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D9.17 – CONFIDENCE Overview of model improvements and future needs

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ABSTRACT

There are considerable uncertainties associated with the radioecological simulation models used to predict the transfer of radionuclides in human foodstuffs. Initially after an accidental release of radioactivity, the factors determining the contamination of foodstuffs will largely be defined by vegetation interception and the time of year. During the transition phase, factors controlling the uptake of radionuclides to vegetation from soil will become more important and these will dominate during the long-term rehabilitation phase. However, predictions made using radioecological models will be used in the early part of the transition phase to make longer-term decisions, such as those associated with remediation strategies. Therefore, models must be sufficiently robust and fit for purpose with uncertainties reduced where practicable.

This deliverable presents an overview of activities within the CONFIDENCE project to improve the capabilities of radioecological models used to make predictions of radionuclide contamination in human foodstuffs. The work programme addressed three over-arching and interlinked tasks: (i) 'Improving models' (uncertainty/sensitivity analyses, ^{131}I tracer studies, evaluation of extrapolation approaches, parameter dataset compilation); (ii) an evaluation of process-based soil-plant models; (iii) consideration of the inclusion of fuel particles in radioecological models.

The key outputs and findings of these activities were:

- The incorporation of the food chain transfer module (FDMT) from the JRodos Decision Support System into a flexible modelling platform (ECOLEGO) allowing, for instance, sensitivity analyses, investigation of regionalisation and the replacement of default empirical model components with process-based models.
- Development of process-based soil-plant models for Sr.
- Identification of the strengths and weaknesses of the Absalom process-based soil-plant model for Cs.
- Development of a model of the behaviour of particle associated radionuclides in soil-plant systems.
- Recommendation that in the short-term, process-based soil-plant models (for Cs, Sr and fuel particles) will generally give no added benefit, i.e. models such as FDMT are sufficient for predictions during this phase (because soil-plant transfer contributes little to radionuclide activity concentrations of crops in the short-term). However, longer-term predictions made using FDMT, or similar models, during the early phase after a deposition event should be communicated with care.
- Recommendation that for remediation planning, process-based models are applied once reliable deposition maps are available to enable the identification of areas where food products are likely to remain contaminated in the longer-term.
- Demonstration of the predictive power (and problems) of proposed phylogenetic models for predicting Cs and Sr activity concentrations in crops.
- Publication of a dataset of radionuclide biological half-lives for farm animal products.
- Derivation and publication of a dataset of transfer parameters for Mediterranean systems including regionally important foodstuffs.
- Experimental studies showing that: (i) there is negligible root uptake of ^{131}I by crops; (ii) there is transfer of ^{131}I deposited onto foliage to fruits and tubers; (iii) the presence of (goitrogenic) rapeseed in the diet of cows reduced the transfer of ^{131}I from blood to milk.
- The parameters in the FDMT model, as used in JRodos, should be reviewed and updated.

Recommendations for future model improvements (including experimental and communication requirements) based upon the findings of the studies conducted and consultations with end-users are presented.

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1 Introduction

There are considerable uncertainties associated with the radioecological simulation models used to predict the transfer of radionuclides along the human food chain. Initially after an accidental release, the factors determining the contamination of foodstuffs will largely be defined by vegetation interception and the time of year. During the transition phase, factors controlling the uptake of radionuclides to vegetation from soil will become more important and these will dominate during the long-term rehabilitation phase. However, predictions made using radioecological models will be used in the early part of the transition phase to make longer-term decisions, such as those associated with remediation strategies. Therefore, models must be sufficiently robust and fit for purpose with uncertainties reduced where practicable. A classic example of where predictions were made using models/information not fit for purpose is the post-Chernobyl case in upland United Kingdom. In 1986, it was stated that restrictions on sheep management because of high radiocaesium levels following the Chernobyl accident would last for a matter of weeks (Wynne 1992), however, restrictions remained in place until 2012.

The objective of the CONFIDENCE project's Work Package 3 (WP3) was to improve the capabilities of radioecological models used to predict activity concentrations in foodstuffs and to better characterise, and where possible, reduce uncertainties. Our work programme addressed key challenges identified in the Radioecology ALLIANCE Strategic Research Agenda (Hinton et al. 2013) and specifically those of the Human Food Chain Roadmap[1].

The work programme of CONFIDENCE WP3 had three over-arching and interlinked tasks:

1. *Improving models* – i) characterise and analyse the underlying probability distribution functions (PDFs) associated with transfer parameters to better enable uncertainty/sensitivity analyses; ii) conduct targeted field ^{131}I tracer studies on the plant-animal-milk pathway; iii) characterise the behaviour of radionuclides in Mediterranean production systems (including seasonality and key regional produce); iv) consider how recent knowledge would change/improve terrestrial food and dose module predictions; v) learn from post-Fukushima experiences; vi) evaluate the application of extrapolation approaches (phylogeny, allometry, stable elements) to improve predictive ability for poorly studied radionuclides.
2. *Can process-based models reduce uncertainties?* – i) determine why existing process-based approaches for Cs gave poor predictions post Fukushima; ii) investigate the applicability of process-based Cs model to European soil types (focusing on soil types not included in model parameterization/validation studies); iii) investigate process-based model options for Sr; iv) assess the added value of using process-based models; v) investigate how (spatial and temporal) process-based models can be incorporated into Decision Support Systems (DSS).
3. *Including 'hot particles' in radioecological models* – incorporate hot particles into models to improve predictions.

Much of our work programme has already been described in detail in published deliverable reports. In Brown *et al*. (2018a) we compared radionuclide transfer parameters as used in the JRodos DSS with the latest international recommendations; incorporated the JRodos food chain transfer module into an adaptable modelling platform (ECOLEGO); conducted a sensitivity analysis and investigated the impact of regional parameters. We presented a dataset of radionuclide transfer parameters for food products in Mediterranean systems in Guillén (2019). In Almahayni et al. (2019a) we reviewed soil-plant modelling approaches for Cs; assessed a process-based Cs soil-plant model for a range of European soils and crops; developed soil-plant process-based models for Sr; demonstrated how soil-plant process-based models

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[1] https://radioecology-exchange.org/sites/default/files/T1_WG_for%20Radioecology%20Roadmap_Human%20Food%20Chain_version02022015.pdf

can be incorporated in a DSS; reported on consultations with end-users regarding the use of soil-plant process-based models. Finally, in Lind et al. (2019) we developed a compartment model for the behaviour of fuel (or 'hot') particles in soils to investigate the potential importance of fuel particles in the contamination of food products.

This deliverable presents an overview of all of the work conducted by WP3, including some studies not included within our earlier deliverable reports, and concludes with recommendations for future research and model development arising directly from the studies we have conducted and also from consultation with the end users of radioecological research. A list of refereed papers and published datasets from WP3 can be found in Appendix 2.

2 Improving models

2.1 A comparison of FDMT with the latest international data compilation

The FDMT (Food Chain and Dose Module for Terrestrial Pathways) software (Müller et al. 2004) has been implemented in the Real-time On-line Decision Support System (RODOS, now referred to as JRodos) (Levdin et al. 2010). FDMT is largely based upon the earlier dynamic model ECOSYS-87 (Müller & Pröhl 1993). Much of the developmental work including the numerical specification of many of the parameters used in ECOSYS-87 (and therefore FDMT) was completed in the 1980s and hence did not consider the large numbers of radioecology studies prompted by the 1986 Chernobyl accident. Furthermore, the original parameter collation was mainly specific to Southern German agricultural conditions.

In Brown et al. (2018a), we compared the default FDMT transfer parameter values for crops (F_v) and animal products (F_m *or* F_f) to data presented in the latest International Atomic Energy Agency (IAEA) handbook (IAEA 2010). Where,

(i) F_v, is the soil-to-plant concentration ratio (defined in FDMT as Bq kg^{-1} fresh mass (FM) plant to Bq kg^{-1} dry mass (DM) soil);

(ii) F_m (for milk), F_f (for meat) are the transfer coefficients for animals products (Bq kg^{-1} in animal product (FM) to the daily radionuclide intake, Bq d^{-1}), referred to as TF_m in FDMT.

Where comparison was possible, 90% of the 139 default FDMT F_m and F_f values were within an order of magnitude of the latest recommended IAEA value. Only the F_f for iodine and pork was more than an order of magnitude lower in FDMT than that quoted in IAEA (2010). However, for crops, less than 70% of the 192 default FDMT F_v values were within an order of magnitude of the value in IAEA (2010). Of the 10 values where the FDMT value was more than an order of magnitude lower than the IAEA value, seven were for Te. All of the Te values presented in IAEA (2010) are based on single values and hence confidence in them is low. The other values in FDMT that were more than an order of magnitude lower than the IAEA value were single values for Ce (grass), Mo (cereals) and Zr (root vegetables). Most of the 49 FDMT values that were more than an order of magnitude higher than in IAEA (2010) (some values were three to four-orders of magnitude higher) were for Ag, I, La, Na, Pu, Sb and Y.

Although in many instances, the default transfer parameter values in FDMT were within an order of magnitude of those in the latest international compendium (i.e. IAEA, 2010), in a number of cases there is considerable disagreement between the FDMT and IAEA values. Therefore, we recommend that the default values in FDMT be reviewed and updated.

2.2 Iodine-131 studies

2.2.1 Field plant studies

The consumption of contaminated agricultural products by humans can be a major exposure pathway following a radioactive release to the environment. Hence, from an emergency preparedness perspective, estimating the radioactive content in crops is an essential step in assessing and managing the risk after an accident. Although the Chernobyl accident has provided knowledge on the behaviour of radiocaesium in European agricultural systems, there is still limited knowledge with regard to the behaviour and fate of other radionuclides following an atmospheric release. In the early phase of an emergency situation, ^{131}I is one of the most important radionuclides for which information on contamination of human foodstuffs is essential. There is also the potential for economic and societal consequences from the loss of crops that are vulnerable to contamination, particularly those with a short harvest to market window, such as soft fruits or new potatoes.

Because of the short physical half-life of ^{131}I, foliar uptake and translocation within plants are major factors influencing the activity concentrations in foodstuffs. Both translocation and soil-to-plant transfer could be dependent on stable iodine status. To test this hypothesis a series of field tracer experiments using ^{131}I have been carried out at two sites in Norway (Figure 2.1): a coastal site (Fureneset) with high sea salt and stable iodine deposition, and an inland site (Apelsvoll) with low salt and iodine deposition. In the first set of experiments conducted in 2017, ^{131}I tracer (in artificial rainwater) was sprayed on grass and barley three times during the growing season (June-August); samples of soil and vegetation taken for three weeks after each spraying. Spraying on grass was also carried out in 2018 and 2019, although only during July. In 2019, potato and strawberry plants were also sprayed to investigate the potential for translocation of the tracer from leaves to tubers, and from leaves/flowers to fruits. In both cases, the spraying was carried out 2-3 weeks prior to the expected time of harvest, which represents the most vulnerable time for these crops.

Figure 2.1. Location of the two field sites in Norway.

Results showed that ^{131}I concentrations in grass and barley at both sites were dominated by interception and changes in biomass, with little wash-off from plant to soil (see example in Figure 2.2). There was also no discernible soil to grass transfer and no effect of stable I on vegetation activity concentrations. However, mass balance calculations indicated a loss of between 5 and 20% of the total ^{131}I activity per m^2, during the first 24 hours. The mass balance calculations demonstrated that the reduction could not be accounted for by wash-off to soil (i.e. no increases in soil concentrations), suggesting that there had also been a loss due to evaporation.

Results from barley spraying showed that ^{131}I concentration in seed heads was about 1/3 of that in the whole plant. While there was little change in the concentration in whole barley grain after spraying, there was an increase in the percentage found in barley grain, due to increase in grain weight. Later in the growing season, a slight transfer from the outer shell to the grain could be seen five days after spraying. Results from the potato and strawberry spraying showed a small, but measureable transfer from leaves to tubers and from leaves/flowers to fruit in the three weeks after spraying (leaves/flower to fruit/tuber concentration ratio of <0.02 and <0.10, by mass FM, respectively). Activity distribution in the new potatoes was 50:50 between flesh and skin.

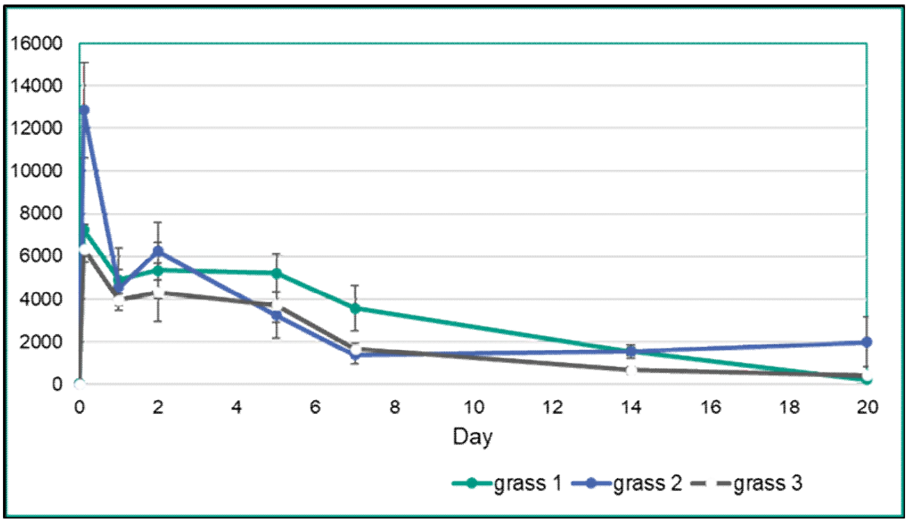

Figure 2.2. Grass ^{131}I (Bq m^{-2}) - Apelsvoll June –July.

Overall, the results support previous studies on the importance of biomass on ^{131}I interception, but also demonstrate that changes in grass concentrations after a deposition can be adequately modelled by biomass changes. Follow-up studies will focus on improved mass balance calculations and investigating the impact of climatological conditions and crop growth stage. Data should help to improve analysis of the potential contribution of accidentally released ^{131}I on human ingestion doses, as well as to support decisions about potential socio-economic impacts of crop contamination.

2.2.2 The influence of protein source in feed on the transfer of iodine to milk

As an essential element, the recommended daily intake iodine is 120 µg d^{-1} for 6-12 year olds (WHO 2007). However, iodine deficiency is re-emerging in certain population groups in many developed countries (WHO 2007). In addition to marine fish, dairy is an important source of stable iodine, accounting for around 60 % of stable iodine needs of children in some countries. Screening of milk from regions in Norway at different seasons has shown that the iodine concentration in winter milk almost halved between 2000 and 2008, while no difference was observed in summer milk (Haug et al. 2012). The hypothesis proposed to explain this was that the decrease was due to a change in the protein source in feed of the cows, namely that a change from soy to rapeseed was responsible for the decrease in transfer of iodine from blood to milk in the winter (rapeseed being goitrogenic). The decrease in milk iodine is relevant to nuclear emergency preparedness for two reasons: (i) a change in the diet of dairy cattle could potentially reduce the transfer of ^{131}I to milk after an accident; (ii) lower stable iodine concentrations in milk and hence in the diet of young people would be expected to result in increased transfer of radioiodine to the thyroid, representing an important risk factor for human health.

