrations during the harvesting period, it has been assumed that there are no losses to either the activity or the mass of the fruit in the field during harvesting. The overall loss of activity from the system is accounted for at the end of the harvesting period, when all of the activity in and on the fruit is removed. As for orchard fruit, it is assumed that any remaining activity on the plant is returned to the soil at the end of the harvesting period, reflecting leaf fall or the plant dying back.

The fruition life of the fruit plants/trees is not taken into account but the assumptions made in running the model mean that this does not have any influence on the predicted activity concentrations. As old fruit plants come to the end of their useful life, it is assumed that newer plants will be producing their first fruits for consumption. In this way, the total amount of fruit that is grown per area of soil is assumed to remain the same throughout the period that the model is run for. Any loss of activity from the system due to old plants being removed from the field has been ignored to give a conservative estimate of the activity in the soil. In the case of herbaceous and shrub fruit, this may be thought of as the plants being ploughed back into the soil at the end of their useful life.

Everbearer strawberries are produced later in the year than regular strawberries to extend the length of time for which strawberries are available in the UK. For modelling purposes, these two sets of agricultural practices have been merged. As a result, the total length of the growing and harvesting periods appear long, but the results produced by the model are a robust measure of the activity in the consumed strawberries for the duration of the harvesting period, taking into account the range of varieties. The harvesting period is shown in Table 13.

It is not necessary to model the distinct growing periods explicitly a long time after the initial deposition because the transfer processes important in the long term do not lead to activity concentrations varying significantly with time. It is sufficient to adopt an averaging approach to estimating activity concentrations for these later times and thus, the periods of harvesting, growing and the period when there is no fruit present are merged into one continuous cropping period.

The time of the year when a single deposition occurs has a marked influence on the subsequent transfer to fruit. This explains the major differences observed between the predicted activity concentrations in the fruit at harvest for deposition occurring at the three times of the year considered, as presented later in Section 6. For the application of the model to assessments on the effect of continuous releases to atmosphere, the assumptions made on agricultural practices can be simplified. The assumption is made that the deposition is continuous and constant throughout the year. It is therefore unnecessary to model explicitly the details of agricultural practices, e.g. the start of the growing season and harvesting periods, and the relation of these to the time of deposition. Further details are given in Section 6.2.

4.8 Processing and storage losses

Fruit is often consumed in an unprocessed state, although many types are usually washed prior to eating. The model presented here does not include extra losses from preparation or processing of fruit prior to consumption. It is however possible to take account of these losses by adjusting the predicted activity concentrations. It is important to note that, if preparation factors, such as washing, are applied to the results of the model, they should only be applied to the contamination on the external surfaces of the fruit.

As orchard fruit are harvested and then stored throughout the year for consumption, radioactive decay between harvest and the time of consumption following each harvest should also be considered in the calculation of radiation doses arising from ingestion of orchard fruit. This is also the case if it is known that a large proportion of the fruit harvested, for example some types of soft fruit, is frozen prior to consumption. Typical storage times for fresh and preserved fruit are given in Section 3.9.

4.9 Types of model

Two different modelling approaches have been adopted in the terrestrial foodchain models reviewed in this study. Some of them use dynamic compartment models to predict the flow of contamination through the plant/soil system. Others, such as ECOSYS, [Müller and Pröhl, 1993] use a series of separate formulae to calculate the final activity concentrations in the fruit. The ECOSYS formulae contain exponential decay and multiplying factors and so are essentially equivalent to a compartment model. For example, in a compartment model exponential decay is modelled using transfers out of a compartment and multiplying factors can be modelled using two transfers between two compartments, so that they will be in the required ratio at equilibrium.

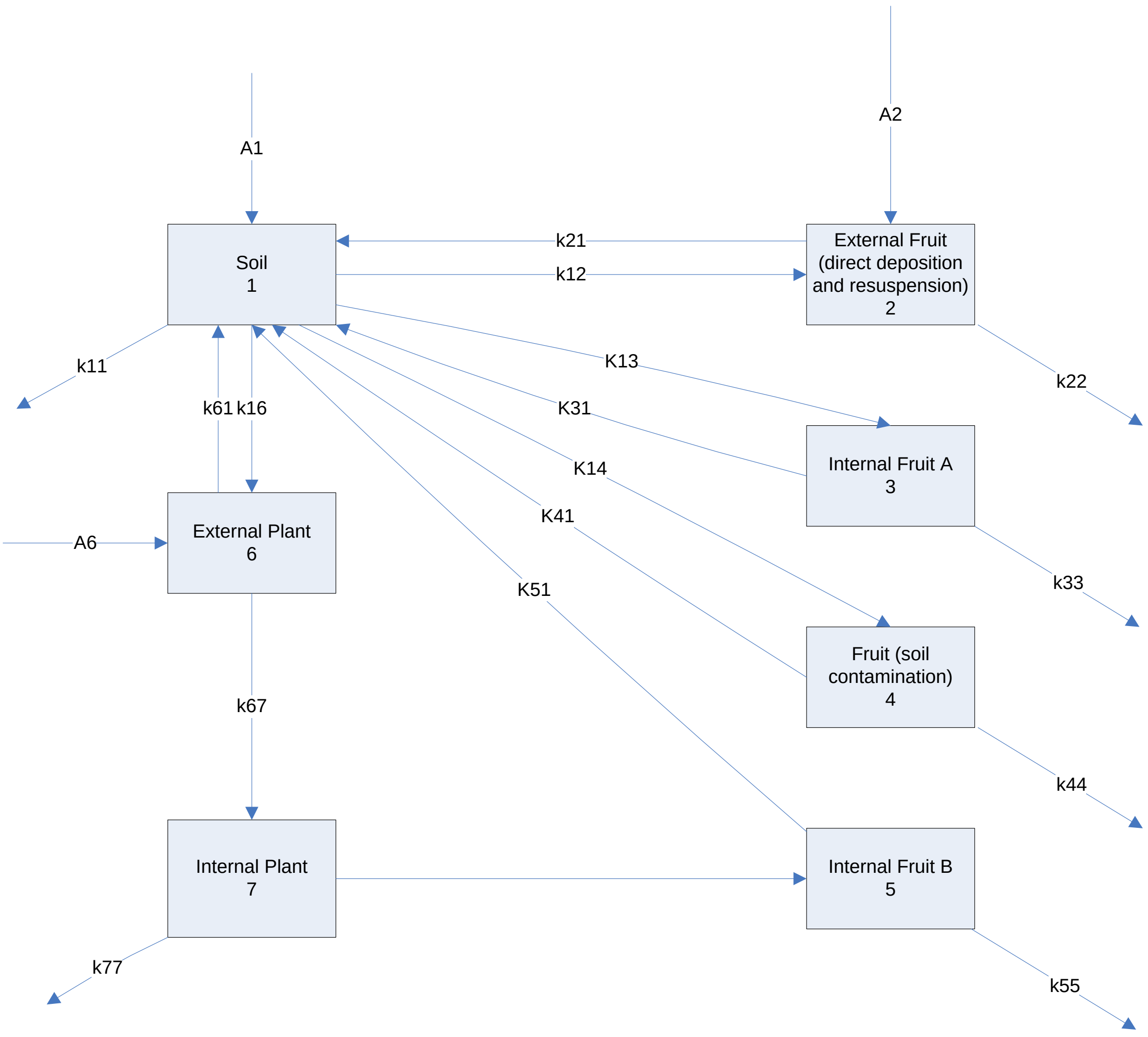
Compartment models have the advantage of allowing several different pathways to interact with one another, for example, as contaminants are weathered off the fruit surface onto the soil, the activity concentration in the soil increases, and hence the contamination due to root uptake will increase. Although such effects are likely to be small, compartment models manage the transfer of activity in a more controlled way and are therefore recommended for the model developed in this study.

The review of the processes included in the available models and the BIOMASS conceptual fruit model [Carini *et al*, 2005] has ensured that all processes that could contribute to the contamination of fruit have been considered in the modelling approach developed for the transfer of radionuclides to fruit.

5 MODEL DESCRIPTION

The reviewed data have been used to produce a compartment model, and this is shown in Figure 2. The default parameter values used to calculate the transfer rates, losses and sources for the model are given in Table 14 -Table 16. Two fruit categories are considered in the model, orchard fruit and soft fruit. Where necessary, different parameter values have been used for the two fruit categories. The orchard fruit model is to be used for fruits such as apples, pears and plums. The soft fruit model is to be used for fruits such as strawberries, raspberries and blackcurrants. In the following

Section, the term 'plant' is used as a generic term for plant, woody shrub or tree, i.e. the foliar part.



Notation:

Ai is the initial inventory (accident) or the source (continuous) for compartment i
kij is the transfer rate (d^{-1}) from compartment i to compartment j (i≠j)
kii is the loss rate (d^{-1}) from compartment i

Figure 2 Compartment Model Structure

Table 14 Element-Independent default parameter values used in model

Parameter	Description	Default Value	Units	Reference / Section
WM	Fresh mass of fruit	1.7 (orchard fruit)	kg m^{-2}	See Appendix B
		1.3 (soft fruit)		
%WTR	Percentage water content of fruit	84 (orchard fruit)	%	Carini, 2001
		90 (soft fruit)		
SDEN	Soil density (dry)	1.5 10^3	kg m^{-3}	Brown and Simmonds, 1995
SDEP	Soil depth	0.3	m	Green *et al*, 1997
P_f	Interception fraction (fruit)	0.007 (orchard fruit)	-	See Appendix B
		0.003 (soft fruit)		
P_p	Interception fraction (plant)	0.74	-	See Section 4.1
V_d	Deposition velocity	86.4	m d^{-1}	See Section 4.4
λ_f	Weathering half-life (fruit)	14	d	See Section 4.3
λ_p	Weathering half-life (plant)	14	d	See Section 4.3
λ_s	Soil migration half-life	36500	d	Brown and Simmonds, 1995
RF	Resuspension factor	8 10^{-8}	m^{-1}	See Section 4.4
X	Percentage of fruit dry mass that is present as soil at harvest	0 (orchard fruit)	%	See Section 4.6
		0.1 (soft fruit)		
EQ	Equilibrium factor	8.64 10^4	d^{-1}	See Section 5.1.5
DEP	Deposition	Run dependent		-

Table 15 Parameters calculated directly from Default Parameters in Table 14

Parameter	Description	Default Value	Units	Formula
DM	Dry mass of fruit	0.27 (orchard fruit)	kg m^{-2}	$WM \cdot \frac{100 - \%WTR}{100}$
		0.13 (soft fruit)		
SMASS	Soil mass (dry)	4.5 10^2	kg m^{-2}	SDEN * SDEP

Table 16 Element-Dependent default parameter values used in model

Parameter	Description	Element	Default Value		Units	Reference
			Orchard fruit	Soft fruit		
TF	Root Uptake Transfer Factor	Caesium	3.0 10^{-3}	3.0 10^{-3}	Bq kg^{-1} fresh mass fruit / Bq kg^{-1} dry mass soil	Green *et al.*, 1997 Carini, 2001
		Strontium	2.0 10^{-2}	2.0 10^{-2}		
		Plutonium	1.0 10^{-5}	1.0 10^{-5}		
		Americium	1.0 10^{-5}	1.0 10^{-5}		
		Phosphorus	1.0 10^{0}	1.0 10^{0}		Brown and Simmonds, 1995 (Root uptake transfer factors have been revised for polonium and radium since the publication of Brown and Simmonds, 1995)
		Sulphur	6.0 10^{-1}	6.0 10^{-1}		
		Chlorine	5.0 10^{0}	5.0 10^{0}		
		Chromium	3.0 10^{-4}	3.0 10^{-4}		
		Manganese	1.0 10^{-1}	1.0 10^{-1}		
		Iron	4.0 10^{-4}	4.0 10^{-4}		
		Cobalt	5.0 10^{-3}	5.0 10^{-3}		
		Nickel	1.0 10^{-2}	1.0 10^{-2}		
		Zinc	1.0 10^{0}	1.0 10^{0}		
		Bromine	2.0 10^{-2}	2.0 10^{-2}		
		Selenium	1.0 10^{0}	1.0 10^{0}		
		Rubidium	1.0 10^{-1}	1.0 10^{-1}		
		Yttrium	1.0 10^{-2}	1.0 10^{-2}		
		Zirconium	1.0 10^{-4}	1.0 10^{-4}		
		Niobium	1.0 10^{-2}	1.0 10^{-2}		
		Molybdenum	1.0 10^{-1}	1.0 10^{-1}		
		Technetium	5.0 10^{0}	5.0 10^{0}		
		Ruthenium	1.0 10^{-2}	1.0 10^{-2}		
		Silver	2.0 10^{-1}	2.0 10^{-1}		
		Tin	2.0 10^{-1}	2.0 10^{-1}		
		Antimony	1.0 10^{-2}	1.0 10^{-2}		
		Tellurium	3.0 10^{-3}	3.0 10^{-3}		
		Iodine	2.0 10^{-2}	2.0 10^{-2}		
		Barium	1.0 10^{-2}	1.0 10^{-2}		
		Lanthanum	3.0 10^{-3}	3.0 10^{-3}		
		Cerium	1.0 10^{-3}	1.0 10^{-3}		
		Promethium	3.0 10^{-3}	3.0 10^{-3}		
		Europium	3.0 10^{-3}	3.0 10^{-3}		
		Iridium	1.0 10^{-2}	1.0 10^{-2}		
		Lead	1.0 10^{-2}	1.0 10^{-2}		
		Polonium	3.0 10^{-2}	3.0 10^{-2}		
		Radium	7.0 10^{-3}	7.0 10^{-3}		
		Actinium	1.0 10^{-3}	1.0 10^{-3}		
		Thorium	5.0 10^{-4}	5.0 10^{-4}		
		Protactinium	4.0 10^{-2}	4.0 10^{-2}		
		Uranium	1.0 10^{-3}	1.0 10^{-3}		
		Neptunium	2.0 10^{-3}	2.0 10^{-3}		
		Curium	2.0 10^{-5}	2.0 10^{-5}		

5.1 Calculation of model transfer rates

5.1.1 Interception

For a deposit during the growing or harvesting season while the fruit is present, the proportion of the deposit that is intercepted by the external fruit is dependent on the fruit yield, as described in detail in Appendix B. A fixed value for the interception by the plant is used while the fruit crop is growing or during the harvesting period. All of the deposit is assumed to be onto the soil when there is no plant present in the field. The interception fractions, A1, A2 and A6 are calculated using the parameters in Table 14, where the parameter abbreviations used below are also defined.

