MANAGING RADIOACTIVELY CONTAMINATED LAND: A METHOD TO ASSIST THE DESIGN OF LONG-TERM REMEDIATION STRATEGIES

by

Glen Michael Cox

Thesis submitted to the University of Nottingham

for the degree of Doctor of Philosophy, June 2004

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABBREVIATIONS

α, alpha	**…………………………..Monetary value of a unit of collective dose**
AFCF	**……………………………..Ammonium Ferric hexa-Cyano Ferrate**
ALARA	**…………………………………..As Low As Reasonably Achievable**
CFIL	**……………………………………Council Food Intervention Levels**
DEFRA	**…………Department of the Environment, Food and Rural Affairs**
DMI	**……………………………………………………Dry Matter Intake**
DSS	**……………………………………………..Decision Support System**
DW	**…………………………………………………………Dry Weight**
EC	**………………………………………………..European Commission**
ECD	**……………………………………………..Exported Collective Dose**
ESA	**……………………………………...Environmentally Sensitive Area**
FW	**……………………………………………………..Fresh Weight**
GIS	**…………………………………Geographical Information Systems**
IAEA	**………………………………..International Atomic Energy Agency**
ICRP	**……………..International Commission on Radiological Protection**
IT_{Max}	**…………………Maximum value of an Implementation Threshold**
IT_{Min}	**…………………..Minimum value of an Implementation Threshold**
LCD	**…………………………………………………Local Collective Dose**
LDNP	**…………………………………….Lake District National Park**
MAFF	**………………………...Ministry of Agriculture, Fisheries and Food**
MAUA	**……………………………………...Multi-Attribute Utility Analysis**
NRCP	**…….National Council on Radiation Protection and Measurements**
NRPB	**……………………………..National Radiological Protection Board**
TD	**…………………………………………………...Total ingestion Dose**
TV	**……………………………………………………Trigger Variable**
TV_{Max}	**……………………………..Maximum value of a trigger variable**
TV_{Min}	**…………………………...Minimum value of a trigger variable**
UNSCEAR	**…….United Nations Scientific Committee on the Effects of Atomic Radiation**
WTP	**……………………………………………………Willingness To Pay**

ABSTRACT

This thesis describes the development of a system to assist the design of long-term remediation strategies for radioactively contaminated land. Existing radiological models, that estimate the uptake of radionuclides by plants and the doses arising from exposure to external radiation, were combined with a spatially implemented food-chain model, to allow the temporal and spatial variation of radionuclide transport through the terrestrial environment, and the resulting doses of exposed human populations, to be estimated. Doses are estimated using a novel method for the simulation of human populations, which includes the generation of sub-populations by Monte-Carlo sampling and consideration of the geographical origins of consumed food products. Various simulated radiological countermeasures have been incorporated into the system (e.g. clean-feeding of livestock), allowing the effects of potential remediation strategies to be assessed. Furthermore, a method has been developed which efficiently identifies the optimum set of countermeasures for a given scenario according to a defined merit function using cost benefit analysis, which can be extended to include terms that account for the preference for averting high levels of individual dose, and the social costs of a number of countermeasure side-effects (e.g. disruption of normal daily life).

To assess the applicability of the system, it was used to evaluate potential remediation strategies for hypothetical, large-scale nuclear accidents within two contrasting case study sites (Cumbria, UK and Zaragoza, Spain). In both case studies the system successfully identified optimal remediation strategies which were, according to the defined merit function, significant improvements upon simple food and dose rate restriction strategies.

ACKNOWLEDGEMENTS

I would like to thank my supervisor, Neil Crout, for his guidance, enthusiasm, understanding, patience and support throughout my PhD, and for gambling on damaged goods in the first place. I am also grateful to the members of the STRATEGY project, which was funded by the EC: Brenda Howard, Nick Beresford, Cath Barnett, Simon Wright, Anne Nisbet, Nick Hesketh, Joanna Marchant, Tøne Bergan, Astrid Liland, Havard Thorring, Deborah Oughton, Ingrid Bay, Ellen-Marie Forsberg, Jane Hunt, José Gil, Begoña Álvarez, Katalin Eged, Zsoltan Kis, Jørn Roed and Kasper Andersson for their assistance with the work contained in this thesis.

I would also like to thank everyone in the department of Environmental Science at Nottingham University, and in particular: Marcello "March" Di Bonito and Davide "Dave" Tarsitano for coming over here and stealing all our jobs, Catherine "The Beast" Morris, Lee "insert appropriate term of abuse here" Stapleton for being such a good sparring partner over the past four years, Matt " El Banco Matto" Beardsley, Jessica Lenham, Julian Hutchinson, Andrew Tye, Chad Marshall, Nanette Marshall-Madan for putting up with all the sighing, swearing and mess, John Corrie, Darren Hepworth, Mike Gubbins and Jim Craigon.

I would also like to take this opportunity to formally express my gratitude to all of the people who helped/put up with me through my previous attempt at "post-graduate research" "in Leeds" (a.k.a. The Nightmare), and in particular: Steve "Balls up" Ball, Andy "Shandy" Marris, Mike "Gimpman" Simms, Dimitris "Domestos"

Roukounas, Tim Green, Dave “The Captain” Pleynet, Andrew “Dr B” Boa, Saj “Bunny” Mohammed, Zsolt Zsoldos, Denis Bayada, Alex Clarke, Jon Baber, Miklos Vargyas, Zsuzsana Zsabo, Michelle McTiernan, Damian Howells, Tanya from Mass Spec and Francis. The support from my parents when ending The Nightmare is also greatly appreciated.

I am also greatly indebted to Angela Barlow/Kane for her enthusiasm, dedication, professionalism and downright pushiness.

Finally, and most importantly, I would like to thank Kate (although words are inadequate) for her enduring patience and support in the face of countless months of moaning and stress, and for blessing me with Tom and Joe, who helped keep everything in perspective and let me get at least a little bit of sleep.

“Then as it was, then again it will be.

An' though the course may change sometimes,

rivers always reach the sea.”

From “Ten years gone” by Led Zeppelin

DEDICATION

For Kate, with infinite indefinables.

CHAPTER 1: GENERAL INTRODUCTION

1.1 ENVIRONMENTAL RADIOACTIVITY

Radionuclides are natural phenomena which are ubiquitous throughout the atmosphere, hydrosphere and terrestrial environment. Many of the radionuclides present on Earth were formed as a result of the capture of neutrons released by cosmic-ray interactions in the atmosphere (e.g. ^{14}C and ^{3}H), while others, with half-lives comparable to the age of the earth (e.g. ^{40}K, ^{238}U and ^{232}Th), were present during the formation of the Earth itself. In addition, some naturally occurring radioactive isotopes are formed as part of the decay of ^{238}U, ^{232}Th and ^{235}U; known as the uranium, thorium and actinium series respectively. However, in addition to these naturally occurring radio-isotopes, an estimated 1×10^{21} Bq of radioactivity has been released into the environment from anthropogenic sources (UNSCEAR, 2000) since the discovery of nuclear fission by Hahn and Strassmann in 1939 (Hahn and Strassman, 1989). These sources have varied from the testing and deployment of nuclear weapons to routine and accidental releases from the nuclear power industry. Amongst the most notable releases of anthropogenic radionuclides into the environment include: the nuclear bombs dropped on the Japanese cities of Hiroshima and Nagasaki in 1945; the atmospheric weapons testing programs of USA, Britain, China, France, USSR and India, carried out between the 1950s and 1980s; the accidents at the military facilities in Kyshtym, Russia and Windscale, UK in 1957; and the accidents at the nuclear power stations at Three Mile Island, USA in 1979, and at Chernobyl, Ukraine in 1986, the latter representing the largest single release of anthropogenic radionuclides into the environment to date.

1.2 LIMITING HUMAN EXPOSURE TO IONISING RADIATION

The biological effects of ionising radiation in humans were first reported soon after the discovery of X-rays by Roentgen in 1895 (Scott, 1897). Since then, many studies have investigated the relationship between human exposure to ionising radiation and the resultant biological effects, and these have been extensively reviewed at regular intervals (UNSCEAR, 2000, 1988, 1982, 1977). Although the picture is far from complete, it has been said that "… more is known about the effects of ionising radiation exposure than about the effects of any other of the many noxious agents that have been introduced artificially into the environment" (Eisenbud, 1987).

Human exposure to radiation is quantified in terms of absorbed dose, for which the unit is the Gray (Gy). However, because the extents of the biological effects of ionising radiation are dependent upon the types of particle involved, and the energies of those particles, the absorbed dose is often converted into a weighted quantity called the "effective dose", which has units of Sieverts (Sv). References to dose hereafter will refer to effective dose, unless otherwise stated.

Ionising radiation is damaging to humans at the molecular level: it can destroy or modify biologically important molecules such as proteins, DNA and RNA which may lead to cell death or alter the way in which a cell functions (UNSCEAR, 2000). Much of this damage can be repaired by the body's own repair mechanisms. However, if there is too much damage, or the damage occurs for prolonged periods, the body may not be able to repair itself effectively or may actually reproduce radiation-induced defects. The effects of the damage caused by ionising radiation can be grouped into two categories: deterministic (i.e. acute effects associated with high doses) and stochastic (i.e. long-term effects associated with relatively low doses). Deterministic effects include organ failure and even death, and are caused when the dose received exceeds a certain threshold value, usually within a short time period. Stochastic effects can be divided into two groups: cancers and hereditary effects. When a single cell is damaged, the body may be able to function as normal; however, over time, that cell may be replicated, leading to malignant growths, a loss of function and possibly death. When the DNA in a gamete cell is damaged, the radiation-induced defect may be passed on to the next generation and subsequently be expressed as an hereditary effect.

In general, much of the dose that is received by humans is from natural sources, estimated to be an average of 2.4 mSv per year worldwide, with approximately half of that dose due to exposure to ^{222}Rn (UNSCEAR, 2000). In contrast, the dose received from radiation produced as a result of human activity is estimated to be only 0.2 μSv per year: one ten thousandth of that from natural sources. It would appear then that if society wishes to reduce the risk of the detrimental health effects associated with radiation that the focus of attention should be on radiation from natural sources. However, to try and reduce our collective exposure to radiation from these sources would, in most cases, be extremely difficult, if not impossible, requiring a colossal use of time and resources, to the detriment of other aspects of normal life. Therefore, except in exceptional circumstances (e.g. some high level exposures to Radon), exposure to radiation from natural sources, and the resulting effects on human health, must be must be accepted as an inevitable consequence of our existence on this planet.

In contrast, the decision to produce and utilise anthropogenic radionuclides was taken by humans, and, therefore, society has the power to limit human exposure to these sources of ionising radiation. This power exists in the form of certain international and national authorities who produce recommendations and advice on statutory limits for the protection of humans from ionising radiation, both from natural and anthropogenic sources. The most eminent of these bodies is the International Commission for Radiological Protection (ICRP), which was formed in 1928, and currently consists of around 80 experts, including medical doctors, biologists, physicists and radio-ecologists (Lindell, Dunster and Valentin, 2004). The aim of the commission is to review the current state of the science involved in radiation protection and to publish recommendations based on that scientific evidence, and the judgements of its members. The commission only operates in an advisory capacity and does not have any legal standing to enforce its recommendations. Usually, the establishment and enforcement of regulations regarding radiation protection is the responsibility of national governments under the guidance of local agencies associated with radiation protection, such as the NRCP in the United States, and the NRPB in Great Britain. In practice, however, the regulations drawn up by these national authorities generally follow the advice of the ICRP.

The three central tenets of the commission's recommendations relating to "practices" (i.e. human activities which increase the overall exposure to radiation; not including accidents) are (ICRP, 1990):

i. That no practice should be adopted unless its introduction produces a net benefit.

ii. All exposures should be kept as low as reasonably achievable, economic and social factors being taken into account.

iii. That the dose equivalent to individuals shall not exceed the limits recommended for the appropriate circumstances by the commission.

These three principles are generally referred to as the “justification of a practice”, the “optimisation of protection” (also known as the “ALARA” principle) and “individual dose limitation” respectively. The most important implication of these principles is that, even if the doses resulting from a practice are below the appropriate statutory limits, the competent authorities still have a duty to try and reduce those doses further, providing that the resources to do so do not outweigh the benefit obtained. This precautionary approach has been adopted because it has been assumed that, even at very low levels, ionising radiation may be damaging to living cells, resulting in an increased risk of detrimental health effects in exposed individuals.

Because of the strict regulations controlling the handling of anthropogenic radionuclides, and any routine releases into the environment, these do not generally constitute a major source of dose to the general population. However, radionuclides from anthropogenic sources do have the potential to cause extremely high levels of individual dose in the event of the use of nuclear weapons, or large-scale accidents at nuclear installations, as described in the previous section of this chapter. For example, the absorbed doses received by emergency workers at the Chernobyl incident have been estimated to be as high as 11 Gy, whilst the effective doses of some individuals evacuated from Belarus from external radiation were found to be above 400 mSv within the first year after the accident (UNSCEAR, 2000).

In the event of such accidents, there are various "countermeasures" that can be implemented, which reduce the risk of detrimental health effects in the general population. In the acute phase during, and immediately after, such accidents the competent authorities may enact some protective measures to minimise the acute exposure of the population (e.g. evacuation, sheltering or administration of prophylactic iodine tablets). However, to restore and sustain acceptable living and working conditions for the population in the long-term, as well as for future generations, decision makers may need to devise a coherent and sustainable remediation strategy, consisting of numerous agricultural and urban countermeasures. Many of these countermeasures have been known for many years (e.g. potassium fertilisation of soil, which can reduce the uptake of radiocaesium by plants (Nisbet et al., 1993)), while new techniques have also been developed (e.g. skim and burial ploughing (Roed, Andersson and Prip, 1996)). Consequently, when designing remediation strategies for radioactively contaminated land, decision makers now have an array of countermeasures to choose from, and these have been extensively reviewed and compiled (STRATEGY 2004; BMU, 2000; NKS, 2000; IAEA, 1994).

When designing remediation strategies following nuclear accidents, the ICRP (1990) recommends that decision makers should adhere to the first two principles proposed for the introduction of practices (i.e. the "justification" and "ALARA" principles). However, the commission stresses that the third principle (that of "individual dose limits") should not be employed as the basis for deciding whether interventions should be implemented or not. This stance has been taken because the use of dose limits for deciding whether intervention is required or not, could lead to the introduction of countermeasures where the resources required for their implementation would not be justified by the benefit derived from them; which would be in direct conflict with the first two principles.

To ensure that the first two principles are adhered to when designing remediation strategies, decision makers must attempt to assess the potential benefits and detriments of all available options. When considering the introduction of practices in controlled environments, such as nuclear power stations, this may be fairly straightforward, as relatively precise information should be available about likely exposures pathways, levels of exposure and financial costs. However, in the event of a large-scale nuclear accident, large areas of land may be contaminated. Within these areas there may exist many spatially variable characteristics (e.g. agricultural practices, population density, soil properties etc.) that affect the exposure of the human population to radiation to different extents and on various timescales. Consequently, decision makers must not only decide *which* countermeasures should be implemented, but also *where* and *when*. The processing of the information required to make these decisions, much of which may be uncertain, and the identification of the optimal set of countermeasures to mitigate the risks to human health, are not trivial tasks. They include: acquiring accurate data at the desired resolution over large areas of land; predicting the transfer of many radionuclides through many different environments; estimating the exposure levels of various types of human populations; estimating the effectiveness of numerous radiological countermeasures and assessing their environmental, social and psychological impacts; determining the priorities and objectives for potential remediation strategies based upon the needs of affected stakeholders, including the general public; and finally, selecting a remediation strategy which fulfils as many of those objectives as possible.

Following the Chernobyl accident, off-site management procedures and practices were found to vary widely across Europe, and to be deficient in many respects (Liberatore, 1999). As a result, in its 3rd, 4th and 5th framework research programmes, the European Commission (EC) instigated the development of numerous Decision Support Systems (DSS) to assist decision makers in the event of future accidents.

1.3 DECISION SUPPORT SYSTEMS

Decision support systems (DSS) can take many forms, ranging from data acquisition models to fully integrated data assimilation, prediction and decision making programs (Table 1.1). Many of the DSS developed as part of the European 3rd, 4th and 5th framework programmes were limited to analysing and predicting the current and future consequences of a nuclear accident (Levels 0 and 1 in Table 1.1), while others included a restricted number of countermeasures, often with a limited assessment of their benefits and detriments (Level 2). However, only a few systems have attempted to evaluate countermeasure strategies and rank them according to the preferences of decision makers (Level 3). Given below are brief descriptions of three Level 3 DSS, corresponding to the level of the system described in this thesis.

TABLE 1.1 Levels, descriptions and examples of DSS funded by the EC. (Schulte, Kelly and Jackson, 2002)

Level	Description	Example
0	Acquisition and checking of radiological data and their presentation directly, or with minimal analyses, to decision makers, along with geographical and demographic information.	STRESS DAONEM ECCOMAGS
1	Analysis and prediction of the current and future radiological situation (i.e. the distribution over space and time of the radioactive material in the absence of countermeasures) based upon monitoring data, meteorological data and models, including information on the material released from the installation to the environment.	STEPS SAVE (Gillet et al., 2001) ENSEMBLE SPARTACUS (van der Perk et al., 2000)
2	Simulation of potential countermeasures, in particular, determination of their feasibility and some quantification of their benefits and detriments.	FORECO RESTORE (Voigt and Semioschkina, 1999) TEMAS (Montero et al., 2001)
3	Evaluation and ranking of alternative countermeasure strategies by balancing their respective benefits and detriments taking account of the judgements and preferences of decision makers.	MOIRA (Monte et al., 1999) CESER (Salt and Dunsmore, 2000) RODOS (Erhardt et al., 1993)

1.3.1 CESER (Countermeasures:Environmental and Socio-Economic Responses)

The objective of the CESER project was to produce a system which focussed on the environmental and socio-economic effects of remediation strategies. Two versions of the system were developed in parallel: a non-spatial DSS designed for typical Scottish farmland, and a more widely applicable spatial DSS (SDSS).

The environmental side-effects of the countermeasures considered most likely to be employed in long-term remediation strategies were determined by a variety of methods, including mathematical model simulations, laboratory experiments and expert judgement (Salt et al., 1999). These side-effects included: soil erosion and sedimentation; soil organic matter; soil nutrient transport to water; soil pollutant transport to water; animal welfare; product quality; product quantity; ammonia emissions; landscape quality and biodiversity.

In the non-spatial DSS, the user is asked to select the level of deposition of radionuclides (from one of four different types of scenario), the type of agricultural system under consideration, soil characteristics and information regarding the availability of alternative feedstuffs. The system then generates a list of appropriate countermeasures which can be ranked according to the user's preferences for the environmental side-effects using Ideal Point Analysis.

In the SDSS, the area under consideration is represented by a raster-based Geographical Information System (GIS) database, containing information regarding land use, soil characteristics and topography (Salt and Dunsmore, 2000). The feasibility of each countermeasure within each raster cell is assessed according to predefined criteria (e.g. the feasibility of potassium fertilisation is dependent upon soil pH, CEC, slope and height of vegetation), and the results displayed as "suitability maps", which illustrate the areas in which the implementation of a countermeasure is feasible. The GIS data are combined with the estimated environmental side-effects of the countermeasures to produce "impact maps" which identify, for each countermeasure/side-effect combination, the spatial variation of the normalised magnitude of the side-effects, resulting from the countermeasure's implementation. The system can then identify the "most suitable" countermeasures for a given area according to the preferences of decision makers for the attributes considered.

Although CESER represents a significant advance in the consideration of countermeasures' side-effects during the design of remediation strategies, there are a number of limitations to the approach:

i. The system does not calculate the doses arising from the defined scenarios. Without estimating the level of dose arising from a scenario it is not possible to assess whether the environmental and socio-economic side-effects of a countermeasure are outweighed by the benefit derived from it. Therefore, although CESER may identify those countermeasures which would lead to the minimal amount of environmental and socio-economic disruption, it cannot identify those countermeasures which would be the most effective at reducing doses.

ii. CESER does not consider combinations of countermeasures. However, where more than one countermeasure is implemented within an area, the combined environmental and radiological effects of those countermeasures may not be equal to the sum of the effects of the countermeasures when implemented individually. Therefore, because CESER considers countermeasure implementation in isolation, it cannot identify the most appropriate *strategy* for an area: merely the countermeasure which, on its own, has the least environmental and socio-economic impact.

In summary, CESER represents a useful tool for the identification of areas in which the implementations of countermeasures are feasible and the magnitudes of the environmental and socio-economic side-effects associated with the implementation of individual countermeasures. However, it cannot identify optimal remediation strategies as it does not consider the radiological effects of scenarios or the combined effects of countermeasures' implementations.

1.3.2 MOIRA (MOdel-based computerised system for management support to Identify optimal remedial strategies for Restoring radionuclide contaminated Aquatic ecosystems and drainage areas)

MOIRA is a DSS for radioactively contaminated aquatic ecosystems, including rivers, lakes and coastal areas (Monte et al., 1999). It combines GIS databases, which contain input data regarding the characteristics of the aquatic system under consideration, with radioecological models that estimate the transport of radionuclides, not only through aquatic environments, but also in agricultural systems which utilise the water contained within them. In addition, the system estimates the doses arising from a scenario and identifies optimal remediation strategies considering the radiological, environmental and socio-economic effects of a number of countermeasures. The identification of optimal remediation strategies is performed using "objectives trees" and Multi-Attribute Utility Analysis (MAUA). Objectives trees are hierarchical structures which help to formally define the preferences of decision makers. The lowest levels of the tree (leaves) are associated with model attributes, which are described using either existing or constructed scales. For example, the collective dose resulting from a scenario would be measured on an existing scale with units of man-Sv, whereas the stress caused by exposure to radiation may be measured on a constructed scale with values between 0 and 100. Utility functions and weightings for each attribute are then elicited from decision makers using a combination of a certainty equivalent and probability equivalent methods. The optimum remediation strategy can then be identified as the one with the greatest overall utility. To enhance confidence in the selection of an appropriate remediation strategy, decision makers can then perform sensitivity analyses on the results from the MAUA, in order to establish the estimated ranges of overall utility for each remediation strategy based on the uncertainties involved in eliciting the utilities and weights assigned to attributes and objectives respectively.

The MOIRA system has all the necessary components of an advanced DSS, including validated radioecological models, a comprehensive array of countermeasures, and the ability to identify optimal countermeasure strategies incorporating the consideration of countermeasures' side-effects. However, the system is focussed upon the aquatic environment, and only gives limited consideration to terrestrial environments.

1.3.3 RODOS (Real-time, Online, DecisiOn Support)

By far the most comprehensive DSS commissioned by the EC as part of its 3rd, 4th and 5th framework programmes has been the RODOS DSS (Ehrhardt et al, 1993). Its development has involved the collaboration of more than 40 institutes in 20 countries from within the European Union, Central Eastern Europe and former countries of the Soviet Union. The aim of the RODOS project was to develop a DSS which could provide support at every stage of a nuclear accident (i.e. before, during and after a release of radionuclides) that would be generally applicable across Europe.

The system is divided, conceptually, into three subsystems: the analysing sub-system (ASY); the countermeasure sub-system (CSY) and the evaluating sub-system (ESY), each of which contains modules with defined functions, such as data assimilation, state-of-the-art predictive modelling for estimating radionuclide transport through all aspects of the environment, the simulation of numerous short-term and long-term countermeasures and the identification of optimal short-term remediation strategies.

The Analysing Subsystem (ASY) contains modules which continually update the diagnosis and prognosis of the radiological situation, in the absence of countermeasures, using GIS and online meteorological data as inputs for atmospheric dispersion models, and radioecological models which estimate the transfer of radionuclides through terrestrial and aquatic environments. Modules within the ASY also estimate the individual and collective doses arising from a scenario, including: inhalation and external doses received during the passing of a radioactive plume; external doses resulting from contaminated surfaces; inhalation of resuspended material; ingestion doses from food products; ingestion doses from aquatic sources (fish and water). The human population is simulated using five representative individual types corresponding to different age groups (1, 5, 10, 15 years and adults) (RODOS, 2004). Mean residence times, and consumption and inhalation rates for these age groups are used to calculate the average individual and collective doses. For the ingestion pathway additional groups can also be defined to account for some special groups (e.g. vegetarians, hunters or fishermen). All food products consumed are assumed to be produced locally.

Due to the different approaches taken for estimating the collective ingestion dose and the collective doses from other pathways, the collective dose from all pathways is not calculated. The collective ingestion dose at a location is estimated by assuming that all food products produced at that location, for which production data are available, are eaten by adults *somewhere* (i.e. not necessarily within the location in which they were produced). The total collective ingestion dose is then the sum of the collective ingestion doses at each location. The collective doses arising from all other pathways at a location are estimated simply as the product of the predicted individual dose of an adult and the number of inhabitants at that location.

The Countermeasure Subsystem (CSY) contains modules which simulate and quantify the effects of numerous short- and long-term countermeasures, and estimate any resultant reductions in collective and individual doses in addition to the economic costs associated with countermeasure implementation.

The tasks of the modules that comprise the Evaluating Subsystem (ESY) are to assess the merit of short-term remediation strategies, according to the preferences specified by decision makers, and to identify optimal remediation strategies based on those preferences. This is accomplished via Multi-Attribute Utility Analysis (MAUA) and a Coarse Expert System (CES) module which limits the number of strategies to be assessed using a system of constraints and preferences (Papamichail and French, 1999), which will be discussed in more detail in Chapter 4.

Despite the use of state-of-the-art predictive models within RODOS, the system still has a number of significant limitations. For example, when estimating collective and individual ingestion doses at a location, it is assumed that all food products consumed are produced locally. However, throughout Europe, significant proportions of many people's diets are sourced from outside their immediate locality. Therefore, because food products sourced from other countries, or even from other parts of a contaminated region, may be uncontaminated following a deposition of radionuclides, it is likely that RODOS will overestimate the levels of individual dose in those areas where significant levels of deposition occur, and underestimate in those areas where little or no deposition occurs. Consequently, depending upon the preferences of decision makers, this could lead the ESY subsystem to suggest countermeasure strategies that could either be unwarranted by the actual levels of individual dose in a contaminated area or, perhaps more worryingly, would not be extensive enough; leaving some individuals exposed to unacceptably high levels of radiation.

In addition, although some limited consideration has been given to public acceptability and the stress caused by remediation strategies, RODOS does not consider the environmental side-effects of countermeasures' implementation, and therefore may suggest remediation strategies which would be unacceptable to the general public and other stakeholders. Furthermore, the optimisation procedure developed within RODOS only considers short-term countermeasures, and thus the system cannot identify long-term remediation strategies.

1.4 SUMMARY

Humans are exposed to radiation from a variety of sources. Many of these sources are naturally occurring (e.g. cosmic radiation, radon gas), while others are the result of human activities (e.g. the testing of nuclear weapons or nuclear power production). These exposures are associated with detrimental health effects which range from acute effects, such as organ failure and death, to long-term effects such as cancer and hereditary defects. Although natural sources of radiation are, on average, the biggest contributors to the doses received by individuals worldwide, attempts to mitigate these exposures would be unjustified in most cases as the resources required to do so would greatly outweigh the benefit derived from them. Exposure to natural radiation, therefore, must be accepted as an inevitable part of human existence. However, in the case of anthropogenic sources of radiation, society has the power to choose what level of exposure is acceptable, and this is expressed in the form of regulations controlling the exposure of humans to radiation and the release of radionuclides into the environment. Consequently, exposure to radiation from anthropogenic radionuclides generally does not pose a serious threat to health. However, accidents involving anthropogenic radionuclides do occur, and when they do, they have the potential to lead to the contamination of large areas of land, and present a serious danger to the welfare of affected populations. In the event of such accidents, the relevant authorities must make a series of decisions, involving many complex issues such as the site specific radioecological, economic, social and environmental characteristics of the affected area, to firstly ensure the safety of the human population and secondly to decide whether remediation of the contaminated area is desirable, feasible and justified. This involves processing a large volume of information, much of which may be uncertain, a task which is virtually impossible without some form of computer assistance. As a result, numerous DSS have been developed to assist decision makers to process the required information following a nuclear accident and to assess potential remediation strategies according to decision makers' objectives. However, these DSS have tended to focus on short-term responses to nuclear emergencies and only consider the direct radiological and economic effects of remediation strategies. There is scope, therefore, for a DSS which addresses the design of long-term remediation strategies and explicitly considers the side-effects resulting from the implementation of countermeasures.

1.5 OBJECTIVES AND PLAN OF THESIS

The primary aim of this work was to develop a methodology to assist the design of sustainable, long-term remediation strategies following the deposition of four long-lived radionuclides (^{137}Cs, ^{90}Sr, ^{239}Pu and ^{241}Am) into the terrestrial environment. To achieve this task, several secondary aims were defined:

- To combine existing radionuclide transport models with a raster-based GIS database to enable spatial predictions of the radiological consequences of a nuclear accident to be performed, and to generate detailed outputs from these predictions to facilitate the decision making process.

- To incorporate relevant radiological countermeasures within the radionuclide transport models to allow the investigation of their effects.
- To develop a new methodology to improve the simulation of human populations, particularly to take account of the geographical origins of food products.
- To incorporate the social and environmental impacts of countermeasures' side-effects within the assessment of potential restoration strategies, in an attempt to generate more publicly acceptable, and consequently more sustainable, remediation strategies.
- To develop a methodology to identify optimal remediation strategies for a given scenario, taking into account the site-specific, and spatially variable, radiological, environmental, economic and social characteristics of the location.

In addition to the above objectives, it was also important that the system should be as fast, user-friendly and transparent as possible, to ensure that it could be used interactively by decision makers, with limited training, to investigate the effects of various restoration strategies, with all relevant information provided.

1.5.1 Chapter 2

This chapter describes the amalgamation of existing radioecological models with a GIS database, allowing the prediction of the temporal and spatial variation of radionuclide transport through the terrestrial environment. In addition, the estimation of individual and collective doses is described, incorporating novel techniques for the creation and simulation of human populations using Monte-Carlo sampling of statistically defined attributes, which include the geographical origins of consumed food products.

1.5.2 Chapter 3

Chapter 3 describes the simulation of relevant countermeasures within the radioecological models described in Chapter 2. The method by which the implementation of countermeasures is controlled using model predictions and other system parameters is also described.

1.5.3 Chapter 4

The methodologies developed to assist the selection of remediation strategies are described in Chapter 4, including an optimisation procedure that identifies optimal remediation strategies using an extended cost benefit analysis which can incorporate the indirect costs of countermeasures' side-effects.

1.5.4 Chapter 5

In Chapter 5, the results of two case studies are presented, which demonstrate the applicability of the system to different scenarios, and the success of the countermeasure selection methodology in identifying optimum remediation strategies.

CHAPTER 2: RADIONUCLIDE TRANSPORT AND DOSE MODELLING

To design appropriate remediation strategies for radioactively contaminated land, the likely radiological consequences of the contamination must be determined, in order that the benefits and detriments of potential strategies can be compared, in accordance with the ALARA principle, as described in Chapter 1. In this chapter, the model used to predict the doses resulting from the ingestion of contaminated food products and exposure to external radiation is described.

2.1 INTRODUCTION

Following the release of radionuclides into the environment, human populations are generally exposed to ionising radiation via four main pathways: inhalation during the passage of a radioactive plume; ingestion of contaminated food products; ingestion and inhalation of contaminated water; and external exposure to contaminated surfaces (Figure 2.1). The main objective of the system described here is to assist the design of *long-term* remediation strategies and, therefore, the inhalation of radionuclides during the passage of a radioactive plume, which is associated with acute responses (e.g. evacuation, sheltering and administration of prophylactic iodine tablets), is not considered. In addition, the ingestion and inhalation of contaminated water is not considered, as these pathways do not generally contribute significantly to the total doses received following an atmospheric release of radionuclides into the environment (UNSCEAR, 2000). The foci of this work are therefore (i) the modelling of the pathways resulting in the ingestion of contaminated food products, and (ii) the external exposure to contaminated surfaces (as highlighted in Figure 2.1).