To test the hypothesis that changing the source of protein in feed could impact transfer of iodine to milk, a tracer experiment was carried out wherein a single dose of ^{131}I was administered to the vein of four fistulated cows as $^{131}I^-$ and two weeks later as $^{131}IO_3$ via the rumen of the cows. The experiment was designed as a 2x2 Latin square where the cows were their own control. Two cows received rapeseed cake and two soybean meal, and then the feed was swapped. The stable iodine concentration in the feed was ~4 mg kg^{-1} DM, ^{131}I tracer was administrated after a week of acclimatization to the feed.

The results showed that rapeseed in the diet resulted in lower ^{131}I activity concentrations in milk (Figure 2.3) as a consequence of reduced transfer of ^{131}I from blood to milk (Figure 2.4); there was increased excretion of ^{131}I via urine. Results suggest that, if feasible, given potential constraints of timing and availability of feed stocks, it may be possible to reduce ^{131}I transfer to the milk of farm animals by between 50-90% by adding rapeseed to their diet.

The results are being used to improve feed-cow-milk biokinetic models of ^{131}I metabolism and transfer as well as to investigate factors behind the reduction in blood-to-milk transfer (e.g. the content of glucosinolate and metabolites such as goitrin, indole acetonitrile, thiocyanate in rapeseed that could compete with iodine blood/milk transfer).

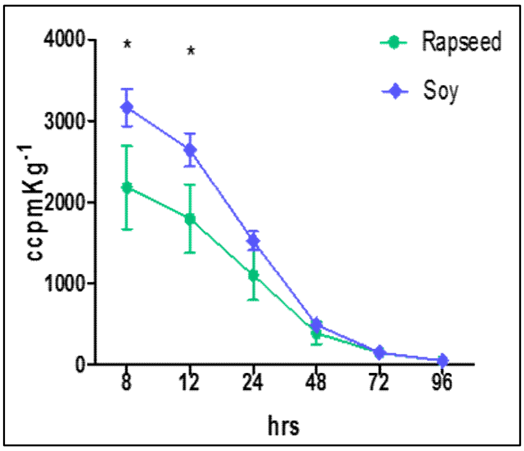

Figure 2.3. ^{131}I in milk from cows fed diets containing different protein sources (soy or rapeseed).

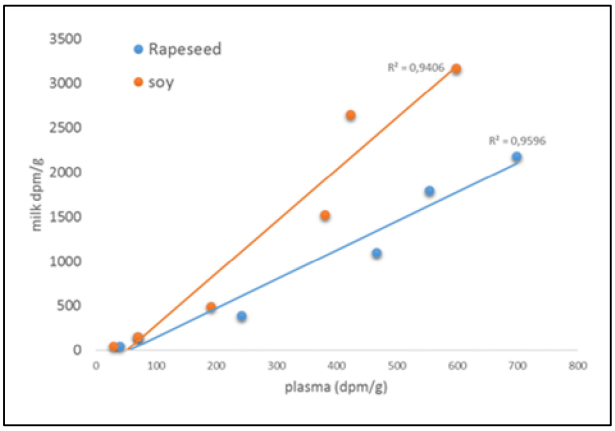

Figure 2.4. Blood-to-milk transfer of ^{131}I, depending on the protein source in the feed.

2.3 Biological half-life dataset

Many predictive models use biological half-lives (or rate constants derived from them) to describe the rate of loss of radionuclides from animal tissues and products (e.g. Müller & Pröhl, 1993; Brown & Simmonds, 1995). However, whilst there have been international compilations of transfer parameters for modelling purposes (e.g. IAEA, 2010) these have not considered biological half-life values. To address this, we have conducted a review of biological half-life values for farm animal products (meat, milk, eggs, etc.) and compiled a dataset of quality-controlled entries.

2.3.1 Dataset

Entries into the dataset comprise a compilation of quality-controlled biological half-life values (and associated information) from a focussed literature review for farmed animals, which contribute to the human food chain. In addition to the English language literature, our review took into account studies originally reported in the Russian language literature and Japanese data sources. The final dataset contains over 600 entries for 12 animal types (cattle, sheep, goats, deer, geese, hens, horses, pigs, rabbits, camels, ducks and red grouse) for 33 elements relevant to radiological protection. Entries include values for milk, muscle (meat), eggs, whole body, carcass and various tissues (e.g. liver and kidney); the number of entries available for each element/food-chain product combination is highly variable. The dataset also contains values for other sample types (e.g. urine, faeces etc.) that are not associated with the human food but are included as these data appeared in the same source reference as those values for human food chain products and they may be useful for modelling purposes.

Values for milk represent approximately 30% of all the data; half of these values being for Cs, Sr and I. Almost 70% of the entries for milk are for cow milk with 25% being for goat milk and <1% for sheep milk. Values for muscle (meat) comprise approximately 20% of the dataset; the majority of these data (~87%) are for Cs and Sr. Data for cattle comprise ~30% of the data for meat; sheep ~32%, hens 19% and pigs 8%. Values for eggs comprise approximately 5% of the dataset with almost half of these being for the whole egg (all of the egg data are for hens). The full dataset has been published as Barnett et al. (2019a) which includes all the source references.

2.3.2 Recommendations from the dataset

Summarising the dataset is not straightforward, unlike for compilations of transfer parameters, as it is not possible to derive means and associated probability distribution functions. This is because authors report differing numbers of components of loss (e.g. for Cs in milk between one and five loss components are reported). Therefore, in giving recommendations for a given element – food product combination a degree of subjective judgement is required. In the case of milk for all elements and species, the majority of loss appears to take place rapidly with a biological half-life in the range 1-3 days. This likely reflects a relatively rapid change in radionuclide activity concentrations in blood following cessation of a contaminated diet. Longer-term biological half-lives in milk will reflect those in the main storage compartment (which are element dependent, e.g. bone for ^{90}Sr, liver for ^{110m}Ag).

An initial review of the dataset enables us to make the following 'best estimate' recommendations:

Cs cow milk - two components of loss: 1.7 days (80%), 17 days (20%)
I cow milk - single component of loss: 1 day
Cs hen eggs - single component of loss: yolk 5 days; albumen 3 days
Cs sheep muscle - single component of loss: lamb 17 days; adult 23 days
Sr adult cattle muscle - two components of loss: 4 days (50%), >200 days (50%)
Cs deer whole body - two components of loss: 1 day (30%), 15 days (70%)

2.4 Investigation of extrapolation approaches

It is unlikely that we will ever have data for all of the parameters required for all of the crops, animal products and radionuclides included in predictive models. For instance, it is evident that FDMT has many default values that are not based upon data. However, greater transparency is required on how these values have been derived, though some values may now be available (e.g. in IAEA, 2010). In this section, we report on our considerations of some extrapolation techniques.

2.4.1 Phylogenetic models

The soil-plant transfer of a number of elements of radiological interest (e.g. Cl, Co, Cs, Ru, Sr) have been related to plant evolutionary history, or phylogeny (Beresford et al. 2016). It has been suggested that such 'phylogenetic relationships' offer a scientifically supported extrapolation approach to determining radionuclide activity concentrations in plants (Willey, 2010). However, to our knowledge, the approach has never been tested for crops.

In Almahayni et al. (2019a), we report a study in which a range of crops (radish (*Raphanus sativus*); lettuce (*Lactuca sativa*); grass (*Agrostis capillaris*); chard (*Beta vulgaris subsp. vulgaris*); courgette (*Cucurbita pepo var. cylindrical*); strawberry (*Fragaria × ananassa*) and potato (*Solanum tuberosum*)) were grown in six soils with differing characteristics. The resultant dataset (now published as Barnett et al. 2019b) has been used to test the phylogenetic models proposed for Sr (Willey & Fawcett 2006) and Cs (Beresford & Willey 2019). The models are presented as crop type specific REML (residual maximum likelihood) mean values and can be used to make predictions using the formula:

$$\text{Activity concentration for measured crop} \times \frac{REML\ mean\ for\ crop\ Z}{REML\ mean\ for\ measured\ crop}$$

where 'crop z', is the crop type for which a prediction is required.

Here we have used the Sr and Cs concentrations in grass as the 'measured crop' to predict concentrations in the other crops (note Barnett et al (2019b) presents data for stable element concentrations). REML means for Sr and Cs were taken from Willey & Fawcett (2006) and Beresford & Willey (2019) respectively.

Figures 2.5 and 2.6 compare predicted crop concentrations to measured values for Sr and Cs respectively.

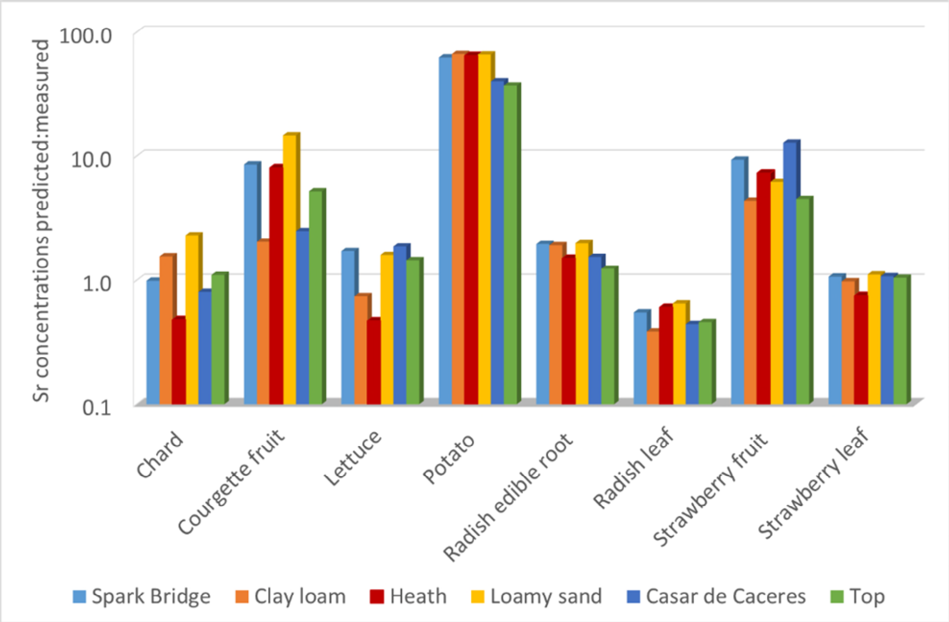

Figure 2.5. A comparison of predicted to measured Sr concentrations in crops. A value of '1' would mean the predicted and measured values were the same, predictions were made using the REML means reported in Willey & Fawcett (2006).

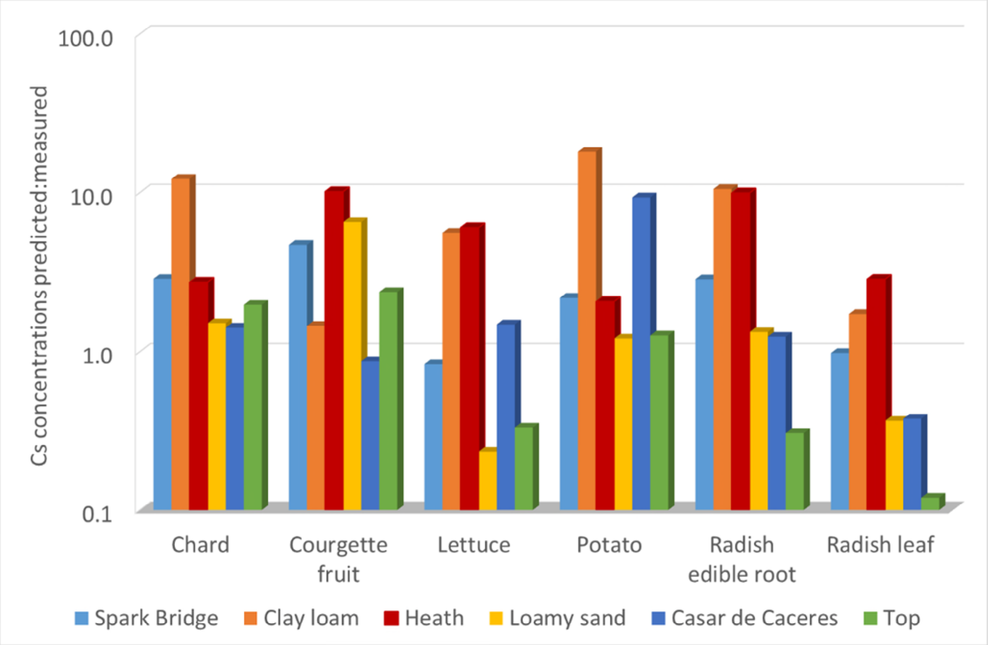

Figure 2.6. A comparison of predicted to measured Cs concentrations in crops. A value of '1' would mean the predicted and measured values were the same, predictions were made using the REML means reported in Beresford & Willey (2019).

For Sr, predictions were close to the measured values for chard, lettuce, radish leaf, radish edible root and strawberry leaf. Concentrations of Sr in potatoes were over-predicted by more than an order of magnitude for all soil types. There was also consistent over-prediction for strawberry fruit and, for most soils, for courgette. For Cs, predictions looked reasonable, virtually all being within an order of magnitude of the measured values. Unlike for Sr, there was no bias for specific crop types for Cs although there was more variation for a given crop type in agreement with measured values across the six study soils.

The existing phylogenetic (or REML) models tend to have been derived using the concentrations of elements in shoots and not the portion of plants which are consumed. Therefore, if there was any difference in the element concentrations in shoots versus the fruits/tubers then we may expect the existing models to predict shoot/leaf concentrations better than they predict for edible plant parts. This is what we observe for Sr (Figure 2.5) but not Cs (Figure 2.6). However, there is evidence that Ca concentrations in fruits are lower than those in leaves, whereas those for K are more similar (Adeyeye 2005; Tůma et al. 2004; van Goor & Wiersma 1973; Xiloyannis et al. 2001). Therefore, we may expect better predictions for Cs concentrations in fruits than those for Sr which we would expect to be over-predicted. This is in agreement with what we observed.

We suggest that there is merit in pursuing the use of phylogenetic models, they allow predictions for a wide range of crops for a given site without the need for soil type specific studies. However, the models need to be parameterised using the component of plants consumed.