- Growing and harvesting

A1: deposition onto soil = (1-P_f-P_p) . DEP
A2: deposition onto external fruit = P_f . DEP
A6: deposition onto plant = P_p . DEP

- Plant present, but no fruit present

A1: deposition onto soil = (1-P_p) . DEP
A2: deposition onto external fruit = 0
A6: deposition onto plant = P_p . DEP

- No fruit present, no plant present

A1: deposition onto soil = DEP
A2: deposition onto external fruit = 0
A6: deposition onto plant = 0

5.1.2 Resuspension and subsequent interception

It was decided in Brown and Simmonds (1995) that due to the uncertainties inherent with the approach adopted for modelling resuspension and the similarities between the resuspension factors calculated for the different crops for continuous and routine release applications, the use of a single default resuspension factor was justified. In order to maintain consistency with the existing FARMLAND crop models it was decided that this resuspension factor should also be used for the fruit model. Default values are given in Table 17. The interception fractions, P_f and P_p, are the same as those used in Section 5.1.1 for the initial interception. Other parameter values are given in Table 14 where the parameter abbreviations used below are also defined.

- Growing and harvesting, up to first harvest

k12: resuspension to fruit = RF . V_d . P_f
k16: resuspension to plant = RF . V_d . P_p

- Plant present, but no fruit present, up to first harvest

k12: resuspension to fruit = 0
k16: resuspension to plant = RF . V_d . P_p

• No fruit present, no plant present, up to first harvest

k12, k16: resuspension = 0

• After first harvest

k12, k16: resuspension = 0

Table 17 Resuspension Factors (RF) up to the end of the first harvest

Release	Fruit	Resuspension Factor (m^{-1})
Accidental	Orchard	$8\ 10^{-8}$
	Soft	$8\ 10^{-8}$
Continuous	Generic	$8\ 10^{-8}$

5.1.3 Weathering

Weathering is modelled using a transfer from the external fruit and the external plant to the soil, based on a weathering half-life, the default value for both the plant and fruit (14 days) is given in Table 14 where the parameter abbreviations used below are also defined.

• Growing, harvesting (first harvest only)

k21: fruit weathering rate = ln2 / λ_f
k61: plant weathering rate = ln2 / λ_p

• No fruit

k21: fruit weathering rate = 0
k61: plant weathering rate = ln2 / λ_p

• After first harvest

k21: fruit weathering rate = 0
k61: plant weathering rate = EQ

After the first harvest, all activity on the external surfaces of fruit is removed via harvesting and is not present in subsequent years. All activity on the external plant surfaces is assumed to be removed at the end of the harvesting period either from the plant dying back or leaf fall; this activity is returned to the underlying soil.

• All subsequent years

k21: fruit weathering rate = 0
k61: plant weathering rate = 0

5.1.4 Translocation

Translocation is modelled using three transfers: one from the external plant to the internal plant, the second from the internal plant to the internal fruit, and the third from the internal fruit to the soil.

- Growing and harvesting, up to first harvest

Translocation transfer rates, k67, k75 and k51, have been fitted to experimental data based on the mobility of the radionuclides. The transfer rates are given in Section 5.2, Table 23.

- After first harvest

k67, k75, k51: translocation = 0

5.1.5 Root uptake

Data on root uptake are in the form of a transfer factor, which describes the ratio between activity concentrations in the fruit and those in the soil at equilibrium (see Section 3.1). To model this process, a pair of transfer rates is used between the soil and the internal fruit compartment of the model. To ensure that the ratio of the activity concentration in the fruit to that in soil agrees with the measured transfer factor at harvest, it is important that equilibrium between the two compartments of the model is reached quickly. To achieve this, a very fast transfer rate from internal fruit to soil is used with a value of $8.64\ 10^{4}\ d^{-1}$, i.e. $1\ s^{-1}$. The parameters needed to calculate the root uptake transfer rates are given in Table 14 and Table 15. Table 14 also gives the definitions for the parameter abbreviations used below.

- Growing, harvesting and continuous cropping

k13: uptake = TF . (WM / SMASS) . EQ
k31: uptake balance = EQ

- No fruit

k13: root uptake = 0
k31: root uptake balance = 0

5.1.6 Direct soil contamination

Direct soil contamination is modelled using a pair of transfer factors that are in the correct ratio to achieve the required percentage, x, of fruit mass that is present as soil at harvest. The parameters needed to calculate the soil contamination transfers are given in Table 14 and Table 15. Table 14 also gives the definitions for the parameter abbreviations used below.

- Growing, harvesting and continuous cropping

k14: uptake = x / 100 . (DM / SMASS) . EQ
k41: uptake balance = EQ

• No fruit

k14: root uptake = 0
k41: root uptake balance = 0

5.1.7 Cropping

A fast loss from each of the fruit/plant compartments is used to model the instantaneous loss of activity at the end of the harvesting period, as described in Section 4.7. During the continuous cropping period it is assumed that activity is lost from the system due to the continual turnover of fruit in the field, i.e. the contaminated fruit is harvested whilst new fruit is being grown to replace it. The loss of activity through harvesting is represented by a cropping loss from the fruit for the whole year at a rate equivalent to one harvest per year.

• Growing and harvesting (discrete harvests)

k22, k33, k44, k55, k77: no cropping loss = 0 d^{-1}

• No fruit (following discrete harvests)

k22, k33, k44, k55, k77: fast loss = 8.64 10^4 d^{-1}

• Continuous cropping

k22, k33, k44, k55, k77: continuous cropping = 1/365 d^{-1} = 2.74 10^{-3} d^{-1}

5.1.8 Soil migration

The loss of activity down the soil column and out of reach of the roots can be modelled using a loss from the soil compartment based on a soil migration half-life. The default migration half-life is 3.65 10^4 d, as given in Table 14 which also gives the definitions for the parameter abbreviations used below.

• All times

k11: soil migration = $\ln 2 / \lambda_s$

5.2 Model transfers

The transfer rates and losses in the model are dependent on the different periods modelled, reflecting the agricultural practices assumed. Table 18 gives the times of the year assumed for the different modelling periods, representing typical UK agricultural practices. Apples and strawberries dominate the consumption of UK grown fruits in their respective categories, and the agricultural practices given are therefore based on these fruits.

Table 18 Default agricultural practices for fruit model

	No fruit	No fruit	Fruit growing	Harvesting
	No plant	Plant present	Plant present	Plant present
Orchard fruit	15th Sept – 1st Apr	1st Apr – 15th Apr	15th Apr – 15th Sept	15th Sept
Soft fruit	31st Oct – 1st Apr	1st Apr – 15th Apr	15th Apr – 15th Jun	15th Jun – 31st Oct

The default transfer rates for use with the model for each period are given in Table 19 - Table 23. The transfer rates representing resuspension are also dependent on the length of time over which the fruit is subject to resuspension prior to harvest. Default transfer rates have been calculated for a single deposition occurring at three times of the year and for continuous deposition over a growing season. The default resuspension transfer rates for each of the four situations are given in Table 21 -Table 22.

Table 19 Element-independent default model transfer rates[a]

		Default value (d^{-1})
k11	ALL	$1.90\ 10^{-5}$
k22	GH	0
	NF	$8.64\ 10^{4}$
	C	$2.74\ 10^{-3}$
k33	GH	0
	NF	$8.64\ 10^{4}$
	C	$2.74\ 10^{-3}$
k44	GH	0
	NF	$8.64\ 10^{4}$
	C	$2.74\ 10^{-3}$
k55	GH	0
	NF	$8.64\ 10^{4}$
	C	$2.74\ 10^{-3}$
k77	GH	0
	NF	$8.64\ 10^{4}$
	C	$2.74\ 10^{-3}$
k21	GH, C	$4.95\ 10^{-2}$
	NF, >1	0
k61	GH (1)	$4.95\ 10^{-2}$
	NF-P	$8.64\ 10^{4}$
k31	GH, C	$8.64\ 10^{4}$
	NF	0
k41	GH, C	$8.64\ 10^{4}$
	NF	0
k14	GH, C	0 (orchard fruit)
		$2.53\ 10^{-2}$ (soft fruit)
	NF	0
k12	GH (1)	Situation dependent (see Table 21)
	NF, >1	0
k16	GH, P (1)	Situation dependent (see Table 22)
	>1	0

a) All rate constants are given to 3 significant figures for modelling purposes and it does not indicate a precise knowledge of the parameter values.

Key

GH Fruit growing and harvesting periods (fruit present)

NF No fruit present

C Continuous cropping

P Plant growing, but no fruit present

NF-P Neither fruit nor plant is present

(1) First growing season only

>1 All periods after the first harvest

ALL For all periods

Table 20 Default model transfer rates for root uptake

			Default value (d^{-1})[a]
Caesium	k13	GH, C	$9.73\ 10^{-1}$ (orchard fruit)
			$7.55\ 10^{-1}$ (soft fruit)
		NF	0
Strontium	k13	GH, C	$6.49\ 10^{0}$ (orchard fruit)
			$1.76\ 10^{1}$ (soft fruit)
		NF	0
Plutonium	k13	GH, C	$3.25\ 10^{-3}$ (orchard fruit)
			$2.52\ 10^{-2}$ (soft fruit)
		NF	0
Americium	k13	GH, C	$3.25\ 10^{-3}$ (orchard fruit)
			$2.52\ 10^{-2}$ (soft fruit)
		NF	0
Phosphorus	k13	GH, C	$3.25\ 10^{2}$ (orchard fruit)
			$2.52\ 10^{2}$ (soft fruit)
		NF	0
Sulphur	k13	GH, C	$1.95\ 10^{2}$ (orchard fruit)
			$1.51\ 10^{2}$ (soft fruit)
		NF	0
Chlorine	k13	GH, C	$1.62\ 10^{3}$ (orchard fruit)
			$1.26\ 10^{3}$ (soft fruit)
		NF	0
Chromium	k13	GH, C	$9.73\ 10^{-2}$ (orchard fruit)
			$7.55\ 10^{-2}$ (soft fruit)
		NF	0
Manganese	k13	GH, C	$3.25\ 10^{1}$ (orchard fruit)
			$2.52\ 10^{1}$ (soft fruit)
		NF	0
Iron	k13	GH, C	$1.298\ 10^{-1}$ (orchard fruit)
			$1.006\ 10^{-1}$ (soft fruit)
		NF	0
Cobalt	k13	GH, C	$1.62\ 10^{0}$ (orchard fruit)
			$1.26\ 10^{0}$ (soft fruit)
		NF	0
Nickel	k13	GH, C	$3.25\ 10^{0}$ (orchard fruit)
			$2.52\ 10^{0}$ (soft fruit)
		NF	0
Zinc	k13	GH, C	$3.25\ 10^{2}$ (orchard fruit)
			$2.52\ 10^{2}$ (soft fruit)
		NF	0
Bromine	k13	GH, C	$6.49\ 10^{0}$ (orchard fruit)
			$5.03\ 10^{0}$ (soft fruit)
		NF	0
Selenium	k13	GH, C	$3.25\ 10^{2}$ (orchard fruit)
			$2.52\ 10^{2}$ (soft fruit)
		NF	0

Table 20 Default model transfer rates for root uptake

			Default value (d^{-1})[a]
Rubidium	k13	GH, C	$3.25\ 10^{1}$ (orchard fruit)
			$2.52\ 10^{1}$ (soft fruit)
		NF	0
Yttrium	k13	GH, C	$3.25\ 10^{0}$ (orchard fruit)
			$2.52\ 10^{0}$ (soft fruit)
		NF	0
Zirconium	k13	GH, C	$3.25\ 10^{-2}$ (orchard fruit)
			$2.52\ 10^{-2}$ (soft fruit)
		NF	0
Niobium	k13	GH, C	$3.25\ 10^{0}$ (orchard fruit)
			$2.52\ 10^{0}$ (soft fruit)
		NF	0
Molybdenum	k13	GH, C	$3.25\ 10^{1}$ (orchard fruit)
			$2.52\ 10^{1}$ (soft fruit)
		NF	0
Tecnicium	k13	GH, C	$1.62\ 10^{3}$ (orchard fruit)
			$1.26\ 10^{3}$ (soft fruit)
		NF	0
Ruthenium	k13	GH, C	$3.25\ 10^{0}$ (orchard fruit)
			$2.52\ 10^{0}$ (soft fruit)
		NF	0
Silver	k13	GH, C	$6.49\ 10^{1}$ (orchard fruit)
			$5.03\ 10^{1}$ (soft fruit)
		NF	0
Tin	k13	GH, C	$6.49\ 10^{1}$ (orchard fruit)
			$5.03\ 10^{1}$ (soft fruit)
		NF	0
Antimony	k13	GH, C	$3.25\ 10^{0}$ (orchard fruit)
			$2.52\ 10^{0}$ (soft fruit)
		NF	0
Tellurium	k13	GH, C	$9.73\ 10^{-1}$ (orchard fruit)
			$7.55\ 10^{-1}$ (soft fruit)
		NF	0
Iodine	k13	GH, C	$6.49\ 10^{0}$ (orchard fruit)
			$5.03\ 10^{0}$ (soft fruit)
		NF	0
Barium	k13	GH, C	$3.25\ 10^{0}$ (orchard fruit)
			$2.52\ 10^{0}$ (soft fruit)
		NF	0
Lanthanum	k13	GH, C	$9.73\ 10^{-1}$ (orchard fruit)
			$7.55\ 10^{-1}$ (soft fruit)
		NF	0
Cerium	k13	GH, C	$3.25\ 10^{-1}$ (orchard fruit)
			$2.52\ 10^{-1}$ (soft fruit)
		NF	0

Table 20 Default model transfer rates for root uptake

			Default value (d^{-1})[a]
Promethium	k13	GH, C	$9.73\ 10^{-1}$ (orchard fruit)
			$7.55\ 10^{-1}$ (soft fruit)
		NF	0
Europium	k13	GH, C	$9.73\ 10^{-1}$ (orchard fruit)
			$7.55\ 10^{-1}$ (soft fruit)
		NF	0
Lead	k13	GH, C	$3.25\ 10^{0}$ (orchard fruit)
			$2.52\ 10^{0}$ (soft fruit)
		NF	0
Polonium	k13	GH, C	$6.49\ 10^{-2}$ (orchard fruit)
			$5.03\ 10^{-2}$ (soft fruit)
		NF	0
Radium	k13	GH, C	$3.25\ 10^{-1}$ (orchard fruit)
			$2.52\ 10^{-1}$ (soft fruit)
		NF	0
Actinium	k13	GH, C	$3.25\ 10^{-1}$ (orchard fruit)
			$2.52\ 10^{-1}$ (soft fruit)
		NF	0
Thorium	k13	GH, C	$1.62\ 10^{-1}$ (orchard fruit)
			$1.26\ 10^{-1}$ (soft fruit)
		NF	0
Protactinium	k13	GH, C	$1.30\ 10^{1}$ (orchard fruit)
			$1.01\ 10^{1}$ (soft fruit)
		NF	0
Uranium	k13	GH, C	$3.25\ 10^{-1}$ (orchard fruit)
			$2.52\ 10^{-1}$ (soft fruit)
		NF	0
Neptunium	k13	GH, C	$6.49\ 10^{-1}$ (orchard fruit)
			$5.03\ 10^{-1}$ (soft fruit)
		NF	0
Curium	k13	GH, C	$6.49\ 10^{-3}$ (orchard fruit)
			$5.03\ 10^{-3}$ (soft fruit)
		NF	0

a) All rate constants are given to 3 significant figures for modelling purposes and it does not indicate a precise knowledge of the parameter values.