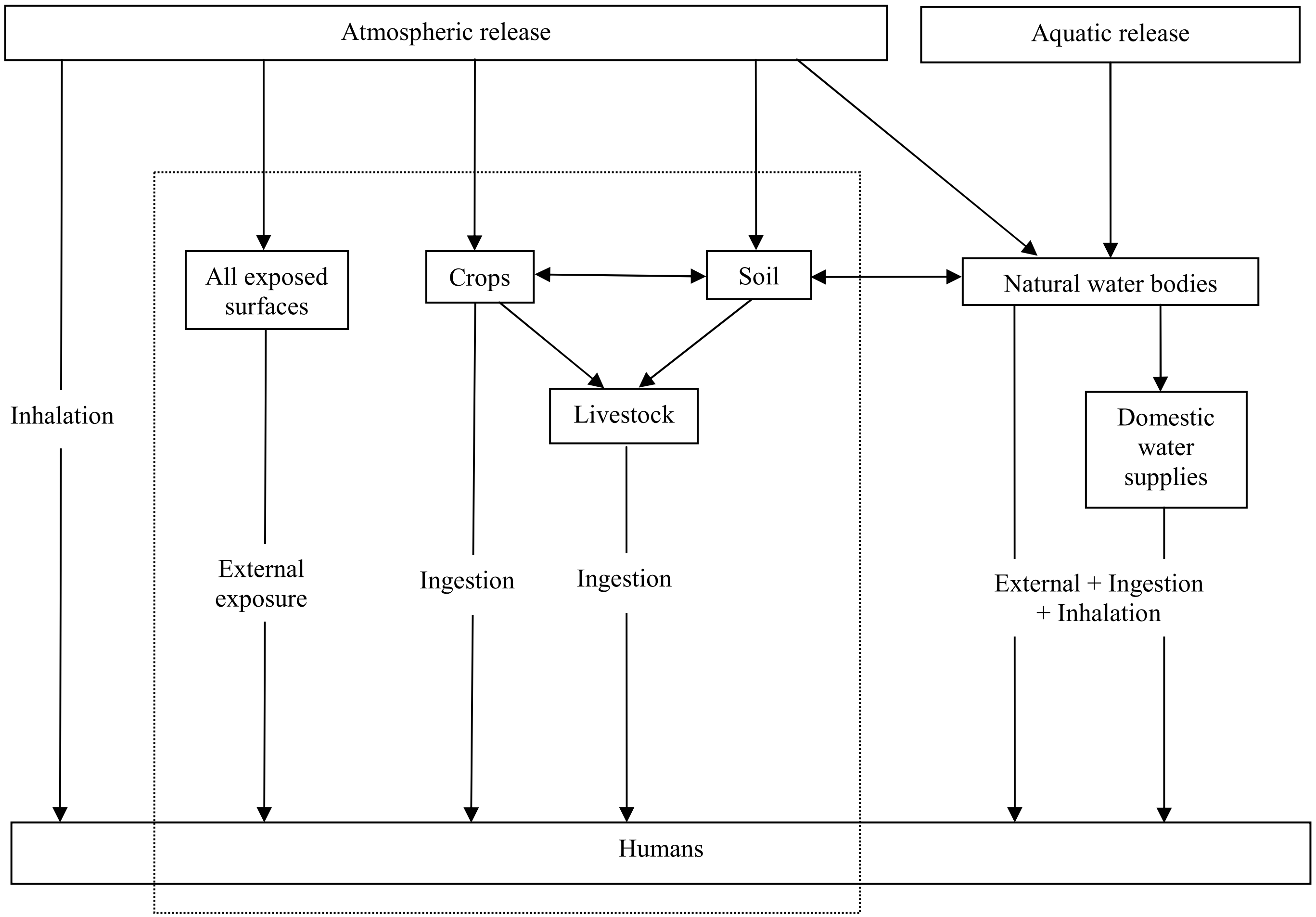

Figure 2.1 Major exposure pathways for humans following releases of radionuclides into the environment (the dotted line encloses the components considered within the system described here).

2.1.1 Food-chain models

The transfer of radionuclides through the human food-chain is a complex process which depends upon many factors, such as soil characteristics, the quantities and species of plants grown and agricultural management practices (Ehlken and Kirchner, 2002; Nisbet and Woodman, 2000; Nisbet et al., 1998). Within a contaminated area, each of these factors may vary spatially and temporally. Previously, however, the models developed to estimate the transfer of radionuclides through the food chain (e.g. ECOSYS-87 (Müller and Pröhl, 1993); PATHWAY (Ward-Whicker and Kirchner, 1990); FARMLAND (Brown and Simmonds, 1995); COMIDA (Abbott and Rood, 1994); DYFOM-95 (Er-Bang et al., 1998)) have not considered the spatial variability of model inputs within an affected area. More recently, with the advent of computers with fast processing speeds, the SAVE system (Gillett et al., 2001) has been developed which combines radio-ecological models with GIS databases to account for the spatial variation in the transport of radiocaesium through the food chain.

To prevent the modelling task becoming too onerous, or too time consuming, all of the systems mentioned make numerous simplifying assumptions regarding the processes involved in radionuclide transfer through the environment, and include many rationalisations. For example, with the exception of SAVE, all of the systems predict the plant uptake of radionuclides using transfer factors, which simply relate the activity concentration of plants to the total activity concentration within soil. During the past few decades, comprehensive databases of transfer factors have been compiled (Nisbet, Woodman and Haylock, 1999; IAEA, 1994; IUR, 1992); however, the measured values of a transfer factor for a specific combination of plant, soil and radionuclide can vary by several orders of magnitude. These variations occur because transfer factors represent a crude aggregation of the numerous processes that take place between soils, radionuclides and plants. For example, the uptake of radionuclides by plant roots can be highly dependent on their chemical speciation. Valcke and Cremers (1994) demonstrated that radiocaesium complexed to organic matter remains available for uptake by plants, whereas it becomes “fixed” (i.e. unavailable for plant uptake) when complexed to clay particles. However, this speciation is not taken into consideration when deriving transfer factors, rather, the total activity within an arbitrary soil depth is used. Another factor that can influence the plant uptake of radionuclides is the presence of competing ions or chemical analogues. Smolders et al. (1997) found the uptake of radiocaesium by plants related to the level of exchangeable potassium in the soil solution, as potassium and radiocaesium compete for sorption sites on the frayed edges of mica particles.

Transfer factors are also used to predict the uptake of radionuclides by animals, and the use of these is also associated with several assumptions. One such assumption is that the activity concentration of a radionuclide within an animal achieves equilibrium. However, for some radionuclides (e.g. plutonium and americium) equilibrium is never reached within the lifetime of an animal, and for others, equilibrium may not be achieved before the animal is slaughtered. ECOSYS-87 (Müller and Pröhl, 1993) accounts for periods of build up or loss of radionuclides using biological transfer rates for each animal-derived food product:

$$C(T) = TF \sum_{j=1}^{J} \left\{ \, a \int_{0}^{T} A(t) \lambda_j \exp[-(\lambda_j + \lambda_r)(T - t)] dt \, \right\}$$

where C (Bq kg^{-1}) is the activity concentration in the animal food product at time T, TF (d kg^{-1}) is the transfer factor for the animal product, J is the number of biological transfer rates, a is the fraction of biological transfer rate j, A (Bq d^{-1}) is the animal's activity intake rate, λ_j (d^{-1}) is the biological transfer rate and λ_r (d^{-1}) is the radioactive decay constant.

A further common assumption in the prediction of animal uptake of radionuclides is that all of the radionuclides consumed by an animal are available for uptake. However, the availability of radionuclides for absorption by animals' guts may depend on their chemical form and on other components present in the diet (Desmet, Loon and Howard, 1990). The chemical speciation of radionuclides associated with plant material used for animal feed may depend on whether they have been incorporated into plant tissue (either via root or foliar uptake), or whether they are present as deposits on leaf surfaces. Radionuclides incorporated into plant tissues may become tightly bound to various biological molecules such as hemes and proteins, or form less stable complexes with carboxylic acids or nucleotides (Desmet, 1986). Furthermore, the ingestion of contaminated soil particles attached to feedstuffs may be a significant pathway for the intake of radionuclides by animals (Healy, McCabe and Wilson, 1970). However, Crout, Beresford and Howard (1993) argue that, for radiocaesium at least, the contribution to an animal's activity concentrations from contaminated soil particles attached to feedstuffs is negligible because the absorption by ruminants of radiocaesium adhered to soil particles is significantly lower than the absorption of radiocaesium contained within plant material, as shown by Hansen and Hove (1991).

Despite the assumptions, rationalisations and uncertainties associated with them, several studies have shown that food-chain models generally give reasonable estimates of activity concentrations in food products (Köhler, Peterson and Hoffman, 1991; IAEA, 1995, 1996; Crout et al., 1999) and, as a result, can provide decision makers with valuable information regarding the potential consequences of nuclear accidents.

2.1.2 Models for the estimation of external doses

Following the deposition of radionuclides into the human environment, irradiation from external sources (largely gamma sources) may constitute a significant proportion of the total dose received by the affected human population (Kelly, 1987; UNSCEAR, 2000). For a given level of deposition, the dose received by an individual depends on many factors, such as the size and construction of the buildings occupied (Burson and Profio, 1977), the characteristics of contaminated surfaces (Andersson, Roed, and Fogh, 2002; Wilkins, 1987), and the residence times of affected individuals (Brown, 1984; Francis, 1986). The understanding of the processes involved in the interception and retention of radionuclides by urban surfaces, together with the knowledge regarding the shielding properties of common building structures, has precipitated the development of models which estimate the dose arising from exposure to external radiation in the urban environment (e.g. EXPURT (Crick and Brown, 1990); Meckbach, Jacob and Paretzke (1988); Meckbach and Jacob (1988); Kis et al., (2003)). By considering the contributions of various contaminated surfaces to the external doses received, these models provide a means of simulating the mitigating effects of radiological countermeasures which act upon those surfaces (e.g. roof hosing and wall washing (Eged et al., 2003)), and consequently the inclusion of the remediation of urban environments within DSS.

2.1.3 Modelling of human populations

The purpose of the radio-ecological models used in DSS is to estimate the doses received by the affected human population. This assists decision makers in identifying the major exposure pathways, and selecting the appropriate measures to mitigate them. Generally, the most useful radiological parameters for decision makers are the level of collective dose, and the levels and distribution of individual doses. To estimate these parameters for a given scenario, it is necessary to model the behaviour and characteristics of the human population. However, within an affected area there may be hundreds of thousands, perhaps millions, of individuals. To estimate the dose received by every individual, and in turn the collective dose, would require a large volume of data, regarding each individual's dietary and activity characteristics. These data would not only be impractical to use, but also difficult to obtain. Consequently, the modelling of a population's behaviour must be rationalised.

The simplest approach for modelling a human population is the definition of a representative individual based on the mean characteristics of the population. However, basing radiological protection decisions on mean values could lead to inadequate protection for individuals whose behavioural characteristics give them significantly higher exposures than the mean. This limitation has led to the development of the "critical group" concept. The critical group is defined as those individuals who receive the highest dose from a particular source, and should be small enough that the characteristics which give rise to those doses are relatively homogenous within the group (ICRP, 1990). The predicted mean dose to the critical group can then be compared with the relevant dose constraint, and if it is found that the critical group is adequately protected, then it is assumed that all other individuals are protected too. Whilst this concept reduces the computational processing time required, by reducing the number of representative individuals to be assessed, it is open to criticism for a number of reasons:

i. The approach relies on the appropriate identification of the critical group. As highlighted earlier, the prediction of radionuclide transport through the human food-chain is associated with many inherent uncertainties. In addition, all of the techniques used to determine the food consumption rates used in radiological dose assessments (e.g. 24 hour recalls, dietary records, duplicate diets, food frequency questionnaires and dietary histories) are associated with disadvantages and limitations, and introduce further uncertainties into the estimation of ingestion dose (Biró et al. 2002; Löwik et al., 1999). Given these uncertainties it is possible that the critical group may not be appropriately identified. Moreover there may be considerable variation in the doses received by members of that group due to the variability of the habits and metabolisms between group members (Cabianca et al., 1998). Consequently, any decisions based solely upon the mean dose to the critical group may still leave some individuals exposed to unacceptable dose levels.

ii. If only the doses received by the critical group are used to determine which, if any, protective actions should be implemented, it is possible that other actions, which primarily benefit individuals who do not form part of the critical group and are “reasonably achievable”, will not be considered. This would be in breach of the ALARA principle.

Therefore, in this thesis, a methodology is described which simulates the behaviour of as wide a range of people as possible; encompassing both “average” and “extreme” behavioural characteristics. Numerous sub-populations can be simulated which can be defined either manually, or automatically according to the statistical attributes of the overall population. This approach is used in an attempt to better reflect the variations in behaviour that exist within human populations, and furthermore, it facilitates the estimation of the collective dose of the affected population and allows the characteristics of the individuals who receive high levels of dose to be identified and investigated.

2.2 METHODOLOGY

2.2.1 General structure

A raster-based GIS database, derived from the SAVE system (Gillet et al., 2000; Crout et al., 1999), is used which allows the spatial variation in model inputs and outputs to be represented. The area under study is represented as a two dimensional array of cells, whose scale is determined by the resolution of the input data (whilst high-resolution data is desirable, this must be traded against computational processing time). Each cell is associated with an input dataset within the database, which contains information about radionuclide deposition levels, soil characteristics, topography, land use, number of livestock animals present, and the number of humans inhabiting the cell (Table 2.1). Cells are aggregated into regions that are also associated with an input dataset within the database. Regional input datasets contain information that is either not available or practical to use at cell-level resolution, such as food production rates and crop and livestock management procedures (Table 2.2). The data held in the regional input data-set are assumed to apply to all cells within the region. The contaminated area can have any number of regions defined, as appropriate.

Existing plant uptake models (i.e. SAVE (Gillett et al., 2001) and ECOSYS-87 (Müller and Pröhl, 1993)) are combined with cell-level data, regarding soil characteristics and regional-level data regarding crop management (e.g. sow and harvest dates), to predict the activity concentrations of ten crops in each cell. The crops considered are: pasture grass; cereals; maize; potatoes; leafy vegetables; root vegetables; fruit; grass for silage; maize for silage; cereals for silage. These are assumed to be representative of all similar crops and species. The predicted activity concentrations of crops used for animal fodder within a cell (i.e. pasture grass and maize, grass and cereals for silage) are then combined with the regionally defined feeding regimes of six livestock animals (dairy cows, beef cattle, sheep, goats, pigs and chickens) to estimate the activity concentrations of the food products derived from them within each cell.

The human population is assumed to be comprised of numerous sub-populations whose characteristics can be defined manually or generated automatically by Monte-Carlo sampling of the defined statistical attributes of the overall population in the affected area. This approach allows the different radiological consequences experienced by each sub-population to be assessed and incorporated in the decision making process. Within each cell the dietary habits of each sub-population are combined with the predicted activity concentrations of the considered food products to estimate the resulting ingestion dose to each individual of a sub-population and to the population as a whole.

In addition to the ingestion dose received, the effective dose from external radiation is also predicted for each sub-population within each cell. This is estimated using the activity profiles of the sub-populations (i.e. how much time individuals spend at various locations) in combination with the external dose model developed by Meckbach, Jacob and Paretzke (1988).

Table 2.1 Required input data at cell-level resolution.

Deposition (Bq m^{-2})	Number of lambs from lowland grass killed per annum
Exchangeable soil potassium (cmol kg^{-1})	Number of mutton sheep from lowland grass killed per annum
Soil pH	Total number of beef cows on rough grassland/heath
Percentage carbon in soil	Number of beef cows from rough grassland/heath killed per annum
Percentage clay in soil	Total number of lambs on rough grassland/heath
Number of human inhabitants	Number of lambs from rough grassland/heath killed per annum
Average slope (0 = > 16°; 1 = < 16°)	Number of mutton sheep from rough grassland/heath killed per annum
Organic farm (0 = no, 1 = yes)	Total number of lambs on upland grass
Environmental constraints (0 = no, 1 = yes)	Number of lambs from upland grass killed per annum
Amount of lowland grass (hectares)	Number of mutton sheep from upland grass killed per annum
Amount of rough grassland/heath (hectares)	Number of urban buildings
Amount of upland grass (hectares)	Area of urban walls (m^2)
Tilled area (hectares)	Area of urban roofs (m^2)
Soil depth (1 = not suitable for ploughing, 3 = suitable for ploughing)	Area of urban pavement (m^2)
Number of milking cows on lowland grass	Area of urban lawns (m^2)
Total number of dairy cows on lowland grass	Number of industrial buildings
Total number of beef cows on lowland grass	Area of industrial walls (m^2)
Number of beef cows from lowland grass killed per annum	Area of industrial roofs (m^2)
Total number of lambs on lowland grass	

Table 2.2 Required input data at regional level.

Sow date for each crop (Day of year)
Harvest date for each crop (Day of year)
Yield for each crop (kg m^{-2})
Harvest index for each crop
Minimum biomass for each crop (kg)
Number of grass silage cuts
Time between grass silage cuts (days)
Dry Matter Intake (DMI) for Dairy cows (kg d^{-1})
Dry Matter Intake (DMI) for Beef cows (kg d^{-1})
Dry Matter Intake (DMI) for Sheep (kg d^{-1})
Dry Matter Intake (DMI) for Chickens (kg d^{-1})
Dry Matter Intake (DMI) for Goats (kg d^{-1})
Dry Matter Intake (DMI) for Pigs (kg d^{-1})
Food production rates for intensively produced food products (kg y^{-1})

During the first year post-deposition, when the changes in activity concentrations and doses are likely to be greatest, model calculations are performed at monthly intervals. Subsequently, calculations are performed at yearly intervals using annual averages of system parameters where appropriate. Input data and model predictions for the activity concentrations in crops, livestock animals, and food products at each time-step may be viewed as raster maps, which illustrate the spatial variations of parameters within a scenario. In addition, a text-file is created which summarises the level and distribution of collective and individual doses, and the total contributions to ingestion doses by each food product.

2.2.2 Food-chain modelling

The model chosen to predict the transport of radionuclides through the human food-chain was the SAVE system, developed by Gillett et al. (2001), and it is briefly described here. The main advantage of this model is that it considers the spatial variation of a contaminated region's characteristics, allowing the resulting spatial variation in the transport of radionuclides to be assessed, which, in turn, allows the design of efficient remediation strategies that focus on the most radiologically sensitive areas. In addition, the system incorporates a semi-mechanistic model (Figure 2.2) which predicts the plant-root uptake of radiocaesium using soil characteristics (Absalom et al., 2001).

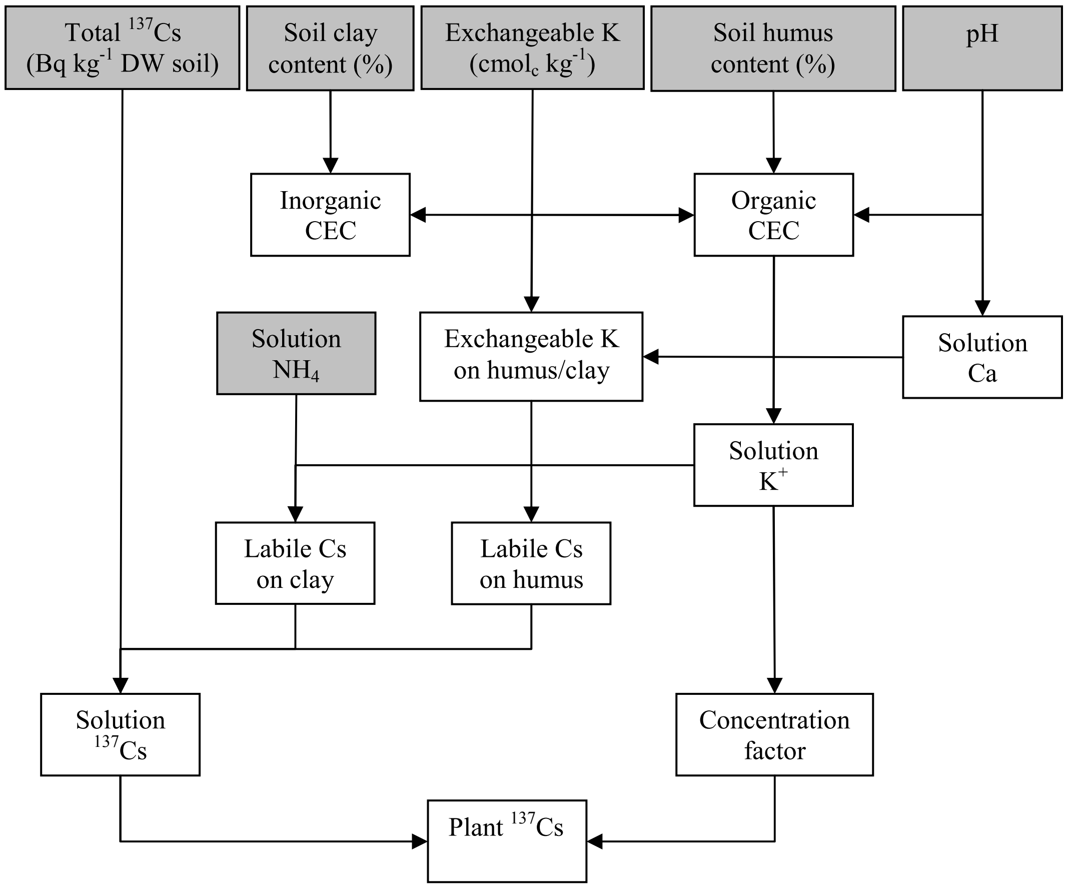

Figure 2.2 Schematic of the Absalom et al. (2001) model for the prediction of radiocaesium uptake by plants. Shaded boxes indicate model inputs; open boxes indicate calculated variables.

Soil characteristics are particularly important when predicting the plant uptake of radiocaesium, as soils with high levels of organic matter and low levels of exchangeable potassium may lead to the long-term availability of radiocaesium to plants, as seen in the upland areas of Cumbria and North Wales in the UK, following the Chernobyl accident (Nisbet and Woodman, 1999).

2.2.2.1 Crop modelling

The growing seasons for all crops other than pasture grass are defined by the sow and harvest dates specified in the regional dataset. The biomass density, *B* (kg m^{-2}), of the plants during the growing season is then estimated using a logistic growth curve derived from Thornley and Johnson (1990):

$$B(t) = \frac{B_{\min} Y}{B_{\min} + \left(Y - B_{\min}\right)\exp[-(k.GD.F(t))]}$$

$$k = \ln\left\{ \frac{GD(Y - B_{\min})}{2B_{\min}} \right\}$$

where B_{min} (kg m^{-2} DW) is the minimum biomass density of a crop, *Y* (kg m^{-2} DW) is the yield of the edible portion of the crop, *GD* (days) is the duration of the growth period (defined as the time between the sow and harvest dates) and *F* is the fraction of the growth period that has passed.

An alternative method is used in the case of pasture grass, as it is assumed that this crop is not routinely sown or harvested. In this case, the days of the year when pasture grass biomass density is at its maximum and minimum (DOY_{max} and DOY_{min} respectively) are specified for each region. Its biomass density, B_p (kg m^{-2}), for any given day of the year, DOY, is then estimated using an exponential growth curve (Green and Gregson, 1984) where:

$$B_p = B_{\min}\left(1 - \frac{DOY}{DOY_{\min}}\right)^{\lambda_p GD_p} e^{\lambda_p DOY}$$

$$\text{Where } \lambda_p = \frac{\ln\left(\frac{Y}{B_{\min}}\right)}{DOY_{\min} + GD_p \ln\left(\frac{GD_p}{DOY_{\min}}\right)} \text{ and } GD_p = DOY_{\min} - DOY_{\max}$$

For crops that are sown (i.e. all crops except pasture), routine ploughing is assumed to take place immediately prior to the sow date.

The internal activity concentration of plants due to root uptake of radiocaesium, P_i (Bq kg^{-1}), is estimated using the model developed by Absalom et al. (2001), where:

$$P_i = Cs_{sol} CF$$

where Cs_{sol} (Bq dm^{-3}) is the activity concentration in the soil solution and CF (dm^3 kg^{-1}) is a concentration factor:

$$\log[CF] = -(k_2 \log[m_k] + k_1)$$

where k_1 and k_2 are empirical constants, and m_k (mol dm^{-3}) is the concentration of potassium ions in the soil solution (assumed to be in equilibrium with potassium ions adsorbed on the humic or clay fractions of soil and in competition with calcium and magnesium ions). The relationship between radiocaesium adsorbed on soil particles and radiocaesium in soil solution, Cs_{sol}, is described using a distribution coefficient that is dependent upon the quantities of clay and humus present and the concentrations of potassium and ammonium ions in the soil solution. The increase in the fixation of radiocaesium to clay particles over time is described using a dynamic factor, *D*, which varies between 0 and 1, and is used to reduce the predicted concentration of radiocaesium in the soil solution over time:

$$D(t) = P_{fast} \exp[-k_{fast} t] + (1 - P_{fast}) \exp[-k_{slow} t]$$

where P_{fast} represents the proportion of radiocaesium in soil that is subject to rapid fixation and k_{fast} and k_{slow} are empirically derived rate constants.

The major advantage of the Absalom model, over the more traditional transfer factor approach, is its ability to predict the long-term availability of radiocaesium for uptake by plant roots using readily available soil parameters (i.e. pH, exchangeable potassium, organic matter content and clay content). In combination with a GIS database, this allows the spatial variation of soil characteristics, observed in real situations, to be used to predict the resulting variation in the uptake of radiocaesium by plants. In contrast, other models generally assume that root uptake is independent of soil characteristics, resulting in the predicted uptake of radiocaesium by plants being uniform across regions with diverse soil characteristics.

The root uptake, P_i (Bq kg^{-1}), of the other radionuclides considered in this system is modelled according to the approach of Müller and Pröhl (1993):

$$P_i = TF\left(\frac{D}{L\delta}\exp[-(\lambda_l + \lambda_f + \lambda_r)t]\right)$$

where *TF* is the soil-plant transfer factor, *D* (Bq m^{-2}) is the total deposition to soil, *L* (m) is the depth of the rooting zone, δ (kg m^{-3}) is the soil bulk density and λ_l, λ_f and λ_r are the rate constants for leaching from the root zone, fixation of radionuclides within the soil (only considered for radiostrontium) and radioactive decay respectively. This simple transfer factor approach is used due to the lack of reliable, more mechanistic models for the root uptake of these radionuclides.

The activity concentrations of plants due to external and translocated radionuclides are estimated from the interception of the initial deposition and the biomass of the plants throughout the growing season according to the SAVE system (resuspension is not considered).

2.2.2.2 Modelling of livestock management

For livestock animals, four feeds are considered: pasture grass, grass silage, cereal concentrates and maize silage. With the exception of chickens and pigs, which are assumed to consume only cereal concentrates, all animals can consume all of the feeds. All feeds are assumed to be sourced from within the cell in which an animal resides. The intake of a feed by an animal is specified at the regional level so that all animals of the same type residing within a region have the same diet. To account for seasonal variations in animals' diets the daily dry matter intake (DMI, kg day^{-1}) of each feed is defined for six two-month intervals (Jan-Feb, Mar-Apr, May-Jun, Jul-Aug, Sep-Oct, Nov-Dec) for all animals. The slaughter rate for all livestock animals is assumed to be constant throughout the year.

2.2.2.3 Activity concentrations in food products.

Twenty-seven food products are considered:

1. Cows' milk	10. Chicken	19. Freshwater fish
2. Goats' milk	11. Pork	20. Red deer
3. Sheep milk	12. Lamb	21. Roe deer
4. Cream	13. Beef	22. Reindeer
5. Butter	14. Cereals	23. Moose
6. Cow cheese	15. Potatoes	24. Other game/wildfowl
7. Goat cheese	16. Leafy vegetables	25. Wild boar
8. Sheep cheese	17. Root vegetables	26. Wild fungi
9. Eggs	18. Fruit	27. Wild berries

The fresh weight activity concentrations of food products derived directly from crops are estimated as the product of the plants dry matter activity concentration, and the fraction of dry matter. For food products derived from livestock animals, activity concentrations are estimated as the product of the animal's dry matter intake, the activity concentration of the feeds, and an equilibrium transfer coefficient. Although this method does not account for the dynamics of radionuclide uptake and loss from animals, as mentioned previously, it is numerically simple. The activity concentrations of semi-natural food products are estimated using aggregated transfer factors, which simply relate the activity concentration in a food product to the density of deposition.

The activity concentration of a consumed food product is estimated as the product of the activity concentrations of the pre-processed food product and a processing factor, which accounts for changes in the activity concentration due to common food processing techniques (Green and Wilkins, 1995; IAEA, 1994).

2.2.3 External dose modelling

The external dose to humans is calculated using the model developed by Meckbach, Jacob and Paretzke (1988) and extended by Kis *et al.* (2003), which estimates the air kerma rate from a range of surfaces at different locations within standard building types; taking into account radionuclide interception, fixation, and weathering processes. These models were selected because, by considering the contributions of various contaminated urban surfaces to the total external dose received at locations within the urban environment, they allowed the prospect of simulating the effects of countermeasures which act upon those surfaces.

Two environments are considered within each cell: the urban (i.e. where people live) and the industrial (i.e. where people work). In the urban environment, three building types are considered for habitation by the human population:

i. Semi-detached houses.

These are assumed to be of standard brick type construction, consisting of a ground floor, first floor and attic, with gardens and trees surrounding them.

ii. Terraced houses.

These are also assumed to be of standard brick type construction, consisting of a ground floor, first floor and attic, with gardens and trees surrounding them.

iii. Flats.

Flats are assumed to be a standard five storey brick and concrete construction with a courtyard within its centre.

In the industrial environment, two building types are considered:

i. Factory/Supermarket

These buildings are of standard concrete construction with steel roofs.

ii. Offices

The construction of offices is assumed to be the same as for residential flats.

For each building type, neighbouring buildings are assumed to be of the same type.

Although the simulation of residential and industrial areas used in this system represents a great simplification of the urban environment, which is usually a complex combination of architectural designs and construction materials, this approach does allow a tentative estimation of the levels of external dose to be performed, and, furthermore, provides a means of simulating potential remediation strategies to mitigate those doses.

2.2.4 Population modelling and dose calculations

Accurate modelling of the human population is critical to the success of the decision making process when selecting the appropriate course of action following a release of radionuclides into the environment. The approach taken here is to assume that the overall population in the study area is comprised of various sub-populations, which are assumed to be present in every cell in equal proportions. Therefore, the total number of individuals of a sub-population residing within a cell is equal to the total number of residents within the cell (the value of which is obtained from the database) divided by the number of defined sub-populations. In principle, the relative proportions of the sub-populations could be allowed to vary between cells, which would allow more "urban" and fewer "rural" sub-populations to be assigned to cells in urban areas and *vice versa*. However, due to the limited data available to describe this distribution, such distinctions have not been considered. In theory, there is no limit to the number of sub-populations that can be defined; however, as the time taken for model simulations increases with the number of defined sub-populations their number does need to be constrained to ensure that the system remains as interactive as possible.

The behaviour of each sub-population is described by a number of attributes, which can be broadly divided into four main characteristics (for the full list of attributes see tables 3, 4 and 5 in Appendix B):

1. Dietary habits

   The consumption rate of each food product considered, together with the geographical origins of groups of the consumed food products (i.e. dairy, meat, fruit and vegetables, semi-natural, and cereals) are defined. The food origin attributes are considered in an attempt to account for the fact that, in reality, individuals generally obtain their diet from many different sources, ranging from back gardens, allotments, local farms and farmers' markets to national and international supermarkets who source their produce not only from various regions within a country, but also from around the world. Four sources are defined:

i. Home-grown produce.

This category only applies to leafy vegetables, root vegetables, fruit and potatoes. These are assumed to be grown for personal consumption in gardens or allotments, from within the cell in which an individual resides, and are assumed to be cultivated in a similar manner to their marketed counterparts. Agricultural countermeasures do not apply to this category.

ii. Local produce.

This category represents marketed and semi-natural food products produced within the cell in which an individual resides.

iii. Regional produce.

This category represents marketed food products which are produced somewhere within the region in which an individual resides. The activity concentrations of regionally produced food products are taken as the production weighted mean of the foods' activity concentrations from all of the cells within the region.

iv. External produce.

By default the activity concentrations of foods sourced from outside the affected area are assumed to be zero, however, this value could be altered. This category does not apply to semi-natural food products.