2.4.2 Allometry

Mass dependent, or allometic, relationships have previously been demonstrated for radionuclide biological half-life and wildlife (e.g. Beresford & Vives i Batlle, 2013). We have attempted to fit allometric relationships to the data for the most abundant element-product combinations (e.g. Cs and milk) in the farm animal biological half-life dataset described above. The aim of doing this was to derive an approach to predict half-life values for species-element combinations for which we have no data. However, whilst there is an indication that allometric relationships may exist for farm animal product biological half-lives, data are insufficient to establish robust models and we were unable to derive a generic relationship across elements as previously done for wildlife (Beresford & Vives i Batlle, 2013).

2.4.3 Stable isotopes

Stable elements are increasingly being used to derive transfer parameter values for radionuclides in both human food chain and wildlife assessment models. This is based on the assumption that stable and radioelements behave in the environment in the same way. For Cs, there is some evidence that stable and radioisotopes had similar behaviours within a few years of the Chernobyl accident (Oughton 1989). Conversely, more recent data from a limited number of sites indicate that the transfer of ^{137}Cs and stable Cs is not the same - even though radiocaesium deposition occurred more than 30 years ago (e.g. Barnett et al. 2014; Beresford et al. 2020).

To investigate the applicability of using stable element concentrations as a proxy for radionuclides to determine F_v values we have: (a) carried out bespoke sampling and analyses; and (b) conducted a bibliographical review (though few published studies report radio- and stable- isotope transfer parameters for the same site).

Grass and soil (0-10 cm) were collected from Spain, Ukraine, the UK and Kazakhstan (Semipalatinsk Test Site). These sites encompassed a number of source terms: global fallout ($\Delta t \approx 50y$) (dominant source in Spain, contributor in UK); the 1986 Chernobyl accident ($\Delta t \approx 30y$) (dominant source in Ukraine, contributor in UK); the 1957 Windscale accident ($\Delta t \approx 60y$) (contributor in UK); and nuclear weapons tests ($\Delta t \approx 65y$) (dominant source in Kazakhstan).

Tables 2.1 and 2.2 present the ratio of ^{137}Cs/Cs^{+} and ^{90}Sr/Sr^{2+} F_v values respectively determined for the collected samples and from literature sources. For both Cs and Sr, there is a tendency for the radioisotope F_v value to be higher than that for the stable element. This implies that F_v values estimated from stable element concentrations will likely underestimate the radionuclide concentration in vegetation. Consequently, we recommend that the application of transfer parameters derived from stable elements in radioecological models is further reviewed.

Table 2.1. Range in the F_v (^{137}Cs)/F_v(Cs$^+$) ratio for various plant types from different locations as reported in the literature or estimated in this work.

Location	**Plant type (N)**	**Sampling year**	**F_v(^{137}Cs)/F_v(Cs)**	**References**
Ukraine (CEZ)	Grass*	2014	5.5	Beresford et al. 2020
	Pine tree*	2014	11.6	Beresford et al. 2020
	Grass (5)	2017	0.94 – 27.3	This work
Japan	Potato (24)	1991-94	6.64 (1.26-19.4)	Tsukada et al. 1999
	Rice (20)	1996-97	3.61 (0.98-13.41)	Tsukada et al. 2002
	Rice*	2002-05	0.8	Kamei-Isikawa et al. 2008
	Various crops*	2005-05	2.04 – 10.8	Kamei-Isikawa et al. 2008
	Rice (12)	2002-03	1.5 (0.16-3.63)	Uchida et al. 2007
	Various crops (18)	2002-03	6.54 (1.97-35.43)	Uchida et al. 2007
Nordic	Grass (16)	1994-95	1.72 (0.17 – 2.7)	NKS 1995
UK	Grass (7)	1992, 2017	6.22 (1.09 – 12.0)	This work
	Grass*	1986-87	7.6 – 21.5	Oughton 1989
Kazakhstan	Grass (10)	2017	10.95 (0.38 – 33.7)	This work
Spain	Grass (4)	2017	1.57 (0.21 – 2.0)	This work

*Mean value of multiple samples presented in source reference.

Table 2.2. Range in the F_v (^{90}Sr)/F_v(Sr^{2+}) ratio for various plant types from different locations as reported in the literature or estimated in this work.

Location	**Plant type (N)**	**Sampling year**	**F_v(^{90}Sr)/F_v(Sr)**	**References**
Ukraine (CEZ)	Grass*	2014	1.75	Beresford et al. 2020
	Pine tree*	2014	73.7	Beresford et al. 2020
UK	Grass (1)	2017	41.9	This work
Kazakhstan	Grass (2)	2017	0.33 – 2.2	This work
Spain	Grass (4)	2017	0.37 – 4.2	This work

*Mean value of multiple samples presented in source reference.

3 Process-based soil-plant models

Vegetation interception and the time of year will largely determine the contamination of foodstuffs immediately following an accidental release. During the transition phase, uptake of radionuclides by vegetation from soil will increase in importance and root uptake will dominate during the long-term rehabilitation phase. Predictions made using radioecological models will be used to make long-term decisions, e.g., with regard to remediation strategies.

Models must be sufficiently robust and fit for purpose with uncertainties reduced where practicable. Most radioecological models use empirical transfer factors to estimate soil-to-plant transfer of radionuclides and these do not credibly cope with variation in root uptake caused by variation in soil properties (Almahayni et al. 2019b). Consequently, process-based soil-to-plant models were developed to predict radionuclide (predominantly radiocaesium) transfer based upon relatively readily available soil properties.

The model originally developed by Absalom et al. (1999) and further improved by Absalom et al. (2001) and Tarsitano et al. (2011) is a typical example of a process-based transfer model. The model has been applied in various contexts (i.e. in different regions and for different foodstuffs) (e.g. Gillett et al. 2001; Beresford et al. 2002; Wright et al. 2002; Cox et al. 2005; Keum et al. 2007; Uematsu et al. 2016).

3.1 Process-based models in CONFIDENCE

The focus of Almahayni et al. (2019a) was to consider the use of process-based models for post-accident predictions.

We began by assessing the applicability of the 'Absalom model' to a range of European soil and plant types that were not included in its initial parameterization. We demonstrated that the Absalom model is a useful tool for predicting radiocaesium transfer to the human food chain. Its predictions for grass and radish (edible root) were mostly within an order of magnitude of the measurements for most of the study soils. We recommend expanding the model database by considering more soils (with different mineralogies) and plant types in its parameterisation.

To date, most consideration in the development of process-based soil-plant transfer models has been focused on radiocaesium. We have successfully established two process-based models to predict strontium concentrations in a range of crops using relatively few soil parameters and the calcium concentration in crops as inputs. To support these methodologies, we produced a collation of calcium concentrations in crops consumed by humans and farm animals (Chaplow et al. submitted). The approach removes the need for empirical concentration ratios and is able to make predictions for crop types for which no radioecological data exist.

Whilst the approaches developed for strontium produced predictions that compared well with measured data, and better than predictions using the commonly used concentration ratio approach, they require further testing against a wider range of soil types and crops. A weakness of the strontium approaches developed is that they can only be used to make equilibrium predictions. However, they would be sufficient to aid the identification of longer-term 'at risk areas' in the event of an accidental release. The models could be used to estimate parameters to replace existing concentration ratios in models such as FDMT, which would enable their application in dynamic predictions. However, it would be preferable for future studies to consider trying to parameterise dynamic processes in soils within these process-based approaches.

3.1.1 Process-based models - end-user views

Although progress was made on the development of process-based soil-plant models for Cs in the 1990's-2000's these models have not been adopted for application in emergency planning/management. To begin a discussion of process-based models with end-users, a workshop was held (September 2019) with representatives of industry, regulatory organisations, international organisations and scientists (Almahayni et al. 2019a).

Participants in the workshop expressed some reservations about process-based models:

- Process-based models are too complicated, requiring a considerable amount of data to implement them.
- Because of their complexity, process-based models are difficult to communicate to stakeholders, including the public.
- Process-based models have not been sufficiently tested and hence end users are not confident in their use.
- Scientists have not 'made the case' for process-based models.

Conversely, a number of advantages offered by process-based models were highlighted:

- Process-based models offer an approach to understand/cope with the high degree of variability in empirical plant-soil concentration ratios and provide predictions more relevant to a given site.
- Process-based models (if not too complex) may be easier to explain to the public than a 'black-box' model as they better reflect reality (e.g. a model that bases predictions on easily understandable soil parameters such as percentage clay, organic matter content and/or soil potassium is easier to explain than a 'black-box' model with ratios and rate constants).
- Process-based models may be useful for site-specific assessments of existing exposure scenarios.
- Process-based models may be useful in emergency planning (though site-specific data such as soil properties would be needed).
- Process-based models may help to justify model simplifications.

Overall, there was support for process-based models, however, as scientists we need to make a better case for using them and be clear when they would be useful (see Section 4.1 below). We also have to ensure models are sufficiently tested/validated and provide training in their use.

4 Implementation of FDMT into the ECOLEGO modelling platform

The main focus of Brown et al. (2018a) was an evaluation of the FDMT (Food Chain and Dose Module for Terrestrial Pathways) as implemented in the JRodos and ARGOS decision support systems.

The ECOSYS-87/FDMT model was successfully transferred to the ECOLEGO modelling platform. ECOLEGO is a platform for creating dynamic models and performing deterministic or probabilistic simulations (Avila et al. 2005); http://ecolego.facilia.se/ecolego/show/HomePage). The new version of the model has been tested through the application of scenarios. In Søvik et al. (2017) two "simple" dry and wet deposition scenarios were specified with a deposition date (1st August) and magnitude of deposition 1000 Bq m^{-2} for four radionuclides (^{134}Cs, ^{137}Cs, ^{90}Sr and ^{131}I). Using these scenarios, we have compared the ECOLEGO and EXCEL implementations of ECOSYS-87/FDMT for both wet (assuming 3 mm of rainfall) and dry depositions. The results of this quality assurance through model-model comparison were satisfactory.

The review of underlying FDMT parameters has been extensive and forms a substantial part of Brown et al. (2018a). Some updating of datasets, especially with regard to regional parameters has taken place earlier in both the HARMONE (Staudt 2016a, 2016b) and COMET projects (Thørring et al. 2016) and these were considered within the parameter updating undertaken within CONFIDENCE. Data have been collated, primarily for element-dependent/radioecological parameters such as soil-to-plant transfer factors and feed-to-animal transfer coefficients, to provide a 'current state-of the-art' update to the ECOSYS-87/FDMT in ECOLEGO model. Unlike previous considerations of this subject, data have also been collated on underlying statistical information for parameters that enable uncertainty and sensitivity analysis. EXCEL spreadsheets have been populated using data extracted from published reviews (largely IAEA (2010)) and elsewhere. These datasets are available in Brown et al. (2018b).

To demonstrate the probabilistic functionality introduced by providing underlying statistical information for FDMT parameters and the probabilistic-enabled modelling platform, numerous scenarios (using Monte Carlo methods) were simulated. The output in Figure 4.1 are typical of such simulations and illustrate the considerable (aleatory) uncertainty associated with predictions once the spread (of some but not all) of the underlying parameters are included.

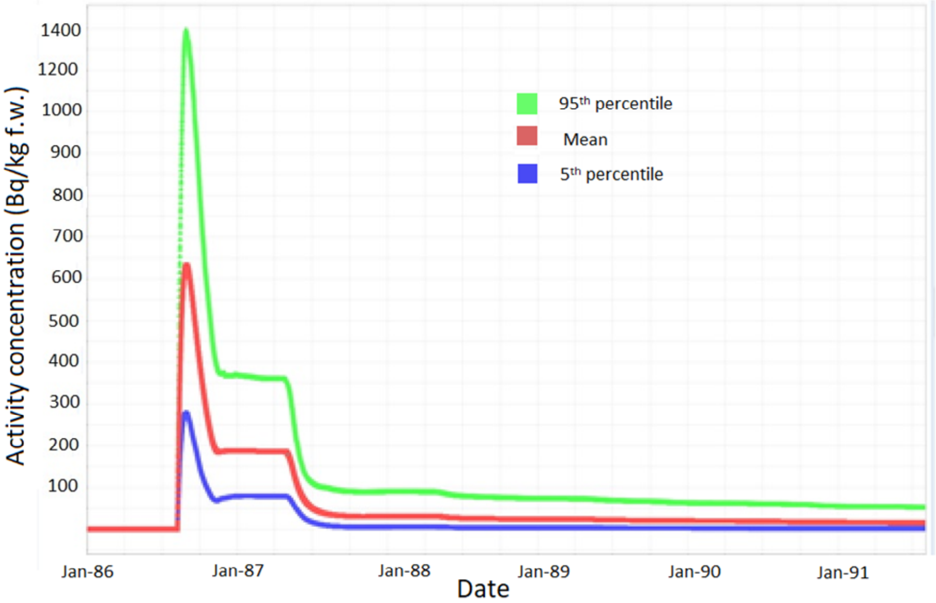

Figure 4.1. Probabilistic simulation of activity concentration of Cs-137 in lamb for a dry deposition scenario; 5th percentile (blue), mean (red) and 95th percentile (green) (from Brown et al. 2018a).

Sensitivity analysis can be defined as the study of how the variation in the output of a model (numerical or otherwise) can be apportioned, qualitatively or quantitatively, to different sources of variation, and how the given model depends upon the information fed into it (Saltelli et al. 2004). Several sensitivity analysis methods of varying degrees of complexity have been proposed in the literature (Saltelli et al. 2004). Variance based methods are universal methods that can be applied to any type of model. In recent years, an alternative variance-based method, called the Effective Algorithm for Global Sensitivity Indices or EASI method (Plischke 2009), has been developed, that can yield first and second order sensitivity indexes from an ordinary probabilistic simulation, i.e. by Monte Carlo or Latin Hypercube sampling methods. This method is available within the ECOLEGO modelling platform.

A preliminary sensitivity analysis for selected cases (e.g. a given deposition of Cs-137 at a particular date) shows that the importance of different parameters changes with time for the selected endpoints (leafy vegetables and lamb meat) considered. The example of Cs-137 in lamb meat for a given scenario is shown in Figure 4.2. Parameters such as retention coefficients and weathering rates were found to be important in the initial phases following a deposition event and parameters dictating radionuclide soil processes were shown to be important at later stages (decades into the simulation). Soil-to-plant transfer for Cs-137 was identified as being an important parameter throughout most of the simulation period with the exception of periods soon after deposition (up to 2 months).