Key

GH Fruit growing and harvesting periods (fruit present)

NF No fruit present

C Continuous cropping

Table 21 Default values for fruit resuspension transfer, k12, up to the end of the first harvest

Release	Fruit	Transfer rate[a], d^{-1}
Accident	Orchard fruit	$4.83\ 10^{-8}$
	Soft fruit	$2.07\ 10^{-8}$
Continuous	Generic	$4.83\ 10^{-8}$

a) All rate constants are given to 3 significant figures for modelling purposes and it does not indicate a precise knowledge of the parameter values.

Table 22 Default values for plant resuspension transfer, k16, up to the end of the first harvest

Release	Fruit	Transfer rate[a], d^{-1}
Accident	Orchard fruit	$5.11\ 10^{-6}$
	Soft fruit	$5.11\ 10^{-6}$
Continuous	Generic	$5.11\ 10^{-6}$

a) All rate constants are given to 3 significant figures for modelling purposes and it does not indicate a precise knowledge of the parameter values.

Table 23 Default model transfer rates for translocation (mobility given in Table 9)

			Default value[a], d^{-1}
Mobile	k67	GH (1)	$1.00\ 10^{-1}$
		NF, >1	0
	k75	GH (1)	$3.00\ 10^{-2}$
		NF, >1	0
	k51	GH (1)	$7.00\ 10^{-2}$
		NF, >1	0
Semi-Mobile	k67	GH (1)	$1.50\ 10^{-3}$
		NF, >1	0
	k75	GH (1)	$3.00\ 10^{-2}$
		NF, >1	0
	k51	GH (1)	$7.00\ 10^{-2}$
		NF, >1	0
Immobile	k67	ALL	0
	k75	ALL	0
	k51	ALL	0

a) All rate constants are given to 3 significant figures for modelling purposes and it does not indicate a precise knowledge of the parameter values.

Key

GH Growing and harvesting periods (fruit present)

NF No fruit present

(1) First growing season only

>1 All periods after the first harvest

ALL For all periods

6 APPLICATION OF MODEL FOR ACCIDENT AND CONTINUOUS RELEASE SITUATIONS

6.1 Accidental release applications

As discussed in Section 4.7, it is not necessary to model the distinct growing periods explicitly a long time after the initial deposition because the transfer processes important in the long term do not lead to activity concentrations varying significantly with time. The model is run using the agricultural practice periods given in Table 13 up to the end of the second harvest. A period when no fruit is present is taken from the second harvest to the 730th day, after which time continuous cropping is assumed.

An initial deposition of 1 Bq m^{-2} (activity per unit area of ground surface) has been used; this gives the sources A1, A2 and A6, to soil, external fruit and external plant, respectively. Default values are given in Table 24. The sources in the table are the initial activity concentrations (Bq m^{-2}) in the soil, external plant and external fruit compartments.

Table 24 Sources[a] for accidental release application (Bq m^{-2})

		Default value[b]
Soil (A1)	GH	$2.53\ 10^{-1}$ (orchard fruit)
		$2.57\ 10^{-1}$ (soft fruit)
	NF	$1.00\ 10^{0}$
External Fruit (A2)	GH	$7.00\ 10^{-3}$ (orchard fruit)
		$3.00\ 10^{-3}$ (soft fruit)
	NF	0
External plant[c] (A6)	GH	$7.40\ 10^{-1}$ (orchard fruit)
		$7.40\ 10^{-1}$ (soft fruit)
	NF	0

Key

GH Growing and harvesting periods (fruit present)

NF No fruit present

a) Initial activity in each of the compartments identified , Bq m^{-2}

b) All rate constants are given to 3 significant figures for modelling purposes and it does not indicate a precise knowledge of the parameter values.

c) The activity concentration in the external plant compartment is set to 0 at the start of the second harvesting period.

A series of tables of the predicted activity concentrations in orchard fruit and soft (herbaceous and shrub) fruit at harvest have been produced. These are listed for convenience in Table 25.

In Table 26 - Table 30 activity concentrations are given at the time of harvest for the first two harvests for orchard fruit. For soft fruit (herbaceous), activity concentrations are given at the beginning and end of the first and second harvesting periods.

The integrated activity concentrations in consumed fruit have also been calculated for a series of defined periods. These are given in Table 31 - Table 35. Values for the first and second harvests are the integrated concentrations from the start of the first harvest (or time of deposition if this is later) to the time when all of the fruit from that year's harvest has been consumed. For orchard fruit this includes the time it takes to consume all of the stored fruit arising from the harvest. For soft fruit, the integration period ends at the end of the harvesting period, on the assumption that most of the fruit will be consumed within this time. The integrated activity concentrations have been expressed so that the values in Table 31 - Table 35 can simply be multiplied by the annual ingestion rate (kg y^{-1}) to calculate the total activity intake from ingestion of the fruit category (Bq).

Details of how the compartment model output is used to generate the activity concentrations are given in Appendix C.

Table 25 List of tables of activity concentrations in fruit at harvest for an instantaneous deposit of 1 Bq m^{-2} occurring on 1st January, 1st May and 15th September

Table	Table description
26	Activity concentrations of ^{90}Sr in fruit at harvest as a function of time
27	Activity concentrations of ^{106}Ru in whole fruit at harvest as a function of time
28	Activity concentrations of ^{131}I in whole fruit at harvest as a function of time
29	Activity concentrations of ^{137}Cs in whole fruit at harvest as a function of time
30	Activity concentrations of ^{239}Pu in whole fruit at harvest as a function of time
31	Time integrated activity concentrations of ^{90}Sr in whole fruit
32	Time integrated activity concentrations of ^{106}Ru in whole fruit
33	Time integrated activity concentrations of ^{131}I in whole fruit
34	Time integrated activity concentrations of ^{137}Cs in whole fruit
35	Time integrated activity concentrations of ^{239}Pu in whole fruit
36	Time integrated activity concentrations of ^{90}Sr in peeled fruit
37	Time integrated activity concentrations of ^{137}Cs in peeled fruit
38	Time integrated activity concentrations of ^{239}Pu in peeled fruit

As discussed in Sections 3.7.1 and 4.2, for immobile elements, such as plutonium, the majority of the contamination of the fruit will be on the outer surface of the fruit. If fruit, particularly orchard fruit such as apples, is peeled prior to consumption, most of the activity concentration predicted to be in the fruit at the first harvest is likely to be removed. If deposition occurs shortly before harvest there is likely to be negligible activity in the peeled fruit and activity concentrations will be significantly lower in peeled orchard fruit if deposition has occurred during the period when the fruit is already formed. In order to estimate total intakes of activity from consumption of fruit if it has been peeled, integrated activity concentrations arising from contamination of the internal fruit have also been calculated for ^{90}Sr, ^{137}Cs and ^{239}Pu, representing mobile, semi-mobile and immobile elements, respectively (see Table 36 - Table 38). The Tables show that the lowest activity concentrations are for immobile elements and the highest for mobile elements, reflecting the amount of translocation that takes place over the growing season. It is important, therefore, that for immobile elements, any peeling of fruit is taken into account in site specific dose assessments where fruit is an important contributor to radiation doses.

Table 26 Activity concentrations of ^{90}Sr (Bq kg^{-1} fresh mass) at harvest for an instantaneous deposit[a] of 1 Bq m^{-2}

Deposition date	First harvest		Second harvest		3 y	5 y	10 y	50 y
	Start[b]	End	Start[b]	End				
Orchard fruit								
1st Jan	4.5 10^{-5}		4.2 10^{-5}		4.1 10^{-5}	3.8 10^{-5}	3.3 10^{-5}	9.5 10^{-6}
1st May	3.9 10^{-4}		4.3 10^{-5}		4.0 10^{-5}	3.8 10^{-5}	3.3 10^{-5}	9.5 10^{-6}
15th Sept	4.1 10^{-3}		4.3 10^{-5}		4.0 10^{-5}	3.8 10^{-5}	3.2 10^{-5}	9.5 10^{-6}
Soft fruit								
1st Jan	1.5 10^{-4}	1.5 10^{-4}	1.5 10^{-4}	1.5 10^{-4}	1.4 10^{-4}	1.3 10^{-4}	1.1 10^{-4}	3.3 10^{-5}
1st May	3.2 10^{-3}	2.3 10^{-4}	1.5 10^{-4}	1.5 10^{-4}	1.4 10^{-4}	1.3 10^{-4}	1.1 10^{-4}	3.3 10^{-5}
15th Sept	2.3 10^{-3}	3.2 10^{-3}	1.5 10^{-4}	1.5 10^{-4}	1.4 10^{-4}	1.3 10^{-4}	1.1 10^{-4}	3.3 10^{-5}

a) Total deposit to the crop and soil

b) When deposition occurs during a harvesting period, the activity concentration at the start of the harvest is taken as the activity concentration at the time of deposition

Table 27 Activity concentrations of ^{106}Ru (Bq kg-1 fresh mass) at harvest for an instantaneous deposit[a] of 1 Bq m-2

Deposition date	First harvest		Second harvest		3 y	5 y	10 y	50 y
	Start[b]	End	Start[b]	End				
Orchard fruit								
1st Jan	1.4 10^{-5}		6.8 10^{-6}		2.8 10^{-6}	6.9 10^{-7}	2.1 10^{-8}	4.6 10^{-16}
1st May	2.1 10^{-5}		8.6 10^{-6}		2.8 10^{-6}	6.9 10^{-7}	2.2 10^{-8}	4.9 10^{-16}
15th Sept	4.1 10^{-3}		1.1 10^{-5}		2.8 10^{-6}	6.9 10^{-7}	2.1 10^{-8}	4.4 10^{-16}
Soft fruit								
1st Jan	1.7 10^{-5}	1.3 10^{-5}	8.2 10^{-6}	6.3 10^{-6}	2.8 10^{-6}	7.0 10^{-7}	2.2 10^{-8}	5.0 10^{-16}
1st May	2.3 10^{-4}	1.6 10^{-5}	1.0 10^{-5}	7.9 10^{-6}	2.8 10^{-6}	7.0 10^{-7}	2.2 10^{-8}	4.7 10^{-16}
15th Sept	2.3 10^{-3}	2.3 10^{-4}	1.3 10^{-5}	1.0 10^{-5}	2.8 10^{-6}	7.0 10^{-7}	2.2 10^{-8}	4.6 10^{-16}

a) Total deposit to the crop and soil

b) When deposition occurs during a harvesting period, the activity concentration at the start of the harvest is taken as the activity concentration at the time of deposition

Table 28 Activity concentrations of ^{131}I (Bq kg^{-1} fresh mass) at harvest for an instantaneous deposit[a] of 1 Bq m^{-2}

Deposition date	First harvest		Second harvest		3 y	5 y	10 y	50 y
	Start[b]	End	Start[b]	End				
Orchard fruit								
1st Jan	$1.1\ 10^{-12}$		$1.1\ 10^{-18}$		$5.5\ 10^{-24}$	$2.6\ 10^{-27}$	$3.2\ 10^{-32}$	$2.6\ 10^{-40}$
1st May	$4.1\ 10^{-8}$		$2.7\ 10^{-16}$		$6.5\ 10^{-23}$	$3.0\ 10^{-26}$	$3.7\ 10^{-31}$	$3.0\ 10^{-39}$
15th Sept	$4.1\ 10^{-3}$		$1.1\ 10^{-14}$		$5.5\ 10^{-21}$	$2.6\ 10^{-24}$	$3.1\ 10^{-29}$	$2.6\ 10^{-37}$
Soft fruit								
1st Jan	$5.0\ 10^{-11}$	$5.5\ 10^{-13}$	$7.1\ 10^{-18}$	$7.2\ 10^{-20}$	$3.4\ 10^{-25}$	$1.6\ 10^{-28}$	$1.9\ 10^{-33}$	$1.6\ 10^{-41}$
1st May	$1.3\ 10^{-3}$	$6.1\ 10^{-10}$	$1.4\ 10^{-16}$	$1.4\ 10^{-18}$	$1.0\ 10^{-24}$	$4.8\ 10^{-28}$	$5.9\ 10^{-33}$	$4.8\ 10^{-41}$
15th Sept	$2.3\ 10^{-3}$	$1.3\ 10^{-3}$	$1.3\ 10^{-14}$	$1.3\ 10^{-16}$	$6.3\ 10^{-23}$	$2.9\ 10^{-26}$	$3.6\ 10^{-31}$	$2.9\ 10^{-39}$

a) Total deposit to the crop and soil

b) When deposition occurs during a harvesting period, the activity concentration at the start of the harvest is taken as the activity concentration at the time of deposition

Table 29 Activity concentrations of ^{137}Cs (Bq kg^{-1} fresh mass) at harvest for an instantaneous deposit[a] of 1 Bq m^{-2}

Deposition date	First harvest		Second harvest		3 y	5 y	10 y	50 y
	Start[b]	End	Start[b]	End				
Orchard fruit								
1st Jan	$3.5\ 10^{-5}$		$6.3\ 10^{-6}$		$6.1\ 10^{-6}$	$5.7\ 10^{-6}$	$4.9\ 10^{-6}$	$1.5\ 10^{-6}$
1st May	$4.3\ 10^{-3}$		$6.3\ 10^{-6}$		$6.0\ 10^{-6}$	$5.6\ 10^{-6}$	$4.9\ 10^{-6}$	$1.5\ 10^{-6}$
15th Sept	$4.1\ 10^{-3}$		$6.4\ 10^{-6}$		$6.0\ 10^{-6}$	$5.7\ 10^{-6}$	$4.9\ 10^{-6}$	$1.5\ 10^{-6}$
Soft fruit								
1st Jan	$3.5\ 10^{-5}$	$4.3\ 10^{-5}$	$6.6\ 10^{-6}$	$6.5\ 10^{-6}$	$6.3\ 10^{-6}$	$5.9\ 10^{-6}$	$5.1\ 10^{-6}$	$1.5\ 10^{-6}$
1st May	$6.8\ 10^{-2}$	$1.4\ 10^{-3}$	$6.6\ 10^{-6}$	$6.6\ 10^{-6}$	$6.3\ 10^{-6}$	$5.9\ 10^{-6}$	$5.1\ 10^{-6}$	$1.5\ 10^{-6}$
15th Sept	$2.3\ 10^{-3}$	$6.8\ 10^{-2}$	$5.1\ 10^{-6}$	$5.0\ 10^{-6}$	$4.8\ 10^{-6}$	$4.5\ 10^{-6}$	$3.9\ 10^{-6}$	$1.2\ 10^{-6}$

a) Total deposit to the crop and soil

b) When deposition occurs during a harvesting period, the activity concentration at the start of the harvest is taken as the activity concentration at the time of deposition