The food-origin attributes are expressed as the percentage of a sub-population's intake of a particular food group that is produced from a particular source. For example, a sub-population may obtain 5% of their fruit and vegetables from their gardens, 5% from local sources, 35% from within their region, and 55% from outside the affected area. As previously stated, this approach is used to try and give a more realistic representation of the geographical origins of sub-populations' diets. With the exception of the RESTORE system (Voigt and Semioschkina, 1999) which gives limited consideration to the origins of food products, all other decision support systems assume that all consumed food products are produced locally. This approach may be reasonable when assessing the dose to critical groups, as they are likely to be individuals who source a large proportion of their diet locally. However, when attempting to develop sustainable restoration strategies that will be publicly acceptable, it is imperative that the modelling of human behaviour is as accurate as possible to ensure that the scale of any restoration strategy is appropriate to the level of collective and individual dose, in accordance with the ALARA principle. The assumption that all individuals source their diet from their immediate locality may result in considerable over-estimations of individual doses, and consequently the level of collective dose. As a result of these over-estimations, decision makers may select restoration strategies which are unduly drastic, resulting in wasted time and resources, and unnecessary damage to the environment.

2. Activity habits

These attributes describe the proportion of time that each sub-population spends at the various locations considered within the external dose model. For each sub-population, the type of building occupied in the urban environment (i.e. where people live) and the industrial environment (i.e. where people work), the proportion of time spent at each and the residency times for various locations in and around each of the buildings are defined. All individuals are assumed to live in one of three types of urban building, and (within the same cell) work in one of two types of industrial building.

3. Social preferences

In an attempt to use a more holistic approach to the decision making process, a limited number of social preferences are considered, which relate to the side-effects of countermeasure implementation. By including these preferences in the optimisation process, restoration strategies will be generated which will be more acceptable to the general public than strategies generated from a simple cost-benefit analysis. The social preferences are described in terms of the monetary values that individuals are willing to pay to safeguard selected environmental and social attributes. It is assumed that, as this system is concerned with *long-term* restoration strategies, there would be ample time following a nuclear accident to determine these values using standard techniques (for a review of possible methods see Álvarez and Gil (2002)).

The environmental and social attributes currently considered are:

i. Landscape/biodiversity. This attribute refers to the aesthetic quality of the environment and the diversity of biota present within it.

ii. Animal welfare. Referring to the normal treatment of livestock animals.

iii. Heritage. This attribute refers to the maintenance of culturally important customs and buildings.

iv. Water quality for recreation. Refers to the use of lakes and rivers for leisure activities.

v. Normal daily life. Refers to the continuation of normal daily activities (e.g. travelling to work).

This list is far from comprehensive, however, the intention here is merely to demonstrate that this approach is a viable means of computationally introducing a social element into the decision making process. This is discussed in more detail in Chapter 4.

4. Compliance

The compliance attribute has been included to account for individuals who do not heed advice given to them. In particular, this relates to the dietary advice countermeasure described in Chapter 3.

A major assumption within the modelling of human populations is that all attributes are temporally constant. However, in reality, diets, activities and social preferences are likely to change over time. These changes may be simple seasonal variations (e.g. individuals may have a higher consumption of leafy vegetables during summer months than winter months), but may also be changes in a population's behaviour either as part of natural, long-term trends or in response to fears about contaminated food products or high risk activities (Grande et al., 1999). Seasonal effects are not considered here as predictions after the first year post-deposition are based upon mean annual activity concentrations and consumption rates. Changes due to long-term trends, or in reaction to the radiological situation, are also not considered due to the complexities involved in their prediction.

2.2.4.1 *Monte-Carlo population generation*

Within a contaminated area the user may wish to simulate many different sub-populations. To manually define all of the attributes for every required sub-population would be a tedious task. Therefore, within this system, a facility has been included which automatically generates sub-populations by Monte-Carlo sampling of the defined statistical attributes of the whole population.

For each attribute, a probability function is defined by the mean value for the whole population, the standard deviation and (where appropriate) the percentage of individuals to whom the function does not apply (e.g. some individuals may not eat certain food products). For each of the desired number of sub-populations, the system selects a value for each attribute according to its probability distribution. All probability functions are assumed to be normally distributed, although this could be modified if required. In addition, all attributes are assumed to be independent, although, in reality, there are often correlations between attributes. For example, an individual who has a relatively high intake of root vegetables may have a higher than average intake of fruit or leafy vegetables (MAFF, 1994). However, these relationships have not been considered here due insufficient data to describe them.

Due to the nature of Monte-Carlo sampling, it is possible that, if the number of sub-populations to be defined is not sufficient, certain atypical behavioural characteristics may not be represented by any sub-population. However, atypical behaviour is likely to be a characteristic of critical groups, who must be considered if restoration strategies are to protect the most vulnerable individuals from exposure to radiation. Therefore, to ensure that critical groups, or other desired minority groups, are represented in the model, these can be defined manually and included with the Monte-Carlo generated populations if desired.

2.2.4.2 *Individual ingestion doses*

The annual effective ingestion dose received by an individual of a sub-population within a cell, $D_{Ing,a}$ (Sv), is estimated as:

$$D_{Ing,a} = E\sum_{i,l} F_{i,l}\, pf_i C_i P_{i,l}$$

where E (Sv Bq^{-1}) is the effective dose coefficient for ingestion, $F_{i,l}$ (Bq kg^{-1}) is the annual average activity concentration of food product i from location l, pf_i is the processing factor for food product i, C_i (kg y^{-1}) is the annual consumption rate of food product i and $P_{i,l}$ is the fraction of food product i that an individual sources from location l. The total effective ingestion dose received by an individual of a sub-population within a cell, $D_{Ing,tot}$ (Sv), can then be calculated as:

$$D_{Ing,tot} = \sum_{a=1}^{a=n} D_{Ing,a}$$

where n is equal to the number of years simulated.

2.2.4.2 *Individual external doses*

The approach taken here, focussing solely on the gamma emitter ^{137}Cs, is that developed by Meckbach, Jacob and Paretzke (1988) and Kis et al. (2003). These models estimate the air kerma rates (Gy m^{-2}) at various locations within standard building types (described previously) from a range of surfaces (i.e. roofs, walls, windows, lawns, trees and pavements). The effective source strengths, S_{Sur} (γ mm^{-2} s^{-1}), of the various surfaces are estimated as:

$$S_{sur}(t) = D\ y\ s_{sur} e^{-\lambda_r t}\left(ae^{-bt} + (1-a)e^{-ct}\right)$$

where D (Bq mm^{-2}) is the initial deposition, y (γ s^{-1} Bq^{-1}) is the yield of photons per decay, s_{sur} is the fraction of the initial deposition retained by a surface, a is the mobile fraction of the deposit and b and c are weathering rate constants. The kerma rate, K (Gy s^{-1}), at each location, l, can then be estimated as:

$$K_l(t) = \sum_{sur} S_{sur}(t)\ k_{sur,l}$$

where $k_{sur,l}$ (Gy γ^{-1} mm^2) is the air kerma per photon per unit area deposition at location l from surface *sur*. The predictions from the external dose model, regarding the kerma rates of the various surfaces in the urban environment, are then combined with the activity profiles of each sub-population to estimate the annual effective dose received by an individual from external sources, $D_{Ext,a}$ (Sv), where:

$$D_{Ext,a} = c\sum_{l} R_l \int K_l(t)dt$$

where c (Sv Gy^{-1}) is a conversion factor and R_l is the proportion of an individual's time that is spent at location l. Cells in which the external dose rate of the 97th percentile sub-population exceed a defined maximum threshold are assumed to have been evacuated, resulting in the appropriate loss of production of food products within the cell for the duration of the evacuation period.

The total effective dose received by an individual from external sources is:

$$D_{Ext,tot} = \sum_{a=1}^{a=n} D_{Ext,a}$$

2.2.4.3 *Collective doses*

The collective effective dose received by a sub-population within a cell, CD_{sub} (man Sv), is estimated as:

$$CD_{sub} = (D_{Ing,tot} + D_{Ext,tot})\frac{N}{N_{sub}}$$

where N is the total number of residents within the cell and N_{sub} is the number of defined sub-populations. The "local collective dose" (i.e. the dose received by the entire population resident within the study area), LCD (man Sv), can then be calculated as:

$$LCD = \sum_{i,N_{sub}} CD_{sub}$$

where i is the number of cells.

The collective ingestion dose received by individuals living outside the contaminated region as a result of exported food products, *ECD* (man-Sv), is estimated as:

$$ECD = TD - LCD_{Ing}$$

where LCD_{Ing} (man Sv), is the local collective ingestion dose from marketed food products and *TD* (man Sv) is the total ingestion dose from the marketed food products produced within a region, calculated as:

$$TD = \sum_{f,t} A_{f,t} P_{f,t}$$

Where $A_{f,y}$ (Bq kg^{-1}) is the production weighted mean activity concentration of food product *f* at time-step *t*, and $P_{f,t}$ (kg a^{-1}) is the quantity of food product *f* produced within time-step *t*.

It is assumed that all of the exported dose is consumed before any appreciable reduction in activity concentrations due to radioactive decay.

2.3 SUMMARY

The SAVE system, developed by Gillett et al. (2001), has been extended to predict the transfer of ^{90}Sr, ^{239}Pu and ^{241}Am through the human food-chain, using the root uptake model of the ECOSYS-87 system (Müller and Pröhl, 1993), and the doses resulting from external exposure to ^{137}Cs, using the models of Meckbach, Jacob and

Paretzke (1988) and Kis et al. (2003). In addition, a novel method for the generation and simulation of human populations has been developed, which considers the geographical origins of food products, and the social preferences of individuals affected by countermeasures' side-effects.

CHAPTER 3: THE SIMULATION OF COUNTERMEASURES

3.1 INTRODUCTION

The Chernobyl accident, in 1986, led to the contamination of large areas of land within countries of the former Soviet Union (FSU) and Western Europe. Following this contamination, numerous radiological countermeasures were applied in attempts to reduce the resulting doses received by exposed populations. The countermeasures implemented ranged from mechanical and chemical treatment of contaminated agricultural soils, to alternative crop and livestock management programmes and dietary advice for the affected human population (Vovk et al., 1993; Alexakhin, 1993; Beresford et al., 2001; Roed and Andersson, 1996). Some of these countermeasures were known prior to the accident, while others were developed or improved upon due to the renewed interest in the mechanisms of radionuclide transport through the environment. As a result of these investigations, knowledge regarding the effectiveness of countermeasures has increased greatly since the Chernobyl accident, culminating in the development of several countermeasure databases which aim to provide decision makers with information to assist the selection of appropriate interventions following a nuclear accident (STRATEGY 2004; BMU, 2000; NKS, 2000; IAEA, 1994). Furthermore, this increased knowledge has facilitated the simulation of countermeasures within radio-ecological models, allowing the prospect of computationally identifying the most appropriate set of countermeasures for a given scenario. Several decision support systems (DSS) have been developed with this objective (e.g. RODOS, RESTORE), however, as mentioned previously, these systems have generally only considered a limited number of short-term countermeasures and the direct effects and costs of countermeasure implementation. Recently, more emphasis has been placed upon evaluating the side-effects and indirect costs of countermeasure implementation, so that the social aspects of countermeasure implementation can be considered when designing countermeasure strategies, in accordance with the recommendations of the ICRP (1990). During the development of the CESER DSS (Salt and Dunsmore, 2000), the potential environmental side-effects of various countermeasures were assessed using a mixture of mathematical modelling, laboratory experiments and expert judgement (Salt et al., 1999). The DSS can then be used to predict the magnitude and spatial variation of these environmental impacts due to the implementation of the countermeasures within a specific area. However, to date, the most comprehensive critical review of countermeasures has been carried out as part of the STRATEGY project (STRATEGY, 2004). The effectiveness, feasibilities, costs, associated wastes, and social and environmental impacts of 101 agricultural, urban and social countermeasures were assessed and compiled, with particular emphasis placed upon countermeasures' side-effects, and in addition some consideration given to ethical issues which may arise as a result of countermeasure strategies. The information in this compendium has been used in the work presented here to guide the incorporation of a selected number of countermeasures within the radio-ecological models described in Chapter 2.

This chapter describes how the selected countermeasures are simulated within the radio-ecological models, and how the extent of a countermeasure's implementation is controlled using model variables and other defined system parameters.

3.2. COUNTERMEASURE SIMULATION

All of the countermeasures assessed by the STRATEGY project (STRATEGY, 2004) were considered for inclusion within the system described here; however, to ensure the modelling task was manageable within the constraints of this project, the number of countermeasures included was restricted to those considered most likely to be implemented (Nisbet et al., 2001, personal communication).

The countermeasures considered by the system described here are:

1. Normal (shallow) ploughing to a depth of 25cm.
2. Deep ploughing to a depth of 50cm.
3. Skim and burial ploughing to a depth of 50cm.
4. Addition of potassium fertiliser to agricultural soils.
5. Addition of lime to agricultural soils.
6. Administration of ammonium ferric hexa-cyano ferrate (AFCF) to livestock animals.
7. Clean feeding of livestock animals.
8. Food restrictions.
9. Roof washing of urban and industrial buildings.
10. Wall washing of urban and industrial buildings.
11. Street sweeping and vacuuming of pavements.
12. Tree pruning in the urban and industrial environments.
13. Urban snow removal.
14. Urban lawn mowing.
15. Urban topsoil removal by ‘Bobcat’.

16. Triple digging of urban gardens.
17. Industrial air-filter removal.
18. Dietary advice.

Countermeasure simulation is performed on a cell by cell basis. The spatial extents of countermeasures' implementations can then be displayed using raster maps, and the estimated implementation and social costs, together with the amount of associated wastes generated, are summarised in an output text-file.

Before simulating the implementation of a countermeasure within a cell the system assesses whether various conditions have been met:

i. The countermeasure must have been selected as available for implementation. All of the considered countermeasures may be selected as available for implementation.
ii. The countermeasure must be permitted within the cell. In some cells the implementation of a countermeasure may not be permitted, either due to feasibility or regulatory constraints (e.g. it is assumed that it would not be possible to plough in cells where the average slope is greater than 16°, and the addition of potassium fertilisers to unimproved pasture is not allowed in cells designated as environmentally sensitive areas (ESA)). In addition, some countermeasures are mutually exclusive, and cannot therefore be implemented at the same time within the same cell (e.g. normal and deep ploughing).
iii. The value of the appropriate "trigger-variable" within the cell must be greater than the defined "implementation threshold" for the countermeasure. The definitions of these terms are discussed below.

3.2.1 Trigger-variables

A trigger-variable is an attribute whose value in each cell is predicted by the radio-ecological models described in Chapter 2, and which is affected by a countermeasure's implementation. For example, the trigger-variable for the normal ploughing of pasture countermeasure is the activity concentration of pasture grass. An attribute may be the trigger-variable for multiple countermeasures, as different countermeasures may target the same environmental pathway (e.g. the activity concentration of milk is the trigger-variable for both the clean-feeding of dairy cows countermeasure and the administration of AFCF to dairy cows countermeasure). In addition, some countermeasures may have more than one trigger-variable associated with them (examples are given in the next section).

3.2.2 Implementation thresholds

A countermeasure's implementation threshold is the defined reference level to which the value of the appropriate trigger-variable in each cell is compared, to determine whether the countermeasure should be simulated within the cell. If the predicted value of the trigger-variable in a cell exceeds the implementation threshold for a selected countermeasure, then that countermeasure is simulated within the cell (provided that it is not subject to one of the restrictions mentioned previously). Implementation thresholds may be user-defined or selected automatically by the system. Increasing the value of an implementation threshold reduces the number of cells in which a countermeasure is implemented, as fewer cells will have predicted values of the trigger-variable greater than the implementation threshold, and *vice versa*.

During the optimisation procedure (described in Chapter 4) countermeasures' implementation thresholds are varied to produce alternative strategies for assessment. This is a computationally intensive process, and the time taken to complete the task is largely dependent upon the number of thresholds to be optimised. In principle, some countermeasures could be applied separately to different components within the model. For example, deep ploughing could be applied independently to each of the ten crops considered within a cell. This would, in computational terms, mean that there were ten separate deep ploughing countermeasures, each of which would require an implementation threshold. However, this would result in a total of 40 implementation thresholds being required for the deep ploughing, skim and burial ploughing, addition of potassium fertiliser and addition of lime countermeasures alone. If the user wished to select all countermeasures for optimisation, the process would be severely hindered by this many adjustable parameters. Therefore, to reduce the computational burden during optimisation, and to ensure that the optimisation process is as user-friendly and interactive as possible, the number of implementation thresholds has been rationalised.

For agricultural countermeasures which could be applied to more than one crop (i.e. deep ploughing, skim and burial ploughing, addition of potassium fertiliser and addition of lime), three implementation thresholds are defined which apply to different crop types: pasture, edible crops (cereals, potatoes, leafy vegetables, root vegetables and fruit) and silage crops (cereals for silage, maize and grass for silage) respectively. The activity concentration of each of the crops acts as a trigger-variable for the entire group. For example, if the activity concentration of potatoes is above the implementation threshold for a countermeasure applied to edible crops then that countermeasure will be applied to all crops within the group.

A similar rationalisation has been performed for the urban and industrial countermeasures. In principle, urban or industrial countermeasures could also be applied independently to each of the buildings considered within the model. For example, roof washing could be applied separately to terraced houses, semi-detached houses and flats. However, urban and industrial countermeasures have been ascribed only one implementation threshold which is compared to the trigger-variables from each of the building types considered. Therefore, if the predicted kerma rate from a surface (which acts as a trigger-variable) of any one of the buildings is above the defined threshold, the countermeasure is applied to all building types within that environment.

These rationalisations may not be unreasonable as, in practice, it may be publicly unacceptable to decontaminate one type of house within an area while leaving others contaminated, or to treat one type of crop but not another similar one in the same location.

3.2.3 Accounting for different radionuclides

For any countermeasure which affects more than one radionuclide (e.g. normal ploughing), the implementation threshold may be scaled for each radionuclide, according to defined weightings. For example, if the implementation threshold for the food restrictions countermeasure was defined as 1000 Bq kg^{-1}, and the weightings for ^{137}Cs, ^{90}Sr, ^{239}Pu and ^{241}Am as 1, 0.2, 0.05 and 0.08 respectively. Restrictions would be applied within a cell to a food product whose ^{137}Cs, ^{90}Sr, ^{239}Pu or ^{241}Am activity concentrations were predicted to be above 1000, 200, 50 or 80 Bq kg^{-1} respectively.

Alternatively, the *combined* activity concentration of the four radionuclides may be considered. In this case the 1000 Bq kg^{-1} implementation threshold from the previous example would refer to the total activity concentration in a food product, considering all radionuclides. The value of the trigger-variable for this countermeasure would then be the sum of the weighted activity concentrations for each of the four radionuclides. For example, the value of the trigger-variable, *TV* (Bq kg^{-1}), for a food product with predicted activity concentrations of ^{137}Cs, ^{90}Sr, ^{239}Pu and ^{241}Am of 900, 900, 10 and 20 would be:

$$TV = 900 \times 1 + 900 \times 0.2 + 10 \times 0.05 + 20 \times 0.08 = 1082.1$$

This food product would be restricted, therefore, as its combined activity concentration exceeds the defined implementation threshold.

3.3 DESCRIPTIONS OF COUNTERMEASURE SIMULATIONS

Given below are brief descriptions of the countermeasures considered within this system. Only information pertinent to the simulation of countermeasures within the system is given here; for a full description of each countermeasure, see the countermeasure datasheets developed as part of the STRATEGY project (STRATEGY, 2004).

3.3.1 Normal ploughing

As highlighted in the previous chapter, the ploughing of agricultural land can reduce the uptake of radionuclides by the plants cultivated upon it by redistributing the radionuclides within the soil column (Maubert et al., 1993). However, this procedure is assumed to be routinely applied to the edible and silage crops considered within this system, and is, therefore, not considered as an intervention or countermeasure for these crops. Consequently, as an existing practice, the implementation costs and side-effects of normal ploughing are not considered when applied to these crop types. However, pasture grass is not assumed to be ploughed routinely, and therefore normal ploughing can be considered as a countermeasure when applied to pasture land.

Applies to: pasture grass.

Radionuclides affected: ^{137}Cs, ^{90}Sr, ^{239}Pu and ^{241}Am.

Trigger-variables: the activity concentration of pasture grass.

Mutually exclusive countermeasures: deep ploughing and skim and burial ploughing.

Restrictions: cannot be performed in cells where the average slope is greater than 16° or the soil depth is less than 30cm. By default, normal ploughing is not allowed in cells designated as ESAs, however, this restriction can be overridden if desired.

Simulation: the activity concentration within the plant-rooting zone of soil is reduced by the specified reduction factor for all time-steps after the initial implementation. It is assumed that the land is immediately reseeded and is consequently not available for grazing by animals for four months, during which time alternative feed and housing is required for affected livestock.

Implementation costs: service costs of ploughing plus the cost of replacement feed and housing for grazing animals.

Side-effects: loss of scenic landscape and biodiversity with an increase in water pollution.

3.3.2 Deep ploughing

Although the crops considered within this system are routinely ploughed, this is usually only to a depth of approximately 25cm. Therefore, deep ploughing to a depth of 45cm is considered as an intervention rather than an existing practice.

Applies to: pasture grass, edible crops or silage crops independently.

Radionuclides affected: ^{137}Cs, ^{90}Sr, ^{239}Pu and ^{241}Am.

Trigger-variables: the activity concentrations of pasture grass, edible crops or silage crops respectively.

Mutually exclusive countermeasures: normal ploughing and skim and burial ploughing.

Restrictions: cannot be performed where the average slope is greater than 16° or the soil depth is less than 50cm. By default, deep ploughing is not allowed on pasture in cells designated as ESAs, however, this restriction can be overridden if desired.

Simulation: the activity concentration within the plant-rooting zone of soil is reduced by the specified reduction factor for all time-steps after the initial implementation. If performed on pasture land it is assumed that the land is immediately reseeded and is consequently not available for grazing by animals for four months, during which time alternative feed and housing is required for affected livestock.

Implementation costs: service costs of ploughing (plus the cost of replacement feed and housing for grazing animals if pasture is ploughed).

Side-effects: loss of scenic landscape and biodiversity with an increase in water pollution.

3.3.3 Skim and burial ploughing

A skim and burial plough removes the top few centimetres of the soil horizon, which is generally the most contaminated layer following a deposition of radionuclides, and buries it at a depth of approximately 45cm without inverting the previously underlying soil column (Roed, Andersson and Prip, 1996). This reduces the availability of the contamination for uptake by plants and direct exposure to radiation by humans, without affecting the soil quality significantly.

Although currently there are only a few skim and burial ploughs in existence (located in Denmark) this countermeasure has been included to allow the investigation of its applicability in comparison with the more established methods of normal and deep ploughing. Furthermore, in the event of a nuclear accident it may be possible for these ploughs to be manufactured specifically for proposed remediation strategies.

Applies to: pasture grass, edible crops or silage crops independently.

Radionuclides affected: ^{137}Cs, ^{90}Sr, ^{239}Pu and ^{241}Am.

Trigger-variables: the activity concentrations of pasture grass, edible crops or silage crops respectively.

Mutual exclusive countermeasures: normal ploughing and deep ploughing.

Restrictions: cannot be performed where the average slope is greater than 16° or the soil depth is less than 50cm. By default, skim and burial ploughing is not allowed in

cells designated as ESAs, however, this restriction can be overridden if desired.
Simulation: the activity concentration within the plant-rooting zone of soil is reduced by the specified reduction factor for all time-steps after the initial implementation. If performed on pasture land it is assumed that the land is immediately reseeded and is consequently not available for grazing by animals for four months, during which time alternative feed and housing is required for affected livestock.

Implementation costs: service costs of ploughing (plus the cost of replacement feed and housing for grazing animals if pasture is ploughed).

Side-effects: loss of scenic landscape and biodiversity with an increase in water pollution.

3.3.4 Addition of potassium fertiliser to soil.

The addition of potassium fertiliser to soil reduces the uptake of radiocaesium by plants grown in the soil as potassium ions compete with caesium ions for absorption by plant roots (Nisbet et al., 1993; Smolders, van den Brande and Merckx, 1997). However, the effectiveness of this countermeasure depends upon the original potassium status of the soil: being more effective on soil with low levels of exchangeable potassium than on soils with high levels of exchangeable potassium.

Applies to: pasture grass, edible crops or silage crops independently.

Radionuclides affected: ^{137}Cs.

Trigger-variables: the activity concentrations of pasture grass, edible crops or silage crops respectively.

Mutually exclusive countermeasures: none.

Restrictions: cannot be performed in cells where the average slope is greater than 16°, and is not permitted on pasture land in cells designated as ESAs or on any agricultural land in cells designated as organic farmland. Can be permitted within ESAs if desired.

Simulation: the amount of potassium fertiliser required to bring the exchangeable K^+ concentration in the soil solution to the level above which there is assumed to be no reduction in plant-uptake, as defined by Absalom et al. (1999), is assumed to be applied on a regionally defined date. The exchangeable K^+ concentration in the soil is then assumed to decrease linearly throughout the year, returning to its original value after twelve months.

Implementation costs: cost of potassium fertiliser and service costs of spreading.

Side-effects: loss of scenic landscape and biodiversity with an increase in water pollution.

3.3.5 Addition of lime fertiliser to soil.

Increasing the pH of soil, by the addition of lime, shifts the sorption equilibrium of radionuclides towards the solid phase, thus reducing their availability for uptake by plants (Konoplev et al., 1993). Although this is true for most radionuclides, the effect is only considered for radiocaesium here as the models used to predict the plant uptake of the other radionuclides do not use soil characteristics as input parameters.

Applies to: pasture grass, edible crops or silage crops independently.

Radionuclides affected: ^{137}Cs.

Trigger-variables: the activity concentrations of pasture grass, edible crops or silage crops respectively.

Mutually exclusive countermeasures: none.

Restrictions: cannot be performed in cells where the average slope is greater than 16°, and is not permitted on pasture land in cells designated as an ESA or on any agricultural land in cells designated as organic farmland.

Simulation: the pH of the soil is adjusted to a regionally defined value, on a regionally defined date, and is then assumed to decrease linearly throughout the year, returning to its original value after twelve months.

Implementation costs: cost of lime fertiliser and service costs of spreading.

Side-effects: loss of scenic landscape and biodiversity with an increase in water pollution.

3.3.6 Clean-feeding of livestock animals

Replacing contaminated feedstuffs with uncontaminated, or less contaminated, feeds reduces an animal's intake of radionuclides and consequently the activity concentrations of the food products derived from them. Grazing animals may be kept in existing buildings to prevent them consuming contaminated pasture. Animals used to produce meat food products may be given clean feed, or less contaminated feed, for some time before slaughter to ensure that the activity concentration of the final food product is at an acceptable level. Dairy animals may need to be clean-fed continually during lactation to ensure that milk products remain below the relevant limits.

Applies to: dairy cows, beef cattle, sheep, goats, chickens and pigs.

Radionuclides affected: ^{137}Cs, ^{90}Sr, ^{239}Pu and ^{241}Am.

Trigger-variables: the activity concentrations of dairy cows, beef cattle, sheep, goats, chickens and pigs respectively.

Mutually exclusive countermeasures: none.

Restrictions: none.

Simulation: the cheapest method for reducing the animal's activity concentration to below the implementation threshold is calculated, according to the cost of the feedstuffs and the animals' daily mean intakes. For dairy cows, the percentage of each feed type that should be uncontaminated is calculated for each time-step. For other animals, the duration of clean-feeding required to reduce the animal below the implementation threshold at time of slaughter is calculated for each feed type. For example, to reduce a beef cow's activity concentration to below the implementation limit may require the clean feeding of silage for two months prior to slaughter, while the other feeds can be continued as normal.

Implementation costs: If the feed replaced is pasture, then the costs considered are the costs of replacing the feed, housing the animals and grassland management. For the other feeds only the cost of replacement feed is considered.

Side-effects: Animal welfare due to the housing of grazing animals, and loss of scenic landscape due to the absence of livestock.

3.3.7 Administration of AFCF to livestock animals

AFCF is a chemical which binds to radiocaesium in the guts of ruminants. The resulting complex is not absorbed and passes out in excreta, thus reducing the animal's intake of radiocaesium (Giese, 1988). This may be administered as boli or in salt licks for free-grazing or infrequently handled animals, or incorporated into concentrates, especially for dairy animals (Hove, 1993). Reductions of up to between 70-80% have been observed for milk and meat products respectively (Giese, 1989).

Applies to: dairy cows, beef cattle, sheep, goats, chickens and pigs.

Radionuclides affected: ^{137}Cs.

Trigger-variables: the activity concentrations of dairy cows, beef cattle, sheep, goats, chickens and pigs respectively.

Mutually exclusive countermeasures: none.

Restrictions: not permitted in cells designated as organic farms.

Simulation: dairy cows may be administered with AFCF concentrates continually, while other animals are assumed to have been treated with boli prior to slaughter. It is assumed that the treatment is effective immediately.

Implementation costs: if administered as concentrates then only the cost of the concentrates is considered. For boli, the cost of the boli and administration are considered.

Side-effects: Animal welfare, damage to heritage.

3.3.8 Food restrictions

Food products which exceed statutory limits, such as Council Food Intervention Levels (CFILs) as specified by the Council of European Communities (1989), may be prevented from entering the food chain by the relevant authorities. This is an extremely effective countermeasure as it completely removes contamination from the food-chain; however, it may lead to the production of large amounts of contaminated waste.

Applies to: all food products produced for commercial markets.

Radionuclides affected: ^{137}Cs, ^{90}Sr, ^{239}Pu and ^{241}Am.

Trigger-variables: the activity concentrations food products produced for commercial markets.

Mutually exclusive countermeasures: none.

Restrictions: none.

Simulation: any food product exceeding the defined implementation threshold is deemed unavailable for consumption. The method of disposal for milk and milk-derived products is assumed to be land-spreading. On-farm burial is assumed as the waste disposal method for meat food products, and for food products derived form intensively produced crops, it is assumed that the crop is ploughed back into the soil if the deposition event occurred between the sow date and the harvest date, and the food product is from the first harvest post-deposition. However, if the deposition event took place before the sow date, or the current date is past the first harvest post-deposition, then it is assumed that the crop would not be grown and consequently no waste is generated.

Implementation costs: market cost of food product plus costs of disposal (if applicable).

Side-effects: loss of scenic landscape due to absence and burial of livestock or absence of crops; increase in water pollution due to leaching of waste milk and animal waste into water courses; damage to heritage due to loss of rare breeds; and disruption to daily life due to the absence of common food products.

3.3.9 Roof hosing (Urban and Industrial)

High pressure (15,000 kPa) hosing, using hot water (approximately 65°C), can be an effective method for reducing the contamination of roofs following the deposition of radionuclides (Roed and Andersson, 1996). The resulting waste, which can be collected via guttering, can be filtered to remove contaminated solids and the residual water fraction disposed of.

Applies to: urban or industrial buildings.

Radionuclides affected: ^{137}Cs.

Trigger-variables: the kerma rate due to roofs on semi-detached houses, terraced houses or flats for roof-hosing in the urban environment, and the kerma rate due to roofs on supermarkets or offices for roof-hosing in the industrial environment.

Mutually exclusive countermeasures: none.

Restrictions: none.

Simulation: the kerma rate of treated roofs is reduced according to the specified reduction factor, for all time-steps after the initial treatment.

Implementation costs: service cost including waste disposal.

Side-effects: Damage to heritage due to damage to historical buildings, disruption to daily life while the operation is performed.

3.3.10 Wall washing (Urban and Industrial)

This countermeasure involves the same procedure as for roof hosing, however, as any waste generated is extremely difficult to collect (Andersson and Roed, 1999), it is assumed that no costs are incurred for waste disposal.

Applies to: urban or industrial buildings.

Radionuclides affected: ^{137}Cs.

Trigger-variables: the kerma rate due to walls on semi-detached houses, terraced houses or flats for wall-washing in the urban environment, and the kerma rate due to walls on supermarkets or offices for wall-washing in the industrial environment.

Mutually exclusive countermeasures: none.

Restrictions: none.

Simulation: the kerma rate from treated walls is reduced according to the specified reduction factor for all time-steps after the initial treatment.

Implementation costs: service cost.

Side-effects: as for roof hosing.