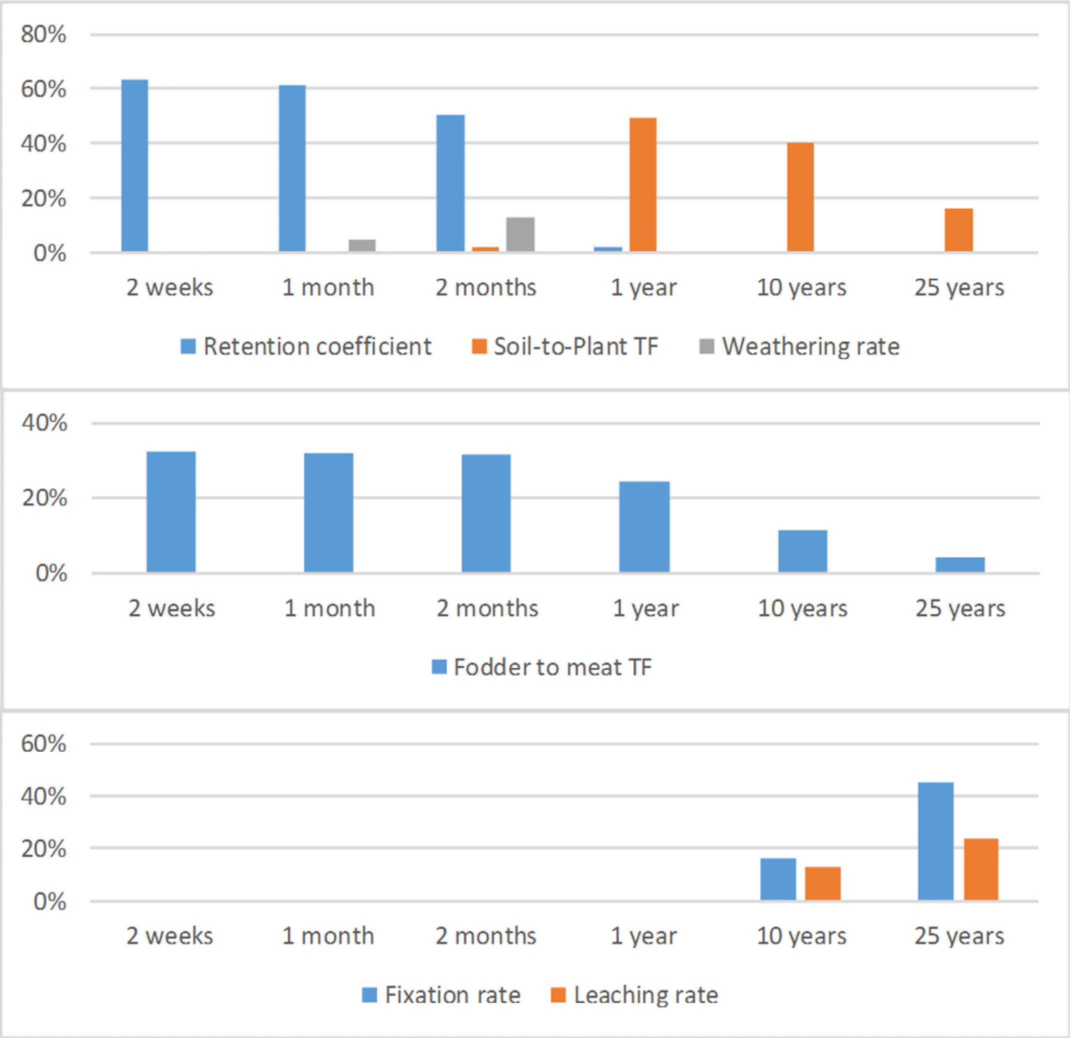

Figure 4.2. Effective Algorithm for Global Sensitivity Indices (EASI) as a function of time – Cs-137 in lamb meat for a wet deposition scenario.

The ECOSYS-87/FDMT in ECOLEGO model has also been modified for regional conditions, examples specifically for Norway and Spain were provided in Brown et al. (2018a); an overview of this work can be found in Section 5 below.

Implementation of FDMT within the EGOLEGO modelling platform also allows components of the model to be modified and replaced, as required, and opens the possibility of employing powerful numerical solvers to more challenging model configurations. Following the publication of Brown et al. (2018a), further developments have been made to the ECOSYS-87/FDMT in ECOLEGO model by introducing a library structure. The advantage of organising the model in this way is that the user can select specifically what they are interested in for any given model run without invoking the entire FDMT model. Beyond this, structural changes have been made to the model within blocks in the library. Most importantly for our analyses has been the separation within relevant receptor blocks, between plant and soil models, allowing new model components to be replaced and tested as discussed below.

4.1 Soil-plant process-based models in FDMT-ECOLEGO

An example of the new flexibility that has been introduced by the ECOLEGO implementation of FDMT was the implementation of the Absalom process-based soil-plant model (see Section 3 above) replacing the default soil-plant model of FDMT. The mathematical specification of Absalom et al. (2001) model as presented in Appendix 1 of Tarsitano et al. (2011) was the Absalom model version implemented within the ECOLEGO platform (after fixing some errors in Tarsitano et al. in consultation with the originating authors).

As a demonstration of the application of process-based models, we have run the Absalom model implemented within FDMT-ECOLEGO for five different soil types; this used soils characterised within Almahayni et al. (2019a). We also generated Sr F_v values for the same soil types using one of the models we developed in Almahayni et al. (2019a) where:

$$Plant\ Sr\ dry\ mass\ activiy\ conc.\,(Bq/kg) = \frac{(Plant\ Ca\ dry\ mass\ conc.\ \ (mg/kg)) \times (Soil\ Sr\ dry\ mass\ activiy\ conc.\ \ (Bq/kg))}{Soil\ Ca\ dry\ mass\ conc.\ \ (mg/kg)}$$

and using a grass calcium concentration from the compilation of Chaplow et al. (submitted). The application of the Sr F_v in FDMT-ECOLEGO is simplistic as all other soil parameters remain at the default values. Figures 4.3 and 4.4 present predicted ^{137}Cs and ^{90}Sr activity concentrations in milk, respectively, assuming a 1 kBq m^{-2} deposition of both radionuclides. At the end of the prediction period (*c*. 27 years after deposition) there is a two-orders of magnitude difference between the minimum and maximum predicted ^{137}Cs activity concentration in milk; for ^{90}Sr the difference is approaching one-order of magnitude. However, if we look only at the first 90 days after deposition, it can be seen that predictions for all soil types are generally similar and comparable to those using the FDMT default parameterisation (Figures 4.5 and 4.6); the exception is the prediction for ^{137}Cs and the organic soil type which has predicted ^{137}Cs activity concentrations approaching an order of magnitude higher than the other soil types after 90 days. The similarity in most predictions is because retention and loss by vegetation surfaces dominate over the shorter period after a deposition event. Therefore, in the first months after a deposition event process-based soil-plant models offer little added benefit to using models such as FDMT (because soil-to-plant transfer contributes little to the activity concentration of radionuclides in crops). For predictions after the first few months then process-based models will become increasingly useful as soil-plant transfer begins to dominate. We recommend that for remediation planning, process-based models are applied once reliable deposition maps are available, to enable the identification of areas where food products are likely to remain contaminated in the longer-term. Whilst FDMT, or similar models, are fit for purpose to make predictions in the early post-deposition phase, any longer-term predictions made using such models during the early phase after a deposition event should be communicated with care.

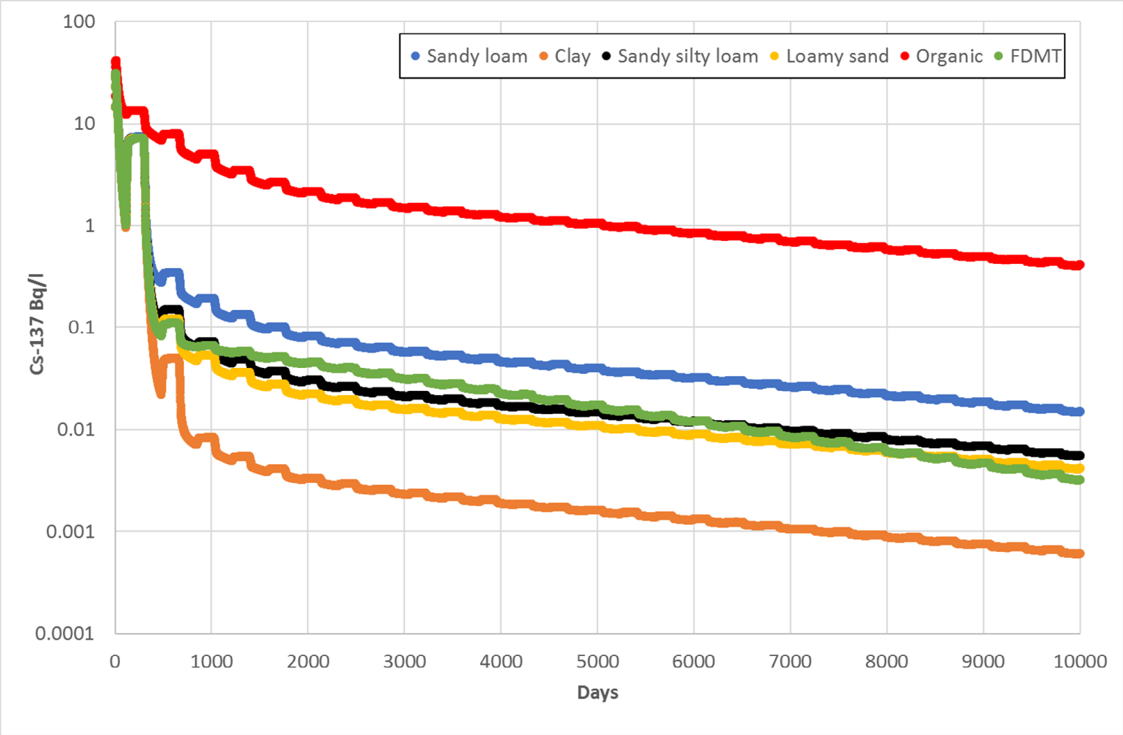

Figure 4.3. Predicted ^{137}Cs activity concentrations in cow milk for five different soil types using the Absalom model implemented in FDMT-EGOLEGO; for comparison, predictions using default FDMT parameters are also presented.

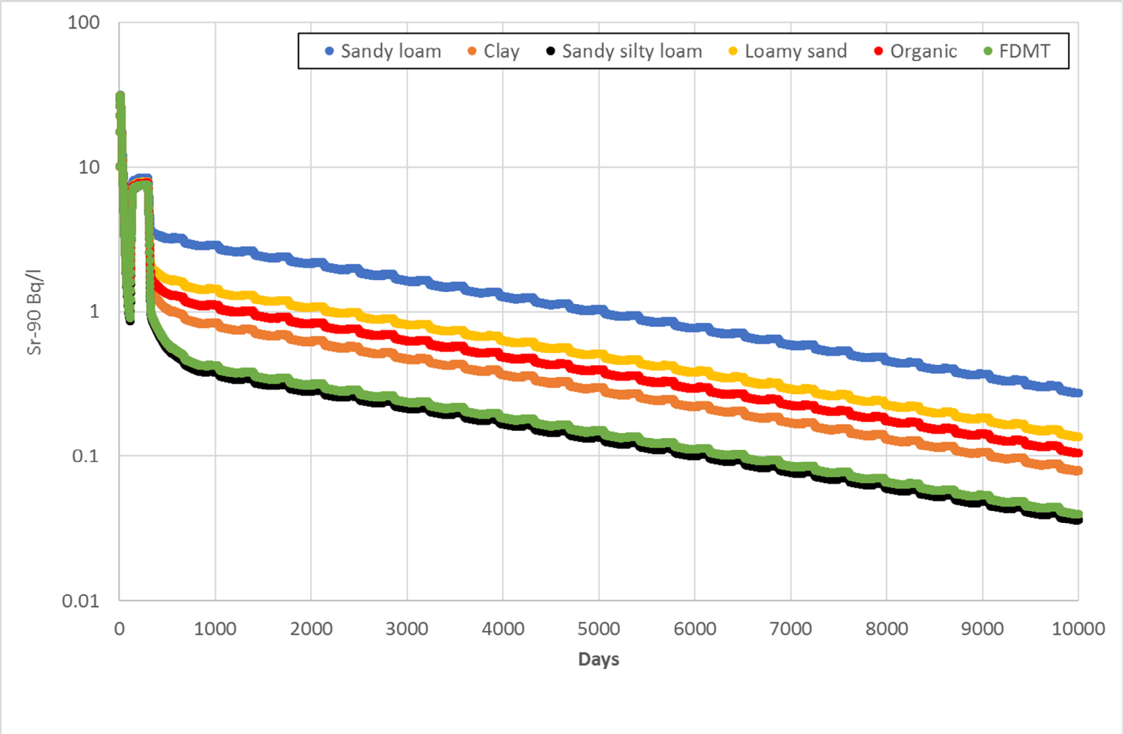

Figure 4.4. Predicted ^{90}Sr activity concentrations in cow milk for five different soil types applying Sr F_v values derived using the model we present in Almahayni et al. (2019a) implemented into FDMT-EGOLEGO; for comparison, predictions using default FDMT parameters are also presented.

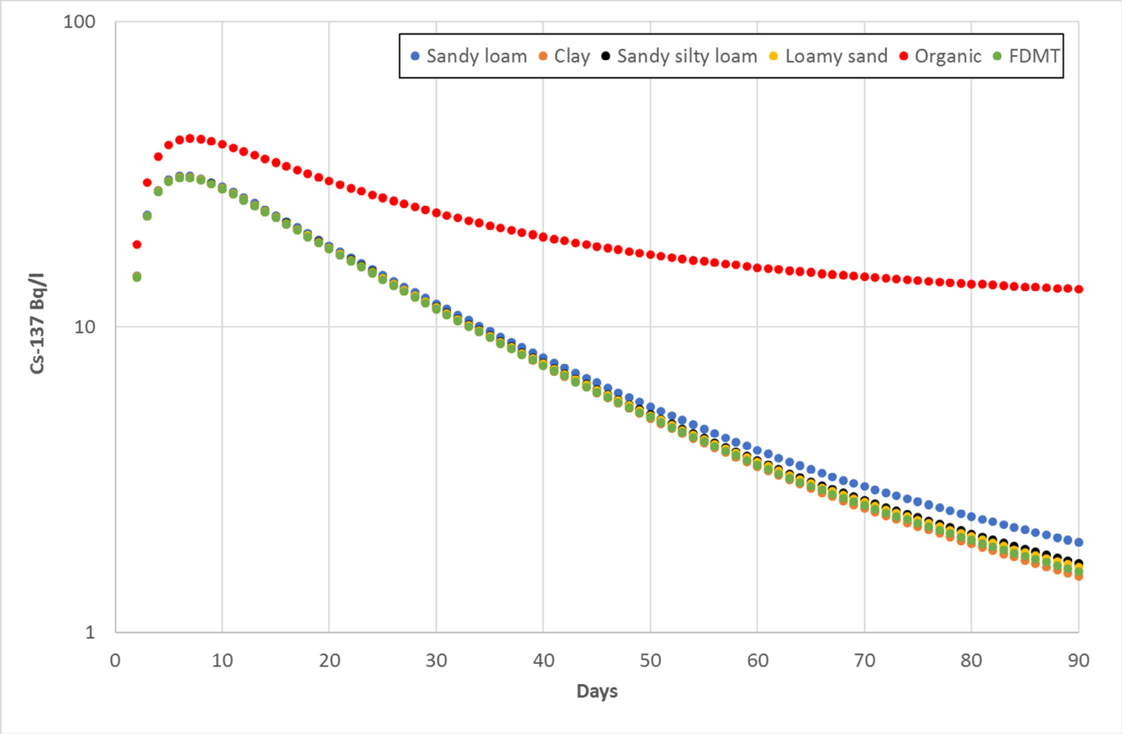

Figure 4.5. Predicted ^{137}Cs activity concentrations in cow milk over the first 90 d after deposition for five different soil types using the Absalom model implemented in FDMT-EGOLEGO; for comparison, predictions using default FDMT parameters are also presented.