Table 30 Activity concentrations of ^{239}Pu (Bq kg^{-1} fresh mass) at harvest for an instantaneous deposit[a] of 1 Bq m^{-2}

Deposition date	First harvest		Second harvest		3 y	5 y	10 y	50 y
	Start[b]	End	Start[b]	End				
Orchard fruit								
1st Jan	$6.0\ 10^{-7}$		$2.2\ 10^{-8}$		$2.2\ 10^{-8}$	$2.1\ 10^{-8}$	$2.1\ 10^{-8}$	$1.6\ 10^{-8}$
1st May	$5.1\ 10^{-6}$		$2.2\ 10^{-8}$		$2.2\ 10^{-8}$	$2.1\ 10^{-8}$	$2.1\ 10^{-8}$	$1.6\ 10^{-8}$
15th Sept	$4.1\ 10^{-3}$		$2.2\ 10^{-8}$		$2.2\ 10^{-8}$	$2.1\ 10^{-8}$	$2.1\ 10^{-8}$	$1.6\ 10^{-8}$
Soft fruit								
1st Jan	$7.5\ 10^{-7}$	$7.6\ 10^{-7}$	$4.4\ 10^{-7}$	$4.4\ 10^{-7}$	$4.4\ 10^{-7}$	$4.3\ 10^{-7}$	$4.2\ 10^{-7}$	$3.1\ 10^{-7}$
1st May	$2.4\ 10^{-4}$	$1.0\ 10^{-6}$	$4.4\ 10^{-7}$	$4.4\ 10^{-7}$	$4.4\ 10^{-7}$	$4.3\ 10^{-7}$	$4.2\ 10^{-7}$	$3.2\ 10^{-7}$
15th Sept	$2.3\ 10^{-3}$	$2.4\ 10^{-4}$	$4.4\ 10^{-7}$	$4.4\ 10^{-7}$	$4.4\ 10^{-7}$	$4.3\ 10^{-7}$	$4.2\ 10^{-7}$	$3.1\ 10^{-7}$

a) Total deposit to the crop and soil

b) When deposition occurs during a harvesting period, the activity concentration at the start of the harvest is taken as the activity concentration at the time of deposition

Table 31 Integrated activity concentrations[a] of ^{90}Sr (Bq y kg^{-1}) in consumed fruit for an instantaneous deposit[b] of 1 Bq m^{-2} (Bq y kg^{-1} fresh mass)

Deposition date	First Harvest[c]	Second Harvest[d]	3y	5 y	10 y	50 y
Orchard fruit						
1st Jan	$4.5\ 10^{-5}$	$8.6\ 10^{-5}$	$1.3\ 10^{-4}$	$2.1\ 10^{-4}$	$3.8\ 10^{-4}$	$1.1\ 10^{-3}$
1st May	$3.8\ 10^{-4}$	$4.3\ 10^{-4}$	$4.7\ 10^{-4}$	$5.5\ 10^{-4}$	$7.2\ 10^{-4}$	$1.5\ 10^{-3}$
15th Sept	$4.1\ 10^{-3}$	$4.1\ 10^{-3}$	$4.2\ 10^{-3}$	$4.3\ 10^{-3}$	$4.4\ 10^{-3}$	$5.2\ 10^{-3}$
Soft fruit						
1st Jan	$1.5\ 10^{-4}$	$3.0\ 10^{-4}$	$4.5\ 10^{-4}$	$7.2\ 10^{-4}$	$1.3\ 10^{-3}$	$4.0\ 10^{-3}$
1st May	$1.1\ 10^{-3}$	$1.3\ 10^{-3}$	$1.4\ 10^{-3}$	$1.7\ 10^{-3}$	$2.3\ 10^{-3}$	$4.9\ 10^{-3}$
15th Sept	$2.8\ 10^{-3}$	$3.0\ 10^{-3}$	$3.1\ 10^{-3}$	$3.4\ 10^{-3}$	$4.0\ 10^{-3}$	$6.6\ 10^{-3}$

a) These values are to be multiplied by annual ingestion rate (kg y^{-1}) to give total activity intake (Bq)

b) Total deposit to the crop and soil

c) Integrated activity concentration in the fruit consumed from the first harvest

d) Integrated activity concentration in the fruit consumed from the first and second harvests

Table 32 Integrated activity concentrations[a] of ^{106}Ru (Bq y kg^{-1}) in consumed fruit for an instantaneous deposit[b] of 1 Bq m^{-2} (Bq y kg^{-1} fresh mass)

Deposition date	First Harvest[c]	Second Harvest[d]	3 y	5 y	10 y	50 y
Orchard fruit						
1st Jan	1.0 10^{-5}	1.5 10^{-5}	1.9 10^{-5}	2.2 10^{-5}	2.3 10^{-5}	2.3 10^{-5}
1st May	1.5 10^{-5}	2.2 10^{-5}	2.6 10^{-5}	2.9 10^{-5}	3.0 10^{-5}	3.0 10^{-5}
15th Sept	3.0 10^{-3}	3.0 10^{-3}	3.0 10^{-3}	3.0 10^{-3}	3.0 10^{-3}	3.0 10^{-3}
Soft fruit						
1st Jan	1.5 10^{-5}	2.2 10^{-5}	2.6 10^{-5}	2.9 10^{-5}	3.0 10^{-5}	3.0 10^{-5}
1st May	4.8 10^{-5}	5.7 10^{-5}	6.2 10^{-5}	6.5 10^{-5}	6.6 10^{-5}	6.6 10^{-5}
15th Sept	8.9 10^{-4}	9.0 10^{-4}	9.1 10^{-4}	9.1 10^{-4}	9.1 10^{-4}	9.1 10^{-4}

a) These values are to be multiplied by annual ingestion rate (kg y^{-1}) to give total activity intake (Bq)

b) Total deposit to the crop and soil

c) Integrated activity concentration in the fruit consumed from the first harvest

d) Integrated activity concentration in the fruit consumed from the first and second harvests

Table 33 Integrated activity concentrations[a] of ^{131}I (Bq y kg^{-1}) in consumed fruit for an instantaneous deposit[b] of 1 Bq m^{-2} (Bq y kg^{-1} fresh mass)

Deposition date	First Harvest[c]	Second Harvest[d]	3 y	5 y	10 y	50 y
Orchard fruit						
1st Jan	2.5 10^{-14}	2.5 10^{-14}	2.5 10^{-14}	2.5 10^{-14}	2.5 10^{-14}	2.5 10^{-14}
1st May	9.7 10^{-10}	9.7 10^{-10}	9.7 10^{-10}	9.7 10^{-10}	9.7 10^{-10}	9.7 10^{-10}
15th Sept	9.9 10^{-5}	9.9 10^{-5}	9.9 10^{-5}	9.9 10^{-5}	9.9 10^{-5}	9.9 10^{-5}
Soft fruit						
1st Jan	4.4 10^{-12}	4.4 10^{-12}	4.4 10^{-12}	4.4 10^{-12}	4.4 10^{-12}	4.4 10^{-12}
1st May	8.7 10^{-5}	8.7 10^{-5}	8.7 10^{-5}	8.7 10^{-5}	8.7 10^{-5}	8.7 10^{-5}
15th Sept	8.7 10^{-3}	8.7 10^{-3}	8.7 10^{-3}	8.7 10^{-3}	8.7 10^{-3}	8.7 10^{-3}

a) These values are to be multiplied by annual ingestion rate (kg y^{-1}) to give total activity intake (Bq)

b) Total deposit to the crop and soil

c) Integrated activity concentration in the fruit consumed from the first harvest

d) Integrated activity concentration in the fruit consumed from the first and second harvests

Table 34 Integrated activity concentrations[a] of ^{137}Cs (Bq y kg^{-1}) in consumed fruit for an instantaneous deposit[b] of 1 Bq m^{-2} (Bq y kg^{-1} fresh mass)

Deposition date	First Harvest[c]	Second Harves[d]	3 y	5 y	10 y	50 y
Orchard fruit						
1st Jan	$3.5\ 10^{-5}$	$4.1\ 10^{-5}$	$4.7\ 10^{-5}$	$5.9\ 10^{-5}$	$8.5\ 10^{-5}$	$2.0\ 10^{-4}$
1st May	$4.3\ 10^{-3}$	$4.3\ 10^{-3}$	$4.3\ 10^{-3}$	$4.3\ 10^{-3}$	$4.3\ 10^{-3}$	$4.5\ 10^{-3}$
15th Sept	$4.1\ 10^{-3}$	$4.1\ 10^{-3}$	$4.1\ 10^{-3}$	$4.1\ 10^{-3}$	$4.1\ 10^{-3}$	$4.3\ 10^{-3}$
Soft fruit						
1st Jan	$4.2\ 10^{-5}$	$4.8\ 10^{-5}$	$5.5\ 10^{-5}$	$6.7\ 10^{-5}$	$9.4\ 10^{-5}$	$2.1\ 10^{-4}$
1st May	$1.9\ 10^{-2}$	$1.9\ 10^{-2}$	$1.9\ 10^{-2}$	$1.9\ 10^{-2}$	$1.9\ 10^{-2}$	$1.9\ 10^{-2}$
15th Sept	$6.0\ 10^{-2}$	$6.0\ 10^{-2}$	$6.0\ 10^{-2}$	$6.0\ 10^{-2}$	$6.0\ 10^{-2}$	$6.0\ 10^{-2}$

a) These values are to be multiplied by annual ingestion rate (kg y^{-1}) to give total activity intake (Bq)

b) Total deposit to the crop and soil

c) Integrated activity concentration in the fruit consumed from the first harvest

d) Integrated activity concentration in the fruit consumed from the first and second harvests

Table 35 Integrated activity concentrations[a] of ^{239}Pu (Bq y kg^{-1}) in consumed fruit for an instantaneous deposit[b] of 1 Bq m^{-2} (Bq y kg^{-1} fresh mass)

Deposition date	First Harvest[c]	Second Harvest[d]	3 y	5 y	10 y	50 y
Orchard fruit						
1st Jan	$6.0\ 10^{-7}$	$6.2\ 10^{-7}$	$6.4\ 10^{-7}$	$6.8\ 10^{-7}$	$7.9\ 10^{-7}$	$1.5\ 10^{-6}$
1st May	$5.1\ 10^{-6}$	$5.1\ 10^{-6}$	$5.1\ 10^{-6}$	$5.1\ 10^{-6}$	$5.3\ 10^{-6}$	$6.0\ 10^{-6}$
15th Sept	$4.1\ 10^{-3}$	$4.1\ 10^{-3}$	$4.1\ 10^{-3}$	$4.1\ 10^{-3}$	$4.1\ 10^{-3}$	$4.1\ 10^{-3}$
Soft fruit						
1st Jan	$7.6\ 10^{-7}$	$1.2\ 10^{-6}$	$1.6\ 10^{-6}$	$2.5\ 10^{-6}$	$4.6\ 10^{-6}$	$1.9\ 10^{-5}$
1st May	$3.5\ 10^{-5}$	$3.6\ 10^{-5}$	$3.6\ 10^{-5}$	$3.7\ 10^{-5}$	$3.9\ 10^{-5}$	$5.3\ 10^{-5}$
15th Sept	$9.0\ 10^{-4}$	$9.0\ 10^{-4}$	$9.0\ 10^{-4}$	$9.0\ 10^{-4}$	$9.1\ 10^{-4}$	$9.2\ 10^{-4}$

a) These values are to be multiplied by annual ingestion rate (kg y^{-1}) to give total activity intake (Bq)

b) Total deposit to the crop and soil

c) Integrated activity concentration in the fruit consumed from the first harvest

d) Integrated activity concentration in the fruit consumed from the first and second harvests

Table 36 Integrated activity concentrations[a] of ^{90}Sr (Bq y kg^{-1}) in peeled fruit for an instantaneous deposit[b] of 1 Bq m^{-2} (Bq y kg^{-1} fresh mass)

Deposition date	First Harvest[c]	Second Harvest[d]	3 y	5 y	10 y	50 y
Orchard fruit						
1st Jan	4.4 10^{-5}	8.6 10^{-5}	1.3 10^{-4}	2.1 10^{-4}	3.8 10^{-4}	1.1 10^{-3}
1st May	3.8 10^{-4}	4.2 10^{-4}	4.6 10^{-4}	5.4 10^{-4}	7.2 10^{-4}	1.5 10^{-3}
15th Sept	0	4.2 10^{-5}	8.3 10^{-5}	1.6 10^{-4}	3.4 10^{-4}	1.1 10^{-3}
Soft fruit						
1st Jan	1.5 10^{-4}	3.0 10^{-4}	4.5 10^{-4}	7.2 10^{-4}	1.3 10^{-3}	4.0 10^{-3}
1st May	1.1 10^{-3}	1.2 10^{-3}	1.4 10^{-3}	1.6 10^{-3}	2.3 10^{-3}	4.9 10^{-3}
15th Sept	1.9 10^{-3}	2.1 10^{-3}	2.2 10^{-3}	2.5 10^{-3}	3.1 10^{-3}	5.7 10^{-3}

a) These values are to be multiplied by annual ingestion rate (kg y^{-1}) to give total activity intake (Bq)
b) Total deposit to the crop and soil
c) Integrated activity concentration in the fruit consumed from the first harvest
d) Integrated activity concentration in the fruit consumed from the first and second harvests

Table 37 Integrated activity concentrations[a] of ^{137}Cs (Bq y kg^{-1}) in peeled fruit for an instantaneous deposit[b] of 1 Bq m^{-2} (Bq y kg^{-1} fresh mass)[b]