3.3.11 Urban topsoil removal by machine

Radiocaesium deposited on urban soils may remain in the top few centimetres of soil for many years. Removal of this soil layer by "bobcats", road scrapers or bulldozers, can reduce the radioactivity present by between 80-100% (Vovk et al., 1993). This countermeasure cannot be applied in the industrial environment, as it is assumed that grassland does not constitute a significant proportion of the land coverage in this environment.

Applies to: urban grassland.

Radionuclides affected: ^{137}Cs.

Trigger-variables: the kerma rate due to grassed areas around semi-detached houses, terraced houses or flats.

Mutually exclusive countermeasures: urban lawn mowing and urban triple digging.

Restrictions: none.

Simulation: the kerma rates from treated grassed areas are reduced according to the specified reduction factor for all time-steps after the initial treatment.

Implementation costs: service cost including waste disposal.

Side-effects: Loss of scenic landscape due to the absence of grass in urban areas; damage to heritage, disruption to daily life while the procedure is performed and due to the subsequent absence of grassed areas.

3.3.12 Urban triple-digging

Triple-digging involves exchanging three layers of the soil profile using a shovel, where the top layer of soil, which is generally the most contaminated, is buried underneath the two previously lower layers (Roed et al., 1999). The technique does not generate any waste, and could be performed by the local population. However, it has been assumed here that the procedure would be performed by contractors and therefore labour costs are incurred.

Applies to: urban grassland.

Radionuclides affected: ^{137}Cs.

Trigger-variables: the kerma rate due to grassed areas around semi-detached houses, terraced houses or flats.

Mutually exclusive countermeasures: urban lawn mowing and urban topsoil removal by machine.

Restrictions: none.

Simulation: the kerma rates from treated grassed areas are reduced according to the specified reduction factor for all time-steps after the initial treatment.

Implementation costs: service cost.

Side-effects: Loss of scenic landscape due to the absence of grass in urban areas; damage to heritage, disruption to daily life while the procedure is performed and due to the subsequent absence of grassed areas.

3.3.13 Urban lawn mowing

Following the dry deposition of radionuclides, significant amounts of radiation may be deposited on grass vegetation in urban areas. Lawn mowing and removal of the resultant waste grass may reduce the dose rate arising from exposure to contaminated soil by between 55 and 69% (Andersson and Roed, 1999). However, to be effective, this procedure should be performed soon after deposition, and before any significant rainfall events, as the transfer process from grass to soil has a half-life ranging from 7 days during wet weather, to 15 days during dry weather. As with triple digging, in principle, this procedure could be performed by the local population, however, here it is assumed to be carried out by contractors.

Applies to: urban grassland.

Radionuclides affected: ^{137}Cs.

Trigger-variables: the kerma rate due to grassed areas around semi-detached houses, terraced houses or flats.

Mutually exclusive countermeasures: urban triple digging and urban topsoil removal by machine.

Restrictions: cannot be performed if snow is present at time of deposition.

Simulation: the kerma rates from treated grassed areas are reduced according to the specified reduction factor for all time-steps after the initial treatment.

Implementation costs: service cost including waste disposal.

Side-effects: disruption to daily life while the procedure is performed.

3.3.14 Street sweeping (urban and industrial)

Vacuum sweepers are used routinely by municipal authorities as part of their street cleaning programmes. These machines can be used to remove radioactive particles from paved areas in the urban and industrial environments; with resultant reductions in contamination of between 50-70% if performed promptly after deposition (Andersson and Roed, 1999).

Applies to: urban and industrial paved areas.

Radionuclides affected: ^{137}Cs.

Trigger-variables: the kerma rate due to paved areas around semi-detached houses, terraced houses or flats for urban street-sweeping, and the kerma rate due to paved areas around factories and offices in the industrial environment.

Mutually exclusive countermeasures: none.

Restrictions: none.

Simulation: the kerma rates from treated paved areas are reduced according to the specified reduction factor for all time-steps after the initial treatment.

Implementation costs: service cost including waste disposal.

Side-effects: none.

3.3.15 Urban snow removal

If the deposition of radionuclides occurs while snow is covering the ground, the dose rate in urban areas over 70 years can be reduced by up to 90% by removal of the top layer of snow before the first thaw using bobcats, tractors or bulldozers (Andersson and Roed, 1999).

Applies to: urban grassland.

Radionuclides affected: ^{137}Cs.

Trigger-variables: the kerma rate due to grass areas around semi-detached houses, terraced houses or flats.

Mutually exclusive countermeasures: none.

Restrictions: can only be performed if snow is present at time of deposition.

Simulation: the kerma rates from treated paved areas are reduced according to the specified reduction factor for all time-steps after the initial treatment.

Implementation costs: service cost including waste disposal.

Side-effects: none.

3.3.16 Pruning or removal of trees and shrubs (urban and industrial)

Trees and shrubs that are in leaf may be particularly efficient at intercepting radionuclides during a dry deposition event (Guillette and Willdrodt, 1993), and consequently may make a significant contribution to external doses received in urban environments, particularly when cited close to residential buildings. Removal of contaminated foliage can reduce the doses received from trees over 70 years by up to 10% (Andersson and Roed, 1999).

Applies to: trees in the urban and industrial environments.

Radionuclides affected: ^{137}Cs.

Trigger-variables: the kerma rate due to trees areas around semi-detached houses, terraced houses or flats for urban tree pruning, and the kerma rate due to trees around factories and offices in the industrial environment.

Mutually exclusive countermeasures: none.

Restrictions: none.

Simulation: the kerma rates from treated trees and shrubs are reduced according to the specified reduction factor for all time-steps after the initial treatment.

Implementation costs: service cost including waste disposal.

Side-effects: Loss of biodiversity, loss of scenic landscape, damage to heritage, disruption to daily life.

3.3.17 Industrial air-filter removal

The filters of air-conditioning units fitted to industrial buildings may become highly contaminated with radionuclides during, and following, dry deposition, as the units actively draw in contaminated particles. Removal of these filters can therefore eliminate the resultant doses to exposed individuals if removed promptly (BMU, 2000).

Applies to: industrial air-filters.

Radionuclides affected: ^{137}Cs.

Trigger-variables: the kerma rate due to air-filters in factories/supermarkets.

Mutually exclusive countermeasures: none.

Restrictions: none.

Simulation: the kerma rates from filters are reduced according to the specified reduction factor for all time-steps after the initial treatment.

Implementation costs: service cost per filter.

Side-effects: none.

3.3.18 Dietary advice

Home-grown and semi-natural food products are not subject to the regulations imposed on food products which are produced for commercial markets. It is possible, therefore, that some individuals may consume home-grown or semi-natural food products whose activity concentrations are above statutory limits. Furthermore, in some cases (e.g. soft fruit and eggs), for a given level of deposition, home-grown products may have significantly higher activity concentrations than their counterparts produced for commercial markets (Prosser et al., 1999). However, agricultural countermeasures which are implemented by the relevant authorities are not applied to food products grown in individuals' gardens or allotments, or in semi-natural environments. Therefore, the only route available for the authorities to reduce the population's intake of radionuclides via home-grown or semi-natural food products is to provide them with information and advice. This can be distributed in the form of leaflets, radio and television broadcasts, or via public meetings. Advice can range from suggestions that the consumption of certain food products should be reduced or discontinued to practical advice regarding methods for actively reducing the contamination of home-grown or semi-natural food products (Beresford et al., 2001). In addition to the benefit of dose reduction, empowering the population with information about methods for reducing their dose may have beneficial psychological effects (Lepicard and Dubreuil, 2001; Tonnessen et al., 1996). However, the effectiveness of this countermeasure, in terms of dose reduction, is dependent not only upon the nature of the advice given but also on the compliance and competence of the population. To account for this, sub-populations may be defined as compliant or non-compliant as described in Chapter 2. It is assumed that compliant sub-populations heed the advice given to them, and consequently the appropriate reduction factors are applied to their dietary intakes.

Applies to: home-grown and semi-natural food products.

Radionuclides affected: ^{137}Cs, ^{90}Sr, ^{239}Pu and ^{241}Am.

Trigger-variables: the activity concentrations of home-grown and semi-natural food products.

Mutually exclusive countermeasures: none.

Restrictions: none.

Simulation: when the activity concentration in a home-grown or semi-natural food product within a cell is above the implementation threshold, the activity intake rate of compliant individuals residing within the cell for that food product is adjusted according to a food-specific reduction factor.

Implementation costs: service cost of administering dietary advice. Where advice is given concerning more than one foodstuff it is assumed that the advice is given concurrently and therefore only one cost is incurred.

Side-effects: none.

3.4 SUMMARY

The effects of 18 commonly implemented countermeasures have been incorporated into the radiological models described in Chapter 2. In addition to the radiological consequences of countermeasures, and the monetary costs associated with their implementation, a limited number of side-effects are also considered, including: the impacts upon the landscape, water quality for recreation, animal welfare, heritage and daily life.

The spatial and temporal extent of a countermeasure's implementation within a scenario is controlled via an implementation threshold, whose value may be a user-defined constant or varied automatically by the system, and various regulatory and physical restrictions. If the implementation of a countermeasure within a cell is not restricted on regulatory or physical grounds, its implementation threshold is compared to the values of associated trigger-variables within the cell (which are predicted by the system) to determine whether the countermeasure will be simulated within the cell or not. Countermeasures are only simulated in those cells in which the values of the trigger-variables are greater than the value of the implementation threshold.

CHAPTER 4: THE SELECTION AND OPTIMISATION OF REMEDIATION STRATEGIES.

4.1 INTRODUCTION

According to the ALARA principle, radiation doses received by exposed individuals should be kept "as low as reasonably achievable, economic and social factors being taken into account" (ICRP, 1990). It follows from this recommendation that, even if individual doses are below statutory limits, the relevant authorities must ensure that every reasonable effort has been made to reduce those exposures, and that in order to determine what is "reasonably achievable" for a given scenario, the benefits, in terms of the dose averted, must be balanced against the economic and social impacts for all available options (i.e. for each potential remediation strategy). However, in the event of a nuclear accident, there is likely to be a large amount of information for decision makers to process, a large number of potential remediation strategies to consider, and numerous factors, many of them uncertain, involved in the assessment of those strategies. Identifying what is "reasonably achievable", therefore, is not a trivial task: in mathematical terms, the search space is large and multidimensional. Consequently, several Decision Support Systems (DSS) have been developed to assist decision makers in selecting the most appropriate course of action following the release of radionuclides into the environment (e.g. RODOS (Erhardt et al., 1993); MOIRA (Monte et al., (1999); PRANA (Yatsalo et al., 1997); TEMAS (Montero et al., 2001); Papazoglou and Kollas (1997); Perny and Vanderpooten, (1998)). These systems incorporate the simulation of radiological countermeasures into radionuclide transfer models which predict the consequences of nuclear accidents, and include procedures for assessing and comparing various potential remediation strategies, in order to identify the most appropriate strategy for a given scenario. This overall process is called "the optimisation of protection" and can be divided into three general steps:

i. Generation of potential remediation strategies.
ii. Assessment of strategies.
iii. Identification of the optimum strategy.

In the following sections the current approaches employed to perform these three tasks are reviewed.

4.1.1 Generation of alternative remediation strategies

Typically, DSS represent affected areas as discrete geographical regions, which are defined either in relation to the source of the contamination (e.g. RODOS (Papamichail and French, 2000), the level of contamination (Papazoglou and Kollas, 1997), or as grid squares which cover the affected area (CESER, Salt and Culligan Dunsmore, 2000). Alternative remediation strategies can then be simulated as combinations of countermeasures within each of the regions. However, even in a simple scenario, where the affected area is represented by just 10 regions and just 10 independent countermeasures with binary implementation (i.e. either implemented or not within a region) are considered, the number of possible strategies is $2^{10\times10}$ ($\approx 1.3 \times 10^{30}$). If it was possible to implement countermeasures by degrees, or more countermeasures and regions were considered, then the number of possible strategies would increase still further. The task of assessing such a large number of possible strategies, many of which may be "bad", would be time consuming for the fastest available computers (e.g. even for a very simple calculation, on a computer capable of 1 billion calculations per second, 1.3 × 10^{30} calculations would take approximately 3 × 10^{13} years!). Clearly, there is a need to limit the number of strategies to be evaluated by DSS, and several approaches have been developed to accomplish this.

One method is to "screen" potential countermeasure strategies according to some crude criteria. For these methods to be of benefit, however, they must strike a balance between being sensitive enough to exclude "bad" strategies, and crude enough to make the process sufficiently fast.

A screening procedure is employed in the RODOS system (Papamichail and French, 2000) where a subsystem (the "coarse expert system") excludes strategies that do not adhere to specified constraints. Examples of these constraints are:

i. Continuity of treatment.

Strategies are excluded where protective actions are applied in regions far away from the source but not in regions close to it. This constraint accounts for the fact that the public expects neighbouring communities to be treated in the same manner.

ii. Wind direction.

Excludes strategies where countermeasures are applied to areas that the plume did not pass over.

iii. Feasibility of countermeasures.

Excludes strategies that would be clearly infeasible (e.g. sheltering and evacuation can not be applied in the same area at the same time).

iv. Intervention levels.

Excludes strategies that include countermeasures that cannot avert more dose than the specified lower intervention level.

v. Evacuation.

Excludes strategies where the time required for safe evacuation is greater than the estimated time taken to perform the task.

These constraints are used to eliminate regions of the search space according to the "first fail principle" (Haralick and Elliot, 1980). The objective of this procedure is to exclude, as early as possible, strategies that do not lead to a reasonable solution. To achieve this, the system assesses strategies against the constraint which is hardest to satisfy first, then against the next hardest constraint to satisfy, and so on for all constraints. In the examples given above, the "Wind direction" constraint is the hardest to satisfy, as the plume either did pass over a region or it did not. Therefore, the system tests each strategy against this constraint and can immediately exclude all strategies that include the implementation of countermeasures in areas where there the plume did not pass over. Where there is a conflict between constraints, preferences are used to decide whether the strategy is excluded or not. For example, if evacuation near to the source is not required by the interventions level constraint, but it is required by the continuity of treatment constraint, then the strategy is not excluded as the continuity of treatment constraint is preferred to the intervention levels constraint. The authors report that this screening method reduces the number of strategies to be evaluated by close to 100%. However, in the simple example given above, with 1.3×10^{30} possible strategies, an efficiency of 99.999% would still result in 1.3×10^{25} strategies suitable for further evaluation, which effectively limits the number of regions which can be defined and the number of countermeasures that can be considered.

A similar screening process is described by Perny and Vanderpooten (1998). Strategies are generated by adjusting the quantities of food products to be treated by various countermeasures within defined areas, and are then filtered using a system of hard and soft constraints. Hard constraints are defined by the basic structure of the decision problem (e.g. the maximum quantity of food which may be treated by a countermeasure) and are irrevocable restrictions; soft constraints may be varied to allow decision makers to investigate the effects of imposing various desired outcomes (e.g. the maximum level of individual dose permitted).

An alternative method for limiting the number of strategies to be assessed has been developed by Papazoglou and Christou (1996), who identify the "efficient frontier" (i.e. the set of efficient alternatives) using a multi-objective optimisation algorithm based upon dynamic programming. The affected area is represented by discrete cells. The consequences of implementing various countermeasures are assessed for one cell, and the "efficient" ones kept (An option is efficient if there is no other feasible alternative which is as good over all criteria and better on at least one criterion). The procedure is then performed for all cells in a stepwise fashion so that at each step the inefficient actions within a cell are rejected, thus greatly reducing the number of possible actions. However, this method assumes that there is no interaction between cells, which may be unrealistic when considering food-chain based countermeasures where the effects of countermeasure implementation may be exported outside of a cell with food produce.

In contrast to the DSS described above, some systems do not employ any form of screening technique. In the CESER DSS (Salt and Dunsmore, 2000) the side effects of every individual countermeasure are estimated in every cell where they are feasible. However, the system does not simulate countermeasure *strategies* (i.e. combinations of countermeasures), which greatly reduces the number of alternatives to be assessed. For example, in the simple scenario described above with 10 independent countermeasures and 10 regions, CESER would only need to perform 100 assessments, compared with $\approx 1.3 \times 10^{30}$ assessments required if all possible combinations of countermeasures were simulated in each cell. In the PRANA DSS (Yatsalo et al., 1997), potential remediation strategies are defined by the user, with limited automation involved in their generation. The number of remediation strategies to be assessed is, therefore, extremely limited.

4.1.2 Assessing remediation strategies

The first step in the process of assessing remediation strategies is the selection of the factors to be considered, and the relative significance of each. This task is critical to the output of the optimisation process. If key factors are not included, or not given the appropriate level of importance, then the output from the optimisation process may suggest the implementation of inadequate or unjustified countermeasure strategies. Until the early 1980s, the ICRP recommended the use of simple cost-benefit analyses to address radiological decisions (ICRP, 1983), where the collective doses received and the costs of the practices or interventions were the only factors to be considered. However, more recently (ICRP, 1988), the commission has emphasised the need for a more holistic approach to the decision making process. This recognises that other radiological and environmental factors, such as the levels of individual dose received, equity in the distribution of individual doses and the social side effects of countermeasure implementation, are also important factors that must be considered if countermeasure strategies are to be acceptable to affected parties.

Once the factors to be included in an assessment have been selected, the next task is to select an appropriate method for the comparison of remediation strategies. ICRP (1988) gives four examples of such methods: cost-effectiveness, cost-benefit analysis, multi-attribute utility analysis and multi-criteria outranking analysis. The ICRP deliberately refrains from recommending a particular analytical technique for use in radiological protection, as the most appropriate technique is situation specific, and depends on the number and nature of the factors to be assessed. The advantages and disadvantages of each of the four methods are discussed below.

4.1.2.1 Cost-effectiveness analysis

Cost-effectiveness analysis allows a quantitative comparison of the implementation costs and collective doses resulting from available options. Options that are not deemed to be cost-effective can then be excluded from further consideration. Constraints can be used to further reduce the set of feasible options. For example, by specifying a maximum allowable collective dose level, those options that give rise to collective doses above that level can be eliminated. Similarly, by specifying a maximum level of expenditure, those options that are too costly can also be eliminated. Although this is a simple method for comparing options, it does not allow the optimum solutions to be identified, and cannot accommodate more complex situations where more than two factors (i.e. dose and cost) need to be considered.

4.1.2.2 Cost-benefit analysis

In cost-benefit analysis all factors are expressed in monetary terms, which are then aggregated to provide an overall measure of the merit of the remediation strategy under consideration. To accomplish this, the collective dose is transformed into a monetary value using a reference value, α (£ man-Sv^{-1}), which is the monetary value of a unit of collective dose. It should be noted that the use of α can be a contentious issue: firstly, because it implies that dose levels and financial costs are commensurable, and, secondly, because of the difficulties in ascertaining an appropriate value, as discussed below.

Various procedures are used to determine the value of α, which is site and situation specific, and related to the societal value of a life. The "Human Capital" approach estimates the societal value of a life using the average earnings of an individual over their lifetime. The annual income that an individual would make throughout their lifetime is brought forward and adjusted to present worth, using a discount value, to allow a single value of worth to be assigned to an individual. However, as several authors have noted (Guenther and Thein, 1997; Lefaure, 1998; Landefeld, 1982), this approach has several shortcomings:

i. It only takes the economic value of human life into account. It does not take into account non-monetary factors such as the enjoyment of life or the desire to live a life free from suffering.
ii. The value is highly dependent upon the value of the discount rate used to adjust the annual incomes throughout a lifetime to present worth.

iii. It can lead to unacceptably low values of α. Lefaure (1998) cites an example in Romania, where the values derived from the Human Capital approach would lead to individual doses that were higher than the dose limits.

iv. It assigns a larger value of life to individuals with higher incomes (e.g. it assigns a higher value of life to men than to women, as, on average, men have higher incomes than women).

To avoid some of these shortcomings, the Human Capital approach can be modified to use the Gross National Product (GNP) per capita, and the risk factor for years of life lost per man-Sv (IAEA, 1985; Eged et al., 2001). However, the ICRP still recommends that the Human Capital approach should be treated as a "minimal approach" and that the values derived from it should be considered as " the absolute minimum that could be spent to avoid a premature death" (ICRP, 1983).

Another method that can be used to determine the value of α is "Willingness-To-Pay" (WTP). For this technique, the societal value of a life is determined according to how much an individual is willing to pay to decrease their risk of death. This can be performed via two methods: "revealed-preference" or "direct-survey". In the revealed-preference approach, societal decisions are analysed to infer the statistical value of a life. Examples of these societal decisions are: the purchasing of additional safety features (e.g. airbags for vehicles); the acceptance of a higher-risk job in return for higher income; paying for more frequent medical check-ups. A major disadvantage of this technique is that it can be difficult to determine which choices are made solely on the grounds of risk reduction, without the influence of external factors, such as an individual's ability to pay for additional risk reduction.

In the direct-survey method, individuals are presented with a questionnaire designed to ascertain how much they would be willing to pay to avoid various hypothetical risks. The societal value of a life can then be estimated by a statistical analysis of the survey results. The disadvantages of this technique are that the values derived are dependent upon the wording of the questionnaire, the individual's ability to assess risk, and the risk environment to which the individual is routinely exposed.

Other methods for estimating the societal value of a life include: jury awards from wrongful death suits; medical expenditures; life insurance; wages and investments. Guenther and Thein (1997) reviewed each of these techniques and used them to derive estimates for the societal value of a life in the USA in 1990 (Table 4.1).

Table 4.1 Recommended values, and ranges, of the societal value of a life as determined by various analytical techniques.

Method for determining the societal value of a life	Recommended societal value of a life (1990 $US)	Range in values (1990 $US)
Jury award for wrongful death	3,454,000	562,000-12,760,000
Medical expenditure	4,222,000	141,000-4,222,000
Life insurance	3,356,000	130,700-3,356,000
Wages and investment	2,670,000	960,000-2,670,000
Human-capital	558,000	201,000-1,124,000
Willingness-To-Pay	2,844,000	83,000-18,400,000

The review highlights two main features. Firstly, it confirms that the human-capital approach can lead to relatively low values for a life. Secondly, it illustrates the range in the derived values within one method of assessment, and between the different methods. Therefore, because these values are used to determine the value of α, it should be borne in mind that there is also uncertainty in the value assigned to α. However, despite this inherent uncertainty, the technique is widely used by radiological protection authorities and the nuclear industry where it is viewed as a useful tool in decision-making frameworks (Lefaure, 1998).

In a simple cost-benefit analysis, the value of α is constant and the monetary value of the collective dose increases linearly, in correspondence with the health effects associated with increasing levels of dose. This results in a purely quantitative comparison of collective dose and protective costs. However, cost-benefit analysis can be extended to incorporate additional factors, which can include qualitative and non-linear terms (ICRP, 1988). An example of an extension that can be made to cost-benefit analysis is the inclusion of a term which accounts for the aversion to high levels of individual dose. As described above, in a simple cost-benefit analysis the value of α is assumed to be constant for all levels of individual dose. From this assumption it follows that a collective dose of 10 man-Sv, comprised of a large number of relatively small individual doses, is viewed as comparable with the same level of collective dose comprised of a small number of relatively large individual doses. However, in radiological protection situations, it is often desirable that more emphasis is placed upon averting high levels of individual dose. Consequently, several methods have been developed to incorporate this consideration within the decision making process (Hardeman et al., 1998; ICRP, 1983; NRPB, 1993, Lochard et al., 1996). An example of this extension to cost-benefit analysis is given in ICRP (1988) where the preference for averting high levels of individual dose is incorporated into the merit function. The level of individual dose is divided into bands (e.g. <5mSv, 5-15mSv, and >15mSv), and an additional value is placed upon the collective dose within each band of individual dose, such that:

$$M = \alpha S + \Sigma \beta_j S_j$$

Where *M* (£) is the merit function, S_j (man-Sv) is the level of collective dose for the *j*th band of individual dose, and β_j (£ man-Sv^{-1}) is the additional value for each unit of collective dose within the *j*th band.

Other extensions can be made to cost-benefit analysis, as in the PRANA DSS (Yatsalo et al., 1997), where the additional benefits (e.g. an increase in crop production) of countermeasure implementation are also included in the assessment of countermeasure strategies.

The main disadvantage of cost-benefit analysis is its inability to accommodate factors that cannot easily be expressed in monetary terms. However, some economists claim that it is possible to obtain monetary values for most of the attributes considered within the sphere of radiation protection (Costanza et al., 1997; Álvarez and Gil, 2002), although the reliability of such estimates may be open to question, and may be criticised on ethical grounds (Oughton, 2003).

4.1.2.3 Multi-attribute utility analysis

One technique that avoids the need for factors to be explicitly expressed in monetary terms is multi-attribute utility analysis (MAUA). In MAUA, each attribute, *a*, considered in the assessment is described by a utility function, *u*, (Figure 4.1).

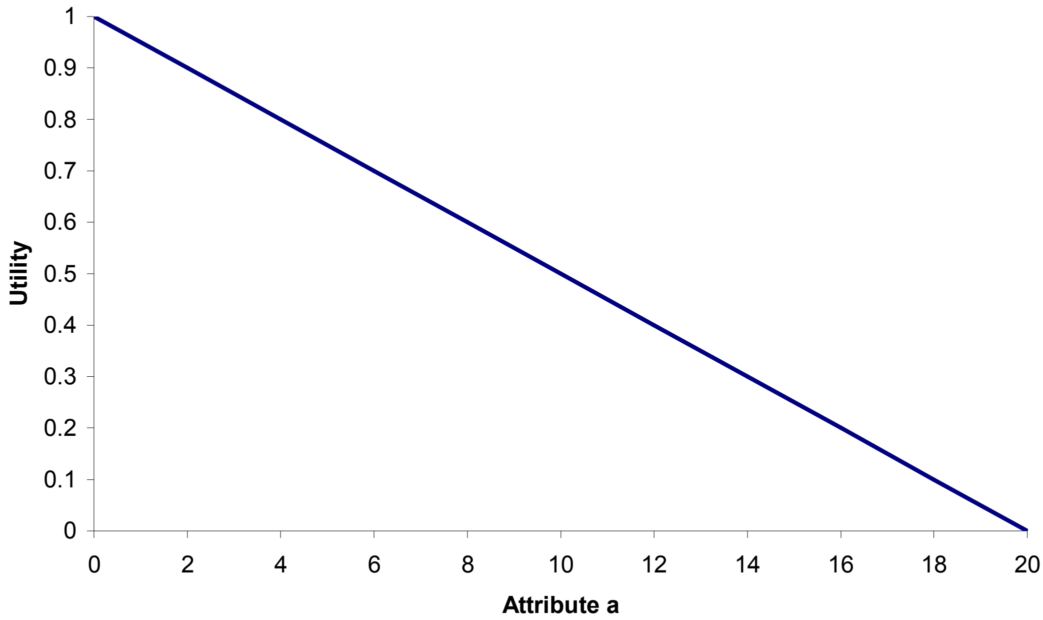

Figure 4.1 A hypothetical utility function for an attribute *a*.

The "merit" of each option, *i*, can then be described by its overall utility, *U*, which is the sum of the *n* attribute utilities multiplied by their respective weightings, *w*:

$$U_i = \sum_{a=1}^{n} w_a u_a$$

The weightings of the attributes, which are subjectively assigned, are typically normalised, such that:

$$\sum_a w_a = 1$$

Thus if $U_i > U_j$, option *i* is preferred to option *j*.

This technique is particularly effective in assessing situations where numerous attributes are considered (Merkhofer and Keeney, 1987). A further advantage is that the utility functions used to describe each attribute do not necessarily need to be linear, allowing more emphasis to be placed on particular attribute levels. However, in order to define a utility function for a particular factor, the range of values for that factor, resulting from all of the possible options, should ideally be known prior to assessment. In situations where there are many possible alternatives, this information may not be easily obtained. In addition, the weightings, which are subjectively assigned to the individual utility of each attribute, may be as difficult to determine as the monetary values associated with cost-benefit analysis.

4.1.2.4 Multi-criteria outranking analysis

In the preceding techniques, the attributes considered in the assessment are aggregated into a single function of merit, expressed either as a monetary or a utility term. For this aggregation to be valid, two conditions must be satisfied. Firstly, the factors considered within the merit function must be commensurable (i.e. all attributes must be convertible into the units of the single aggregate function). Secondly, trade-offs between factors must be legitimate (i.e. the contribution to the merit function by each factor must be compensatory for all other factors, according to the specified weightings). Therefore, factors that cannot easily be expressed quantitatively (e.g. discomfort), or situations where trade-offs between factors are not applicable, can pose problems for such techniques. Multi-criteria outranking analysis is a technique that allows such factors to be taken into consideration, and does not rely on trade-offs between factors. Several different outranking methods exist (see Vincke, 1992), however, the general procedure is outlined below.

The technique uses a "concordance index" to define the extent to which one option is preferred to (or "outranks") another. When one option is preferred to another for a particular factor, the preferred option is scored according to the weighting assigned to the factor under consideration. For example, when comparing two options, *a* and *b*, the concordance index, $C_{a,b}$, is defined as:

$$C_{a,b} = \sum_j k_j f_j$$

where f_j is the concordance index for factor *j* (equal to 1 if option *a* is preferred or equal to option *b*, otherwise equal to 0) and k_j is the weighting factor for factor *j*. $C_{a,b}$ is equal to 1 if option *a* outranks option *b* over all of the *j* factors; it is equal to 0 if *a* does not outrank *b* for any of the factors, and it varies between 0 and 1 when *a* outranks *b* for some of the factors. This procedure is performed for all possible options in a pair wise manner and the results displayed in matrix form.

A "discordance index", $D_{a,b}$, is then calculated in a similar manner to the concordance index. This defines the significance of the disadvantages of option *a* compared to option *b* for the factors where the former is not preferred to the latter. If option *a* is preferred to option *b* for all criteria then $D_{a,b}$ is zero. Otherwise, for each factor where option *a* is not preferred to *b,* the difference between their performances is recorded in an appropriate form (e.g. as the ratio of the difference between the two options to the maximum difference in values for that factor, or as the difference in utility between the to options).

The next step in the assessment is the definition of a concordance threshold, C^*, and a discordance threshold, D^*. Option *a* can then be said to outrank, or dominate, option *b* if $C_{a,b} > C^*$ and $D_{a,b} < D^*$. Options which outrank at least one other option, and are not outranked themselves, should be possible solutions the problem. By adjusting the concordance and discordance thresholds decision makers can attempt to limit the number of outranking options and possibly determine the option which outranks all other options (i.e. the optimum solution).

A major disadvantage of this technique is that, when there are many alternative options available, it is computationally expensive to perform, as each potential option must be compared with each alternative.

4.1.2.5 Discounting

In each of the assessment techniques described, the monetary value, or utility, of the factors considered are assumed to be constant within the time period of the assessment. When the timescale of the problem under consideration is relatively small (e.g. less than one year), this assumption may not be unreasonable, as decision makers will only have to consider the immediate effects on the current population and the real value of money is unlikely to change significantly over this time span. However, following a nuclear accident the environment may be contaminated for many years. Consequently, when designing long-term remediation strategies, decision makers must not only consider the mitigation of doses received by the current population, but also those received by future generations. However, individuals, and society as a whole, generally prefer to receive benefits sooner rather than later, and for detriments to be deferred. The benefits and detriments associated with the implementation of radiological countermeasures may be produced at various stages after an initial deposition of radionuclides, and for varying lengths of time. Some countermeasures may be procedures that are executed only once, but whose benefits are experienced for many years thereafter (e.g. ploughing of pasture land), whilst other countermeasures may require continual application and only produce benefits during, or for a short period immediately after, their implementation (e.g. restrictions on the sale of food products).

To allow the comparison of countermeasure strategies which generate detriments and benefits far into the future with those that only produce detriments and benefits in the short term, decision makers must, therefore, account for society's preference for benefits to be received sooner rather than later, and the change in the real value of money during that time: financial costs which are to be incurred in the future may be more or less expensive than their present values depending on market conditions.
These temporal preferences can be accounted for by the application of discount rates to benefits and detriments. The "utility discount rate" accounts for the social time preference of society, and the "consumption discount rate" accounts for the change in the rate of consumption.
The discounting procedure takes the form:

$$f(t) = f(0)\left(\frac{1}{1+r}\right)^t$$

where *f(t)* is the value of a detriment or benefit at time *t*; *f(0)* is the present value of a detriment or benefit and *r* is the appropriate discount rate, expressed as a fraction.