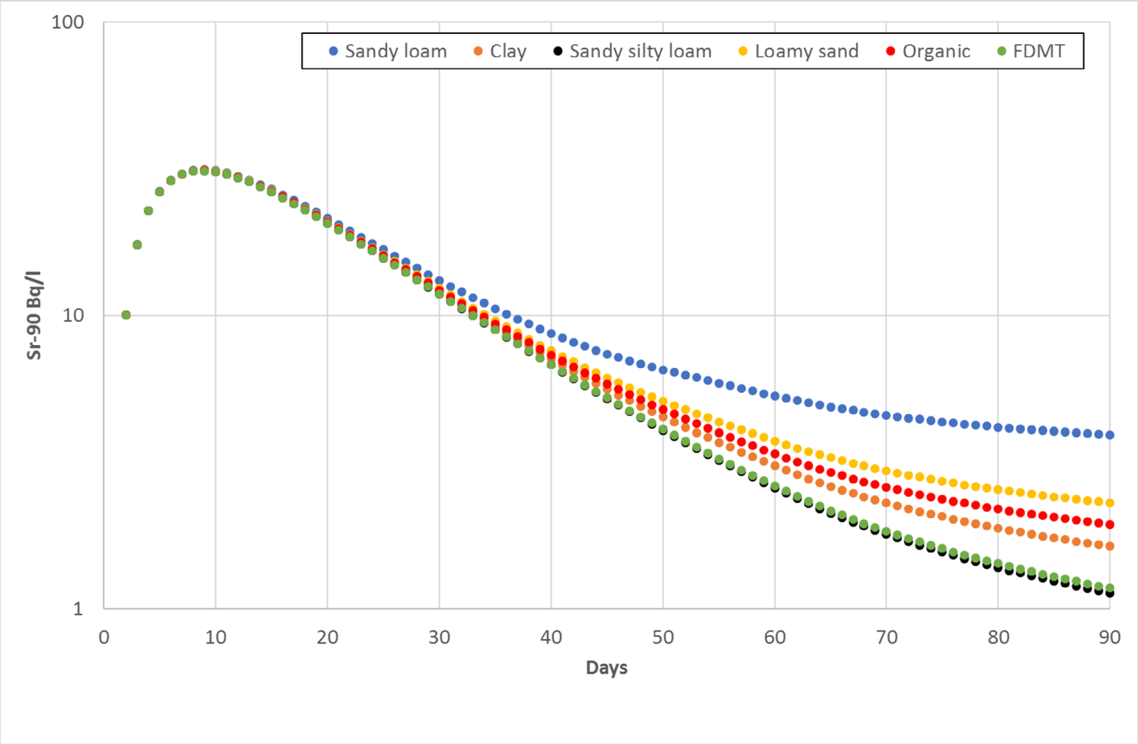

Figure 4.6. Predicted ^{90}Sr activity concentrations in cow milk over the first 90 d after deposition for five different soil types applying Sr F_v values derived using the model we present in Almahayni et al. (2019a) implemented into FDMT-EGOLEGO; for comparison, predictions using default FDMT parameters are also presented.

4.2 Modelling fuel particles in the soil-plant system

Following severe nuclear events, radioactive particles are released and deposited in the environment. A task in WP3 has been the adaptation of the particle concept into the FDMT food chain model, in particular the implementation of uranium (U) fuel particles and their influence on bioavailability and soil to plant transfer of ^{137}Cs and ^{90}Sr (see Lind et al. 2019). A bespoke compartmental model was conceptualised based upon an understanding of particle characteristics and behaviour, based on comprehensive particle archives and associated databases. Parameters, such as those describing particle weathering rates and leaching rates from soils containing particles were derived from laboratory and field experiments. The model parametrisation of U fuel particle weathering rates, which strongly depends on soil pH and solid-state speciation of the carrying matrix (i.e., oxidized or non-oxidized UO_2 fuel particles, or U transformed to extra inert forms such as UZr_xO_y) was based on extensive datasets from the Chernobyl exclusion zone. The developed particle-soil model (Figure 4.7) was then implemented into the FDMT-ECOLEGO model replacing the default soil radionuclide transfer models.

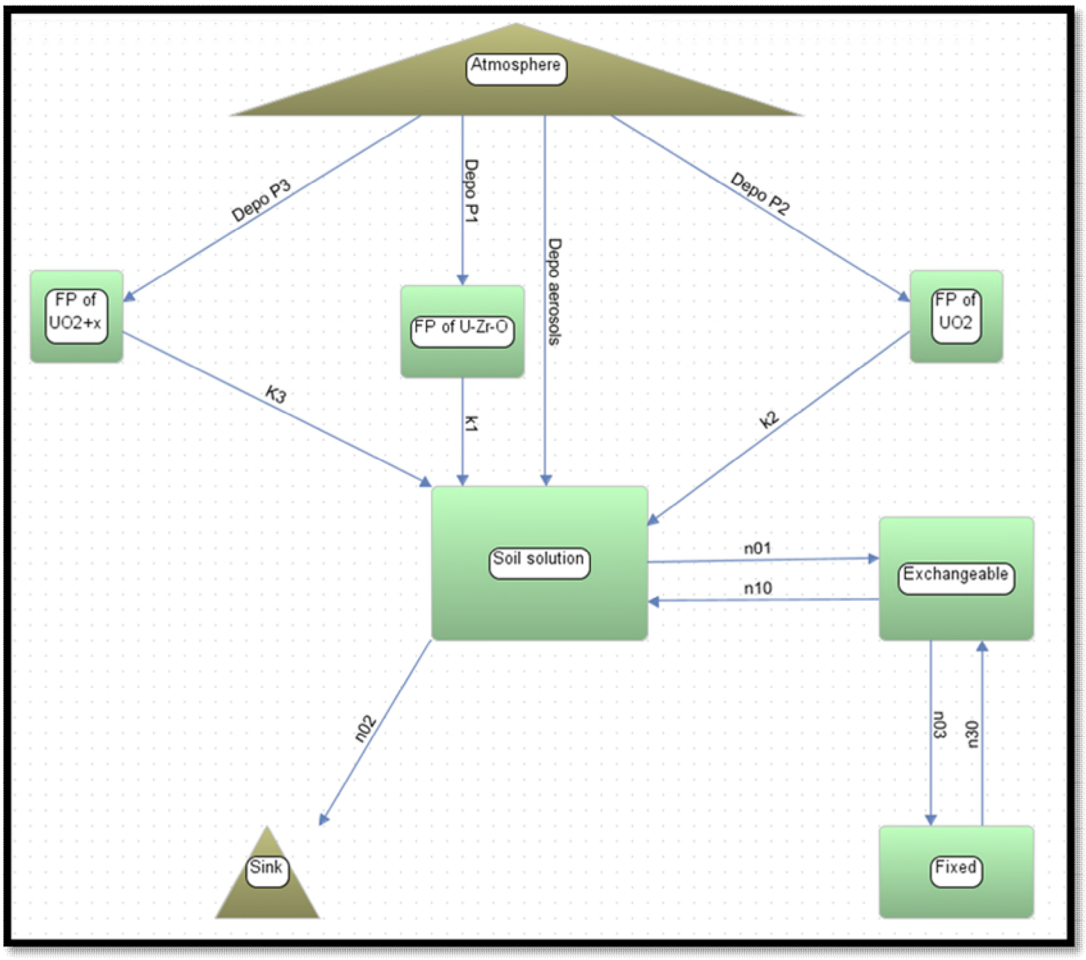

Figure 4.7. Representation of the particle-soil model.

In order to explore the influence of particle composition and soil acidity on radionuclide bioavailability and food-chain transfer (to crops, grass and cow-milk), different scenarios were developed. Differences were observed in the predictions made for ^{137}Cs and ^{90}Sr activity concentrations to selected foodstuffs between the new particle soil model and the FMDT default model. The new particle soil model predicted a delay in the maximum activity concentrations observed in food products (excluding the initial few months post deposition) (see e.g. Figure 4.8), a result that appeared consistent with observations for areas close to the reactor. The model output data were compared with time-series data of ^{137}Cs and ^{90}Sr activity concentrations in grain crops from the Ivankiv district (Ukraine) which is located just south of the

Chernobyl exclusion zone. The results showed that the revised model, considering radioactive particle weathering and soil migration processes, in some respects, exhibited improved prediction capabilities compared to the current FDMT model, especially in the long-term after deposition. However, the current version of the revised model tended to under-predict both ^{137}Cs and ^{90}Sr activity concentrations in grain, although the simulated values were of the same order of magnitude as the empirical data. With respect to soil-grass-cow milk and soil-grain transfer, the modelling results indicated that in the short term following an accidental release, accounting for the potential presence of fuel particles in the soil is unlikely to be critical (ingestion dose rates, from the soil-plant pathway, may be overestimated if particles are not taken into account during this phase). In the longer term (decades), not accounting for particles in the deposit may underestimate ^{137}Cs and ^{90}Sr transfer to food products. However, we have only considered the behaviour of particles in soil and subsequent radionuclide uptake by crops. There is a need to consider deposition, interception and retention of fuel particles, processes which are likely to be important in the early stages (weeks and months) post-accident; such evaluations should also consider the potential for animals (and humans) to ingest fuel particles.

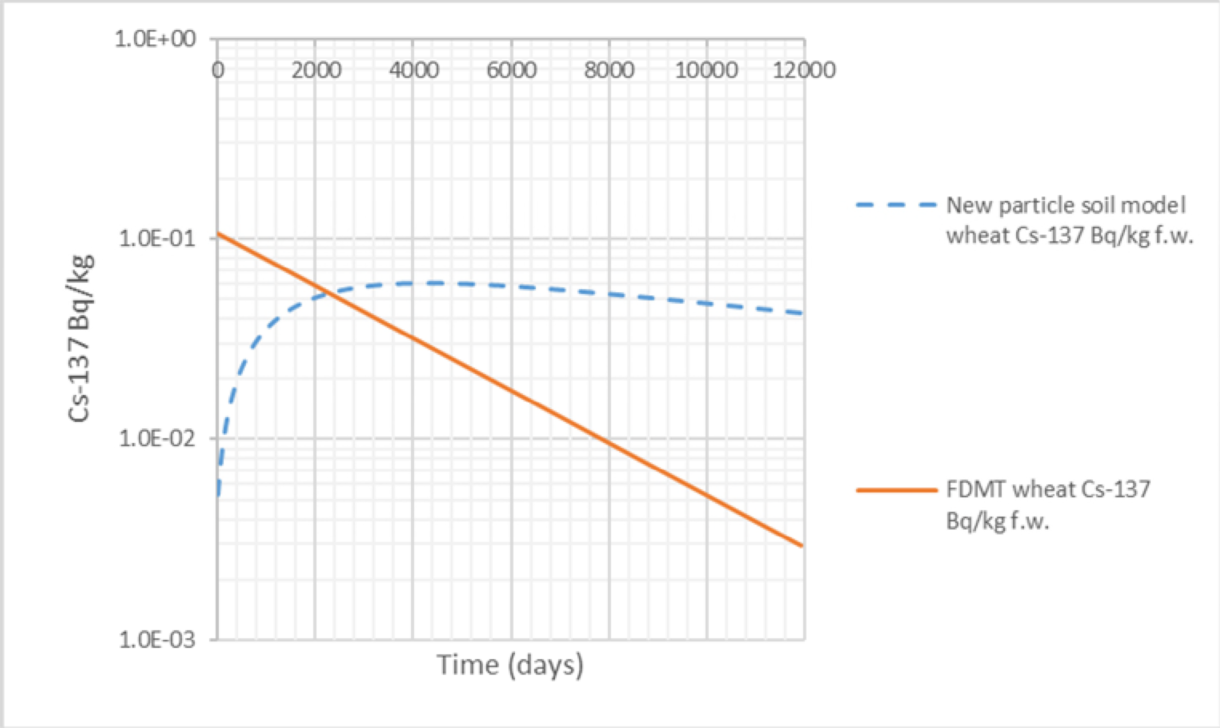

Figure 4.8. A comparision of predicted ^{137}Cs activity concentations in wheat using the fuel-particle soil model with predictions from the default FDMT model.

5 Regionalisation

Regionalisation has been considered in two ways: (i) variation of largely non-radiological parameters within the FDMT-ECOLEGO model to better match specific regions of Europe (specifically Norway and Spain); (ii) the collection of transfer parameter data specifically for Mediterranean systems.

5.1 Exploring regionalisation using the FDMT-ECOLEGO model

5.1.1 Regionalisation for Norway

Regional modifications have been made to the FDMT model in ECOLEGO to better represent Norwegian conditions as elaborated in Brown et al. (2018a). This regionalisation can be split into two categories. The first of these relates to changes in underlying parameters using primarily datasets collated by Thørring et al. (2016) and Staudt (2016a, 2016b). These datasets are mainly related to: (1) the growing season and harvest periods of crops and grass including seasonal development of Leaf Area Index (LAI); and (2) animal feeding practice. The second modification concerns the replacement of component modules used in FDMT with exploratory models. Changes have been made to the grazing system under which cows are categorised, with the option of placing cattle within 'Extensive' pasture as opposed to 'Intensive' pasture. Furthermore, two feedstuffs, spring barley and oats, have been added to the winter diet of cows to better represent Norwegian conditions. The sub-model for lamb meat production has also been changed. The slaughter period for lambs in Norway is generally September–October and this provides most of the meat used for human consumption in the following year. Modifications have been made to allow the user to select a date for lamb slaughter. This date is subsequently used to define the activity concentrations that are used as input to the calculation of human ingestion doses. Figure 5.1 presents a comparison between the FDMT default (for continental Europe) and modified regional (Norwegian) model predictions for lamb (see Brown et al. (2018a) for details of the scenario definition).