Deposition date	First Harvest[c]	Second Harvest[d]	3 y	5 y	10 y	50 y
Orchard fruit						
1st Jan	3.4 10^{-5}	4.0 10^{-5}	4.6 10^{-5}	5.8 10^{-5}	8.5 10^{-5}	2.0 10^{-4}
1st May	4.3 10^{-3}	4.3 10^{-3}	4.3 10^{-3}	4.3 10^{-3}	4.3 10^{-3}	4.5 10^{-3}
15th Sept	0	6.4 10^{-6}	1.7 10^{-5}	2.8 10^{-5}	5.5 10^{-5}	1.7 10^{-4}
Soft fruit						
1st Jan	4.1 10^{-5}	4.7 10^{-5}	5.4 10^{-5}	6.5 10^{-5}	9.2 10^{-5}	2.1 10^{-4}
1st May	1.9 10^{-2}	1.9 10^{-2}	1.9 10^{-2}	1.9 10^{-2}	1.9 10^{-2}	1.9 10^{-2}
15th Sept	5.9 10^{-2}	5.9 10^{-2}	5.9 10^{-2}	5.9 10^{-2}	5.9 10^{-2}	5.9 10^{-2}

a) These values are to be multiplied by annual ingestion rate (kg y^{-1}) to give total activity intake (Bq)
b) Total deposit to the crop and soil
c) Integrated activity concentration in the fruit consumed from the first harvest
d) Integrated activity concentration in the fruit consumed from the first and second harvests

Table 38 Integrated activity concentrations[a] of ^{239}Pu (Bq y kg^{-1}) in peeled fruit for an instantaneous deposit[b] of 1 Bq m^{-2} (Bq y kg^{-1} fresh mass)

Deposition date	First Harvest[c]	Second Harvest[d]	3 y	5 y	10 y	50 y
Orchard fruit						
1st Jan	2.2 10^{-8}	4.4 10^{-8}	6.6 10^{-8}	1.1 10^{-7}	2.1 10^{-7}	9.4 10^{-7}
1st May	2.2 10^{-8}	4.4 10^{-8}	6.6 10^{-8}	1.1 10^{-7}	2.1 10^{-7}	9.4 10^{-7}
15th Sept	0	2.2 10^{-8}	4.4 10^{-8}	8.7 10^{-8}	1.9 10^{-7}	9.1 10^{-7}
Soft fruit						
1st Jan	2.2 10^{-7}	4.4 10^{-7}	6.6 10^{-7}	1.1 10^{-6}	2.1 10^{-6}	9.4 10^{-6}
1st May	2.2 10^{-7}	4.4 10^{-7}	6.6 10^{-7}	1.1 10^{-6}	2.1 10^{-6}	9.4 10^{-6}
15th Sept	1.6 10^{-7}	3.8 10^{-7}	6.0 10^{-7}	1.0 10^{-6}	2.1 10^{-6}	9.3 10^{-6}

a) These values are to be multiplied by annual ingestion rate (kg y^{-1}) to give total activity intake (Bq)

b) Total deposit to the crop and soil

c) Integrated activity concentration in the fruit consumed from the first harvest

d) Integrated activity concentration in the fruit consumed from the first and second harvests

6.2 Continuous release applications

A single generic fruit category has been considered for continuous release applications. Given the dominance of orchard fruit for UK fruit production, the model is taken to be that for orchard fruit. However, it is recognised that the model could be used for a range of plant species and in order that none of the important transfer processes is ignored, direct soil contamination of fruit is also included. In any case, it is unlikely that soil contamination will contribute more than 10% of the total activity in the fruit [Teale and Brown, 2003].

The model is run in the first year for a typical growing period of 150 days followed by a fallow period for the rest of the year. This enables the activity concentration in the harvested fruit from a whole growing period to be calculated, regardless of when in the year the fruit is actually growing. This approach ensures that the activity concentrations in the first year of deposition are not underestimated. Following the first year, the harvesting of the fruit is modelled as a continuous removal of activity from the system. This approximation is equally appropriate for fruits that are harvested discretely or over a period as the temporal accuracy of calculations required for continuous release assessments is not less than one year, as discussed in Section 4.7.

A total deposition rate of 1 Bq m^{-2} s^{-1}, i.e. deposition to fruit, external plant surfaces and soil, for one year has been used in the prediction of activity concentrations for continuous release assessments. The sources in Table 39 are the input rates into the soil, external fruit and external plant compartments for the first year of running the model.

Table 39 Sources[a] for continuous release applications (Bq m^{-2} d^{-1})

		Default Value
Soil (A1)	GH	2.19 10^{4}
	NF	8.64 10^{4}
External Fruit (A2)	GH	6.05 10^{2}
	NF	0
External plant (A6)	GH	6.39 10^{4}
	NF	0

Key

GH Growing and harvesting periods (fruit present)

NF No fruit present

a) The sources are input rates into the identified compartments for 1 year, Bq m^{-2} d^{-1}

Integrated activity concentrations in consumed fruit, with no processing losses, for a continuous deposition of 1 Bq m^{-2} s^{-1} for one year have been calculated for integration periods of 1, 2, 3, 5, 10, 50 and 100 years and are given in Table 40. The intake of activity from the consumption of fruit is calculated by multiplying the integrated activity concentration in the consumed fruit by the mass of fruit that an individual consumes in a year. Details of how the compartment model output is used to generate the activity concentrations are given in Appendix C.

As for accidental release applications, basic preparation of the fruit may significantly reduce the activity concentrations presented in Table 40, particularly if the fruit is peeled and the radionuclide of concern is immobile (see Table 9). However, for general use, it is recommended that the values in Table 40 are used as being representative of those in fruit for continuous release applications, as the results are taken to be appropriate for all fruit categories, many of which are unlikely to be peeled prior to consumption. If more detail on the effects of preparation and processing losses on estimated activity concentrations is required, it is suggested that this is included explicitly in the model, as described in Section 4.8.

Table 40 Time-integrated activity concentrations (Bq y kg^{-1} fresh mass) at harvest for continuous release applications, deposition of 1 Bq m^{-2} s^{-1} for one year

Model	Radionuclide	1y	2y	3y	5y	10y	50y	100y
Generic	^{90}Sr	2.3 10^4	2.4 10^4	2.6 10^4	2.8 10^4	3.4 10^4	5.8 10^4	6.6 10^4
	^{106}Ru	7.2 10^3	7.6 10^3	7.7 10^3	7.9 10^3	7.9 10^3	7.9 10^3	7.9 10^3
	^{131}I	2.9 10^4	2.9 10^4	2.9 10^4	2.9 10^4	2.9 10^4	2.9 10^4	2.9 10^4
	^{137}Cs	3.6 10^5	3.6 10^5	3.6 10^5	3.6 10^5	3.6 10^5	3.6 10^5	3.7 10^5
	^{239}Pu	7.2 10^3	7.2 10^3	7.3 10^3	7.3 10^3	7.3 10^3	7.7 10^3	8.1 10^3

6.3 Peak concentrations in fruit

When responding to a radiation incident involving the contamination of foods, it is helpful to know the maximum concentrations that could be expected in a food and when this is likely to occur with respect to the time of the deposition. As has been discussed in earlier Sections of this report, the agricultural practices for different fruit species grown in the UK are quite diverse. In addition, unlike for other crops, different fruit species tend to be grown by domestic growers compared with those grown by commercial producers [Prosser *et al*, 1999]. It could, therefore, be difficult to assess the possible impact of the accidental release on the various fruit crops that may be produced.

One of the food categories that is usually of concern immediately after an accident is green vegetables, due to the continuous nature of their production and harvesting over the year. Due to their importance, measured activity concentrations in green vegetables are usually available within a day or so of deposition occurring. The maximum concentrations in green vegetables and the fruit categories considered in this study following a unit deposition have been compared to explore whether any guidance can be given on estimating activity concentrations in fruit from those in green vegetables. This would provide a useful scoping tool to assess the possible impact of an accident on fruit harvests.

The maximum activity concentration in green vegetables predicted by the FARMLAND model is 3.0 10^{-1} Bq kg^{-1} (fresh mass) per Bq m^{-2} for all radionuclides [Brown and Simmonds, 1995].

If deposition occurs during the period when no fruit is present, e.g. 1st January, activity concentrations in all fruit categories at harvest will be very low and can be assumed to be at least 3 orders of magnitude lower than the maximum concentrations observed in green vegetables.

Maximum activity concentrations are very similar for the two fruit categories if deposition occurs during the harvesting period (see Table 26 - Table 30). Deposition at this time will give rise to the highest activity concentrations that will be observed in fruit. Activity concentration in any fruit species within the two categories considered can be assumed to be a factor of 75 lower than the maximum concentrations observed in green vegetables.

If deposition occurs during the growing season, the activity concentrations in fruit at harvest will depend on the time when deposition occurs compared with the start of the harvesting period. For deposition on 1st May, maximum activity concentrations in soft fruit are about a factor of 4 lower than the maximum concentrations observed in green vegetables for ^{137}Cs, a factor of 100 lower for ^{90}Sr and ^{131}I and a factor of 1000 lower for ^{106}Ru and ^{239}Pu. If deposition occurs closer to the start of the harvesting period, this factor could be expected to increase or decrease, depending on radionuclide, with all values converging to about a factor of 75, i.e. tending towards the value expected for deposition during the harvesting period (see above).

For orchard fruit, if deposition occurs on 1st May, there is a much longer time between deposition and harvest compared with soft fruit. The maximum activity concentrations in fruit would then be about a factor of 100 lower than the maximum concentrations observed in green vegetables for ^{137}Cs and ^{131}I, a factor of 1000 lower for ^{90}Sr and at least a factor of 10,000 lower for ^{106}Ru and ^{239}Pu. As observed for soft fruit, if deposition occurred during the growing season but closer to the time of harvest, this factor would decrease and tend towards the value expected for deposition during the harvesting period.

7 VALIDATION AND VERIFICATION OF THE MODEL

The developed fruit model will be used for radiological impact assessments and it is important that the model is robust, reliable and suitable for the assessment being undertaken. An important step in the development and use of this model is, therefore, its validation and verification. Verification of the model involves ensuring that it has been implemented correctly, while validation consists of demonstrating that the model is an adequate representation of the real environment [Simmonds, 1997]. One important area of verification is the comparison of model results with problem solutions obtained from other models. Validation of the model can be carried out by comparing the model results with sets of field observations and experimental measurements other than those that were used to develop the model.

The Fruits Working Group of the IAEA BIOMASS Programme [Carini *et al*, 2005] undertook two model intercomparison studies and a model validation study to identify and investigate significant areas of uncertainty and difference in approach between models. These are described in Linkov *et al*, 2006 and Ould-Dada *et al*, 2006. The results of the developed fruit model can be compared with the other fruit models that took part in the intercomparison exercises and against the experimental data used in the model validation exercise [Ould-Dada *et al*, 2006].

An additional source of data for model validation is the study on contamination of orange trees [Pinder III *et al*, 1987]. Here the accumulation of contamination over an exposure period can be compared with the predictions of the model.

The predictions of the model can also be compared with those of the previous fruit model in FARMLAND, which was developed specifically for continuous release applications [Mayall, 1995]. Details of this comparison are given in Appendix D.

7.1 Validation against measured activity concentrations in fruit following continuous deposition

Chamberlain (1970) introduced a quantity, the Normalised Specific Activity (NSA), for use in assessing the contamination on vegetation during conditions of continuous deposition from atmosphere. It is defined as:

$$\text{NSA } (\text{m}^2 \text{ d kg}^{-1}) = \frac{\text{Activity concentration (Bq kg}^{-1}\text{ dry mass of crop)}}{\text{Activity deposition rate (Bq m}^{-2}\text{ d}^{-1}\text{)}}$$

The NSA provides a means of validating the model applied to a continuous release situation by comparing the NSA predicted by the model with that derived from experimental data from the study of ^{238}Pu contamination of orange trees [Pinder III *et al.* 1987]. In the experimental study, ^{238}Pu was deposited at a rate of 0.028 Bq m^{-2} d^{-1} for a 42-day period during the spring of 1983. At the end of this period, the ^{238}Pu concentration in fruit was approximately 0.012 Bq kg^{-1} dry mass. These data give an NSA of 0.43 m^2 d kg^{-1}. If the developed model is run in its default mode for a continuous release situation, the activity concentration in fruit at harvest in the first year is 7.2 10^3 Bq kg^{-1} fresh mass (4.6 10^4 Bq kg^{-1} dry mass) for a deposition rate of 8.64 10^4 Bq m^{-2} d^{-1}. This gives a predicted NSA value of 0.53 m^2 d kg^{-1}. The model therefore provides a close approximation of the measured NSA value from the experimental data in the study by Pinder III *et al*.

7.2 Validation against measured activity concentrations in strawberries following an instantaneous deposition

The model validation scenarios are based on experimental work carried out in Italy over 2 years to investigate the short-term transfer of ^{134}Cs and ^{85}Sr via leaf-to-fruit and soil-to-fruit in strawberry plants after a single deposit [Ould-Dada *et al*, 2006]. Three scenarios were covered. These were as follows:

- foliar contamination at anthesis (22nd April) when the plants had well developed leaves and a few immature green fruits;
- foliar contamination at ripening (18th May), when the plants bore green and red fruits and very few flowers were remaining;
- soil contamination at the antheis stage in the second year (27 April).

Details are provided on the intercepted activity by leaves and fruits and the fruit yield as well as the deposited activity. The default model developed for soft fruit has been used to compare with the experimental data presented in Ould-Dada (2006) and a site-specific model has not been set up. For comparison with foliar contamination at antheis, the model has been run with a deposition date of 1st May, which is approximately at anthesis. For comparison with foliar contamination at ripening, the default model results used were those for deposition occurring during the harvesting period.

7.2.1 Activity concentrations in fruit following foliar deposition

Strawberries were harvested at 28 days and 41 days following foliar deposition at antheis. Measured activity concentrations in the fruit were in the range of 25 - 27 Bq g^{-1} for the 2 harvests for ^{134}Cs. The model overestimated the ^{134}Cs activity concentrations by about a factor of 2, predicting values of 65 Bq g^{-1} and 55 Bq g^{-1} for the 2 harvests. The other models that took part in the validation exercise predicted activity concentrations in the range of 1 - 160 Bq g^{-1}, with four of the models predicting between 1 Bq g^{-1} and 20 Bq g^{-1} (underestimating the activity concentrations by factors ranging between 1.2 and 5) and one model predicting 160 Bq g^{-1}.

Following foliar deposition at fruit ripening, strawberries were harvested at 2 days and 15 days. Measured activity concentrations in the fruit were approximately 2 Bq g^{-1} and 15 Bq g^{-1} for ^{134}Cs at the two harvests and approximately 2 Bq g^{-1} and 4 Bq g^{-1} for ^{85}Sr in the 2 harvests. The model again overestimated the ^{134}Cs activity concentrations by about a factor of 2 for the harvest after 2 days and a factor of about 3 after 15 days, predicting values of 4 Bq g^{-1} and 50 Bq g^{-1} for the 2 harvests. For ^{85}Sr, the model agreed well with the observed activity concentrations, predicting a value of 2 Bq g^{-1} at both harvests. The other models that took part in the validation exercise all overestimated the activity concentrations in the first harvest by factors ranging between 4 and 40 for ^{134}Cs and between 2 and 20 for ^{85}Sr. All of the models predicted lower activity concentrations in the second harvest, contrary to what was observed and what is predicted by the fruit model developed in this study. Results were, however, closer to the observed values.