It should be noted that the values used for utility discount rates have implicit ethical considerations associated with them. Some authors have argued that the only equitable discount rate is a zero discount rate (Ramsey, 1928), implying that equal consideration should be given to future generations and the current generation. However, others suggest that this discriminates against current generations, as future generations are likely to benefit from technological advancements (Marini and Scaramozzino, 2000). Another argument used to justify the use of a positive utility discount rate is that for every point in time in the future, there exists a possibility that humans will become extinct. Therefore, because the existence of future generations is not certain, it is argued that less weight should be given future utility (Perman, Ma and McGilvary, 1998).

4.1.3 Identification of optimal remediation strategies.

The method used by DSS to identify optimal strategies is largely dependent upon the manner in which the potential strategies are generated. The most straightforward method for locating the optimum strategy for a scenario would be to generate, and assess, all possible strategies. The optimum solution would then be simply the strategy that has the best score according to the defined assessment criteria.

However, as previously stated, due to the large number of potential remediation strategies, this task may not be possible within a reasonable time span. Therefore, many DSS (e.g. RODOS, Papazoglou and Kollas) reduce the number of strategies to be assessed using some form of screening process, and then identify the optimum strategy by assessing each of the strategies in the reduced set of alternatives, according to defined criteria.

In contrast, Perny and Vanderpooten (1998) describe a system which identifies efficient strategies using a "scalarizing function", which aggregates the objective functions. These are:

i. To minimise the financial cost.

ii. To maximise the level of averted dose

iii. To maximise public acceptability.

The minimisation process can be operated in three modes: restricted, partial and focussing. In a restricted minimisation the user can restrict criterion values and decision variables to investigate a particular region of the search space. In a partial minimisation, the user can define part of a restoration strategy and then the system will optimise the residual elements. In a focussing minimisation, the user defines aspiration levels for some, or all, criteria and the system then identifies the strategy which is closest to attaining those objectives.

The CESER DSS identifies the most appropriate countermeasure for each cell using Ideal Point Analysis, which measures the distance of an alternative from the ideal solution defined by the specified weightings of each of the criteria. The optimal solution is then the alternative which is the smallest distance from the ideal. However, this system does not simulate combinations of countermeasures whose combined side effects may be greater or less than the sum of their individual effects. Therefore, this system does not identify the optimum countermeasure *strategy*, merely the countermeasure which has the least impact within each cell. Furthermore, the system does not estimate the radiation dose to affected human populations, and consequently the side effects of countermeasure implementation cannot be weighed against the benefit derived from dose reduction. Therefore, although CESER may suggest that a particular countermeasure is the most appropriate for a particular cell based upon its side-effects; it may not be the most appropriate countermeasure in terms of dose reduction.

4.2 METHODOLOGY

Due to the input data regarding the social preferences of individuals for the considered countermeasure side-effects being described in monetary values, the assessment of remediation strategies in this system is performed using either a simple or extended cost-benefit analysis. Although this technique assumes that the considered factors are commensurable, which may be open to question, other techniques which could avoid this issue, such as multi-criteria outranking analysis, are not appropriate in this instance due to the large number of potential alternatives. Cost-benefit analysis is also amenable for use in the classical minimisation technique used to identify optimum remediation strategies. This approach has been taken because, as described above, the efficiency of screening methods when the numbers of potential options are large is generally not sufficient to reduce the number of strategies for assessment to a manageable size. The implementation of these methods within the system is discussed in this section.

4.2.1 Generation of remediation strategies

As described in Chapter 3, remediation strategies may be generated manually, or automatically, according to the defined implementation thresholds of the countermeasures selected as available for implementation. To briefly reiterate, countermeasures are then simulated in those cells where the values of the appropriate trigger-variables are greater than the defined implementation thresholds, and their implementation is not restricted.

4.2.2 Assessment of remediation strategies

In the methodology presented here, remediation strategies can either be evaluated using a simple cost-benefit analysis or an extended cost-benefit analysis. All considered factors are converted into monetary values and aggregated into the merit function. In both cases, discount rates may be applied to all factors under consideration, according to the function described in section 4.1.2.5.

4.2.2.1 Simple cost-benefit analysis

For a simple cost-benefit analysis, the merit function, *M* (£), is defined as:

$$M = C - A$$

Where *C* (£) is the monetary cost of countermeasure implementation, including any associated waste disposal costs, and *A* (£) is the monetary value of the averted dose. The monetary value of the averted dose is calculated as the difference between the monetary value of the collective dose when no countermeasures are implemented (the "do-nothing" strategy), D_0 (£), and the monetary value of the collective dose when countermeasures are implemented, D_{CMS} (£):

$$A = D_0 - D_{CMS}$$

The monetary value of the collective dose in each strategy is calculated as the sum of the monetary value of the local collective dose (received by people living in the affected area), *LCD* (man-Sv), and the monetary value of the exported collective dose (assumed to be received by people living outside of the affected area), *ECD* (man-Sv):

$$D = \alpha(LCD + ECD)$$

In this case, α is defined as a constant value, and the monetary value of the collective dose is linearly related to the stochastic detrimental health effects associated with the level of dose received.

4.2.2.2 Extended cost-benefit analyses

Two extensions to the cost-benefit analysis are considered:

i. A preference for averting high levels of individual dose can be considered, by describing α as a function of individual dose.
ii. The social costs of countermeasures' side-effects can be included.

Aversion to high levels of individual dose.

The method used to include the preference for averting high levels of individual dose is that described by Lochard et al. (1996). According to this model, α is a function of the individual doses received, such that:

$$\alpha_d = \alpha_{base}\left(\frac{d}{d_0}\right)^a \text{ when } d \geq d_0$$

$$\alpha_d = \alpha_{base} \text{ when } d < d_0$$

Where α_d (£ person-Sv^{-1}) is the reference value for the unit of collective dose for the annual level of individual exposure d (Sv a^{-1}); α_{base} (£ person-Sv^{-1}) represents the monetary cost of the health detriment associated with one unit of collective exposure; a is the coefficient reflecting the degree of aversion to the individual exposure level and d_0 (Sv a^{-1}) is the threshold dose below which the aversion is not considered. In this case, α_d is constant for individual doses below the threshold dose, but increases according to the value of the aversion coefficient as the level of individual dose increases above the threshold dose (Figure 4.2).

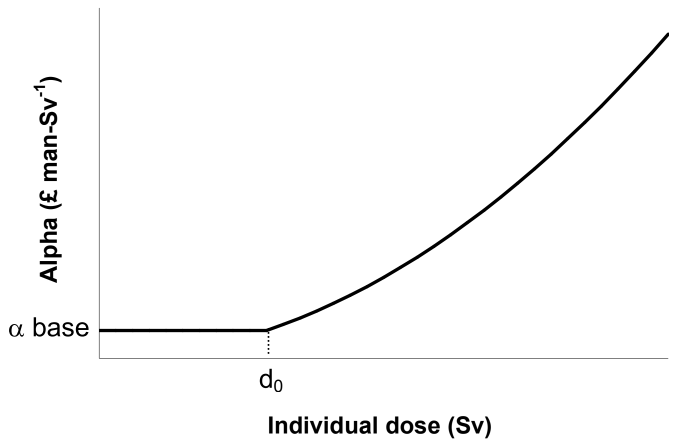

Figure 4.2 An illustration of how the monetary value of the unit of collective dose changes as a function of the individual dose received.

In this model, the value of α is no longer related solely to the stochastic health effects associated with the level of collective dose received: it also includes the subjective value of the aversion to high levels of individual dose. The monetary value of the collective dose for a strategy, *D* (£), then becomes:

$$D = \left\{ \sum_{c,p} \alpha(d)\ LCD_{p,c}(d) \right\} + \alpha_{Base} ECD$$

Where $LCD_{p,c}(d)$ (man-Sv) is the local collective dose of population, *p*, in cell, *c*, at the level of individual dose *d* (Sv). It is assumed that the individual doses received by people living outside of the affected area would be negligible and therefore below the threshold dose. Consequently, the monetary value of the dose exported from the region is simply the product of the exported collective dose and the base value of α.

Social cost of countermeasures' side-effects

As described in Chapter 2, a limited number of environmental and social preferences are considered within the system, which relate to countermeasures' side-effects. These can be included within the merit function in an attempt at a more holistic approach to the decision process. If the side-effects of a countermeasure's implementation impact upon the considered attributes, then the social "cost" of that impact is evaluated according to the social preferences of the affected individuals.

Attribute coefficients, which are derived by expert judgement, are used to scale the impact of a particular countermeasure upon an attribute, relative to the impact descriptions used in the method employed to ascertain the social preferences. For example, Figure 4.3 illustrates a landscape in its normal state and with a potential impact upon its aesthetic quality, respectively. If the impact of a particular countermeasure upon the aesthetic quality of a landscape were deemed to be less than as illustrated in Figure 4.3 then it is assumed that the social cost to an individual would be reduced, and consequently an attribute coefficient of less than one would be used to account for this reduction. It is assumed that the individuals affected by a countermeasure's side-effects are the residents of the cell in which implementation occurs and, if the cell is designated as being within a tourist area, visitors to that cell. The social preferences of visitors to tourist areas, which are assumed to be identical to those of residents, have been included as tourism may constitute a large proportion of a region's revenue. Consequently, maintaining visitor numbers, by the implementation of appropriate countermeasures, may be a critical factor in sustaining the economic viability of an affected area.

Figure 4.3 Examples of illustrations used in the determination of social preferences. The top picture depicts a landscape in its normal state, while the bottom picture depicts the potential impact upon the aesthetic quality of the landscape resulting from countermeasure implementation.

The number of visitors per annum to a cell within a designated tourist area, T_c, is estimated from the total number of visitors, T_{tot}, to the tourist area per annum:

$$T_c = \frac{T_{tot}}{n_c}$$

where n_c is the number of cells within the designated tourist area. This implies that visitors to a tourist area are distributed equally over all cells within the area. Whilst this is a simplification, data regarding the distribution of tourists within a tourist area are not readily available.

The total social cost, S (£), of countermeasures' side-effects can then be incorporated into the merit function as:

$$M = C - A + S$$

Where:

$$S = \sum_{i,p,c,a} A_{c,a} V_{a,p} (N_{p,i} + T_{p,i})$$

Where $A_{c,a}$ is the attribute coefficient for countermeasure c and attribute a; $V_{a,p}$ (£) is the value placed upon attribute a by population group p; $N_{p,i}$ is the number of people of population group p residing in cell i, and $T_{p,i}$ is the number of tourists per annum of population group p that visit cell i, calculated as:

$$T_{p,i} = \left(\frac{W}{NP} \right)$$

Where W is the total annual number of visitors to the tourist area, N is the number of cells within the tourist area and P is the number of population groups defined by the user. Several assumptions are implicit in these calculations:

i. The residents of a cell are only affected by countermeasures implemented within that cell.
ii. The values placed upon the considered attributes by visitors to a cell are equal to those of the local inhabitants.
iii. Tourist numbers are distributed equally over the cells designated as tourist areas.
iv. The demographics of tourists are the same as for the local inhabitants.

These assumptions lead to a simplistic view of which individuals are affected by countermeasures' side-effects. However, to improve the modelling of this aspect of the system would require more detailed social data than was available during this project.

4.2.3 The selection and optimisation of remediation strategies

In addition to the development of a procedure to identify optimum remediation strategies, two further procedures, termed "inspection" and "criterion satisfaction" here, have been developed which, it is hoped, will allow decision makers to gain further insight into the effects of particular countermeasures, or combinations of countermeasures, within a particular scenario. While these procedures may be valuable in themselves, they also act as useful precursors to the computationally intensive optimisation procedure, as they can help to identify those countermeasures which are unlikely to be of benefit within a scenario, and consequently need not be included within the optimisation procedure.

4.2.3.1 Countermeasure "inspection"

Due to the finite spatial and temporal representations of an affected area used in this system, there will inevitably be a maximum extent to which a countermeasure may be implemented for a particular scenario. It is possible, therefore, to investigate the effects of a particular countermeasure, either independently or in combination with other countermeasures, over the full range of its implementation (i.e. from being fully implemented to not being implemented at all).

During countermeasure "inspection", the system evaluates the values of the merit function, the levels of averted dose, the total implementation costs and the social costs of side-effects (if considered) when a particular countermeasure's implementation threshold is at its maximum and minimum value and at a user-defined number of values in between. The thresholds of any other selected countermeasures are maintained at their defined levels throughout the process.

The results of the process are output in tabular form, together with a graph of the countermeasure's implementation threshold versus the merit function, as shown in Figure 4.4. In this example, with ten inspection points, the graph suggests that this countermeasure would be of benefit in this hypothetical scenario, as the value of the merit function is negative for all implementation levels above the minimum (N.B. the minimum implementation threshold corresponds to the maximum implementation level, and *vice versa*).

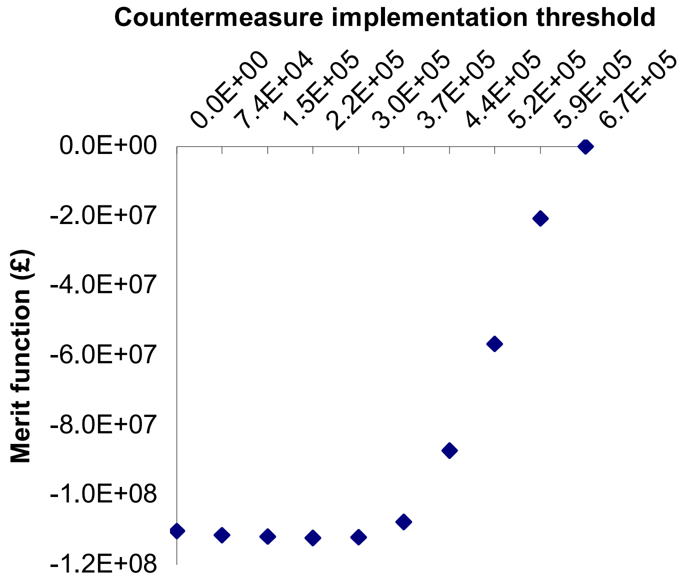

Figure 4.4 An example of an output graph from the "inspection" of a particular countermeasure, showing the value of the merit function for ten values of a countermeasure's implementation threshold.

4.2.3.2 Criterion satisfaction

When designing a remediation strategy decision makers may wish to investigate the effectiveness of a particular countermeasure, or combination of countermeasures, to achieve certain economic or radiological objectives. In this procedure decision makers may define either a target level for expenditure or a desired maximum level of individual dose, with associated tolerances. The system will then adjust the implementation threshold of a selected countermeasure and assess whether the objective can be fulfilled. This can be performed in combination with other "static" countermeasures, whose implementation thresholds are maintained at their defined values. In some cases it may not be possible for a particular countermeasure to fulfil the defined objective, either because the maximum expenditure possible for the countermeasure is below the target value, or because it cannot reduce the level of individual dose to below the maximum level specified. In these cases the system informs the user that the objective cannot be met. The outputs from the procedure are the level of averted dose, the maximum individual dose, the total collective dose, the total implementation cost and the implementation costs for each individual countermeasure.

4.2.3.3 Optimisation of remediation strategies

As described previously, remediation strategies are generated according to the implementation thresholds of selected countermeasures. To identify the most appropriate strategy for a scenario, therefore, involves determining the optimum implementation thresholds of each of the selected countermeasures. Locating the optimum implementation threshold for one countermeasure is a relatively trivial process, and can be accomplished using the "inspection" procedure described above (provided that sufficient inspection points are defined). However, locating the optimum implementation thresholds of multiple, interacting countermeasures is a non-trivial process, as adjusting the implementation threshold of one countermeasure may affect the extent of implementation, or effectiveness, of another. For example, implementing the ploughing of pasture countermeasures within a cell may result in less clean feeding of animals being required in that cell. Consequently, a mathematical procedure has been incorporated, which automatically adjusts the implementation thresholds of countermeasures and attempts to minimise the defined merit function. During the procedure, only undefined implementation thresholds are optimised. Implementation thresholds which have been user-defined remain constant, allowing statutory limits and regulations, such as Council Food Intervention Levels (CFILs) as specified by the Council of European Communities (1989), to be simulated. The minimisation procedure used is a version of Powell's method, taken from Press et al. (1989), and is briefly described below, together with some modifications necessitated by the particular nature of the problem under consideration here.

Powell's method

The value of a function, f_0, at a given point in N-dimensional space specified by the vector, $\boldsymbol{P_0}$, is defined as:

$$f_0 \equiv f(P_0)$$

Powell's procedure minimises the function along each of the N dimensions in turn (termed "line minimisations"), starting from the minima of the previous iteration each time. After minimising along all N dimensions the value of the function at the new point $\boldsymbol{P_N}$ can be calculated as:

$$f_N \equiv f(P_N)$$

The direction vector $\boldsymbol{X}$, which is the average direction moved after N line minimisations, can then be defined as:

$$X = P_N - P_0$$

The function can then be extrapolated to a new point, $\boldsymbol{P_E}$, along this new direction, so that:

$$P_E = 2P_N - P_0 \text{ and } f_E \equiv f(P_E)$$

Then, if $f_E < f_0$ and $2(f_0 - 2f_N + f_E)(f_0 - f_N) - \Delta f)^2 < (f_0 - f_E)^2 \Delta f$ the function is minimised along the direction vector ***X*** (where Δf is the largest decrease along one of the N dimensions). Otherwise the current direction set is discarded, because either extrapolating along the new direction does not decrease the value of the function, or the decrease along the average direction was not primarily due to a decrease in one direction. If the current direction set is discarded then another iteration of N line minimisations is performed along the old set of directions starting from the point $\boldsymbol{P_N}$. The procedure terminates either when a defined number of iterations has been exceeded, or when:

$$2(f_0 - f_N) \leq tol(|f_0| + |f_N|)$$

where *tol* is a defined tolerance value.

This procedure is particularly effective at navigating search spaces which have long narrow "valleys", as it identifies the dimension to which the largest decrease in the function can be attributed. However, it has been modified to address four features of the search space under consideration, which are:

i. The countermeasure implementation thresholds are bounded due to the finite nature of the associated trigger-variables.
ii. The effective bounds of one countermeasure's implementation threshold may be altered by the implementation of another countermeasure.
iii. In certain instances, it may not be possible to form a conventional bracket, due to the shape of the merit function.
iv. The bounding of the implementation thresholds also effectively bounds the direction set.

Each of the modifications relate to the bracketing procedure used in this method, which must be completed before line minimisations can be performed. To facilitate the discussion of these alterations, a brief outline of the normal bracketing procedure is given.

Normal bracketing procedure

A bracket can be said to have been formed when, for three points along an axis, *a*, b and *c,* where either $a > b > c$ or $a < b < c$:

$$f(a) > f(b) < f(c)$$

The normal procedure for forming a bracket can be broken into 3 steps (Figure 4.5):

i. Select a point *a* along the axis and evaluate the merit function at this point (if it is the first line minimisation along this axis then this point is arbitrarily selected, otherwise it is the value corresponding to the minima from the previous line minimisation along this axis).
ii. Evaluate a second point *b* at an arbitrary distance from *a*. If $f(a) > f(b)$ then proceed to step 3. Otherwise if $f(a) < f(b)$, set $a = b$, $b = a$, $f(a) = f(b)$ and $f(b) = f(a)$ and proceed to step 3.
iii. Evaluate a third point *c* in the downhill direction from the first two points. If $f(c) > f(b)$ then a bracket has been formed. Otherwise, if $f(c) \leq f(b)$ a bracket has not been formed, discard point *a*, and set $a' = b$, $b' = c$, $f(a') = f(b)$, $f(b') = f(c)$ and evaluate a new point, c', further from b in the downhill direction. Then if $f(c') > f(b')$ a bracket has been formed by points a', b' and c'. Otherwise repeat the procedure until $f(c') > f(b')$.

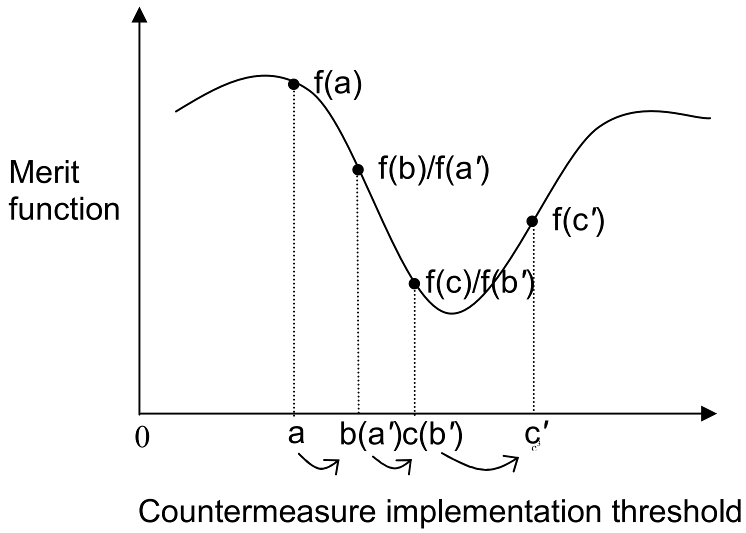

Figure 4.5 Illustration of the normal bracketing procedure. The implementation thresholds *a*, *b*, and *c* do not form a bracket as *f(a) > f(b) > f(c),* where *f(a)*, *f(b)* and *f(c)* are the values of the merit function at these points respectively. However, a bracket is formed by the thresholds *a'*, *b'* and *c'* as the values of the merit function at these points are such that *f(c') > f(b') < f(a')*.

Modification 1:

The first modification of the bracketing procedure is associated with step 2 of the description above, and is required due to the characteristics of the trigger-variables which control the implementation of countermeasures. To briefly reiterate, the implementation of a countermeasure is simulated in a cell if the value of the appropriate trigger-variable in that cell exceeds the implementation threshold for the countermeasure. However, due to the finite spatial and temporal representation of a scenario each trigger-variable will have maximum and minimum values (hereafter the maximum and minimum values of a trigger-variable will be referred to as TV_{Max} and TV_{Min} respectively). In mathematical terms, the values of the trigger-variables are therefore said to be bounded. For example, the maximum activity concentration in pasture grass in an affected area may be 1000 Bq kg^{-1}, and the minimum activity concentration within the time period considered may be 10 Bq kg^{-1}. In theory, the implementation threshold of a countermeasure may be defined as any positive number. It is possible, therefore, that the value of an implementation threshold may be defined as greater than the TV_{Max}, or less than the TV_{Min}, for that countermeasure. If the implementation threshold of a countermeasure is greater than TV_{Max} (e.g. point *a* in Figure 4.6), the countermeasure will not be simulated in any cells as no cell will exist which has a value of the trigger-variable greater than the implementation threshold. Consequently, further increases in the value of the implementation threshold (e.g. point *b*) will have no effect on the merit function (i.e. it will be constant), as it will not be possible for less implementation of the countermeasure to occur.

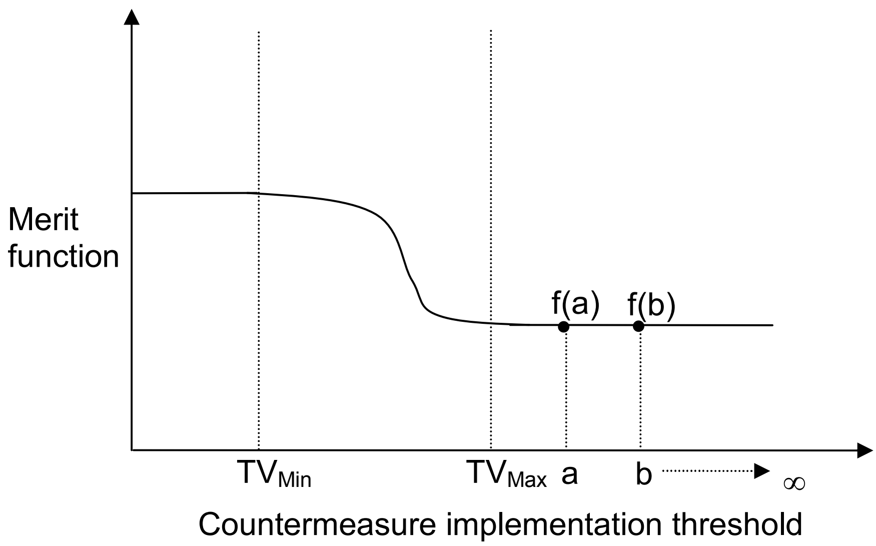

Figure 4.6 Illustration of the "flat" regions in the parameter space outside the bounds of a trigger-variable. TV_{Min} and TV_{Max} are the minimum and maximum values of the trigger variable respectively, and *f(a)* and *f(b)* are the values of the merit function at the implementation thresholds *a* and *b,* respectively. The value of the merit function is constant for all values greater than TV_{Max} and less than TV_{Min}.

Similarly, if the implementation threshold of a countermeasure is set below TV_{Min}, the countermeasure will be simulated in every cell where it is allowed. Therefore, decreasing the implementation threshold further has no effect on the merit function, as the countermeasure would already be implemented to its full extent.

These “flat” regions of the merit function, outside of the bounds of the trigger-variable, present a problem for step 2 of the bracketing procedure. The objective of the step is to locate two values of the implementation threshold, *a* and *b*, such that $f(a) \neq f(b)$. However, if $b > a > TV_{Max}$ then $f(b) = f(a) = f(TV_{Max})$. In fact, point *b* can be extended *ad infinitum* without the objective being realised.

To avoid this problem the maximum and minimum values of all trigger-variables are calculated prior to optimisation, by running the model without any countermeasures simulated. A simple restriction is then applied during the bracketing process, so that:

$$IT_{Min} \leq a, b \leq IT_{Max}$$

Where IT_{Max} and IT_{Min} are the maximum and minimum values of the countermeasure implementation threshold allowed. These are defined as:

$$IT_{Max} = TV_{Max}$$

If $TV_{Min} \neq 0$ then $IT_{Min} = TV_{Min} - 0.001TV_{Min}$

Otherwise $IT_{Min} = TV_{Min} = 0$

The value of IT_{Min} is set as 0.1% below TV_{Min} if $TV_{Min} \neq 0$ to ensure that the system can simulate the full implementation of countermeasures. The system only simulates a countermeasure within a cell if the trigger-variable *exceeds* the countermeasure’s implementation threshold. Therefore, if $IT_{Min} = TV_{Min}$ and $TV_{Min} \neq 0$, a countermeasure will never be implemented in those cells containing the minimum value of the trigger-variable, as it will be *equal* to the implementation threshold. Allowing IT_{Min} to be set below TV_{Min} ensures that the system can select a value of the countermeasure threshold which is below all of the values of the trigger-variable in the cells.

Modification 2:

During the optimisation process, the implementation of one countermeasure may reduce the actual value of TV_{Min} and TV_{Max} for another countermeasure. For example, the activity concentration in pasture grass is the trigger-variable for both the normal ploughing of pasture countermeasure and the administration of potassium fertiliser to pasture countermeasure. With no countermeasures applied, the maximum activity concentration in pasture grass may be estimated to be 1000 Bq kg^{-1}, and this will be the value used for IT_{Max} for both countermeasures. However, if one of the countermeasures were to be implemented, the maximum activity concentration in pasture grass may be reduced to, say, 900 Bq kg^{-1}. Consequently, if the implementation threshold of the other countermeasure were to be set at any level between 900 and 1000 Bq kg^{-1}, it would not be implemented in any cell, and the value of the merit function would be constant within this range. This effect is illustrated in Figure 4.7. Initially, the value of IT_{Max} is defined using the value of TV_{Max} with no countermeasures implemented. However, during the optimisation process, another countermeasure was implemented which reduced the actual value of TV_{Max} to $TV_{Max}(2)$. If the bracketing process selects initial points a and b, such that:

$$TV_{Max}(2) < a < b$$

Then $f(a) = f(b)$ for all points up to, and including $IT_{Max}(1)$. Clearly, the objective of step 2 in the bracketing process (i.e. $f(a) \neq f(b)$) cannot be fulfilled in this direction. The procedure has therefore been modified so that if $f(b) = f(a)$ for all values of b

where $a < b \leq IT_{Max}$ it then explores the values of b where $IT_{Min} \leq b < a$, until $f(a) \neq f(b)$ (e.g. b').

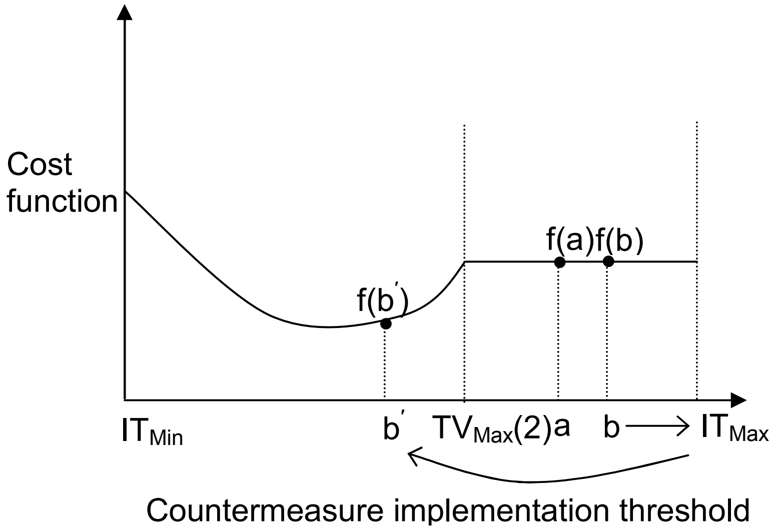

Figure 4.7 Illustration of the "flat" regions in the value of the merit function for one countermeasure's implementation threshold due to the implementation of other countermeasures. Where IT_{Max} and IT_{Min} are the maximum and minimum values of the implementation threshold respectively; $TV_{Max}(2)$ is the maximum value of the trigger variable following the implementation of another countermeasure; $f(a)$, $f(b)$ and $f(b')$ are the values of the merit function at implementation thresholds a, b and b' respectively.

Modification 3:

The third modification to the bracketing procedure has been made because, in some circumstances, a bracket cannot be formed due to the shape of the merit function. This generally occurs when the optimum value of the implementation threshold is either at IT_{Max} (Figure 4.8a) (corresponding to a countermeasure which, according to the merit function, should not be implemented at all), or at IT_{Min} (Figure 4.8b) (corresponding to a countermeasure which should be fully implemented).

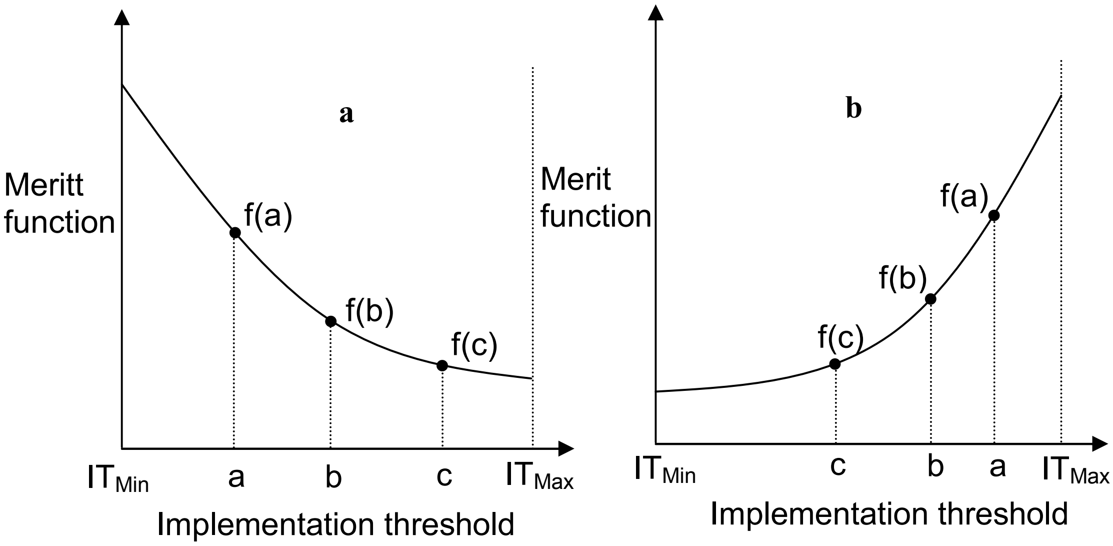

Figure 4.8 Illustrations of cases where a normal bracket cannot be formed. IT_{Max} and IT_{Min} are the maximum and minimum implementation thresholds respectively. In both cases, no values of the implementation thresholds *a*, *b* and *c* can be found where *f(a) > f(b) < f(c)*, where *f(a)*, *f(b)* and *f(c)* are the values of the merit function at the three thresholds respectively.