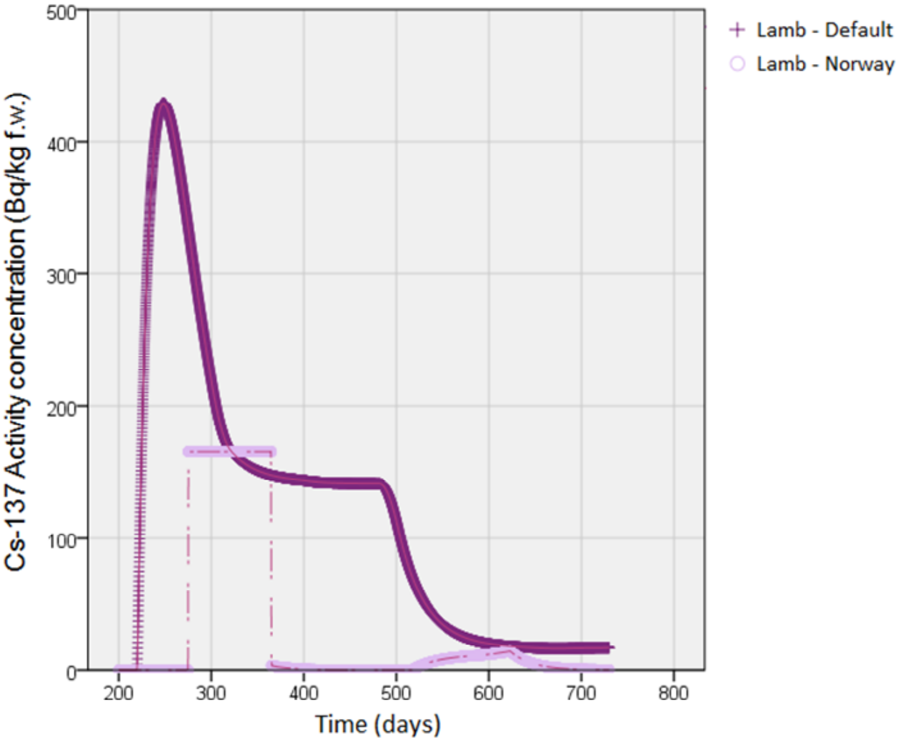

Figure 5.1. ^{137}Cs activity concentration (Bq kg^{-1} FM) versus time (from simulation start) following a dry deposition scenario for lamb meat (regionalised parameters for Norway versus default).

The regionalised set up suggests (logically) that ^{137}Cs activity concentrations in lamb meat would not constitute a source of contamination to the human food-chain until a period after the date of slaughter.

After this time, regional lamb meat would initially have a substantially lower ^{137}Cs level than that derived using the default setting. However, at a later stage (within a few months) the regional levels would slightly exceed the default-derived predictions.

Reindeer herding and husbandry is important in some parts of Norway, most notably the Arctic County of Finnmark, where reindeer meat and products can form a substantial part of the local population's diet (see Thørring & Skuterud 2012). The requirement to include reindeer as a potential source of radionuclides to the human diet has been recognised earlier and some efforts have been made to include this food-product as part of FDMT within JRodos (Staudt 2016b). However, this earlier work is simplistic in nature adapting parameters for beef cattle and assuming a seasonal diet of grass and hay under an extensive grazing system. More realistic models exist which have been initially verified against empirical datasets from Scandinavia (Åhman 2007). The Åhman model accounts for the varied diet of reindeer throughout the year, with heavy reliance on wild forage in the winter months, and the observation that reindeer metabolism changes with season leading to a cyclicity in radiocaesium depuration over time. The model of Åhman has been implemented in the ECOLEGO platform and subsequently linked to the FDMT in ECOLEGO configuration. This has allowed some simple scenarios to be run and initial comparisons to be made with other animals, such as lamb (using FDMT defaults), categorised under extensive (grass) grazing systems (Figure 5.2). The scenario used was based on that described in Brown et al. (2018a) (i.e. ^{137}Cs wet deposition = 1 kBq m^{-2} and Integrated air concentration = 0.55 Bq h m^{-3}).

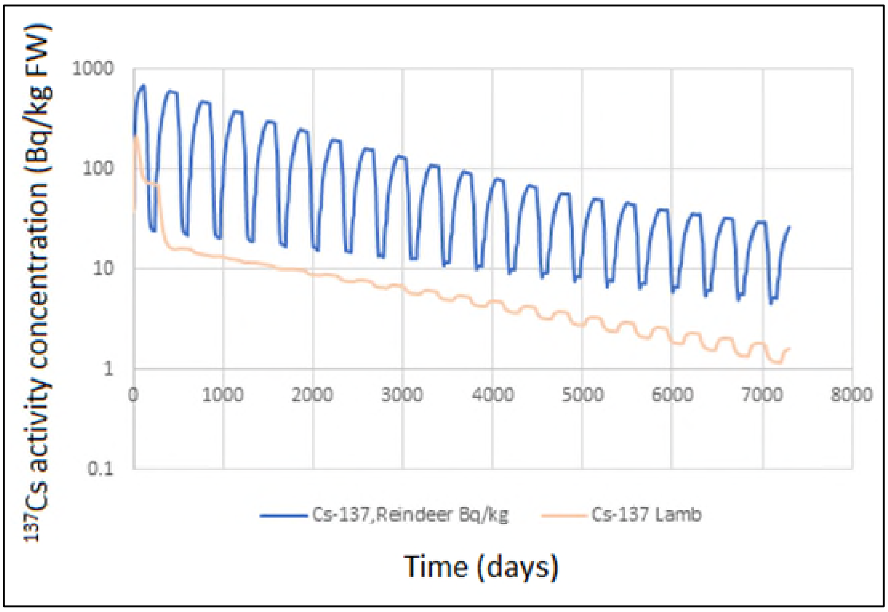

Figure 5.2. ^{137}Cs activity concentrations in reindeer and lamb meat with time following an (approximately) 1 kBq m^{-2} ^{137}Cs wet deposition event.

From this rather simple exploratory exercise, it seems evident that for the same level of deposition, activity concentrations in reindeer meat would be substantially higher than those observed in lamb meat. This reflects numerous factors, the most important of which relates to the diet of the two animals throughout the year. Whereas lambs are assumed to be fed on grass during the summer and hay during the winter, reindeer are assumed to feed primarily on (more contaminated) lichen in the winter returning to grass, herbs and leafy shrubs in the summer months. The predicted winter maxima and summer minima in ^{137}Cs for reindeer meat mirror this change in diet. Note that the intake of fungi during autumn, a potentially important contributor to ^{137}Cs levels in both types of animals, is not included in these model runs.

Further work with regards to regionalisation in Norway will be undertaken to test and formalise (i.e. approve for further institutional, 'within-house', application) these exploratory models.

5.1.2 Regionalisation for Spain

Different characteristics relevant to the Mediterranean conditions of the Iberian Peninsula were implemented in FDMT-ECOLEGO: (i) a dataset for appropriate harvest periods (MAPAMA, 1993) was incorporated; (ii) LAI time series were implemented for a range of cereal crops (winter and spring wheat, winter and spring barley, rye, maize and oats), for extensive and intensive grass the LAI values were calculated using a relationship with yield. Productivity and harvest periods were varied depending largely on the biogeographic regions of the Iberian Peninsula (i.e. Mediterranean and Eurosiberian) and also for Spanish agro-climatic zones. The feeding regimes of different farm animals (cow, lamb, sheep and goat) were also modified to be appropriate for Spain (Álvarez Sánchez-Arjona 2010).

As an example, Figure 5.3 presents a comparison between the FDMT default and modified regional (Spanish) model for lamb.

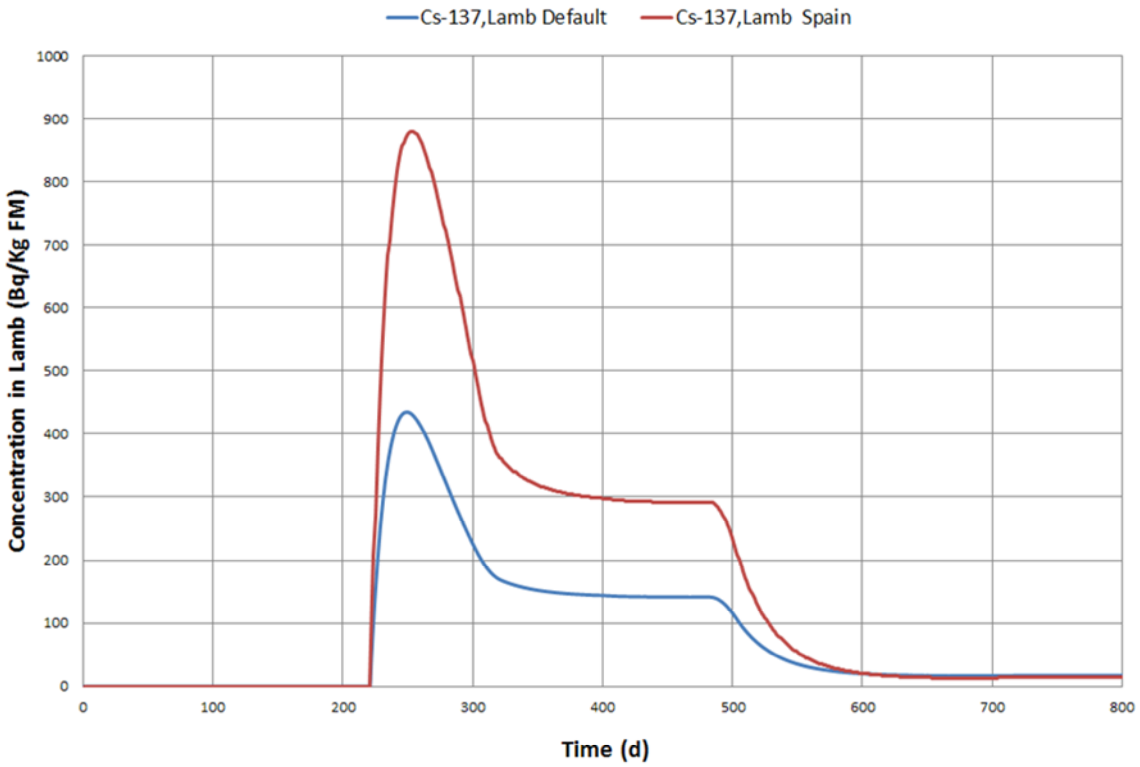

Figure 5.3. A comparison of predicted ^{137}Cs activity concentrations (Bq kg^{-1} FM) versus time (from simulation start) following a dry deposition scenario for lamb meat using regionalised parameters for Spain and FDMT default values (see Brown et al. (2018a) for scenario details).

Calculations were also carried out for winter wheat, leafy vegetables, cow milk and beef. The results obtained show clearly that the highest activity concentrations occur for dry deposition scenarios, both for FDMT default and Spanish parameter values, rather than in wet scenarios (Brown et al. 2018a). The magnitude and temporal development of the activity concentrations of foodstuffs are seasonally dependent and hence using regionally appropriate parameters, such as harvest dates, impacts on the predicted transfer of radionuclides to the human diet.

5.2 Transfer parameters for the Mediterranean systems

Compilations of radionuclide transfer parameters for the human food chain (e.g. IAEA 2010) are dominated by data for temperate ecosystems. With respect to Europe, data are sparse for Mediterranean ecosystems. Seasonal variations in temperature and rainfall, among other variables, may mean transfer parameters in Mediterranean ecosystems differ to those for temperate ecosystems. To begin to address this in Guillén (2019) we reported on the sampling of foodstuffs, including regionally import crops such as grapes and olives, from Spain.

Foodstuffs were collected using two sampling schemes: i) main production regions (sampling preferentially in areas where the main production of a given food occurs according to public information from the Spanish Ministry of Agriculture); and ii) local level (sampling in a dehesa, a typical Mediterranean semi-natural grassland with disperse tree cover which is used for crop production, managed by the regional government in Extremadura). The foodstuffs sampled were wheat, triticale, grapes (including wine), olives (including olive oil), lamb, beef, pork and dairy products from sheep, goats and cows. Gamma-emitting radionuclide and stable element concentrations were determined in the samples. Transfer was determined for plant products as F_v and for animal products as the dietary concentration ratio (activity concentration in animal product (FM)/activity concentration in the diet (DM)). All data from the study including estimated transfer parameters are presented in Guillén et al. (2019).

5.2.1 Comparison of Mediterranean transfer parameters with IAEA (2010)

Figures 5.4 and 5.5 compare transfer parameters estimated from the sampling in Spain with those reported in IAEA (2010). There was no consistent difference between the transfer parameter values for largely temperate environments reported in IAEA (2010) and those estimated for Mediterranean production systems. In part, meaningful comparison of the values is often limited because of the low number of data in IAEA (2010) and/or the Mediterranean sampling.

Although we have substantially increased the number of data for Mediterranean production systems in reality, our sample numbers were low and there are regionally important foodstuffs that have not been considered (e.g. nuts, rice and sunflower products).

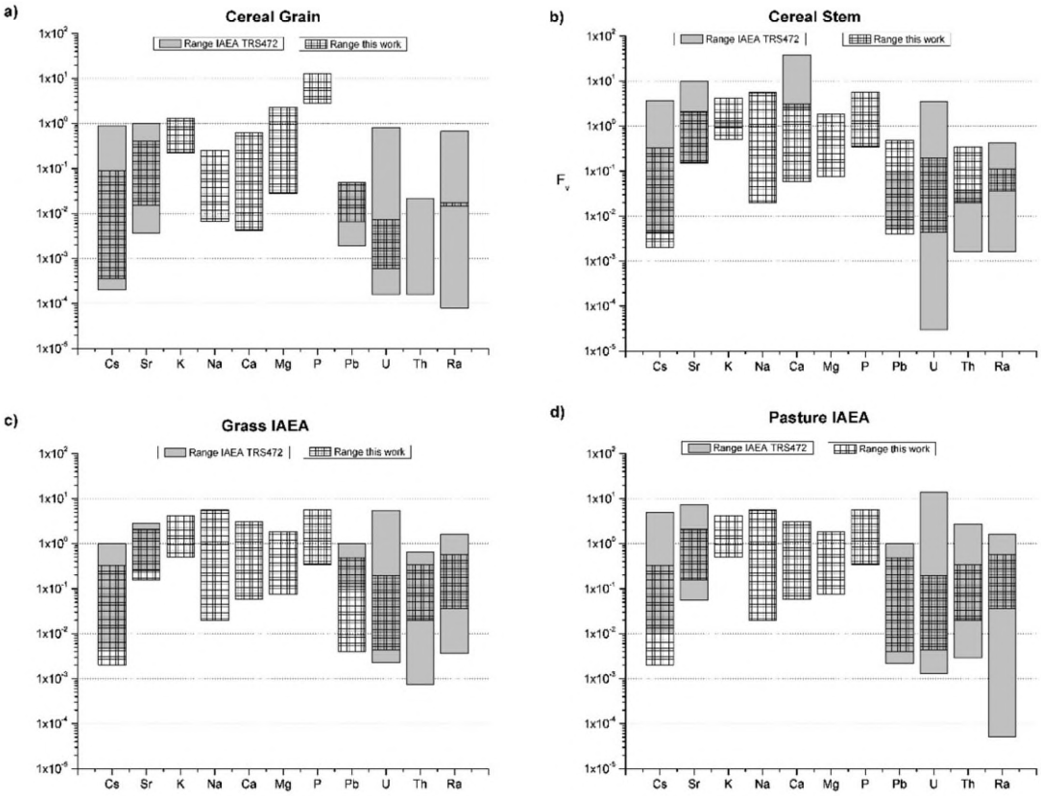

Figure 5.4. Comparison of range in transfer parameter values for crops, F_v, in Mediterranean systems with those reported in IAEA (2010).