The model developed in this study agrees reasonably well with the observed experimental values but tends to overestimate the activity concentrations in strawberries, particularly for caesium. Given the generic nature of the model and the fact that the model was not tailored to the specific experimental conditions, this performance is considered acceptable.

7.2.2 Activity concentrations following soil contamination

Strawberries were harvested at 28 days and 41 days following contamination of the soil at anthesis. Measured activity concentrations in the fruit were 14 Bq g^{-1} and 20 Bq g^{-1} at the 2 harvests for ^{134}Cs. The model underestimated the ^{134}Cs activity concentrations by 3 orders of magnitude, predicting a value of 0.01 Bq g^{-1} for both harvests. The other models that took part in the validation exercise underestimated the activity concentrations by one to three orders of magnitude. For ^{85}Sr, the observed activity concentrations were 1.1 Bq g^{-1} and 2.4 Bq g^{-1} at the 2 harvests. The model underestimated the ^{85}Sr activity concentrations by about a factor of 10, predicting a value of 0.1 Bq g^{-1} for both harvests. The other models that took part in the validation exercise typically predicted values within the same order of magnitude of the observed values but 2 models underestimated the activity concentrations by factors of 3 and 30.

The underestimation of the activity concentration following soil contamination was explored by Ould-Dada *et al* (2006). The experiment was a pot study using peat soils and the pots were irrigated regularly. Root growth is known to be very different between pots and field situations and uptake has been observed to be much higher under irrigated situations compared with dry conditions. The uptake of caesium is also known to be enhanced from peat soils compared with other soil types [Ould-Dada *et al*, 2006]. For example, a five year lysimeter study undertaken in the UK looking at root uptake to crops grown in loam, peat and sand soils [Nisbet and Shaw, 1994] found uptake to carrots and cabbage grown in peat soils was up to an order of magnitude higher than from loam and sandy soils. All of these factors are likely to give rise to transfer from the soil to the strawberries being higher than could be expected under the typical field conditions that the model is aiming to represent.

7.3 Intercomparison of model with other fruit models available

The Fruits working Group of te IAEA BIOMASS programme carried out a model - model intercomparison study [Linkov *et al*, 2006]. Two contamination scenarios were investigated, a continuous deposition of ^{129}I and a single deposition of ^{137}Cs. The intercomparison was intended to serve as a baseline in order to gauge model validation against experimental data. The results from model developed in this study have been compared with the predictions of the 6 models that took part in the intercomparison. An exact comparison is not possible as the values of the predicted activity concentrations for the other models are not available; approximate values have been obtained using the Figures given in the published paper.

For the single deposition scenario, the default models developed for soft fruit and orchard fruit have been compared with the other models for apples and strawberries, respectively. For deposition during flowering time, the model has been run with a deposition date of 1st May, and a harvest date of 46 days after deposition has been used. For deposition 24 hours prior to harvest, the default model results used were those for deposition occurring during the harvesting period. For the continuous release scenario, the default generic fruit model has been used as described in Section 6.2. No adjustments have been made to the parameter values in the default models.

7.3.1 Single deposition on to strawberry plants scenario

Model predictions for a harvest every 10 years following deposition of ^{137}Cs during the flowering time in the first year were compared. The predictions of the models that took part in the intercomparison ranged from about 0.5 - 100 Bq kg^{-1} in strawberries in the first year's harvest and about 5 10^{-4} - 0.1 Bq kg^{-1} in subsequent years. The model developed in this study predicts 70 Bq kg^{-1} in the first year and about 6 10^{-3} Bq kg^{-1} in subsequent years. The model predicts activity concentrations within the range of the other models.

For ^{137}Cs deposition occurring 1 day before harvest, the predicted values in Linkov *et al* range from about 0.2 - 700 Bq kg^{-1} in the first year and about 5 10^{-4} - 0.1 Bq kg^{-1} in subsequent years. The model developed in this study predicts 5 Bq kg^{-1} in the first year and about 5 10^{-3} Bq kg^{-1} in subsequent years. Again, the model predicts activity concentrations within the range of the other models.

Caesium-137 activity concentrations predicted in the strawberry plant at the end of the harvesting period following deposition at flowering time were also compared. The predictions of the models that took part in the intercomparison ranged from about 5 -

700 Bq m^{-2} in strawberry plants after the first year's harvest and about 0.01 - 1 Bq m^{-2} in subsequent years. The model developed in this study predicts 200 Bq m^{-2} in strawberry plants in the first year, which is within the range of values obtained using the other models. Transfer to the plant in subsequent years is not modelled.

Predictions of the amount of ^{137}Cs activity in soil used to grow strawberries were included as part of the intercomparison. The models predicted levels of contamination in soil in the approximate range 300 - 1000 Bq m^{-2} in the first year and these remained fairly constant over subsequent years. The model developed in this study predicts a soil contamination level of 750 Bq m^{-2} in the first year with levels dropping to 560 Bq m^{-2} over 10 years. Again the model predictions fall within the range of the predictions of the other models.

7.3.2 Single deposition on to apple trees scenario

The scenario specified in the intercomparison study was deposition of ^{137}Cs occurring on to apple trees during flowering time, 7 weeks before harvest and 24 hours before harvest. For deposition occurring at flowering time, the models that took part in the intercomparison study predicted activity concentrations in apples at harvest of about 0.3 - 80 Bq kg^{-1} in the first year and 0.05 - 5 Bq kg^{-1} in subsequent years. The model developed in this study predicts 4 Bq kg^{-1} in the first year and 6 10^{-3} Bq kg^{-1} in subsequent years. For deposition occurring 1 day before harvest the model predictions were between about 0.08 and 200 Bq kg^{-1} in the first year and 0.01 - 5 Bq kg^{-1} in subsequent years. This compares with a prediction by the developed model of 4 Bq kg^{-1} in the first year and 6 10^{-3} Bq kg^{-1} in subsequent years (note that the predicted activity concentrations are the same for both 7 weeks and 24 hours before harvest; this is coincidental, the activity concentrations arising from different contamination processes in the two cases). The model agrees well with the other models for the first year's harvest but the predicted activity concentrations are outside the range of the other models, being lower by a factor of 2 for subsequent years. After the first year only root uptake is considered in the model and the choice of value for the root uptake factor based on UK experimental data may be lower that that used in other models.

7.3.3 Continuous release scenario for strawberries, blackcurrants and apples

The generic fruit model has been run and compared with the predicted activity concentrations from the 3 models that took part in the intercomparison for this scenario. The generic fruit model predicts an activity concentration of ^{129}I in the fruit following a continuous deposition of 11 Bq kg^{-1}. This can be compared with the range of other model predictions of about 9 - 70 Bq kg^{-1} for apples, 20 - 200 Bq kg^{-1} for strawberries and 20 - 100 Bq kg^{-1} for blackcurrants. The generic model developed for the UK agrees best with the values for apples which is to be expected, as the model parameters used are for apples reflecting the dominant fruit species grown and consumed in the UK.

8 MODEL RELIABILITY AND LIMITATIONS

The paucity of data on the transfer of radionuclides to fruit has required some assumptions to be made on the transfer processes involved in determining activity concentrations in fruit and their relative importance. The modelling approach recommended is necessarily robust, reflecting the level of detail of the information available. Although limited validation and verification of the model has been carried out, which indicates that the model is in reasonable agreement with other models and measured data, there will be relatively high uncertainty associated with the model predictions.

One process that is highly uncertain is the weathering of contamination from the fruit surface with time following the initial deposition onto the fruit. Investigations using the developed model have indicated that the activity concentrations in fruit at harvest can be very sensitive to the choice of this weathering rate as discussed in Section 4.3 [Teale and Brown, 2003]. This is particularly noticeable for accidental releases when immobile elements, such as plutonium, are involved and deposition onto fruit occurs a long time before harvest. The authors believe that the most justifiable position is to use a value for the weathering rate that is consistent with that used for other crops reported in the literature and used in foodchain models in Europe. However, this is an area where future experimental research would be very valuable in determining an appropriate generic weathering rate that could be used for all fruit species and elements.

8.1 Use of model for different fruit species

In developing the model, it was recognised that the fruit species grown for domestic and commercial production in the UK are diverse and that the model should reflect, where appropriate, any differences in the transfer to the main fruit species grown in the UK. Where possible, this has been taken into account in the parameter values chosen in the model, the basic structure of the model remaining the same for the different species. It is not possible to say that the model is any more appropriate for one of the fruit categories considered than for another, as the data used relate to a number of different fruit species, including those not grown in the UK. The model is, therefore, equally applicable to all fruit species grown in the UK. The most important factor in applying the model is that appropriate assumptions on agricultural practices should be used for the fruit species of concern, particularly for accidental release applications.

9 CONCLUSION

A modelling approach for the transfer of radionuclides to fruit species of importance in the UK has been developed. A robust approach is adopted, reflecting the availability of information on the transfer of radionuclides to fruit, but which builds on the understanding of the behaviour of radionuclides in the foodchain and the important features of radionuclide contamination of crops. The approach takes the form of a compartmental model for use for both continuous release and accidental release applications. The model will form part of the suite of sub-models in the FARMLAND foodchain model. The fruit model replaces a previous version developed solely for use for routine release applications using FARMLAND.

Verification and validation of the model has been carried out where possible through intercomparisons with other fruit models and comparison of the model results with sets of field observations and experimental measurements which were not used in the development of the model. The limited validation and verification of the model carried out shows that the model is in reasonable agreement with other models and measured data; however, there will be a relatively high uncertainty associated with the model predictions due to the limited data available on radionuclide transfer to fruit, particularly for some elements.

10 REFERENCES

Anguissola Scotti, I and Silva, S (1992). Foliar absorption and leaf-fruit transfer of ^{137}Cs in fruit trees. *Journal of Environmental Radioactivity* **16**(2), 97-108.

Baldini E, Bettoli MG, Tubertini O (1987). Effects of the Chernobyl pollution on some fruit trees. Advances in Horticultural Science **1**(2), 77-79.

Bengtsson GB (1992). Mobility of superficially applied caesium-134 and strontium-85 in apple braches under precipitation free conditions. *Analyst*, **177**, 1193-6.

Brown J and Simmonds J (1995). FARMLAND A Dynamic Model for the Transfer of Radionuclides through Terrestrial Foodchains, NRPB-R273, Chilton, UK.

Busby RG (1999). Validation of the PC CREAM Soil Model. In *PC CREAM User Group Report of the First Meeting held at NRPB, Chilton, 3 and 4 December 1998, NRPB-R309, Chilton UK*.

Carini F, Anguissloa Scotti I and D'Alessandro PG (1999). ^{134}Cs and ^{85}Sr in fruit plants following wet aerial deposition. *Health Physics* **77**(5), 520-529.

Carini F (2000). Uptake of Radionuclides by Fruits. *Radiation Protection Dosimetry,* **90**, 39-44.

Carini F (2001). Radionuclide transfer from soil to fruit. *Journal of Environmental Radioactivity,* **52**(2-3), 237-279.

Carini F and Bengtsson G (2001) Post-deposition transport of radionuclides in fruit. *Journal of Environmental Radioactivity* **52**(2-3), 215-236.

Carini F, Brambilla M, Mitchell N and Ould-Dada Z (2003). Cesium-134 and strontium-85 in strawberry plants following wet aerial deposition. *Journal of Environmental Quality* **32**, 2254-2264.

Carini F, Atkinson CJ, Collins C *et al* (2005). Modelling and experimental studies on the transfer of radionuclides to fruit. *Journal of Environmental Radioactivity* **84** 271-284.

Chamberlain AC (1970). Interception and retention of radioactive aerosols by vegetation. *Atmos Environ,* **4**, 57-78.

Defra (2001). Basic Horticultural Statistics 2000. Website, http://www.defra.gov.uk/esg/work_htm/publications/cf/bhs/current/fruit.xls

Defra (2010). Basic Horticultural Statistics 2010. website, www.defra.gov.uk/statistics/foodfarm/landuselivestock/bhs

Delmas J, Disdier R, Grauby A and Bovard, P (1969). Radiocontamination experimentale de quelque especes cultivees soumises a l'irrigation par aspersion. IN *Symposium International de radioecologie*, Cadarache, France (pp 707-724).

Delmas J, Bovard P, Grauby A, Disdier R, Blondel L and Guennelon R (1971). Contamination directe experimentale de l'oranger par le Sr-90 er Cs-137. In Coope A, ed. *Radioecology applied to the protection of man and his environment. Proceedings of an international symposium*. Rome. Commission of the European Communities. P 1081-1101.

Garland JA, Pattenden NJ and Playford K (1992). Resuspension following Chernobyl. In: *Modelling of resuspension, seasonality and loses during food processing. First report of the VAMP Terrestrial Working Group. IAEA-TECDOC-647, Vienna.*

Green N and Wilkins B (1995). Effects of processing on radionuclide content of foods: derivation of parameter values for use in radiological assessments. NRPB-M587, Chilton, UK.

Green N, Wilkins B and Hammond D (1997). Transfer of Radionuclides to Fruit. *Journal of Radioanalytical and Nuclear Chemistry* **226**, 195-200.

Green N, Hammond DJ and Wilkins BT (2005). A long-term study of the transfer of radionuclides from soil to fruit. HPA-RPD-006, Health Protection Agency, UK.

IAEA (1994). Handbook of parameter values for the prediction of radionuclide transfer in temperate environments. Technical Report Series No. 364. Vienna, Austria.

Jones AL and Sherwood JC (2008). Delay times between harvesting or collection of food products and consumption for use in radiological assessments. HPA-RPD-043, Health Protection Agency, Chilton, UK.

Katana H, Bunnenberg C and Kühn W (1988). Studies on the translocation of Cs-134 from leaves to fruit of apple trees. in *Environmental Impact of Nuclear Accidents, Proceedings International Symposium on Radioecology, Cadarache, March 1988.* Cadarache, CEA.

Kinnersley RP and Scott LK (2001). Aerial contamination of fruit through wet deposition and particulate dry deposition. *Journal of Environmental Radioactivity* **52**(2-3), 191-213.

Kopp P, Görlich W, Burkart W et al (1990). Foliar uptake of radionuclidesand their distribution in the plant. in *Proceedings International Symposium on Environmental Contamination following a Major Nuclear Accident, Vieena, October 1989.* Vienna, IAEA, Volume 2, 37-46.

Linkov I, Carini F, Collins C *et al* (2006). Radionuclides in fruit systems: Model-model intercomparison study. *Science of the Total Environment* **364**, 124-137.

MAFF (1996). National Food Survey 1995. MAFF, Her Majesty's Stationary Office, Norwich, UK.

MAFF (2000). National Food Survey 1999. MAFF, Her Majesty's Stationary Office, Norwich, UK.