In both graphs in Figure 4.8, there are no values of *a*, *b* and *c* where either $a > b > c$ or $a < b < c$ and $f(a) > f(b) < f(c)$. Consequently, the bracketing procedure has been modified so that, in these cases, the procedure terminates when point *c* has been extended to either IT_{Max} (Figure 4.8a) or to IT_{Min} (Figure 4.8b). The line minimisation procedure then simply identifies either IT_{Max} or IT_{Min} as the optimum along this axis.

Modification 4:

The fourth problem encountered by the bracketing procedure is associated with the use of the direction vectors. When forming a bracket along the direction vector it is possible for more than one implementation threshold to exceed their boundaries at the same time. To illustrate this, Table 4.2 shows the steps involved in the bracketing procedure for a simple scenario involving three countermeasures.

Table 4.2 Hypothetical example of the violation of boundary conditions (*IT_{Max}* and *IT_{Min}*) due to the use of the direction vector *X*.

	IT_{Max}	IT_{Min}	P_0	P_N	X	P_E	P_C
Implementation threshold 1	4500	0	1000	2000	1000	3000	2666
Implementation threshold 2	5000	0	1000	3500	2500	6000	5166
Implementation threshold 3	2000	0	1000	400	-600	-200	0

An initial point, P_0, is defined with the implementation thresholds of all three countermeasures set to 1000 Bq kg^{-1}. After line minimisations along each of the implementation thresholds, a new point, P_N, is defined. The average direction moved, *X*, during the line minimisations is then equivalent to $P_N - P_0$. The procedure then attempts to evaluate a point, P_E, extended from P_N in the direction of *X* by one unit vector. However, in the example shown, two of the implementation thresholds then exceed their boundaries (i.e. for implementation threshold 2, 6000 > 5000, and for implementation threshold 3, -200 < 0).

If these boundary violations were permitted, the result would be a multi-dimensional version of the problem necessitating "modification 1" above. Therefore, a similar modification has been made to the bracketing procedure so that, when using the direction vector, all implementation thresholds are maintained within the bounds of their trigger-variables. If, during the bracketing procedure, the implementation threshold of one or more countermeasures exceeds the bounds of their respective trigger-variables then the point is contracted along the direction vector until no boundary violations occur. In the example shown, implementation threshold 2 needs to be contracted by a factor of 0.6 (i.e. (5000-3500)/2500) but threshold 3 needs to be contracted by a factor of 0.66 (i.e. (0-400)/-600) along the direction vector X.

Therefore, for no boundary violations to occur, the point must be contracted by a factor of 0.66 along the direction vector *X*, resulting in the point P_C.

4.2.3.4 Example optimisation

Figure 4.9 illustrates the results from a simple optimisation involving two countermeasures (Skim and burial ploughing of pasture and addition of potassium fertiliser to pasture), using the modified method described above.

Initially, the implementation thresholds for both countermeasures were set to zero (corresponding to the full implementation of both countermeasures). The procedure then performed a line minimisation of the skim and burial implementation threshold, (as indicated by the yellow circles along the bottom of the x-axis), and the optimum implementation threshold was found to be at around 300,000 Bq kg^{-1}. Following this, a line minimisation of the K fertiliser threshold was performed (the vertical line of yellow circles) and the optimum implementation threshold was found to be at approximately 120,000 Bq kg^{-1}. The procedure then explored along the direction vector created following the line minimisations (the diagonal line of yellow circles) and new optimum implementation thresholds were found at around 225,000 Bq kg^{-1} and 100,000 Bq kg^{-1} for the skim and burial and potassium countermeasures respectively. A further iteration of line minimisations did not lead to a significant decrease in the merit function, and consequently the procedure terminated with the optimum implementation thresholds found at 220,000 Bq kg^{-1} and 94,000 Bq kg^{-1} respectively.

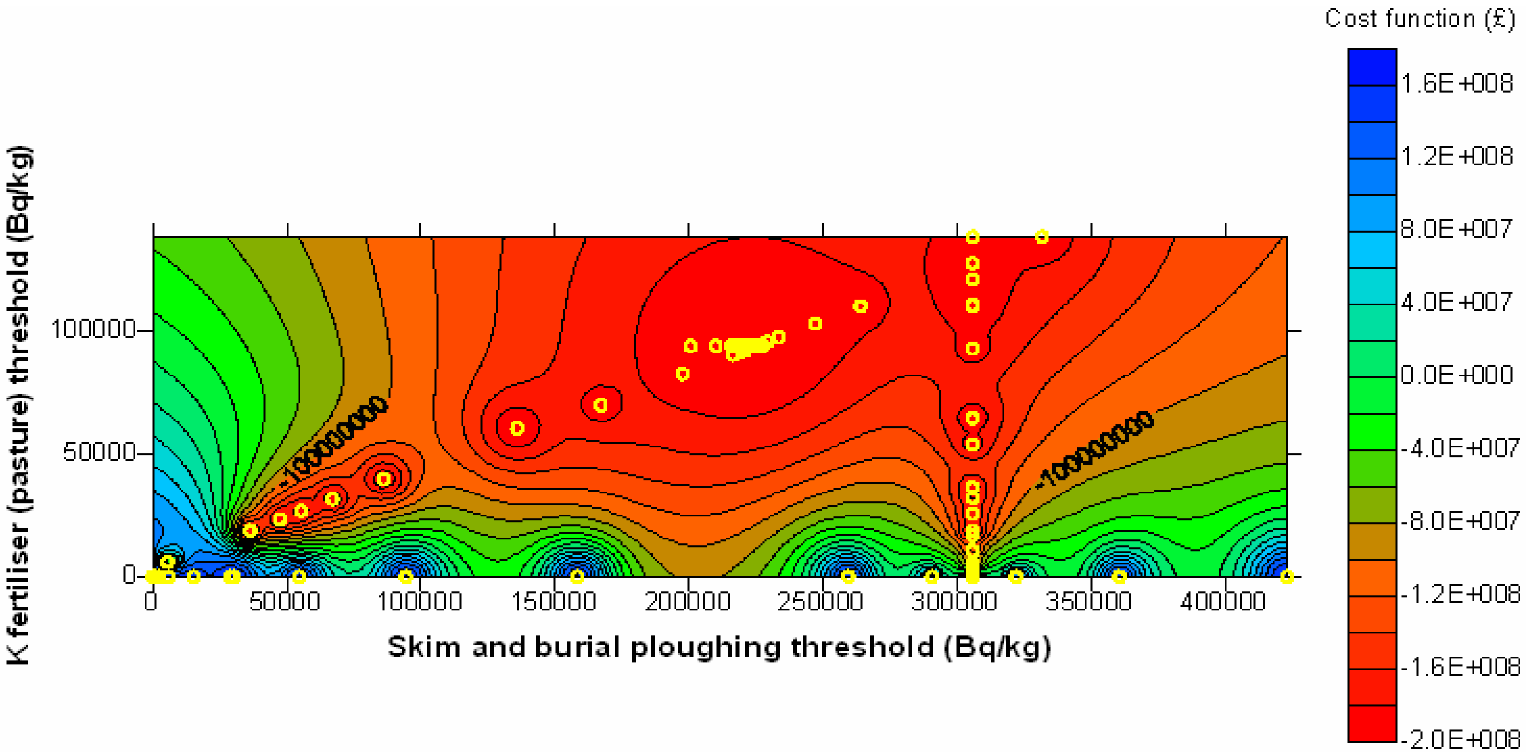

Figure 4.9 Relationship between the merit function (£) and the implementation thresholds (Bq kg^{-1} ^{137}Cs pasture) of the skim and burial ploughing of pasture (x-axis) and addition of potassium fertiliser to pasture (y-axis) countermeasures during an example optimisation. Yellow circles indicate parameter values where the merit function was evaluated (the surface has been interpolated for illustrative purposes only).

4.2.4 Uncertainty

As detailed in previous chapters, the models used to predict the transfer of radionuclides through the environment, the resulting doses to human populations and the effects of radiological countermeasures are subject to uncertainty, and incorporate numerous assumptions and rationalisations. Furthermore, the preferences of decision makers and affected populations, subjectively expressed in terms of either the monetary values or utilities of the considered factors, are also likely to be subject to uncertainties. Consequently, when presented with remediation strategies suggested by DSS, the effects of the uncertainties and assumptions in the underlying models on the output from the strategy selection process, and the sensitivity of that process to the values of system parameters and variables, may be key considerations for decision makers. Sensitivity and uncertainty analyses therefore constitute important tools in developing the confidence of decision makers in the outputs from DSS, and consequently, the facility to perform limited sensitivity analysis has been incorporated into the system described here. To date, the only other comparable DSS which has explicitly incorporated the facility for performing these analyses is the MOIRA DSS, which allows the utilities and weights assigned to the consequences of countermeasures' implementations to be varied stochastically, enabling the uncertainty in the overall utility of remediation strategies to be estimated, and the major factors which lead to those uncertainties to be identified (Insua et al., 2000).

Within the system described here, two procedures, termed SA1 and SA2, have been incorporated which allow limited analyses of the sensitivity of the merit function to countermeasures' implementation thresholds:

SA1

This procedure allows the sensitivity of the merit function about the proposed optimum to be investigated. The implementation thresholds of selected countermeasures are randomly varied within defined ranges of their optimum values, assuming uniform probability distributions within those ranges, and the resulting remediation strategies assessed.

SA2

This procedure allows the variation of the merit function over the full parameter space to be investigated. Strategies are randomly generated by Monte-Carlo sampling from within the full ranges of selected countermeasures' implementation thresholds, assuming uniform probability distributions over these ranges.

The outputs from both procedures are the values of the merit function, the averted dose and the total implementation cost of each strategy produced, in addition to the estimated expenditure on each selected countermeasure.

A limitation to the approaches described is that, over certain ranges, the implementation thresholds of countermeasures are not necessarily related to the extent of their implementation. This is caused by the finite spatial and temporal representation of a scenario which produces "flat" regions in the parameter space. Consequently, when the implementation threshold of a countermeasure is varied by relatively small amounts, there may be no corresponding variation in the extent of its implementation and the value of the merit function (Figure 4.10).

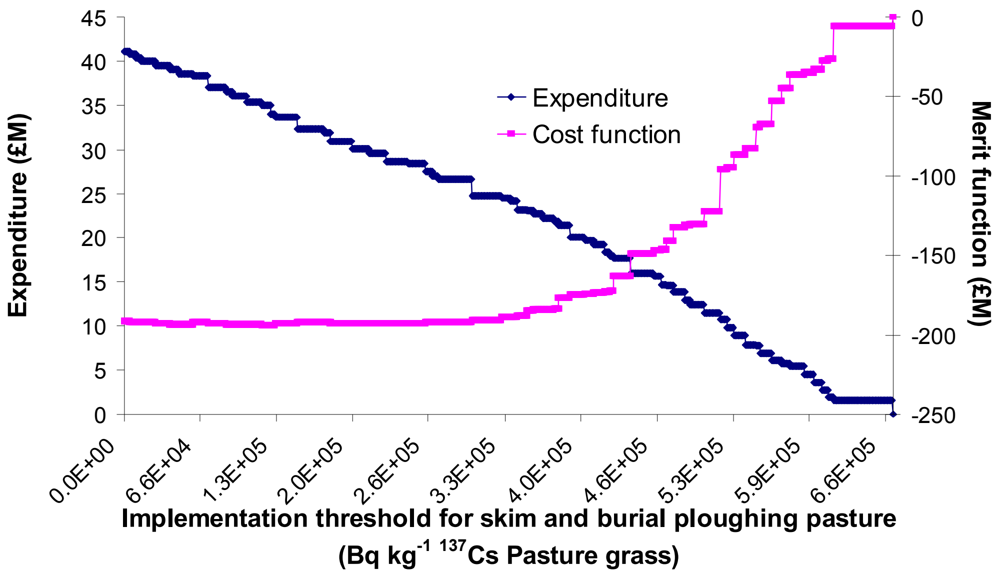

Figure 4.10 Illustration of the "flat" regions in the value of the merit function, for the skim and burial ploughing of pasture countermeasure, due to the spatial and temporal representation of affected areas.

This limitation should be borne in mind when interpreting the outputs from the sensitivity procedures described, as the variation in a countermeasure's implementation threshold may have little effect on the merit function, but the *extent* of implementation may actually have a large effect upon it. This effect may be particularly important for the SA1 procedure, where the variation in the implementation threshold may be relatively small. A potential remedy for this limitation would be to allow the expenditure levels of countermeasures to be altered rather than implementation thresholds; however, due to the structure of the system this is not straightforward.

A further limitation arises because when countermeasures which are mutually exclusive (e.g. the normal and deep ploughing of pasture countermeasures) the countermeasure with the lowest implementation threshold is preferentially implemented. Consequently, if there is a large difference between the optimum implementation thresholds of two mutually exclusive countermeasures, the implementation level of the countermeasure with the highest implementation threshold may not be varied during an SA1 procedure. Furthermore, including mutually exclusive countermeasures within an SA2 analysis will result in high implementation levels of the countermeasures being selected more often than low implementation levels due to the preferential implementation of the countermeasure with the lowest implementation threshold.

Despite these limitations, these procedures still provide useful information on the sensitivity of the merit function about the estimated optimum to the extent of individual countermeasures' implementations, and the overall relationships between countermeasures' implementation levels and the merit function.

4.3 SUMMARY

To account for the spatial variation in the transport of radionuclides, following a significant nuclear accident, DSS typically represent the affected area using numerous discrete regions. Remediation strategies can then be simulated as combinations of countermeasures within each defined region, and assessed in order to determine the optimum strategy. However, even in simple scenarios, using only a few discrete regions and a limited number of countermeasures, the number of potential strategies may be very large. The assessment of such large numbers of options may not feasible within a reasonable time-frame and, consequently, methods have been developed to reduce the number of strategies for evaluation. Previously, screening techniques have been developed to achieve this task. However, use of such techniques effectively limits the number of regions and countermeasures that can be considered, as the screening efficiencies required to reduce the number of potential options to a manageable size may not be attainable for scenarios with many distinct regions and numerous potential countermeasures.

The alternative approach taken here does not employ a screening technique, but rather, uses a classical mathematical minimisation procedure (Powell's direction set method) to identify optimal remediation strategies by adjusting the extents of selected countermeasures' implementations. Strategies are assessed using either a simple or extended cost-benefit analysis, which can take into account the preference for averting high levels of individual dose, or the social impacts of countermeasure side-effects.

In addition, other procedures have been incorporated into the system, which allow decision makers to investigate the effects of a particular countermeasure, or combination of countermeasures, within a scenario, and to assess the ability of countermeasures to meet defined radiological or economic criteria. These procedures can be used to identify those countermeasures which are unlikely to be of benefit in a scenario, and which should not therefore be included within the optimisation procedure, thus limiting the computational effort and time required to perform this numerically intensive task.

Furthermore, a simple Monte-Carlo procedure has been incorporated which provides the ability to perform limited sensitivity analyses on the merit function, either within defined ranges of the suggested optimum implementation thresholds of countermeasures, or over the full range of their possible implementation levels.

CHAPTER 5: CASE STUDIES

5.1 INTRODUCTION

To assess the applicability of the countermeasure selection model to different conditions, it was applied to two contrasting case study sites for which the required input data was collated. The first site was the county of Cumbria in NW England; the second was the province of Zaragoza in the NE Spain. For each site, a simple deposition pattern was created using a source term derived from Kelly and Clarke (1982), who describe potential releases from a pressurised water reactor (PWR) degraded core accident. This provided realistic large-scale accidents, however, it should be noted that this type of reactor site is not present in either case study area. Only ^{137}Cs, ^{90}Sr, ^{239}Pu and ^{241}Am are detailed in these case studies because this system is focussed on long-term remediation strategies, and the other isotopes described by Kelly and Clarke have relatively short half-lives (i.e. days).

In this chapter, the input data used for each case study are described, together with the results of the scenarios investigated. Discussions relating specifically to each case study are presented with the appropriate set of results. To facilitate comparisons, the contrasts between the results of the two case studies are discussed separately.

5.2 OVERVIEW

Both case study sites were represented, geographically, using a two-dimensional array of cells, with a scale of 5 × 5 km. This resulted in 271 cells for Cumbria and

689 for Zaragoza. All mapped inputs and outputs hereafter are shown to this scale (unless otherwise stated). All spatially distributed input data were provided by the Centre for Ecology and Hydrology, Merlewood, Cumbria.

For each case study, the effectiveness of various countermeasure strategies were investigated for a ten-year period post-deposition. These were:

i. **"Do nothing" strategy.**

No countermeasures were implemented. This strategy allowed the full consequences of each scenario to be assessed, and was used as a baseline for the assessment of averted dose in the other remediation strategies.

ii. **"Food restrictions" strategy.**

Food restrictions were implemented at the recommended CFILs (Council Food Intervention Limits, CEC (1989)) for dairy produce (i.e. 1000 Bq kg^{-1} ^{137}Cs, 125 Bq kg^{-1} ^{90}Sr, 20 Bq kg^{-1} for the actinide isotopes). These limits were applied to all food products, resulting in conservative CFILs for non-dairy produce. The CFILs for other major food products are actually 1.25-fold higher for ^{137}Cs, 4-fold higher for actinides and 6-fold higher for ^{90}Sr. No other countermeasures were implemented. This strategy was assessed as it represents the statutory minimum action to be taken following a nuclear accident.

iii. **"Optimised (without side-effects)" strategy.**

The implementation thresholds of selected countermeasures were optimised without considering any side-effects arising from their implementation. Food restrictions were implemented at the recommended CFILs for dairy produce, as above (i.e. for any food product above the CFIL despite the implementation of other countermeasures).

iv. **"Optimised (with side-effects)" strategy.**

The implementation thresholds of selected countermeasures were optimised taking into account a limited number of side-effects arising from their implementation. Food restrictions were implemented at the recommended CFILs for dairy produce, as above.

For each strategy, various discount rates were used to account for the changes in the values of costs and benefits over long time periods. As stated previously, these temporal variations occur because individuals, or society as a whole, may prefer to have benefits sooner rather than later, and to have costs deferred. In addition, costs incurred in the future may be more or less expensive than at present depending on market conditions. However, because discount rates have implicit ethical considerations associated with them, the assignment of their values is a subjective process. For this reason, all restoration strategies were evaluated with zero and non-zero (3% for benefits and 5% for costs) discount rates. However, as there were no significant differences found between the suggested strategies in either of the scenarios when using zero or non-zero discount rates, only the results obtained with zero discount rates will be presented here.

Prior to generating strategies via the optimisation procedure, all countermeasures were assessed individually, using the countermeasure inspection procedure within the system, in order to identify those that were likely to be of benefit within the defined scenarios. This "pre-selection" reduced the number of countermeasures to be included within the optimisation, thus reducing the time taken for computation. For each individual countermeasure, the value of the merit function was assessed with the implementation threshold at its maximum and minimum values, and at eight regular intervals in between. If the merit function was negative, or close to zero, at any point, this suggested that the countermeasure may have been of benefit in the scenario, and was therefore included in the optimisation process.

The countermeasures pre-selected for optimisation within both case studies were the same, and comprised:

- Normal ploughing of pasture.
- Deep ploughing of pasture, edible crops and silage crops.
- Skim and burial ploughing of pasture, edible crops and silage crops.
- Addition of potassium fertiliser to pasture, edible crops and silage crops.
- Clean feeding of dairy cows, beef cows, sheep, chickens and pigs.
- Administration of AFCF to dairy cows, chickens and pigs as concentrates, and to beef cows and sheep as boli.
- Dietary advice.
- Urban lawn mowing.
- Urban topsoil removal.

The ploughing of, or addition of potassium or lime fertilisers to, pasture in cells designated as environmentally sensitive areas (ESAs) was not permitted in any of the optimisations (this amounted to 45 % of the cells within Cumbria and 21% of the cells in Zaragoza as illustrated in Figure 5.1).

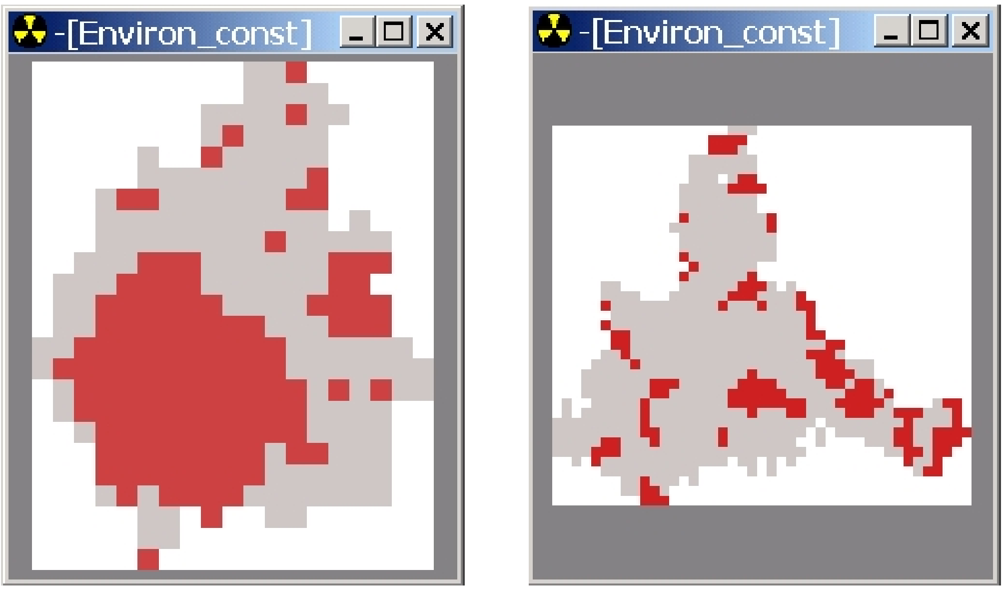

Figure 5.1 Cells (in red) designated as Environmentally Sensitive Areas (ESA) in Cumbria (left) and Zaragoza (right).

The attribute coefficients, used to scale the side-effects of a countermeasure's implementation, were assumed to be the same in both case studies (see Appendix A).

5.3 CUMBRIA

Cumbria is a largely rural county in the northwest of England, covering an area of approximately 6,775 km^2 (Figure 5.2). It contains the Lake District National Park (LDNP), which covers 2,292 km^2 and attracts around 6 million visitors a year (ANPA, 2004). Consequently, tourism is a major source of revenue in the region, employing nearly a quarter of the working population.

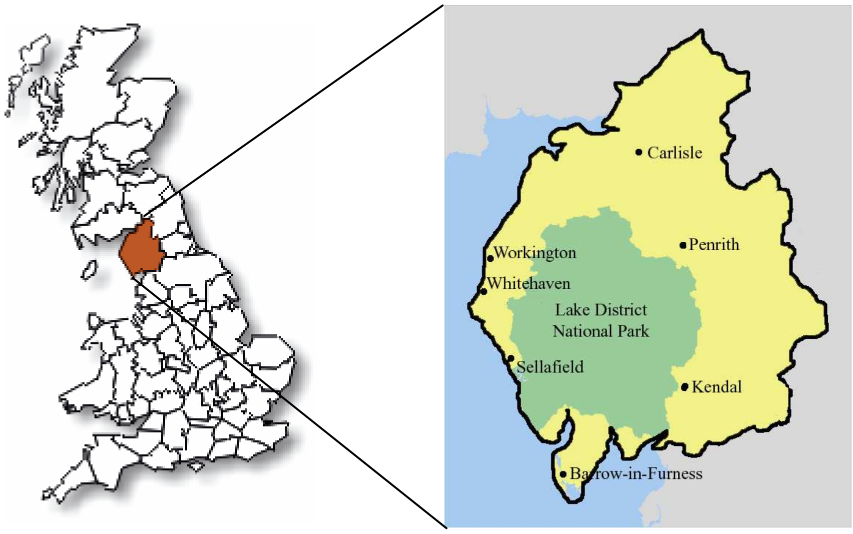

Figure 5.2 Cumbria, UK

National Park status recognises the importance of the area, and confers the highest degree of protection for the landscape, wildlife and human heritage within the park's boundaries available under UK law. This is an important factor that should be considered when designing radiological remediation strategies in the area, as some remediation techniques may not be permitted due to regulation, or desirable due to their impact upon the park's protected attributes. The county also contains the Sellafield (previously called Windscale) nuclear reprocessing plant, situated on the western coast. Historically, Cumbria has experienced radioactive deposition from a number of sources. In 1957, a fire at one of the Windscale piles necessitated restrictions on the entry of milk into the human food-chain due to ^{131}I contamination (UNSCEAR, 2000). In addition, the deposition of radiocaesium in the county, following the 1986 Chernobyl accident, resulted in restrictions on the slaughter and movement of sheep, which are still in place on some farms to date (Wright et al., 2003).

The climate of the region is relatively cool compared to the rest of the UK. Average minimum monthly temperatures range from 0.4°C in January to 10.5°C in July, and average maximum monthly temperatures from 5.7°C in January to 19.4°C in July (Meteorological Office, 2003). It is also the wettest region in England, with an average annual rainfall of over 1000mm, and approximately 150 days of more than 1mm of rainfall.

5.3.1 Deposition scenario

The scenario defined for the Cumbrian case study was a significant accident (with a total deposition of 1.82×10^{14} Bq) at a hypothetical nuclear power station on the western coast. The contaminated plume, resulting from the accident, was assumed to spread north-eastwards due to the prevailing south-westerly wind, in the general direction of Carlisle and Penrith, resulting in the contamination of 71% of the cells representing the region (Figure 5.3).

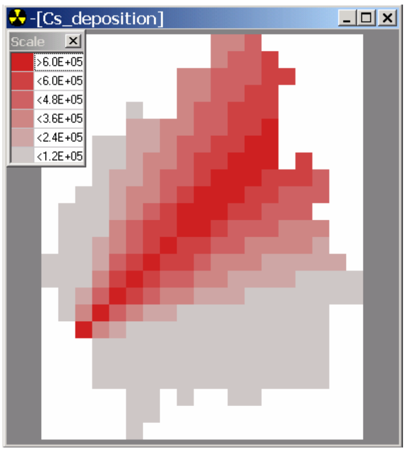

Figure 5.3 Spatial distribution of deposited ^{137}Cs in the Cumbrian case study (Bq m^{-2}).

As a result of the assumed wind direction, the northern portion of the LDNP received significant depositions of radionuclides, while the southern portion received little or none. ^{137}Cs was the biggest contributor to the total deposition, followed by ^{90}Sr, ^{239}Pu and then ^{241}Am (Table 5.1). The relative contribution of each radionuclide to the deposition within a cell was assumed to be the same in each cell within the study area.

Table 5.1 Total and maximum depositions in the Cumbria case study, by radionuclide.

Radionuclide	Total deposition (Bq)	Maximum deposition (Bq m^{-2})
^{137}Cs	1.7×10^{14}	685,000
^{90}Sr	1.2×10^{13}	47,000
^{239}Pu	2.8×10^{10}	11
^{241}Am	5.3×10^{9}	2

5.3.2 Soil characteristics

Soil properties (i.e. pH, exchangeable potassium, % clay and % organic matter) were derived from block-kriging interpolation of measured soil properties from the Geochemical Atlas of England and Wales (McGrath and Loveland, 1992). The Geochemical atlas data were sampled at the centre of 5 × 5 km cells for England and Wales (5648 samples); semi-variogram models were fitted to soil properties for England and Wales and then interpolated for Cumbria at 5 × 5 km resolutions (Figure 5.4). In terms of soil properties, Cumbria can be divided into to two distinct areas. The uplands regions (i.e. within the LDNP and the Pennine hills on its eastern border) are characterised by soils which are acidic, rich in organic matter and, in the case of the Pennines, have relatively low levels of exchangeable potassium.

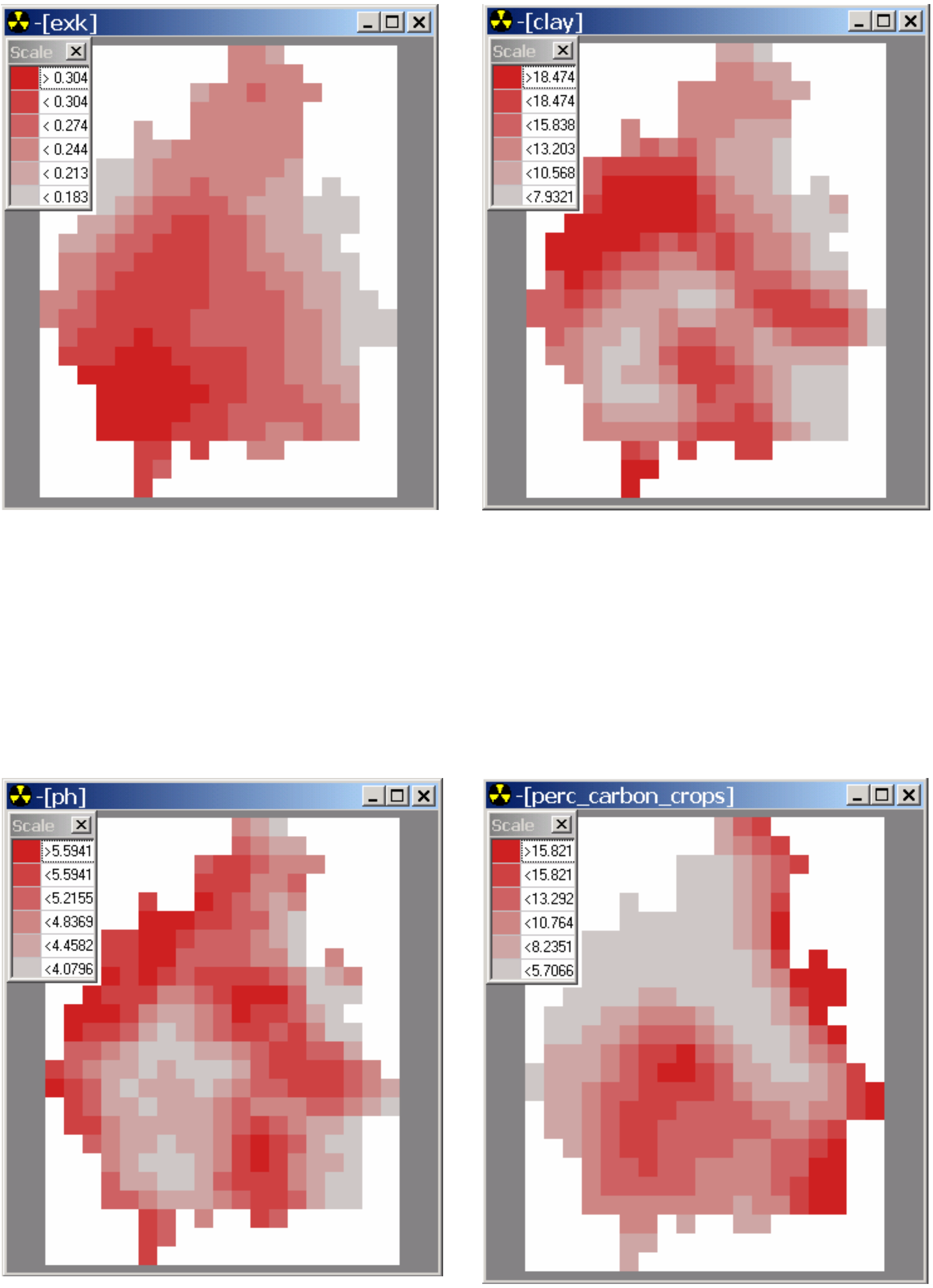

Figure 5.4 Interpolated soil characteristics used in the Cumbrian case study. Exchangeable potassium (cmol kg^{-1}) (top left), % clay (top right), pH (bottom left) and % organic matter (bottom right).

In contrast, the rest of the county is typified by soils with comparatively low organic matter content, higher pH and, particularly in the south-west of the region, high exchangeable potassium status.