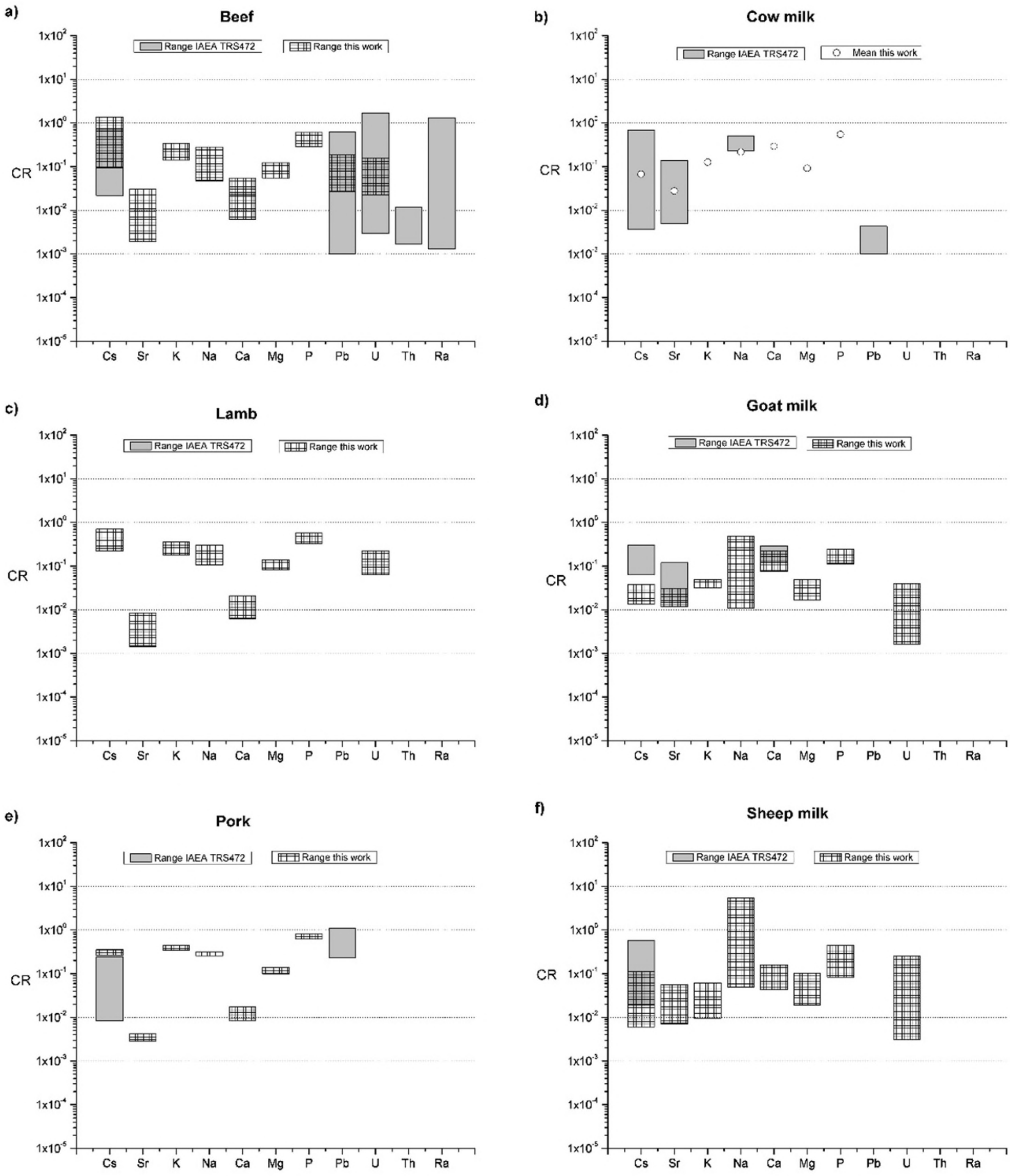

Figure 5.5. Comparison of range in transfer parameter values for animal products, dietary CR, in Mediterranean systems with those reported in IAEA (2010).

6 Key outputs and findings

The key outputs and findings of CONFIDENCE WP3 are:

- The incorporation of the FDMT model into a flexible modelling platform (ECOLEGO) allowing, for instance, sensitivity analyses, investigation of regionalisation and the replacement of default model components with process-based models (Brown et al. 2018a, Almahayni et al. 2019a, Lind et al. 2019).
- Development of process-based soil-plant models for Sr (Almahayni et al. 2019a).
- Identification of the strengths and weaknesses of the Absalom process-based soil-plant model for Cs (Almahayni et al. 2019a).
- Development of a model for fuel particle behaviour in the soil plant system (Lind et al. 2019).
- Recommendation that in the short-term, process-based soil-plant models (for Cs, Sr and fuel particles) will generally give no added benefit, i.e. models such as FDMT are sufficient for predictions during this phase (Lind et al. 2019, Section 4.1 of this report). However, longer-term predictions made using FDMT, or similar models, during the early phase after a deposition event should be communicated with care.
- Recommendation that for remediation planning, process-based models are applied once reliable deposition maps are available to enable the identification of areas where food products are likely to remain contaminated in the longer-term.
- The first demonstration of the predictive power (and problems) of proposed phylogenetic models for Cs and Sr, and crops (Section 2.4.1 of this report).
- Compilation of a dataset of radionuclide biological half-lives for farm animal products (Barnett et al. 2019a).
- Derivation and publication of a dataset of transfer parameters for Mediterranean systems (Guillén et al. 2019).
- Experimental studies showing that: (i) there is negligible root uptake of ^{131}I by crops; (ii) there is transfer of ^{131}I deposited onto foliage to fruits and tubers; (iii) the presence of (goitrogenic) rapeseed in the diet of cows reduced the transfer of ^{131}I from blood to milk. (Section 2.2 of this report).

Refereed publications and published datasets produced by CONFIDENCE WP3 to date can be found in Appendix 2.

7 Recommendations

We present recommendations based upon the outcomes of our work programme as discussed above and reported in previous deliverables. We also present the results of a questionnaire sent to Japanese scientists involved in responding to the Fukushima accident and recommendations from a joint workshop organised by CONFIDENCE WP3 in association with the Radioecology ALLIANCE Human Food Chain Working Group (September 2019). The recommendations and findings from CONFIDENCE WP3 have helped to revise the Strategic Research Agenda (SRA) for radioecology (available early 2020).

7.1 Recommendations for future studies arising from CONFIDENCE studies

We make the following recommendations based upon the work we have conducted within CONFIDENCE WP3:

- Soil-plant process-based models are worth pursuing for Cs and Sr (Almahayni et al. 2019a; Section 4.1 of this report).
    - The 'Absalom' process-based model for Cs soil-plant transfer needs to be tested, and potentially adapted, for a wider range of crops grown on a variety of soil types with differing mineralogies.
    - The soil-plant process-based models developed by CONFIDENCE for Sr need further validation and testing; consideration needs to be given on how to incorporate the models into dynamic food chain models such as FDMT in JRodos.
    - How to use the potential ability of soil-plant process-based models to model the effect of soil based countermeasures (namely K-fertilisation and liming) needs to be considered and included into DSS.
    - Scientists need to clearly make the case for using process-based models and be clear when they would be useful; training (appropriate to specific audiences) in the use of process-based models needs to be developed and provided.
- There is a need to include uncertainties in models and their outputs. This work has been started in CONFIDENCE WP3 for the FDMT in ECOLEGO model, but further work is needed to expand the statistical data collation to parameters not originally covered and to consolidate the information for those parameters that have been considered (Brown et al. 2018a).
- Further work is needed to perform a global sensitivity analysis and investigate the correlation between parameters. Discussion is required on how ignoring interdependency of variables in a model can contribute to uncertainty. This may provide a deeper understanding of the model behaviour by interpreting the dependency and interaction pattern (Brown et al. 2018a).
- It is recommended that FDMT parameters be updated further. Greater transparency should be provided where parameters have to be extrapolated because data are lacking (Brown et al. 2018a); where data are lacking experimental work should be encouraged.
- There is a need to consider deposition, interception and retention of fuel particles, processes which are likely to be important in the early stages (weeks and months) post-accident; such evaluations should also consider the potential for animals (and humans) to ingest fuel particles (Lind et al. 2019).
- Phylogenetic models, which allow predictions to be made for a wide range of crops for a given site without the need for soil type specific studies, need to be validated and where required, parameterised using the component of plants consumed (Section 2.4.1 of this report).
    - Combining process-based soil plant models with phylogenetic models may increase their utility.
- The application of transfer parameters derived from stable elements in radioecological models is further reviewed (Section 2.4.3 of this report).
- Transfer parameters are required for some regionally important agricultural products in Europe (e.g. nuts, rice, sunflower products) (though to some extent if taken forward phylogenetic and potentially soil-plant process-based models (for Sr at least) may negate the need for some data collection) (Section 5.1.2 of this report).

7.2 Survey of Japanese scientists

From personal contacts following the 2011 Fukushima Daiichi accident, we were aware that a number of Japanese scientists involved in the response to the accident found that key radioecological material was lacking; including knowledge on some aspects of human food chain transfer. To try to gain more detailed information on what had been lacking, we circulated a questionnaire during summer 2017 to approximately 100 Japanese scientists involved in radioecology and radiation protection; a total of twenty-three responses were obtained. The survey is described fully in Brown et al. (2018a). Sixty percent of respondents to the questionnaire stated that the information/data needed to understand radionuclide transfer to foodstuffs or make predictions had only 'sometimes' been readily available to them. Issues raised with regard to radioecological knowledge of relevance to CONFIDENCE were:

- The need for transfer parameters appropriate to local conditions
- A need for an ability to predict changes in radionuclide activity concentrations in food products with time (including the need for biological half-life data)
- The lack of transfer parameters for specific foodstuffs (including the transfer of intercepted radiocaesium to fruit)
- Variability (uncertainty) in transfer parameters and problems in communicating this to non-specialists/the public
- Need for guidance on selecting suitable models (circa. 35% of respondents were not involved in radiation protection or radioecology prior to the Fukushima accident)
- Need for pre-accident training in responding to nuclear emergencies
- Need for reliable information sources
- How to deal with contamination of drinking water
- Food processing factors for radiocaesium

The CONFIDENCE WP3 work programme has begun to address a number of the issues raised by Japanese scientists in the survey:

1. *The need for transfer parameters for specific food products that were also appropriate to local conditions* - process-based modelling and phylogenetic models give approaches that, if fully developed, should be applicable anywhere. Of relevance to Europe, we have derived transfer parameters for Mediterranean production systems.
2. *Transfer parameters for some specific foodstuffs (e.g. bamboo shoots) were lacking* –phylogenetic models (and the Sr soil-plant process-based models developed by CONFIDENCE) give scientifically based approaches whereby transfer parameters may be estimated if parameters are lacking for a given foodstuff.
3. *Variability in transfer parameters* – in Brown et al. (2018a) we began to consider uncertainties in food chain models.
4. *A lack of biological half-life data for animal derived foodstuffs* - we have now published a dataset of biological half-life values for farm animal products (Barnett et al. 2019a)
5. *Predicting translocation of deposited radionuclides to fruits* – studies have investigated the translocation of ^{131}I deposited onto vegetation surfaces to strawberry fruits and potato tubers.

7.3 Future priorities for human food chain radioecological studies (CONFIDENCE-Radioecology ALLIANCE workshop)

This workshop[2] followed one considering process-based soil-plant models (see Appendix A in Almahayni et al. 2019a). The workshop was attended by nearly 40 scientists and end-users (representing regulators, industry, governmental agencies and the IAEA; see Appendix 1).

The workshop started with an overview of the current SRA[3] for radioecology (https://radioecology-exchange.org/content/strategic-research-agenda) which the work programme of CONFIDENCE WP3 was focused to address. Human food chain issues fall within **Challenge one** of the radioecology SRA which states '*To predict human and wildlife exposure in a robust way by quantifying key processes that influence radionuclide transfers and exposure'*.

Presentations from workshop attendees were given on recent relevant radioecological studies and/or their suggestions on future research priorities. The presentations included:

(i) Results of studies demonstrating the potential to reduce radionuclide uptake by selecting plant varieties with low radionuclide uptake (see Penrose et al. 2015, 2016, 2017);
(ii) Overview of CONFIDENCE WP3 studies on ^{131}I (see Section 2.2 of this report);
(iii) Results of studies suggesting non-linear transfer for selected radionuclides (U, Ni and Pb);
(iv) Preliminary evaluation of the predictions of 'phylogentic models' by CONFIDENCE WP3 (see Section 2.4.1 of this report);
(v) An overview of recent studies (and future priorities) on the transfer of radionuclides to farm animal products under conditions relevant for the Semipalatinsk nuclear test site (Kazakhstan);
(vi) Current post-Chernobyl situation and associated research requirements for Ukraine;
(vii) Results from recent studies on foliar uptake, retention and translocation following wet deposition of radionuclides;
(viii) An overview of post-Chernobyl activities to develop models of radionuclide transfer through forest ecosystems (e.g. Fesenko et al. 2000);
(ix) An evaluation of the importance of taking local food consumption and production systems into account in predictive models (see Durand et al. 2018);
(x) A presentation by an IAEA representative on MODARIA II (https://www-ns.iaea.org/projects/modaria/modaria2.asp?s=8&l=129) and the planned follow-up programme.