Mayall A (1995). FARMLAND: Transfer of Radionuclides to Fruit, NRPB-M545, Chilton, UK.

Miller CW and Hoffman FO (1983). An examination of the environmental half-time for radionuclides deposited on vegetation. *Health Physics* **45**, 731-744.

Mouchel Consultancy (1999). SPADE Handbook Appendix C. Taken from Report No. 48112.001-R1.

Müller H and Pröhl G (1993). ECOSYS-87: A dynamic model for assessing radiological consequences of nuclear accidents. *Health Physics,* **64**(3), 232-252.

Nisbet, AF and Shaw, S (1994). Summary of a 5-year lysimeter study on the time-dependent transfer of ^{137}Cs, ^{90}Sr, ^{239,240}Pu and ^{241}Am to crops from three contrasting soil types: 1. Transfer to the edible portion. *Journal of Environmental Radioactivity* **23**(1), 1-17.

Outsider's Guide (1995). *The Outsider's Guide to Horticulture*. 1995 edition, Outsider's Guide, Lincoln, UK.

Oncsik MB, Eged K, Kis and Kanyar,B (2002). A validation study for the transport of ^{134}Cs to strawberry. *Journal of Environmental Radioactivity* **61**, 319-329.

Ould-Dada Z (2003). Private communication on study carried out for MAFF by ADAS on 'transfers of radionuclides, deposited onto the external leaf surfaces of plants, to internal compartments'.

Ould-Dada Z, Carini F, Eged K *et al* (2006). Radionuclides in fruit systems: Model prediction-experimental data intercomparison study. *Science of the Total Environment 366*, 514-524.

Pinder III J, Adriano D, Ciravolo T and Doswell A (1987). The Interception and Retention of Pu-238 Deposition by Orange Trees. *Health Physics,* **52**, 707-715.

Prosser SL, Brown J, Smith JG and Jones JA (1999). Difference in activity concentrations and doses between domestic and commercial food production in England and Wales: implications for nuclear emergency response. NRPB-R310, Chilton, UK.

Simmonds JR, Linsley GS and Jones JA (1979). A general model for the transfer of radioactive materials in terrestrial food chains, NRPB-R89, Chilton, UK.

Simmonds JR (editor) (1997). Models for calculating the transfer of radionuclides through the environment: verification and validation. NRPB-R300, NRPB, Chilton, UK

Teale P and Brown J (2003). Modelling approach for the transfer of actinides to fruit species of importance in the UK, NRPB-W46, Chilton, UK.

Vandecasteele C, Baker S, Forstel H et al (2001). Interception, retention and translocation under greenhouse conditions of radiocaesium and rdiostrontium from a simulated accident source. *The science of the Total Environment,* **278**, 199-214.

Wilkins BT, Paul M and Nisbet AF (1996). Speciation and Foodchain Availability of Plutonium Accidentally Released from Nuclear Weapons, NRPB-R281, Chilton, UK.

Zehnder HJ, Kopp P, Oertli JJ and Feller U (1993). Uptake and transport of radioactive cesium and strontium into strawberries after leaf contamination. *Gartenbauwissenschaft **58***(5) 209-213.

APPENDIX A Overview of Modelling Approaches in the ECOSYS Model

The ECOSYS model is described in Müller and Pröhl (1993).

A1 ROOT UPTAKE

The ECOSYS model calculates the activity concentration in plants using the following formula:

$$C_{i,r}(t) = TF_i C_s(t)$$

where:

$C_{i,r}(t)$ is the activity concentration due to root uptake of plant i at time t
TF_i is the soil-to-plant transfer factor for plant i
$C_s(t)$ is the activity concentration in the root zone of soil at time t

For deposition during the growing season, the activity concentration at harvest due to root uptake is reduced by a factor representing the proportion of the growing season that the radionuclides are present in the soil. Unlike FARMLAND, the activity concentration in fruit due to root uptake is therefore dependent on when deposition occurs.

A2 SOIL MIGRATION

The ECOSYS model includes a loss from the rooting zone of the plant due to soil migration. The rooting zone is assumed to be 25cm deep for arable soils and this is used for all crops except pasture.

A3 RESUSPENSION

The ECOSYS model uses an average resuspension factor of 2.5 10^{-8} m^{-1}, which is based on the mean residence time of radionuclides in a 0-1 cm soil layer and a mean dust loading of the near-ground air of about 100 µg m^{-3} in rural areas.

The ECOSYS model uses a default value of 10^{-3} ms^{-1} for the deposition velocity of resupended particles onto the crop surface.

A4 DIRECT SOIL CONTAMIANTION

The ECOSYS model does not include soil contamination explicitly. It is possible that this process may have been included as a part of the resuspension process in this model, via the resuspension factor but no details are available.

A5 INTERCEPTION

The ECOSYS model takes both wet and dry interception of material onto the fruit crop into account. For interception of material deposited under dry conditions, the ECOSYS model uses the air concentration and an element-dependent deposition velocity for the plant, therefore removing the need for an interception fraction. For wet deposition, ECOSYS uses a formula that is dependent on the leaf area index of the crop and the amount of rainfall and retention properties of the element and crop. This formula is described above in the main report, Section 3.5.1.

Interception by the fruit itself is not modelled explicitly in ECOSYS, but implicitly by the assumption that the translocation factor does not go down to zero for times when deposition occurs very close to harvest (see Tables A1 and A2). At these short times, contamination of the fruit is assumed to occur from deposition to the plant leaves, despite the fact that, in reality, there would not be time for the translocation of material from the leaf surface to the fruit to occur.

A6 WEATHERING

The ECOSYS model does not explicitly model weathering for crops such as fruit, where only part of the plant is consumed. Instead, it is implicitly included in the translocation factors used (see Section A7). A weathering half-life of 25 days is used for all other crops.

A7 TRANSLOCATION

In the ECOSYS model, actinides are classed as immobile elements and the authors suggest translocation factors (the fraction of the activity deposited on the foliage that is transferred to the edible parts of the plant at harvest) that are very low. Caesium and strontium are classed as mobile elements, the translocation factors being higher. The translocation factors as a function of time before harvest are shown in Tables A1 and A2 for immobile and mobile elements, respectively. The translocation factors give the proportion of the deposition onto the plant that is transferred to the fruit and does not include a contribution for radioactive decay, which is considered separately. This approach is considered to be a very rough approximation for fruits and berries, since translocation to and storage in stems and branches is not considered due to lack of adequate data.

TABLE A1 Translocation factors for immobile elements for edible parts of the plant (% of total plant deposition)

Days before harvest	0	30	150
Fruit vegetables	2	0.5	0
Fruit, berries	2	0.5	0

TABLE A2 Translocation factors for mobile elements for edible parts of the plant (% of total plant deposition)

Days before harvest	0	14	106	183
Fruit vegetables	2	10	10	0
Days before harvest	0	14	183	184
Fruit, berries	2	10	10	0

A8 AGRICULTURAL PRACTICES

In the ECOSYS model it is assumed that fruit are continuously harvested over a period from 1st July to 15th October.

A9 PREPARATION AND PROCESSING LOSSES

The ECOSYS model assumes that there are no losses in fruit and berries due to processing and hence a processing factor of 1 is used. The model does, however, include losses due to radioactive decay between harvest and consumption, i.e. during storage. For fruit and berries, it is assumed that storage is for 2 days.

A10 REFERENCE

Müller H and Pröhl G (1993). ECOSYS-87: A dynamic model for assessing radiological consequences of nuclear accidents. *Health Physics,* **64**(3), 232-252.

APPENDIX B Calculation of Interception Fractions

Pinder III et al, (1987) conducted their studies on simulated groves comprising 30 orange trees in a 50.4 m^2 area. For these simulated groves, Pinder III *et al* (1987) found that the intercepted fraction for the orange fruits themselves was 0.0011. For mature groves, they claim that there would be approximately 7 times more fruit production per area, and hence the interception fraction should be approximately 0.008. The orange fruit yields and fractions intercepted determined by Pinder *et al* are given in Table B1.

TABLE B1 Interception by fruit from Pinder III *et al*, 1997.

	Yield, dry mass (kg m^{-2})	Intercepted fraction
Simulated grove	0.047*	0.0011
Mature grove (estimate)	0.33	0.008

* Arithmetic mean of the fruit yields from the study

The relationship derived by Chamberlain (1970) relates herbage density (yield) of a crop to the fraction of deposited activity that is intercepted by it. The relationship is given as:

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

where $P =$ fraction of deposited activity that is intercepted
$W =$ dry mass of plant (kg m^{-2}), and
$\mu =$ interception coefficient (varies with vegetation type).

From this relationship, it is reasonable to assume that the interception is approximately proportional to the dry mass of the plant. Pinder III *et* al also claim that the intercepted fraction is approximately proportional to the yield for the yields of oranges observed in the study

Using the interception factor for mature oranges and the dry mass yield of fruit given in Table B1, the fractions of deposition intercepted by the two fruit categories considered in the model, soft fruit and orchard fruit, have been calculated by scaling by the dry mass yields for each fruit category. The estimated interception fractions for the 2 fruit categories considered are given in Table B2.

TABLE B2 Interception fractions for fruit

	Fresh mass (kg m^{-2})	Water content* %	Dry mass (kg m^{-2})	Intercepted fraction
Orchard fruit	1.7	84	0.27	0.007
Soft fruit	1.3	90	0.13	0.003

* Taken from Carini (2001), using the values for apples and strawberries, respectively.

B1 REFERENCES

Carini F (2001). Radionuclide transfer from soil to fruit. *Journal of Environmental Radioactivity* **52**(2-3), 237-279.

Chamberlain AC (1970). Interception and retention of radioactive aerosols by vegetation. *Atmos Environ*, **4**, 57-78.

Pinder III J, Adriano D, Ciravolo T and Doswell A (1987). The Interception and Retention of Pu-238 Deposition by Orange Trees. *Health Physics,* **52**, 707-715.

APPENDIX C Calculating Activity Concentrations and Integrated Activity Concentrations for the Fruit Model

C1 ACCIDENTAL RELEASE APPLICATIONS

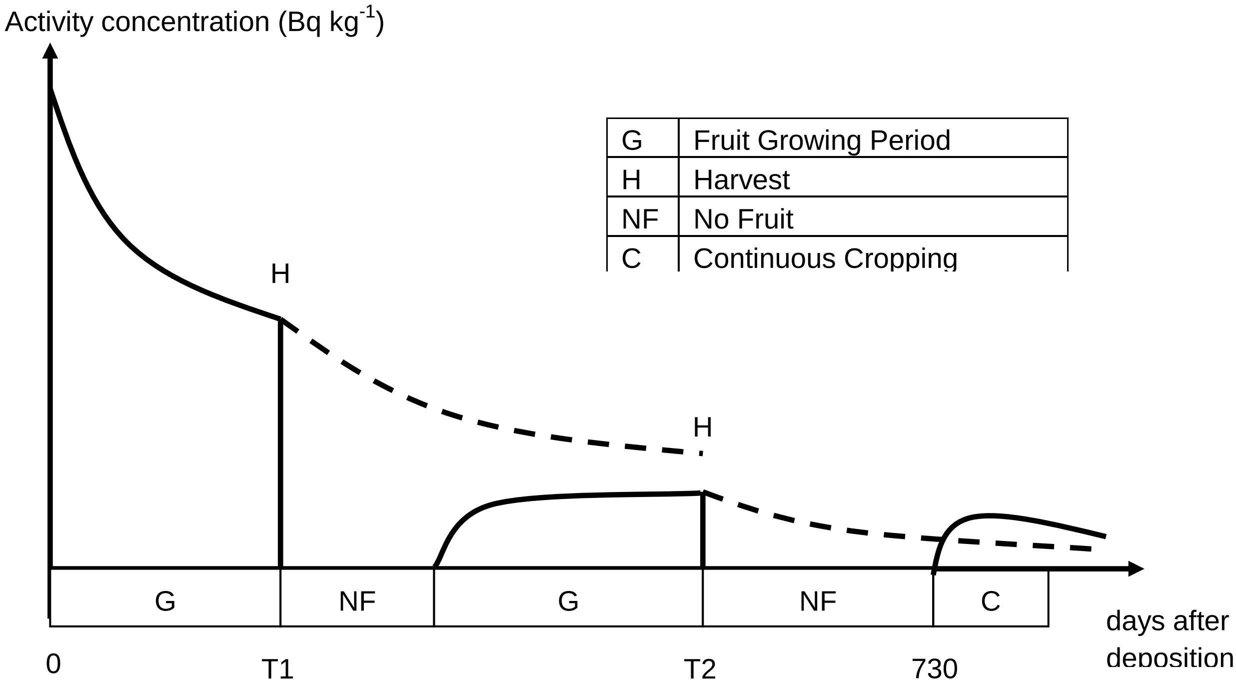
C1.1 Orchard fruit

The compartment model solver generates inventories of activity and time-integrated activities in Bq m^{-2} and Bq d m^{-2}, respectively. The activity concentrations are required per unit mass of fruit and so they need to be converted by dividing by the yield of the fruit.

The activity concentrations (Bq kg^{-1}) in the orchard fruit in the field are shown as the unbroken line in Figure C1. Before the first harvest, activity concentrations in the consumed fruit are zero. After harvest, the fruit is consumed over a period and the activity concentrations are dependent on the activity at harvest in the first two years (dashed line in Figure C1). After the first 2 years, the activity concentrations in the consumed fruit are those in the fruit in the field during the continuous cropping period.

There is a discontinuity in the model at the 730th day, at the changeover between the modelling of discrete harvests and the continuous cropping period, and special consideration needs to be made of the fruit that is still being stored from the second harvest. Before the 730th day, activity concentration in the consumed fruit is that from the second harvest and after the 730th day, the activity concentration is that from the fruit in the field. However, the integrated activity concentrations should not ignore the fruit that is still being stored at the 730th day. Therefore, the integrated activity concentrations for the complete second harvest, and in the continuous cropping period, are calculated based on all of the apples from the second harvest having been consumed, even if the time elapsed since the second harvest is less than a year.

FIGURE C1 Orchard fruit



This figure is purely illustrative, and no inferences about actual activity concentrations should be made from it.

The activity concentrations and integrated activity concentrations in the orchard fruit can be calculated from the model output as described below.