5.3.3 Agricultural management and production

Data regarding the management of crops (i.e. sow and harvest dates, yields and the minimum biomass for each crop) in Cumbria were taken from the SAVE system (Gillet et al., 2001). Livestock feeding regimes were derived from Nix (2001), and Nisbet et al. (1998). (see Appendix B for full details of the agricultural management data used).

Spatial land cover data (Fuller et al., 1994) were combined with county level production statistics (MAFF, 1996), advised stocking rates and regional crop yield data (Nix 2002) to estimate the agricultural output of the region, which is focussed upon the production of animal-derived food products (Table 5.2). Consequently, there is an estimated 534,000 hectares of pasture used for grazing animals within the county, compared with only 44,000 hectares of tilled land.

Although the production rate of cereals was estimated to be the second highest of any food product, only 43% was assumed to be for human consumption: the remainder was assumed to be used for animal feed (47%) and industrial use (10%) according to the approach of Crout et al. (1999).

Table 5.2 Production rates of food products used in the Cumbria case study

Food product	Production rate (Tonnes y^{-1})
Cow milk	780,000
Cereals	135,000
Chicken	43,000
Beef	31,000
Lamb	21,000
Potatoes	16,000
Maize	8,900
Pork	6,200
Fruit	533
Root vegetables	517
Leafy vegetables	460

The majority of dairy and meat food products are produced from animals grazed on lowland pastures, however, a significant proportion of lamb (36%), and to a lesser extent beef (4.3%), are produced from animals grazed on upland pastures (Figure 5.5).

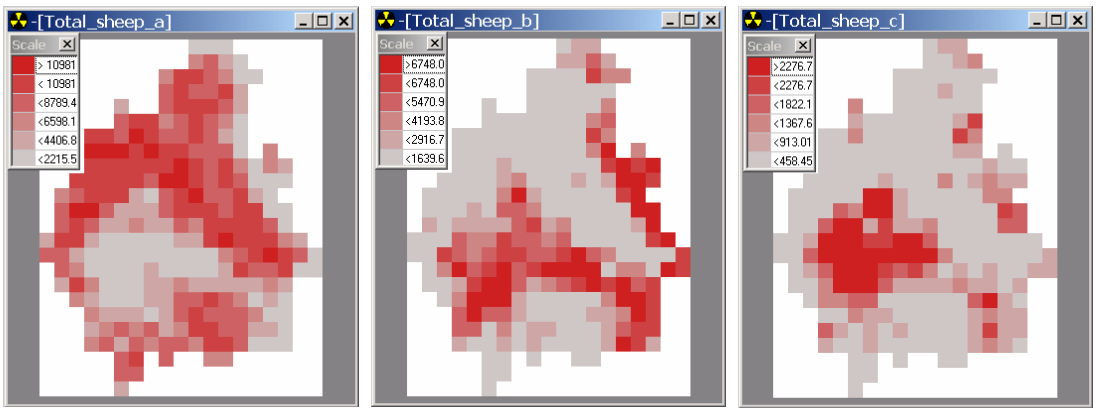

Figure 5.5 Estimated spatial distribution of the total number of sheep grazing on lowland pasture (left), moorland and heathland (middle) and upland pasture (right) within Cumbria.

Cells containing areas subject to environmental constraints (i.e. Sites of Special Scientific Interest (SSSI); National Nature Reserves (NNR) and organic farms) were designated according to land cover data from English Nature (2003), and restrictions on the implementation of countermeasures within these cells were taken from DEFRA (2003) and Soil Association (2003).

5.3.4 Population characteristics

The Cumbrian population was represented by fifty sub-populations, created by Monte-Carlo sampling of the defined statistics for the overall population. Given below is a brief description of the main characteristics of the population (for full details of the characteristics used see Appendix B). Data regarding the spatial distribution of the human population were derived from SURPOP (2003). The population, consisting of approximately 419,000 people, is widely distributed, with the main centres of population being Carlisle (~68,000), Penrith (~15,000), Barrow-in-Furness (~70,000), Whitehaven (~25,000), Workington (~25,000) and Kendal (~27,000) (Figure 5.6).

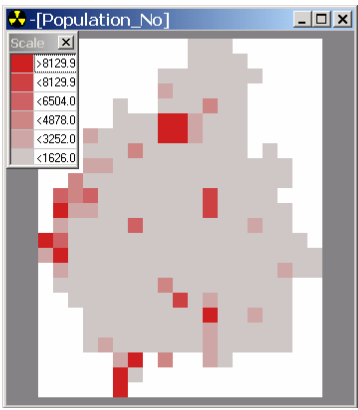

Figure 5.6 Estimated spatial distribution of population density in Cumbria

5.3.4.1 Diet

Mean consumption rates for the food products considered, with associated standard deviations and percentage consumers, were derived from the Nutritional Survey of British Adults (MAFF, 1990), Crout et al. (1999), and Byrom et al. (1995). The dietary consumption of the UK population as a whole (and assumed here to be representative of Cumbria) is typified by relatively high intakes of meat, potatoes and dairy products, and relatively low intakes of fruit and vegetables. Five percent of the population were assumed to be vegetarian (Henderson, Gregory and Swan, 2001).

Information regarding the geographical origins of food products consumed in the UK is limited. However, the dietary habits (including the consumption of home-grown produce) of the population around the Sellafield nuclear processing plant have been surveyed (Stewart, Fulker and Jones, 1990), and this information was used to derive the percentage of home-grown food products consumed by the residents of Cumbria. However, 25% of the survey group in this study were farmers (compared to a national average of 2-3%), who are more likely to consume local or home-produced food products and to have higher than average consumption rates. Therefore, to take account of the bias introduced by the high percentage of farmers, data taken from this source were adjusted accordingly. Consequently, 30% of people were assumed to consume home-grown fruit and vegetables, but, on average, this only constituted 15% of their total intake for this food group. No data were available regarding the sourcing of food products from local sources (not including home-grown), regional sources, or external sources and, therefore, these parameters were estimated using expert judgement. Most of the food products consumed by the residents of Cumbria were assumed to be produced outside of the region, as the majority of people in the

UK obtain their groceries from supermarkets, who source their products not only from the UK, but worldwide. On average, all sub-populations were assumed to source between 10 and 15% of each food group from within the region, and between 80 and 90% from outside of the region. Twenty percent of the population were assumed to source, on average, 20% of their fruit and vegetable intake locally, while for dairy and meat products, 1% of the population was assumed to source 80% and 50% of these food products locally.

5.3.4.2 Activity profiles

The types of buildings occupied by the residents of Cumbria were determined using data from the Office of National Statistics (2003). Sixty-one percent of people in Cumbria live in detached or semi-detached houses, 31% in terraced houses and 7% in flats. For the purposes of this case study, detached and semi-detached houses were assumed to be equivalent. Occupancy factors for the locations considered within the external dose model were derived from Brown (1983). The mean occupancies of home dwellings and work places were assumed to be 77% and 23% respectively. People living in semi-detached or terraced houses were assumed to spend, on average, 60% of their time at home on the first floor, 25% on the ground floor, 5% in attics and 10% immediately outside their house. Individuals living in flats were assumed to spend 95% of their time within their flat (assumed to be on one level only) and only 5% immediately outside of the building. In the industrial environment, 70% of people were assumed to work in offices with the remainder working in factories or supermarkets.

5.3.4.3 Social preferences

The preferences of the Cumbrian population for the limited number of environmental and social attributes considered in this system, described in Chapter 2, were assessed using a Choice Modelling technique by Álvarez and Gil (2003). The preferences were expressed as the monetary value individuals were willing to pay each year, over a five year period, in order to maintain each attribute. The most important attribute to the Cumbrian population was found to be landscape/biodiversity, followed by animal welfare, normal daily life and water quality (Table 5.3). No value could be inferred for the heritage attribute from the outputs of the questionnaire.

Table 5.3 Estimated social and environmental preferences of the Cumbrian population for the considered attributes.

Attribute	Mean value[a] (£)	Standard deviation[a] (£)
Landscape/biodiversity	34.5	7.9
Animal welfare	26.1	6.3
Normal daily life	15.7	4.0
Water quality (for recreational use)	13.3	4.0
Heritage	-	-

[a] Values represent the amount an individual is willing to pay annually over a five year period.

5.3.5 Urban parameters

Required urban parameters (i.e. area of walls, roofs, roads and gardens and numbers of industrial and residential buildings) were derived for seven Cumbrian towns (Barrow-in-Furness, Carlisle, Kendal, Penrith, Ulverston, Whitehaven and Workington) from Ordnance Survey MasterMap data (Ordnance Survey, 2003). These data were compared to the Land Cover Map of Great Britain (Fuller et al., 1994), suburban and urban land cover classes and spatial population data. Spatial data for urban parameters for the whole of Cumbria were then derived using the resultant land cover – urban parameter linear relationships.

5.3.6 Additional system parameters

In addition to the input data required for the database and population characteristics, some supplementary, case-study specific, parameters were also required by the system. The monetary value of the collective dose received in this case study was estimated using a variable α-value, as described by Lochard et al. (1996). The value of α_{base} used (£20,000 man-Sv^{-1}) was the value recommended for use in the UK by the NRPB (1993). The aversion coefficient (2.51) was taken from an assessment of the value of the averted dose for public exposure in Hungary (Katona et al., 2003) and the threshold dose of 1 mSv y^{-1} is the dose limit recommended by the ICRP for additional doses resulting from practices (ICRP, 1990). Although radioactively contaminated land does not constitute “a practice”, many national authorities use recommendations intended for practices as targets in remediation situations (Linsley, 2002), and therefore this value was deemed reasonable for use here.

Market prices for food products, livestock animals, feedstuffs and service costs for countermeasures were taken from DEFRA (2003) and Nix (2002).

5.3.7 Results

5.3.7.1 "Do nothing" strategy

With no countermeasures implemented, exposure to external radiation was predicted to be the major contributor to the collective dose of the population living within Cumbria: contributing approximately three times as much as ingestion sources (Table 5.4). This relatively small contribution from the ingestion pathway is because most of the local population's diet was assumed to be sourced from outside of the region, where food products were assumed to be uncontaminated. As a result, 97% of the dose arising from food products produced within Cumbria was exported outside the region.

Table 5.4. Collective doses for the "Do nothing" strategy in Cumbria.

Local collective ingestion dose (man-Sv)	245
Local collective external dose (man-Sv)	764
Total local collective dose (man-Sv)	1,008
Exported collective ingestion dose (man-Sv)	35,873

The distribution of the individual doses received within the region shows that 90% of the population (~379,000 people) received doses of less than 7.5 mSv over the ten year study period (Figure 5.7). The highest individual doses over this time were close to 75 mSv. The distinguishing features of the sub-population who received this level of dose were that their rate of milk consumption was above average (213 L a^{-1} compared with a mean of 177 L a^{-1}), and that 88% of the milk that they consumed was produced locally (i.e. from within their own cell).

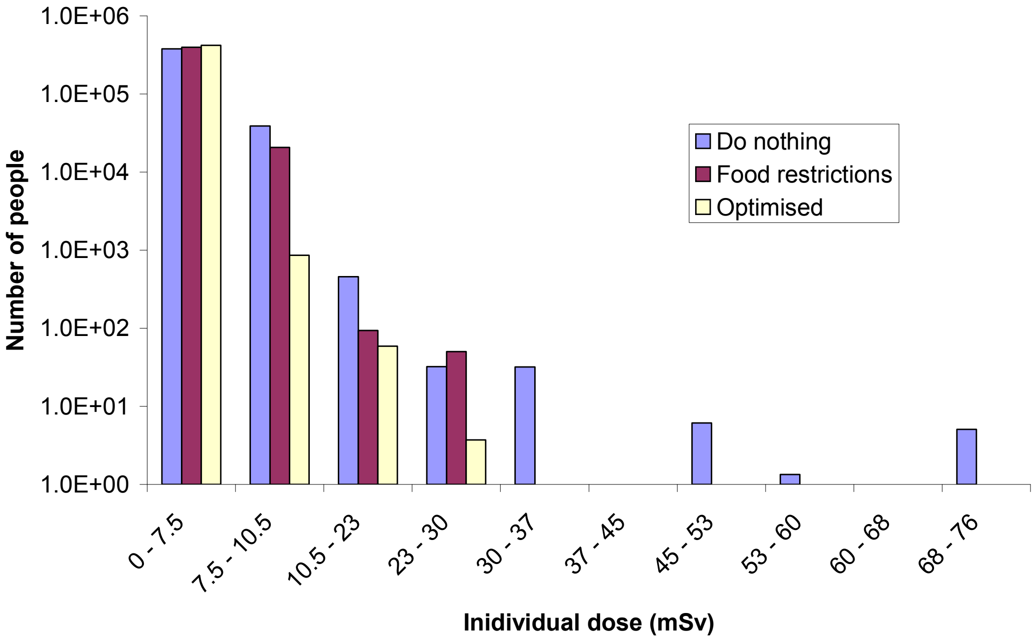

Figure 5.7. Frequency of predicted individual doses received by the residents of Cumbria over the ten year study period for the "Do nothing", "Food restrictions" and "Optimised" strategies.

The food products responsible for the majority of the local collective ingestion dose were potatoes (30.4%), lamb (26.1%), cow milk (13.2%), fruit (12.9%), beef (8.4%) and cereals (4.9%) (Figure 5.8). The contributions from potatoes and fruit are relatively large because their mean consumption rates are high compared to other food products, and because they are often home-grown. A compounding factor in the case of fruit was that the first harvest took place three months post-deposition; when the activity concentrations of the plants were still considerable (the predicted mean radiocaesium activity concentration for contaminated fruit plants, two months post-deposition, was 18,857 Bq kg^{-1}). Cow milk contributed significantly to the local collective ingestion dose, despite the assumption that relatively few people sourced some of their milk intake locally or regionally (1% and 10% of the population respectively), because its mean consumption rate was the highest of any food product.

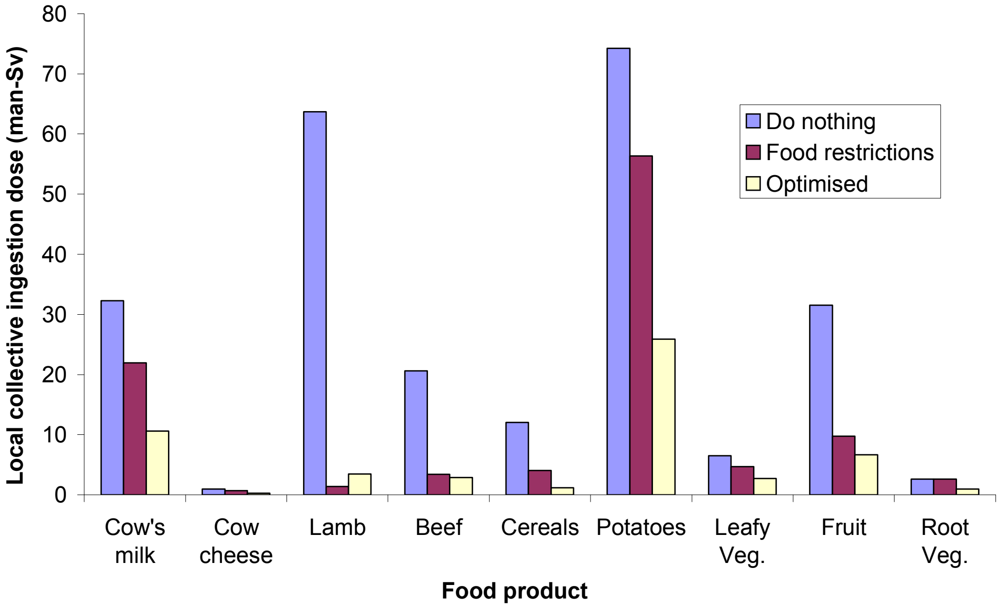

Figure 5.8 Local collective ingestion dose, by food product, for the "Do nothing", "Food restrictions" and "Optimised" strategies.

Lamb and beef products made considerable contributions to the local collective ingestion dose because significant proportions of these products were produced in areas with high radiocaesium bioavailability (i.e. upland areas with nutrient poor soil with high organic matter content). This effect can be seen in Figure 5.9, where the areas with the highest activity concentrations in lamb 12 months post-deposition are the upland regions of the LDNP and the Pennines, rather than the areas which received the highest deposition.

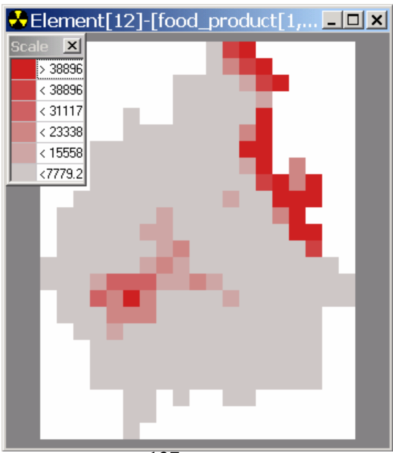

Figure 5.9 Predicted ^{137}Cs activity concentrations in lamb, 12 months post-deposition (Bq kg^{-1} FW)

The exported collective ingestion dose was predominantly due to lamb (27,402 Sv, 76%) and beef (5227 Sv, 14%) (Figure 5.10), as a consequence of the high bioavailability of radiocaesium in upland areas, where the grazing of sheep, and to a lesser extent, cattle, is common.

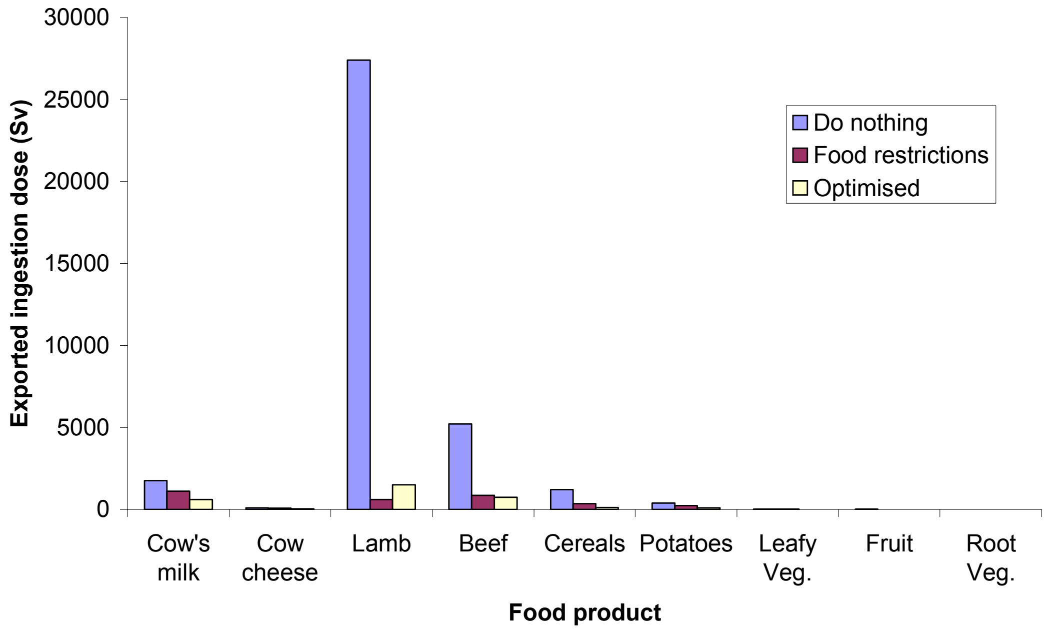

Figure 5.10 Estimated exported ingestion dose (Sv), by food product, for the "Do nothing", "Food restrictions" and "Optimised" strategies in Cumbria.

In terms of radionuclides, ^{137}Cs was predicted to contribute the most to the overall collective ingestion dose (Table 5.5). In part, this was due to its relatively high deposition levels compared to the other radionuclides. However, in the initial deposit, ^{137}Cs contributed only approximately 14 times as much activity as radiostrontium, but the contribution of ^{137}Cs to the collective ingestion dose is over 50 times as much as ^{90}Sr, despite having a lower dose coefficient. This is due to the long-term bioavailability of radiocaesium within Cumbria, caused by the soil characteristics within the region. The immobile nature of the actinide isotopes in the environment is reflected in their relatively insignificant contribution to the collective ingestion dose.

Table 5.5. Contribution to the total collective ingestion dose in Cumbria by radionuclide.

Radionuclide	Collective ingestion dose (Man-Sv)
^{137}Cs	35,444
^{90}Sr	674
^{239}Pu	2.3×10^{-3}
^{241}Am	5.1×10^{-4}

5.3.7.2 "Food restrictions" strategy

This strategy was estimated to cost just over £2,000M, and avert approximately 33,000 man-Sv over the ten-year study period (Table 5.6). Almost all of the averted dose (99%) was due to a reduction in the exported collective ingestion dose, which was reduced by 91% compared with the "Do nothing" strategy, whilst the local collective ingestion dose was only reduced by 61%. The maximum individual dose received by the residents of Cumbria was also reduced from around 75 mSv in the "Do nothing" strategy, to approximately 30 mSv (Figure 5.7).

Table 5.6 Summary results of the "Do nothing" and "Food restrictions" strategies in Cumbria.

	Do nothing	Food restrictions
Local collective ingestion dose (man-Sv)	245	105
Local collective external dose (man-Sv)	764	764
Total local collective dose (man-Sv)	1,008	868
Exported collective ingestion dose (man-Sv)	35,873	3,148
Averted dose (man-Sv)	0	32,864
Implementation cost (£M)	0	2,298
Merit function (£M)	0	+1,630

Restrictions on the entry of lamb into the food chain accounted for 81% of the total reduction in the collective ingestion dose, with restrictions on beef accounting for a further 13% (Figures 5.8 and 5.10). As highlighted previously, significant numbers of the sheep and beef cattle in Cumbria are allowed to graze on land susceptible to long-term radiocaesium bioavailability. Consequently, it was predicted that the activity concentrations of lamb and beef products would remain high throughout the study period, and that the restrictions on these food products would still be required, ten-years post-deposition, in 45% and 31% of cells respectively (Figure 5.11).

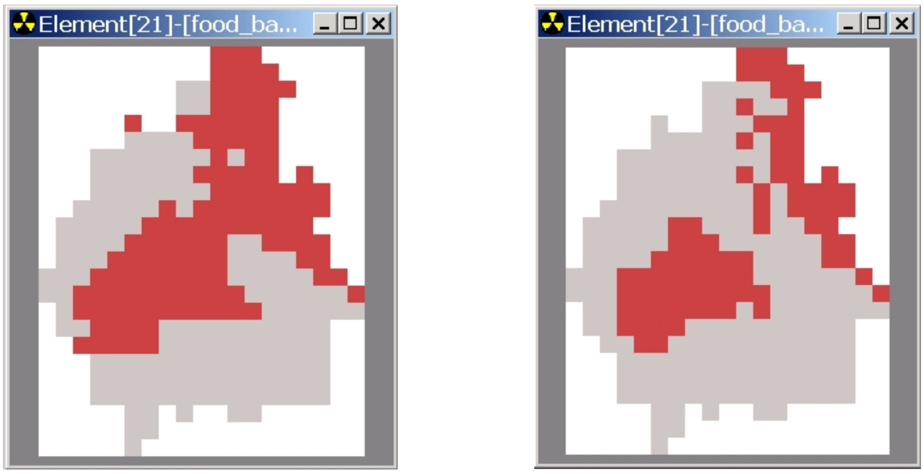

Figure 5.11 Spatial extents of food restrictions in Cumbria (indicated by red cells) on the sale of lamb (left) and beef (right), ten years post deposition.

However, in terms of implementation cost, restrictions on lamb products only accounted for 66% of the total cost, while restrictions on beef products constituted 32% of the total (Table 5.7), reflecting the higher costs assumed for disposing of cattle carcasses as compared with sheep carcasses (£3,724 compared with £266).

The value of the merit function for this scenario is positive, which, according to the ICRP (1998), indicates that this strategy would be unjustified, as the scale of the resources to implement it would outweigh the derived benefits (i.e. the averted dose). Interestingly, this strategy is similar to the actions taken following the Foot and

Mouth disease epidemic in the UK in 2001, albeit on a longer time-scale. In that instance there was no risk to human health, however, a policy of culling infected herds was instigated rather than a system of vaccination, despite widespread public fears regarding animal welfare and environmental pollution, in order to ensure the future economic viability of the meat and dairy industry in the UK.

Table 5.7 Estimated cost of food restrictions by food product, with associated wastage, for the "Food restrictions" strategy in Cumbria.

Food product	Cost of restriction (£M)	Waste generated
Lamb	1,530	5.2×10^6 animals
Beef	728	1.7×10^5 animals
Cow milk	19	9.4×10^7 litres
Cow cheese	15.2	7.5×10^7 litres milk
Cereals	4.2	4.6×10^7 kg
Fruit	0.3	2.7×10^5 kg
Potatoes	0.6	6.0×10^6 kg

5.3.7.3 "Optimised (without side-effects)" strategy

The strategy suggested by the optimisation procedure represents a significant improvement upon the "Food restrictions" strategy. The local collective ingestion dose and the exported collected dose were 47% and 9% lower, respectively, whilst the local collective external dose was reduced by 35% (Table 5.8). In addition, the cost of implementing the strategy was estimated to be less than 10% of the cost of the "Food restrictions" strategy. Furthermore, in contrast to the "Food restrictions" strategy, the value of the merit function for the optimised strategy is negative, indicating that this strategy would be justified according to ICRP principles.

Table 5.8 Summary results of the "Do nothing", "Food restrictions" and "Optimised" strategies in the Cumbrian case study.

	Do nothing	Food restrictions	Optimised
Local collective ingestion dose (man-Sv)	245	105	56
Local collective external dose (man-Sv)	764	764	495
Total local collective dose (man-Sv)	1,008	868	551
Exported collective ingestion dose (man-Sv)	35,873	3,148	2,870
Averted dose (man-Sv)	0	32,864	33,192
Implementation cost (£m)	0	2,298	175
Merit function (£m)	0	+1,630	-511

The countermeasures suggested for implementation by the optimisation procedure are shown in Table 5.9. The marked difference between the implementation costs of the "Food restrictions" and "Optimised" strategies was due to the reductions in the amounts of lamb and beef products that required restriction over the ten year period (Table 5.10).

Table 5.9 Countermeasures suggested for implementation in the Optimised strategy for Cumbria, with associated costs and extent of implementation.

Countermeasure implemented	Cost (£m)	Extent
K fertiliser (Pasture)	49.2	n/a[1]
Skim and burial plough (Pasture)	41.1	116,000 hectares
Food restrictions	37	n/a[1]
Clean feed (Sheep)	20.7	n/a[1]
AFCF (Sheep)	11.9	2.9 million sheep
Deep plough (Silage crops)	8.0	133,000 hectares
Clean feed (Beef cows)	1.96	n/a[1]
AFCF (Beef cows)	1.95	314,000 cows
AFCF (Dairy cows)	1.41	111,000 cow months
Skim and Burial plough (Edible crops)	1.4	11,000 hectares
Urban lawn mowing	0.03	27×10^6 m^2

[1] Output data not available

Table 5.10 Estimated cost of food restrictions, by food product, for the "Food restrictions" and "Optimised" strategies in the Cumbrian case study.

Food product	Cost of food restrictions (£M)	
	"Food restrictions" strategy	"Optimised" strategy
Lamb	1,530	20.6
Beef	728	7.7
Cow milk	19	1.1
Cow cheese	15.2	3.6
Cereals	4.2	2.8
Fruit	0.3	0.6
Potatoes	0.6	0.3

These reductions were achieved by reducing the activity concentrations of the feedstuffs of these animals; particularly that of pasture grass. This was accomplished by skim and burial ploughing pasture in those cells where it was permitted, and by the administration of clean feed and AFCF, throughout the study period, in the cells where it was not (Figure 5.12). Although "skim and burial" is the most expensive type of ploughing, it was preferred to "normal" and "deep" ploughing in this scenario, as it is more effective at reducing the root-zone activity concentrations of radionuclides, and, consequently averts more dose per hectare ploughed.

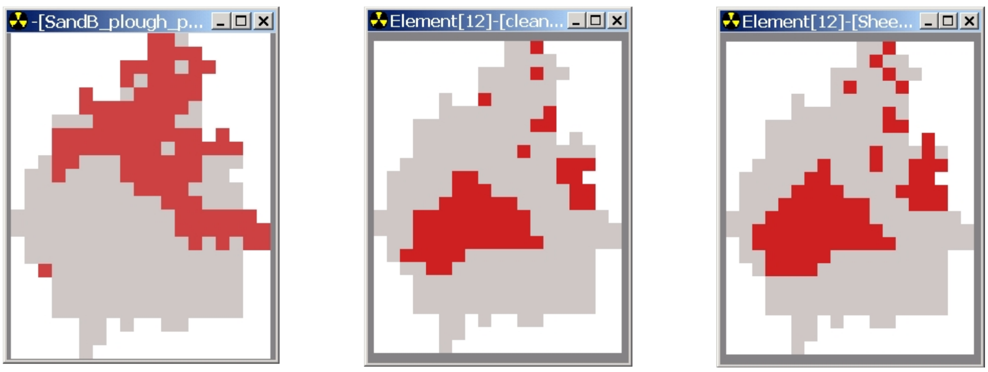

Figure 5.12 Suggested spatial extent (indicated by red cells) of skim and burial ploughing pasture (left), clean feeding of sheep 12 months post-deposition (centre) and administration of AFCF to sheep 12 months post-deposition (right) in the Optimised strategy for Cumbria.

Although the expenditure on the potassium fertilisation of pasture countermeasure is the greatest of any countermeasure in this strategy, its implementation is only suggested in approximately 5% of the cells. The implementation costs are relatively high as it is suggested that this countermeasure should be implemented in those cells annually within the 10 year study period.

Whilst the reduction in the collective ingestion dose in the optimised strategy was still predominantly due to the reduction in the activity concentrations of lamb products (accounting for 77% of the total reduction in ingestion dose), the collective ingestion dose received from lamb was greater than from the "Food restrictions" strategy (Figures 5.8 and 5.10, pages 147 and 148). This was because, in many cells, the predicted activity concentration of lamb was reduced by the additional countermeasures, to below the food restrictions implementation threshold. Consequently, these products did not require restriction and were thus allowed to enter the food chain, resulting in ingestion doses to consumers, rather than being disposed of and not contributing any dose to consumers. The reduction in the local collective external dose in this scenario was due solely to the implementation of the urban lawn mowing countermeasure. However, for this countermeasure to be fully effective, it should be implemented soon after deposition, and before any significant rainfall event (Andersson et al., 2003). In this scenario the system estimated that 2,700 hectares of lawn would require mowing, and it is questionable whether this could be accomplished within the required time-frame. Nevertheless, the knowledge that this countermeasure would be highly effective, if performed quickly enough, may still be useful for decision makers.

In comparison with the "Food restrictions" strategy, although the maximum individual dose received was not further reduced, the number of people receiving the highest levels of dose was reduced (Figure 5.7, page 145).

5.3.7.4 "Optimised (with side-effects)" strategy

The countermeasure strategy suggested by the optimisation procedure, with the social costs of countermeasures' side-effects included within the merit function, resulted in a similar scenario to that produced when side-effects were not considered (Table 5.11).

Table 5.11 Summary results of the "Optimised (without side-effects)" and "Optimised (with side-effects) strategies for Cumbria.

	Optimised (without side-effects)	Optimised (with side-effects)
Local collective ingestion dose (man-Sv)	56	55
Local collective external dose (man-Sv)	495	495
Total local collective dose (man-Sv)	551	550
Exported collective ingestion dose (man-Sv)	2,870	3,077
Averted dose (man-Sv)	33,192	32,986
Implementation cost (£m)	175	177
Side-effect cost (£m)	n/a	188
Merit function (£m)	-511	-318

The main differences between the two resultant scenarios were that the local collective ingestion dose was 2% lower, while the exported ingestion dose was 7.2% higher when side-effects were considered. In addition, the implementation cost was estimated to be £2.4M more than the previous strategy, while the merit function was estimated to be £193M higher. The higher value of the merit function was predominantly due to the inclusion of the social cost of countermeasures' side-effects (estimated to be £188M in total), but was also due to the 206 man-Sv decrease in the averted dose.