Poster presentations were also available on elements of the CONFIDENCE WP3 Programme: (i) radionuclide biological half-lives for farm animals; (ii) collection of transfer parameters relevant to Mediterranean ecosystems; (iii) evaluation of JRodos FDMT parameters.

Following the presentations, participants were given the opportunity to anonymously put their suggestions relating to 'future priorities' onto sticky pad notes. The facilitators grouped the notes by common themes and these notes were used as an aid to the subsequent discussions. Below we summarise these discussions and other inputs of the workshop attendees (where relevant recommendations from the preceding workshop on process-based modelling are also included).

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[2] Held at Ciemat (Madrid), 11th September 2019.

[3] This presentation is available from https://radioecology-exchange.org/sites/default/files/Human%20Foodchain%20Modelling%20Reducing%20Uncertainties%20Beresford.pdf

Radionuclides

There was wide agreement that data on some radionuclides was poor and that some emphasis should be given to providing data and/or recommending modelling approaches. Radionuclides highlighted included:

(i) Those released by medical facilities for which data are poor or often totally lacking (e.g. radioisotopes of Cr, F, Fe, Ga, Ho, In, La, P, Re, Sm, Tc, etc.);

(ii) Radionuclides associated with the decommissioning of nuclear licenced sites (including, ^{108,108m}Ag, ^{243}Am, ^{10}Be, ^{41}Ca, ^{152,154,155}Eu, ^{55,59}Fe, ^{203}Hg, ^{93}Mo, ^{22}Na, ^{93m}Nb, ^{147}Nd, ^{93m}Nb, ^{193}Pt, ^{46}Sc, ^{151}Sm and ^{182}Ta);

(iii) Radionuclides relevant to fusion reactors (including activation products such as Ag, Fe, Mn, Nb, Ni, Tb);

(iv) Other radionuclides highlighted were the actinides and radioisotopes of Cl, Ru, Ra, Po, Th and Pb;

(v) Long-lived radionuclides associated with geological disposal facility assessments (this was raised during the preceding workshop considering process-based models (Almahayni et al. 2019a)).

It was noted that requirements for data for many of these radionuclides was not only restricted to the human food chain, but also to the need for parameters for biota assessments. In some instances, it is likely that doses to the public through food consumption (and also doses to biota) will be low from some of these radionuclides (short-lived radioisotopes discharged from medical facilities likely being an example). However, assessments have to be conducted to assess the potential impact of these radionuclides. Therefore, we need to advise on how best to conduct these assessments such that they are fit for purpose and proportionate. A scoping study on how best to address this need is required as a first step.

Regionalisation

There is a need to take into account potential regional variation in radionuclide transfer and also regional variation in diet and farming practices, including seasonality (e.g. in northern Europe farm stock are fed stored forage in winter, in southern Europe stored forage may be fed in summer); Brown et al. (2018a) discusses the consideration of regionalisation by CONFIDENCE WP3. Radionuclide transfer data in compendia such as IAEA (2010, 2014) are biased towards temperate systems. For current European climate types, the Mediterranean ecosystem is relatively poorly represented in transfer parameter databases for both human foodstuffs and biota. Data are also lacking for what were termed 'exotic foodstuffs' which, in some instances, may be regionally important (e.g. snails, dates, wine). There is also a need to consider our ability to predict radionuclide behaviour under changing climate scenarios.

CONFIDENCE WP3 and other recent work have made a step to providing radioecological data for Mediterranean ecosystems (Guillén et al. 2018, 2019; Guillén 2019).

Novel foodstuffs and changing agricultural practices

Our diets and agricultural practices evolve continually with different (potentially new to Europe or a given country) foods gaining popularity (chia and quinoa would be relatively recent examples, with interest in insect based foods for farm livestock and humans currently increasing (e.g. van Huis et al. 2013)). The workshop recommended that we need to ensure our models (and underlying data) keep up with changes in diet and foodstuffs. To some degree, 'phylogeny-based' extrapolation approaches (see Section 2.4.1) may help us to derive radionuclide transfer parameters for novel foodstuffs.

With respect to agricultural production, it was noted that satellite data could be used to identify agricultural production (what crop is grown where and when) and to estimate crop yields.

Innovative ways of providing transfer parameters

In reality, the breadth of radionuclides and foodstuffs (and for biota assessments, wildlife species) means that, we are never going to have data for everything. In some ways clear acknowledgement of this, and the consideration of open and robust extrapolation approaches, has progressed further for biota/wildlife models (e.g. Beresford et al. 2016) than for human food chain models. During the workshop, a presentation was given on the evaluation by CONFIDENCE of proposed 'phylogenetic' extrapolation approaches to estimate plant concentrations of Cs and Sr (see Section 2.4.1). There was general support for the use of such methods, but with the recommendation that the models needed to be for the plant parts consumed (currently they tend to have been parameterised using green shoot data only (see Section 2.4.1) and that more rigorous testing was required. It was also suggested that the phylogenetic approach could be a useful 'add-on' to process-based models, which have been parameterised for radionuclide transfer to grass (e.g. Absalom et al. 2001; see also discussion in Almayayni et al. 2019a).

Ionomics and/or ecological stoichiometry were also suggested as scientifically based extrapolation approaches, whereby similarities in the behaviour of some elements/radionuclides could be used to make predictions of radionuclide activity concentrations in foodstuffs (or biota) (e.g. Sr predictions based on Ca data would be an example). Whilst this has been suggested previously (see Beresford et al. 2016) to date little progress has been made.

For farm animals, it was recommended that there should be a move away from the transfer coefficient (defined as the ratio of the radionuclide activity concentration in an animal derived foodstuff to the daily intake of the radionuclide) to the dietary concentration ratio (i.e. the ratio of the radionuclide activity concentration in an animal derived foodstuff to that in its diet (on a dry matter basis). Concentration ratios for one animal can be used with some confidence for other animals (farm livestock and potentially wildlife) for which data are lacking (see discussion in Beresford et al. 2016).

Well-founded extrapolation approaches will also help us to address the lack of data for many radionuclides and the need to upkeep parameter databases/models to account for novel foodstuffs (see above).

Foliar uptake

There was general recognition that radionuclide interception by plants and subsequent retention and translocation has received relatively little attention (although two presentations were made at the workshop on recent experimental studies). The lack of relevant data was highlighted after the Fukushima accident with unexpected transfer of radiocaesium to fruit being reported (e.g. Sato et al. 2015).

Remediation

There was discussion of the work of Penrose et al. (2015, 2016, 2017) on the selection of plant varieties with low radionuclides uptake that was presented during the workshop. It was noted that in the event of any future accident (or other need) low accumulating varieties could be identified relatively quickly by collaborating with the many worldwide plant-breeding programmes. There was also the suggestion that CRISPR (clustered regularly interspaced short palindromic repeat; Wang et al. 2019) technology could be used produce crops with low uptakes. However, there are socio-political challenges associated with CRISPR technology as it may be considered as genetic modification of organisms.

There were recommendations that modelling approaches to improve the assessment of soil based countermeasures were needed. Process-based models may have a role here as they have previously been used to predict the effect of soil K fertilisation on radiocaesium uptake (Cox et al. 2005).

The presentation on the post Chernobyl situation in the Ukraine discussed an on-going project working with the local population, to try to bring land back into economic use (see https://tree.ceh.ac.uk/content/iclear-0). Suggestions were made that such an approach would have applicability in other countries.

Though somewhat out of scope of this report, there were also recommendations, prompted by post-Fukushima actions in Japan, that guidelines for remediation in forest ecosystems were required.

Radioecological models

In addition to the specific recommendations above, the needs to communicate radioecological models to end-users and to ensure model validation were stressed. This was emphasised in one of the invited presentations[4]. Users (regulators, governmental agencies and ministries) need to have confidence in the outputs of the models at their disposal. The example was given of the lack of confidence of Japanese authorities to use predictions from the Japanese government's System for Prediction of Environmental Emergency Dose Information (SPEEDI) in the management of the post-Fukushima situation (see Funabashi & Kitazawa 2012). This and other comments made during the two workshops on issues around communication with stakeholders (from the public to governments) demonstrate the potential for collaboration with the SHARE (Social Sciences and Humanities in Ionising Radiation Research) platform.

Model validation would benefit from participation in programmes such as those organised by the IAEA (e.g. MODARIA II[5] follow-on).

Other comments on radioecological models were:

- The need to include uncertainties in models and their outputs.
- Lack of consideration of the presence of other contaminants (this would require new studies/data).
- Parameterise models with parameters which are readily available or relatively easy to determine.
- Predictive models should be linked to monitoring data, such that the monitoring data can be used to refine assessments (this issue is being considered by other CONFIDENCE WPs).
- The need to consider the societal consequence of models being wrong and/or over-conservative.

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[4] Presentation available: https://radioecology-exchange.org/sites/default/files/The%20ECOSYS%20FDMT%20model%20Overview%20advantages%2C%20limitations%20and%20suggestions%20for%20further%20development%20Proehl.pdf

[5] https://www-ns.iaea.org/projects/modaria/modaria2.asp?s=8&l=129

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Appendix 1: Attendance list for CONFIDENCE-ALLIANCE workshop 'Human food chain - future needs' (Sept. 2019, Madrid)

Forename	Surname	Organization	Country
Talal	Almahayni	SCK•CEN (Belgian Nuclear Research Centre)	Belgium
Zhanat	Baigazinov	Institute of Radiation Safety and Ecology (IRSE)	Kazakhstan
Catherine	Barnett	Centre for Ecology & Hydrology (CEH)	UK
Nick	Beresford	Centre for Ecology & Hydrology (CEH)	UK
Geert	Biermans	Federal Agency for Nuclear Control (FANC)	Belgium
Penny	Birtle	Magnox Ltd.	UK
Joanne	Brown	International Atomic Energy Agency (IAEA)	Austria
Antonella	Cristina	SCK•CEN (Belgian Nuclear Research Centre)	Belgium
Neil	Crout	Univeristy of Nottingham	UK
Damien	Didier	Institute for Radiological Protection and Nuclear Safety (IRSN)	France
Vanessa	Durand	Institute for Radiological Protection and Nuclear Safety (IRSN)	France
Sergey	Fesenko	State Scientific Center – Research Institute of Atomic Reactors (RIAR)	Russia
Laureline	Février	Institute for Radiological Protection and Nuclear Safety (IRSN)	France
Simon	French	University of Warwick	UK
Blanca	Garcia-Puerta	Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (Ciemat)	Spain
Javier	Guillén	University of Extremadura	Spain
Ali	Hosseini	Norwegian Radiation and Nuclear Safety Authority (DSA)	Norway
Andra-Rada	Iurian	International Atomic Energy Agency (IAEA)	Austria
Stephen	Lofts	Centre for Ecology & Hydrology (CEH)	UK
Pilar	López Ferrando	The Spanish Nuclear Safety Council (CSN)	Spain
María	López-Ponte	Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (Ciemat)	Spain
Sergey	Lukashenko	Institute of Radiation Safety and Ecology (IRSE)	Kazakhstan
Milagros	Montero Prieto	Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (Ciemat)	Spain
Juan Carlos	Mora	Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (Ciemat)	Spain
Deborah	Oughton	Centre for Environmental Radioactivity (CERAD)/ Norwegian University of Life Sciences (NMBU)	Norway
Danyl	Pérez-Sánchez	Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (Ciemat)	Spain
Gerhard	Proehl	Consultant	Germany
Almudena	Real	Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (Ciemat)	Spain
Päivi	Roivainen	Radiation and Nuclear Safety Authority (STUK)	Finland
Eguchi	Sadao	National Agriculture and Food Research Organization (NARO)	Japan
Lindis	Skipperud	Centre for Environmental Radioactivity (CERAD)/ Norwegian University of Life Sciences (NMBU)	Norway
Justin	Smith	Public Health England (PHE)	UK
Agustina	Sterling Carmona	The Spanish Nuclear Safety Council (CSN)	Spain
Simon	Streeter	Food Standards Agency (FSA)	UK
Yifu	Tong	Univeristy of Nottingham	UK
Jose Angel	Vega Vilanova	Asociación Nuclear Ascó-Vandellós II AIE (ANAV)	Spain
Tamara	Yankovich	International Atomic Energy Agency (IAEA)	Austria
Eduardo	Gallego	Technical University of Madrid (UPM)	Spain

Appendix 2: Outputs

Below are the refereed publications and published datasets produced by CONFIDENCE WP3 to date; a number of additional refereed papers are in preparation.

Refereed papers

Almahayni, T., Beresford, N.A., Crout, N.M.J., Sweek, L. 2019. Fit-for-purpose modelling of radiocaesium soil-to-plant transfer for nuclear emergencies: a review. J. Environ. Radioact., 201, 58-66. https://doi.org/10.1016/j.jenvrad.2019.01.006

Beresford, N.A., Willey, N. 2019. Moving radiation protection on from the limitations of empirical concentration ratios. J. Environ. Radioact., 208-209, 106020. https://doi.org/10.1016/j.jenvrad.2019.106020

Raskob, W., Almahayni, T., Beresford, N.A. 2018. Radioecology in CONFIDENCE: Dealing with uncertainties relevant for decision making. J. Environ. Radioact., 192, 399-404. https://doi.org/10.1016/j.jenvrad.2018.07.017

Datasets

Barnett, C.L., Wells, C., Beresford, N.A., Guillén, J., Gómez Polo, F.M., Thacker, S., Lawlor, A.J., Keenan, P.O. 2019. Elemental concentrations (Ca, Cs, K, Mg, Sr) in a range of crops and associated soils from the UK and Spain. NERC Environmental Information Data Centre. https://doi.org/10.5285/76d6772d-477e-4a49-a4a6-a0fe6a0a9ba9

Barnett, C.L., Wells, C., Fesenko, S., Tagami, K., Beresford, N.A. 2019. Radionuclide biological half-lives for farm animals. NERC-Environmental Information Data Centre. https://doi.org/10.5285/d26ea56a-a692-427c-8f5a-a9bb6eb7da6b

Brown, J.E., Thørring, H., Hosseini, A., Beresford, N.A. 2018. CONFIDENCE FDMT implementation in ECOLEGO. https://www.storedb.org. http://dx.doi.org/DOI:10.20348/STOREDB/1131

Chaplow, J., Beresford, N.A., Barnett, C.L. Submitted. Calcium and magnesium concentrations in plants used as human and animal foods derived from global literature. NERC Environmental Information Data Centre.

Guillén, J., Gómez Polo, F.M., Baeza, A., Ontalba, M.A. 2019. Transfer parameters for radionuclides and radiologically significant stable elements to foodstuffs in Spain. NERC-Environmental Information Data Centre. https://doi.org/10.5285/48d5395e-e9fb-45ed-b69f-1ea0d2d36be6