Notation:

INV:	Activity in compartment of model (Bq m^{-2})
INT:	Time-integrated activity in compartment of model (Bq d m^{-2})
CONC:	Converted model activity concentration (Bq kg^{-1})
INTEG:	Converted model time-integrated concentration (Bq y kg^{-1})
Concentration:	Activity concentration in consumed fruit (Bq kg^{-1})
Integral:	Integrated concentration in consumed fruit (Bq y kg^{-1})

- Before first harvest

Concentration(t) = 0
Integral(t) = 0

- Between first and second harvests

Concentration(t) $= \text{CONC}(T1).e^{-\lambda(t-T1)}$
Integral(t) $= \text{CONC}(T1).(1- e^{-\lambda(t-T1)}) / \lambda$

- Between second harvest and 2 years

Concentration(t) $= \text{CONC}(T2).e^{-\lambda(t-T2)}$
Integral(t) $= \text{CONC}(T2).(1- e^{-\lambda(t-T2)}) / \lambda + \text{CONC}(T1).(1-e^{\lambda.365})/ \lambda$

- After 2 years

$$\text{Concentration}(t) = \text{CONC}(t)$$
$$\text{Integral}(t) = \text{CONC}(T2).(1- e^{-\lambda(365)}) / \lambda + \text{CONC}(T1).(1-e^{\lambda.365}) / \lambda + \text{INTEG}(t) - \text{INTEG}(T2)$$

where,

λ = radioactive decay constant for the radionuclide
t = time after deposition

T1 = time of the first harvest
T2 = time of the second harvest

CONC(t) = (INV(2,t) + INV(3,t) + INV(4,t) + INV(5,t)) / Y
INTEG(t) = (INT(2,t) + INT(3,t) + INT(4,t) + INT(5,t)) / (365.Y)

Y = annual yield (fresh mass) of fruit (kg m^{-2})

INV(a,t) is the activity inventory of compartment a at time t (Bq m^{-2})
INT(a,t) is the integral of activity of compartment a at time t (Bq d m^{-2})

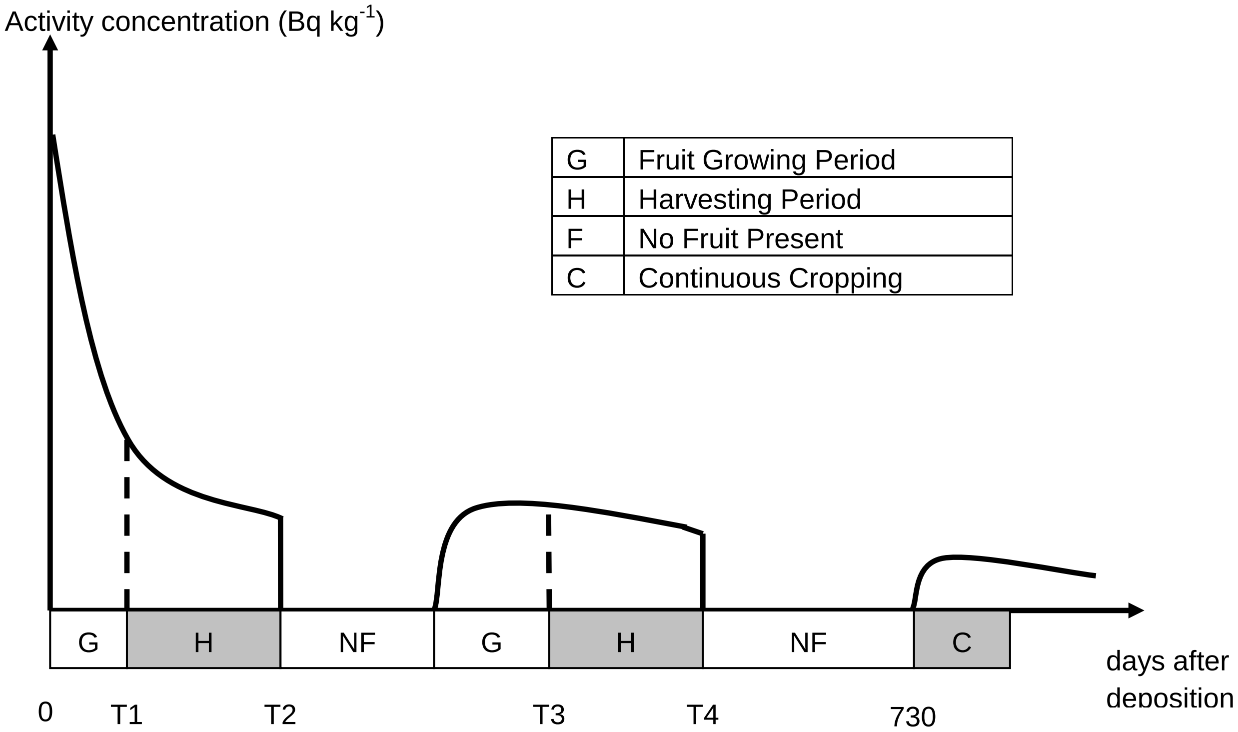
Note: Compartments 2, 3 and 4 are for external fruit, internal fruit and fruit -soil contamination, respectively.

C1.2 Soft fruit

The activity inventories and time-integrated inventories that are calculated by the model have the units Bq m^{-2} and Bq d m^{-2}, respectively. The activity concentrations are required per unit mass of fruit and so they need to be converted by dividing by the yield of the fruit.

The activity concentrations (Bq kg^{-1}) in the consumed fruit are shown in Figure C2. It can be seen from the figure that the fruit is only consumed during the harvesting periods (shaded in Figure C2) and not during the growing periods, nor in periods when there is no fruit present. The fruit is only consumed for a fraction of the year, but the time-integrated activity concentrations are to be calculated so that they can be multiplied by the annual ingestion rate (Bq y^{-1}) to give the total activity intake. Therefore, the time-integrated activity concentrations, as areas under the curve, need to be divided by the fraction of the year that the consumption takes place.

FIGURE C2 Soft fruit



This figure is purely illustrative, and no inferences about actual activity concentrations should be made from it.

The activity concentrations and integrated activity concentrations in the fruit can be calculated from the model output as described below.

Notation:

INV:	Activity in compartment of model (Bq m^{-2})
INT:	Time-integrated activity in compartment of model (Bq d m^{-2})
CONC:	Converted model activity concentration (Bq kg^{-1})
INTEG:	Converted model time-integrated concentration (Bq y kg^{-1})
Concentration:	Activity concentration in consumed fruit (Bq kg^{-1})
Integral:	Integrated concentration in consumed fruit (Bq y kg^{-1})

- Before first harvest period

Concentration(t) = 0
Integral(t) = 0

- During first harvest period

Concentration(t) = CONC(t)
Integral(t) = (INTEG(t) – INTEG(T1)) / ((T2 - T1)/365)

- Between first and second harvest periods

Concentration(t) = 0
Integral(t) = (INTEG(T2) – INTEG(T1)) / ((T2 – T1)/365)

- During second harvest period

Concentration(t) = CONC(t)
Integral(t) = (INTEG(t) – INTEG(T3)) / ((T4 – T3)/365)
+ (INTEG(T2) – INTEG(T1)) / ((T2 – T1)/365)

- Between second harvest period and 2 years

Concentration(t) = 0
Integral(t) = (INTEG(T4) – INTEG(T3)) / ((T4 – T3)/365)
+ (INTEG(T2) – INTEG(T1)) / ((T2 – T1)/365)

- After 2 years

Concentration(t) = CONC(t)
Integral(t) = INTEG(t) – INTEG(T4)
+ (INTEG(T4) - INTEG(T3)) / ((T4 – T3)/365)
+ (INTEG(T2) – INTEG(T1)) / ((T2 – T1)/365)

where,

t = time following deposition

T1 = time of the start of the first harvest period
T2 = time of the end of the first harvest period
T3 = time of the start of the second harvest period
T4 = time of the end of the second harvest period

CONC(t) = (INV(2,t) + INV(3,t) + INV(4,t) + INV(5,t)) / Y
INTEG(t) = (INT(2,t) + INT(3,t) + INT(4,t) + INT(5,t)) / (365.Y)

Y = annual yield (fresh mass) of fruit (kg m^{-2})

INV(a,t) is the inventory of compartment a at time t (Bq m^{-2})
INT(a,t) is the integral of compartment a at time t (Bq d m^{-2})

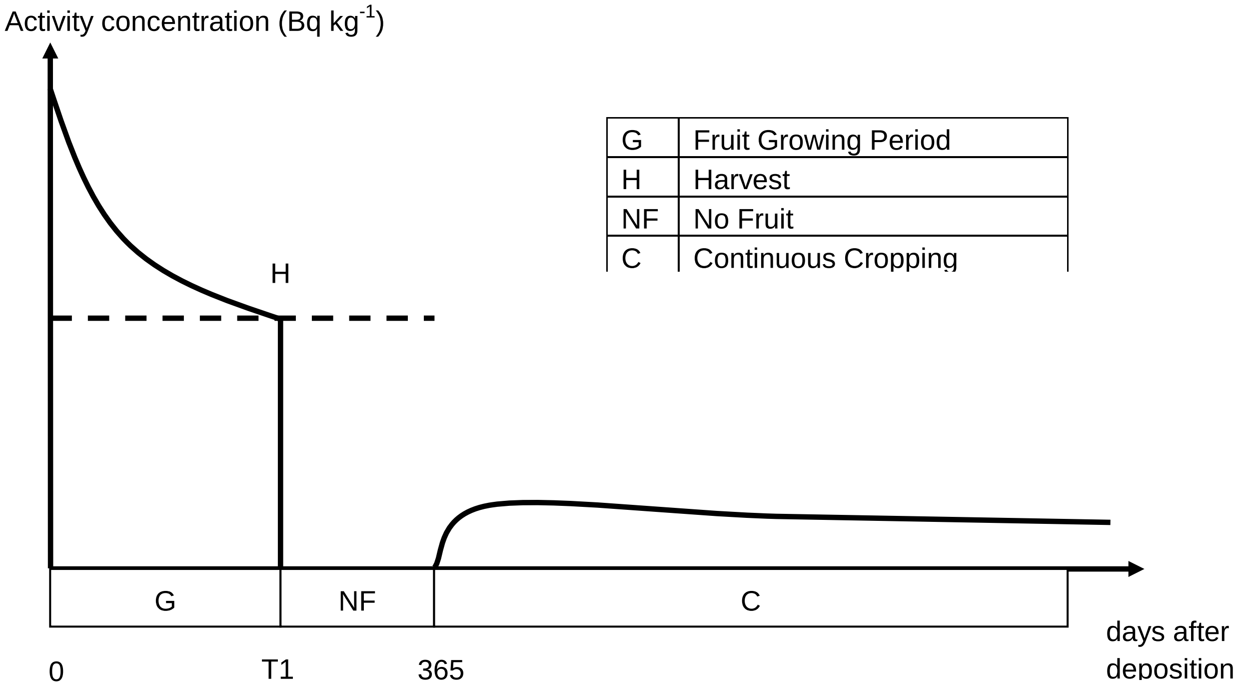
Note: Compartments 2, 3 and 4 are for external fruit, internal fruit and fruit - soil contamination, respectively.

C2 CONTINUOUS RELEASE APPLICATIONS

The activity inventories and time-integrated inventories that are calculated by the model have the units Bq m^{-2} and Bq d m^{-2}, respectively. The activity concentrations are required per unit mass of fruit and so they need to be converted using the yield of the fruit.

The activity concentrations (Bq kg^{-1}) in the consumed fruit are shown in Figure C3. It is assumed that the activity concentration at the time of the first harvest represents the integrated activity concentration in the first year (dashed line in Figure C3) as described in Section 6.2. From the second year onwards, the activity concentration is that from the fruit in the field, and the integral is calculated by summing the contribution from the first year with the area under the curve after the 365th day.

FIGURE C3 Generic fruit for continuous release applications



This figure is purely illustrative, and no inferences about actual activity concentrations should be made from it.

The integrated activity concentrations in the fruit can be calculated from the model output as described below.

Notation:

INV:	Activity in compartment of model (Bq m^{-2})
INT:	Time-integrated activity in compartment of model (Bq d m^{-2})
CONC:	Converted model activity concentration (Bq kg^{-1})
INTEG:	Converted model time-integrated concentration (Bq y kg^{-1})
Integral:	Integrated concentration in consumed fruit (Bq y kg^{-1})

- During first year

$$\text{Integral}(t) = \text{CONC}(T1) \,.\, (t/365)$$

- After first year

$$\text{Integral}(t) = \text{CONC}(T1) + \text{INTEG}(t) - \text{INTEG}(T1)$$

where,

$$\text{CONC}(t) = (\text{INV}(2,t) + \text{INV}(3,t) + \text{INV}(4,t) + \text{INV}(5,t)) / Y$$
$$\text{INTEG}(t) = (\text{INT}(2,t) + \text{INT}(3,t) + \text{INT}(4,t) + \text{INT}(5,t)) / (365.Y)$$

Y = annual yield (fresh mass) of fruit (kg m^{-2})

INV(a,t) is the inventory of compartment a at time t (Bq m^{-2})
INT(a,t) is the integral of compartment a at time t (Bq d m^{-2})

Note: Compartments 2, 3 and 4 are for external fruit, internal fruit and fruit - soil contamination, respectively.

APPENDIX D Verification of Model against Previous FARMLAND Fruit Model for Continuous Releases

The FARMLAND model for fruit [Mayall, 1995] was specifically developed for continuous release applications. The time-integrated activity concentrations from the FARMLAND model have been compared with those predicted by the model developed in this study for a continuous deposition of 1 Bq m^{-2} s^{-1} for 1 year. The results of the two models are broadly comparable for ^{239}Pu and ^{90}Sr (Table D1), although predictions from the developed generic fruit model are lower than those predicted by FARMLAND by up to a factor of 2 for ^{90}Sr at long times. For ^{137}Cs, the new generic fruit model predicts higher activity concentrations by about a factor of 5 at all times.

Table D1 Comparison of activity concentrations in the two models

	Model	Time-Integrated Activity Concentrations (Bq y kg^{-1} per Bq m^{-2} s^{-1})			
		1y	5y	50y	100y
^{90}Sr	Generic Fruit	$2.3\ 10^4$	$2.8\ 10^4$	$5.8\ 10^4$	$6.6.10^4$
	FARMLAND	$1.8\ 10^4$	$2.0\ 10^4$	$1.3\ 10^5$	$1.7\ 10^5$
^{137}Cs	Generic Fruit	$3.6\ 10^5$	$3.6\ 10^5$	$3.6\ 10^5$	$3.7\ 10^5$
	FARMLAND	$7.2\ 10^4$	$7.3\ 10^4$	$7.4\ 10^4$	7.510^4
^{239}Pu	Generic Fruit	$7.2\ 10^3$	$7.3\ 10^3$	$7.7\ 10^3$	$8.1\ 10^3$
	FARMLAND	$9.1\ 10^3$	$9.1\ 10^3$	$1.1\ 10^4$	$1.2\ 10^4$

D1 REFERENCE

Mayall A (1995). FARMLAND: Transfer of Radionuclides to Fruit, NRPB-M545, Chilton, UK.