A comparison of the countermeasures suggested in the two strategies shows that the main differences were that, when countermeasures' side-effects were considered, the optimisation procedure suggested that more potassium fertilisation of pasture and administration of AFCF to sheep should be implemented, whilst the implementation of the administration of AFCF to beef and dairy cows, and clean-feeding of sheep and beef cows should be reduced (Table 5.12). Furthermore, an additional countermeasure, which was not suggested in the preceding strategy, was recommended: the addition of potassium fertilisers to edible crops. No difference was suggested in the extent of skim and burial ploughing pasture; despite this countermeasure having a large impact upon the landscape/biodiversity attribute. This may be because the costs of the side-effects associated with this countermeasure were low in comparison with the cost of the dose which it averts. Table 5.13 shows the estimated cost of the side-effects for each of the countermeasures suggested in this strategy. The total side-effect cost for skim and burial ploughing pasture was estimated to be £10.1M. Although it is not possible to obtain an exact figure for the monetary value of the dose averted by this countermeasure (as the system cannot determine how much dose each individual countermeasure of a strategy averts), an inspection of the countermeasure reveals that, on its own, it would avert approximately 11,400 man-Sv, with a monetary value of £233M.

Table 5.12 Suggested countermeasures, with associated implementation costs, in the "Optimised (without side-effects)" and "Optimised (with side-effects)" strategies for Cumbria.

	Countermeasure implementation cost (£M)		
Countermeasure	Optimised (without side-effects) strategy	Optimised (with side-effects) strategy	Difference
K fertiliser (Pasture)	49.2	53.5	+4.3
Skim and burial plough (Pasture)	41.1	41.1	0
Food restrictions	37	35.6	-1.4
Clean feed (Sheep)	20.7	20.4	-0.3
AFCF (Sheep)	11.9	12.5	+0.6
Deep plough (Silage crops)	8.0	8.0	0
Clean feed (Beef cows)	1.96	1.85	-0.11
AFCF (Beef cows)	1.95	0.57	-1.38
AFCF (Dairy cows)	1.41	1.39	-0.02
Skim and Burial plough (Edible crops)	1.40	1.40	0
K fertiliser (Edible crops)	0.0	0.7	+0.7
Urban lawn mowing	0.3	0.3	0.0

Table 5.13 Estimated side-effect costs (£M) for each countermeasure in the "Optimised (with side-effects)" strategy in Cumbria.

Attribute	Countermeasure											
	Clean feed (Sheep)	Food restrictions	Clean feed (Beef cows)	Skim and burial plough (Pasture)	AFCF (Sheep)	AFCF (Beef cows)	Clean feed (Dairy cows)	K fertiliser (Pasture)	AFCF (Dairy cows)	Skim and Burial (Edible crops)	K fertiliser (Edible crops)	Deep plough (Silage crops)
Landscape	50.1	9.3	26.5	8.5	0	0	0.04	0.02	0	0	0	0
Water quality	13.7	8.5	7.2	0.92	0	0	0.01	0.001	0	0	0	0
Animal welfare	5.3	0	2.8	0.71	6.3	5.4	0.01	0	0	0	0	0
Heritage	0	0	0	0	0	0	0	0	0	0	0	0
Daily life	0	20.7	0	0	0	0	0	0	0	0	0	0
Total	**68.6**	**38.5**	**36.8**	**10.1**	**6.3**	**5.4**	**0.06**	**0.021**	**0**	**0**	**0**	**0**

Consequently, the social cost of the side-effects for this countermeasure may constitute less than 5% of the benefit derived from its implementation, and is, therefore, unlikely to affect the optimum implementation threshold for this countermeasure significantly.

The relatively large social costs associated with the countermeasures that reduce the activity concentrations of lamb and beef food products (i.e. clean feeding, administration of AFCF and food restrictions) appear to be the driving force behind the differences between the two strategies. The system attempts to minimise these costs by reducing the implementation of these countermeasures, and consequently the ingestion doses arising from lamb and beef are 4 man-Sv and 186 man-Sv higher respectively than in the strategy produced when not considering side-effects (Figure 5.13).

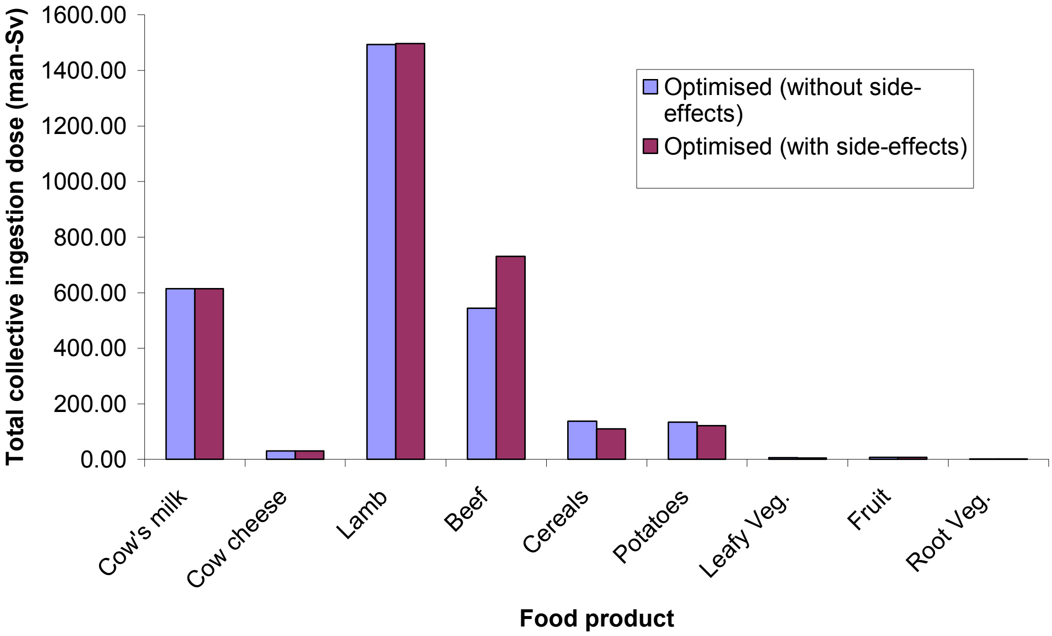

Figure 5.13 Estimated collective ingestion dose, by food product, in the "Optimised (without side-effects)" and "Optimised (with side-effects)" strategies for Cumbria.

However, seemingly to compensate for these increases, the system suggests an increase in the extent of potassium fertilisation for pasture, and its introduction for edible crops (Table 5.12). Furthermore, in the case of lamb, some of the increase in dose resulting from the reduction in clean-feeding is off-set by a small increase in the administration of AFCF to sheep.

5.4 ZARAGOZA

The province of Zaragoza is part of the Aragon region of Spain and covers an area of approximately 17,250 km^2 (Figure 5.14). The province contains the city of Zaragoza, which is situated 200m above sea-level, at the centre of the province and the geo-economic triangle made up of Madrid, Barcelona and Valencia, each of which is approximately 300km away. The climate of the region is generally warm and arid. Average temperatures in July are around 30°C, and in winter rarely drop below 0°C (Gobierno de Aragon, 2003). The region has an annual average rainfall of approximately 400mm and experiences a persistent, dry wind, known as “Cierzo”, which blows along the Ebro river valley. Unless otherwise stated, references to Zaragoza hereafter will refer to the province.

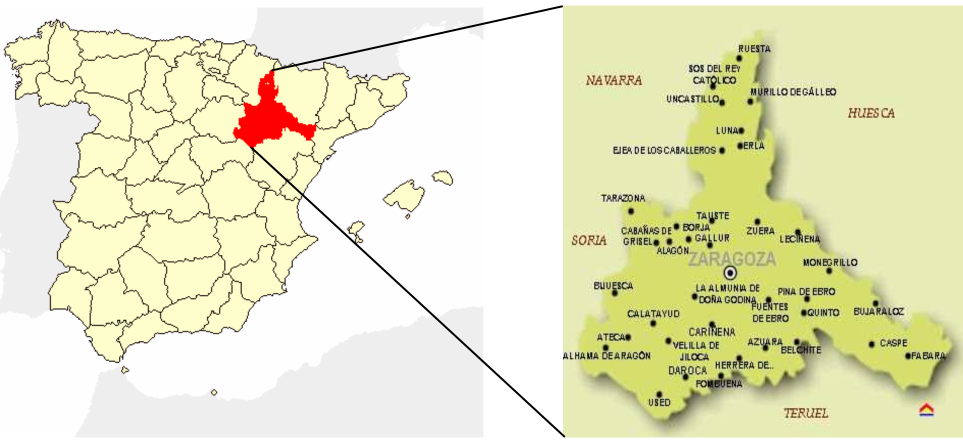

Figure 5.14 Zaragoza, Spain.

5.4.1 Deposition scenario

The hypothetical scenario for this case study was a large-scale accident (resulting in a total deposition of 3.31 × 10^{15} Bq) at a nuclear power station to the south-east of Zaragoza city had occurred, and that the resulting contaminated plume had spread almost due west, contaminating 69% of the cells within the region (Figure 5.15).

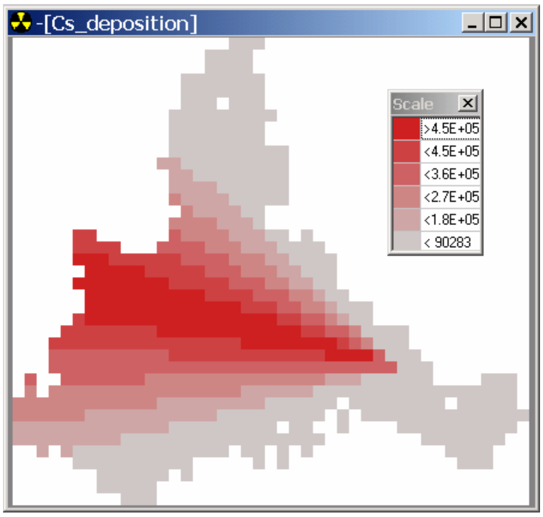

Figure 5.15 Spatial distribution of deposited ^{137}Cs in the Zaragozan case study (Bq m^{-2}).

The deposition was created using the same isotopic composition as for the Cumbrian case study and, consequently, ^{137}Cs was again the biggest contributor to the total deposition, followed by ^{90}Sr, ^{239}Pu and then ^{241}Am (Table 5.14).

Table 5.14 Total and maximum depositions within Zaragoza, by radionuclide.

Radionuclide	Total deposition (Bq)	Maximum deposition (Bq m^{-2})
^{137}Cs	3.1 x 10^{15}	540,000
^{90}Sr	2.1 x 10^{14}	37,205
^{239}Pu	5.1 x 10^{10}	8.8
^{241}Am	9.4 x 10^{9}	1.6

5.4.2 Soil characteristics

The spatial distribution of soil types for Zaragoza was derived from the Soil Geographical Data Base of Europe. Soil properties for these soil types were derived from the Soil Profile Analytical Data Base of Europe as described by Crout *et al.* (1999). The soil within the region of Zaragoza is typified by neutral to alkaline pH levels, relatively low organic matter content, relatively high clay content and high levels of exchangeable potassium (Figure 5.16). The only notable exceptions to this general trend are some of the highlands of the Sistema Iberico in the south-west of the region.

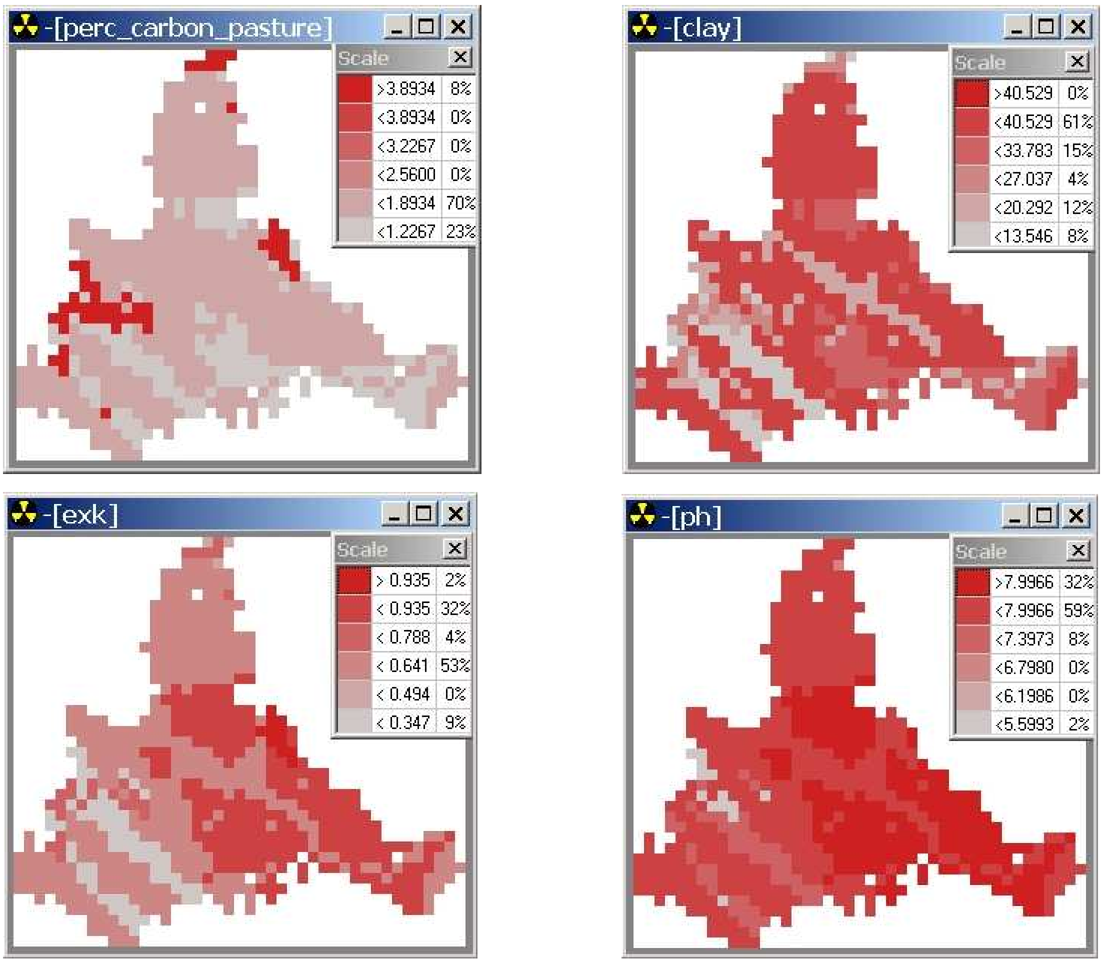

Figure 5.16 Interpolated soil characteristics used in the Zaragozan case study. Exchangeable potassium (cmol kg^{-1}) (top left), % clay (top right), pH (bottom left) and % organic matter (bottom right).

5.4.3 Agricultural management and production

Spatial land cover data for Zaragoza (Gobierno de Aragon, 2003) were combined with food production values for the province (Caldier, 1998). Food production in the region is mainly focused on products derived from arable and fruit crops, with limited production of animal-derived food products (Table 5.15).

Table 5.15 Food production rates in Zaragoza.

Food product	Production rate (Tonnes yr^{-1})
Cereals	480,000
Maize	140,000
Fruit	100,000
Cow milk	63,600
Leafy vegetables	63,000
Potatoes	47,000
Chicken	45,900
Root vegetables	43,000
Lamb	10,100
Beef	31,100
Pork	13.3

5.4.4 Urban parameters

Urban land cover data were not available for Zaragoza. Therefore, the relationships between population density and urban parameters used in the Cumbria case study were applied to the Zaragoza population data to generate the required urban parameters.

5.4.5 Population characteristics

As for the Cumbrian case study, fifty distinct sub-population groups were created by Monte-Carlo sampling of the defined statistical attributes of the overall population (See Appendix C for the full list of characteristics). Data regarding the spatial distribution of the Zaragozan population was taken from Gobierno de Aragon (2003). The total population of the province is approximately 850,000, and of this, around 600,000 live within Zaragoza city and its environs (Figure 5.17).

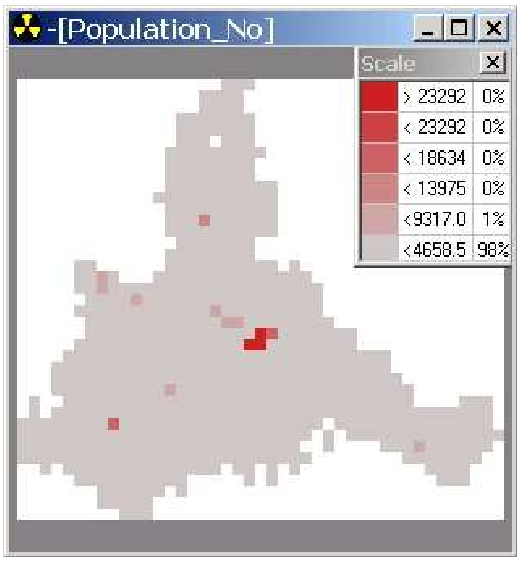

Figure 5.17 Estimated spatial distribution of population density in Zaragoza.

5.4.4.1 Diet

The diet of Zaragozans is characterised by a relatively high consumption rate of fruit and vegetables, and a relatively low intake of dairy and meat products (with the exception of pork) (Institito Nacional de Estadistica, 1992). Data regarding the geographical origins of the population's diet was derived from Mercazaragoza (2002). Based upon this data, it was assumed that, on average, 50% of the whole population's fruit and vegetable intake was derived from within the region. For cereals, this figure was *circa* 35%, and for meat and dairy products it decreases to *circa* 10%. with 40% of the population deriving, on average, 15% from home-grown sources. Forty percent of the population were assumed to consume home-grown fruit and vegetables and this source accounted for approximately 15% of their intake of this food group.

5.4.4.2 Activity profiles

The majority of the region's population live in urban areas, in and around the city of Zaragoza (Álvarez, 2003, personal communication). Consequently, it was assumed that approximately 90% of the population live in apartment blocks, with the remainder living in detached or semi-detached houses. It was assumed that there were no terraced houses in the region. In the absence of specific data for Spain, all occupancy factors were assumed to be the same as for the Cumbrian population, described earlier.

5.4.4.3 Social preferences

The willingness of Zaragozans to pay to maintain the considered environmental and social attributes was assessed using a similar method to that used in the Cumbrian case study by Álvarez and Gil (2003) (Table 5.16). As for the Cumbrian population, the most important attribute was considered to be landscape/biodiversity, and no value could be inferred for the heritage attribute. However, the next most important attributes were water quality followed by normal daily life, and, in contrast to the Cumbrian case study, no value could be inferred for animal welfare.

Table 5.16 Estimated social and environmental preferences of the Zaragozan population for the considered attributes.

Side-effect attribute	Mean value[a] (€)	Standard deviation[a] (€)
Landscape/biodiversity	47.5	7.92
Water quality (for recreational use)	23.73	5.08
Normal daily life	21.04	4.82
Heritage	-	-
Animal welfare	-	-

[a] Values are per person, per year, over five years.

5.4.6 Additional system parameters

In the absence of specific values for Spain, the same values as those employed in the Cumbrian case study (converted to Euros) were used to calculate the cost of the unit of collective dose. In addition, due to limited data regarding the service costs of countermeasures in Spain, these were assumed to be 28% lower than the equivalent costs in Cumbria on the basis of the relative incomes in the UK and Spain (Gil, personal communication). Market prices for food products and livestock animals were taken from Gobierno de Aragon (2002).

5.4.7 Results

5.4.7.1 "Do nothing" strategy

With no countermeasures implemented the main exposure pathway for the population of Zaragoza, accounting for 76% of the total local collective dose, was predicted to be ingestion (Table 5.17). This relatively large contribution is due the large proportion of the population's diet that was assumed to be sourced from within the region, and consequently, 31% of the total dose arising from food products was consumed within the region.

Table 5.17 Estimated collective doses for the "Do nothing" strategy in Zaragoza.

Local collective ingestion dose (man-Sv)	3,418
Local collective external dose (man-Sv)	843
Total local collective dose (man-Sv)	4,261
Exported collective ingestion dose (man-Sv)	7,537

Over the ten year study period, 80% of the population (~680,000 people) were predicted to receive doses of 8.8 mSv or less, whilst the maximum individual doses over this time period were predicted to be 29 mSv (Figure 5.18). The highest levels of dose were experienced by approximately 4000 people, who were characterised by a high consumption rate of fruit (more than 300 kg yr^{-1}), of which approximately 20% was assumed to be home-grown.

The food products predicted to contribute the most to the local collective ingestion dose were fruit (81%), cereals (8.1%), potatoes (5.6%) and leafy vegetables (4.3%) (Figure 5.19). The contribution from fruit was the largest because the crop was assumed to be harvested only two months after the deposition event, when activity concentrations of the plants were still considerable, because its mean consumption rate was relatively high and because, on average, the population were assumed to source 70% of their intake of fruit and vegetables from somewhere within the region.

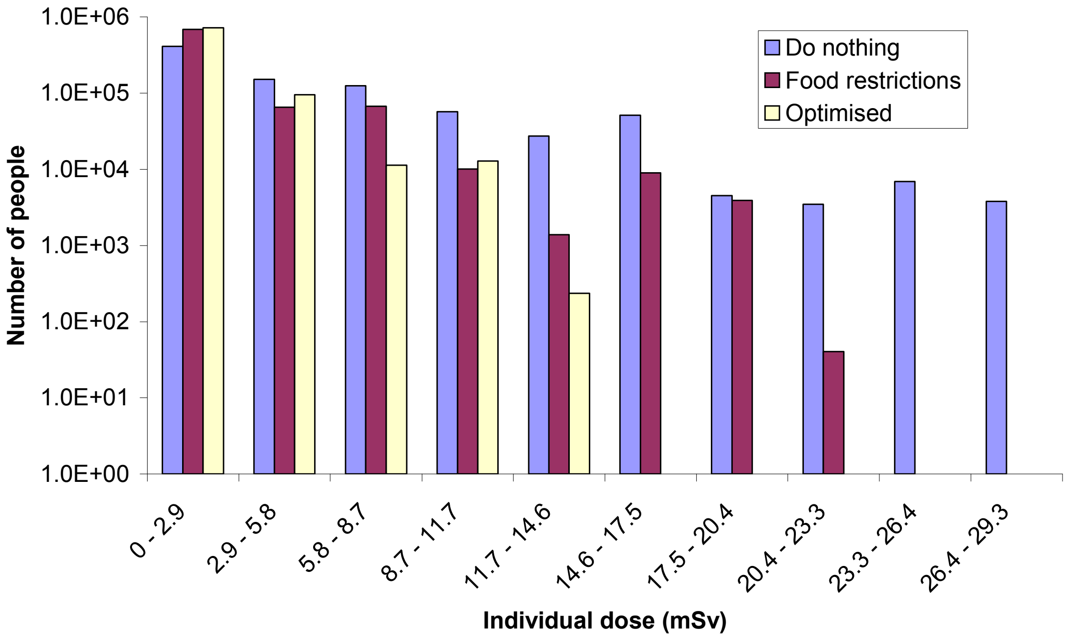

Figure 5.18 Frequency of predicted individual doses (mSv) received by the residents of Zaragoza over the ten year study period for the "Do nothing", "Food restrictions" and "Optimised" strategies.

Food products derived from animals contributed less than 1% to the local collective ingestion dose, due to the relatively low intake of local or regional meat and dairy products assumed. In terms of exported ingestion dose, the main contributors were predicted to be fruit (57%), cereals (27%), beef (6.1%), lamb (2.9%), potatoes (2.4%) and leafy vegetables (2.2%) (Figure 5.20). The contribution from fruit is large once again due to the plants' high activity concentrations at the first harvest, but also because the production rate is relatively high.

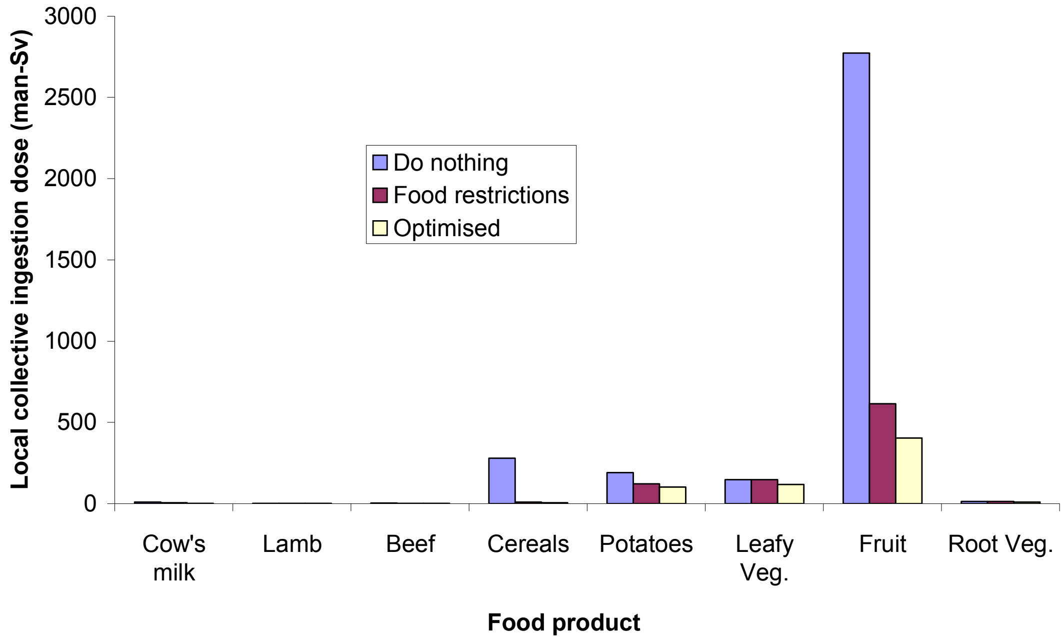

Figure 5.19 Estimated local collective ingestion dose (man-Sv), by food product, resulting from the "Do nothing", "Food restrictions" and "Optimised" strategies in the Zaragozan case study.

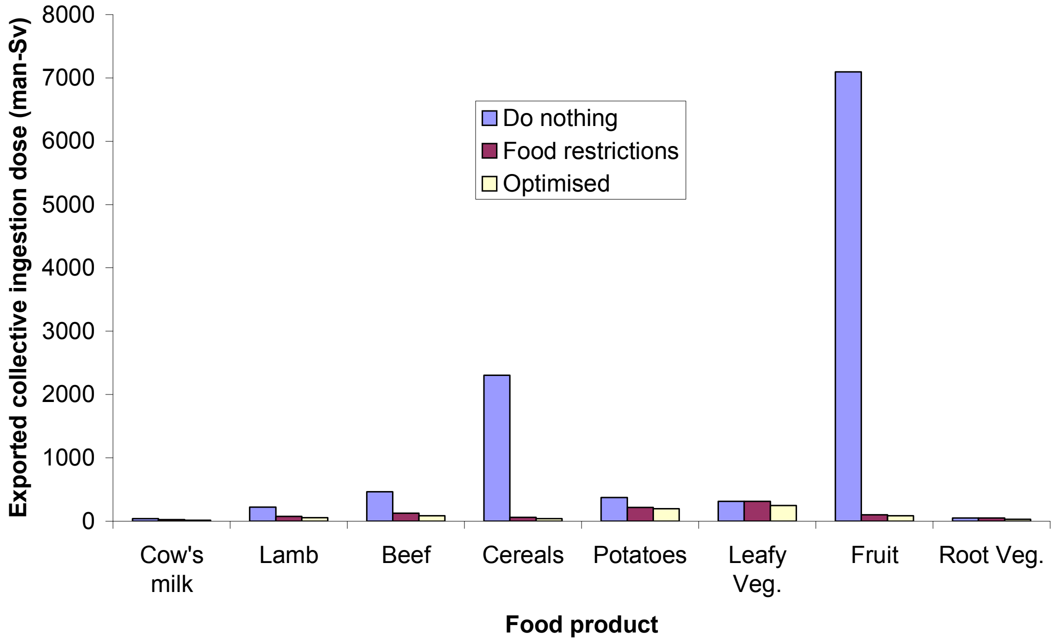

Figure 5.20 Estimated exported collective ingestion dose, by food product, resulting from the "Do nothing", "Food restrictions" and "Optimised" strategies in the Zaragozan case study.

5.4.7.2 "Food restrictions" strategy

This strategy was estimated to cost €187M and avert nearly 10,000 man-Sv (Table 5.18). Compared to the "Do nothing" strategy, the local collective ingestion dose and the exported collective ingestion doses were 73% and 95% lower respectively, whilst the maximum individual dose was reduced from 29 mSv to approximately 8.8 mSv (Figure 5.18). In addition, the value of the merit function for this strategy was negative, indicating that it would be justified according to ICRP principles.

Table 5.18 Summary results for the "Do nothing" and "Food restrictions" strategies in Zaragoza.

	Do nothing	Food restrictions
Local collective ingestion dose (man-Sv)	3,418	913
Local collective external dose (man-Sv)	843	843
Total local collective dose (man-Sv)	4,261	1,757
Exported collective ingestion dose (man-Sv)	7,537	361
Averted dose (man-Sv)	0	9,681
Implementation cost (€M)	0	193
Merit function (€M)	0	-38,361

Although the cost of the restrictions placed upon beef and lamb food products were estimated to represent nearly 70% of the total implementation cost for this strategy (Table 5.19), the system predicted that these restrictions would only be required for the first five months post-deposition (Figure 5.21) and only account for 4.9% of the total reduction in collective ingestion dose (Figures 5.19 and 5.20). In contrast, the costs of the restrictions on fruit and cereal products represent only 24% of the total cost, but account for 93% of the reduction in the total collective ingestion dose.

Table 5.19 Estimated cost of food restrictions, by food product, with associated wastes for the "Food restrictions" strategy in Zaragoza.

Food product	Cost of restriction (€M)	Waste generated
Beef	93	18,600 cows
Lamb	35	125,000 lambs
Fruit	34.5	69,000 tonnes
Pork	17	19,500 pigs
Cereals	10.9	83,900 tonnes
Potatoes	1.6	9,800 tonnes
Cow milk	0.4	1.3M litres

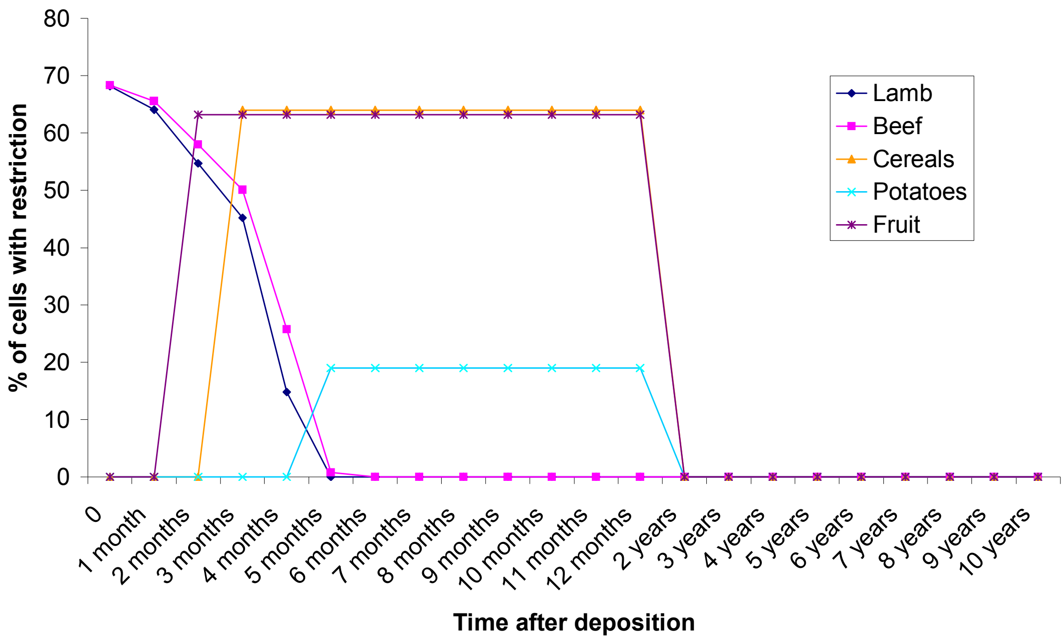

Figure 5.21 The percentage of cells in Zaragoza requiring restrictions on the sale of lamb, beef, cereals, potatoes and fruit as a function of time after deposition.

5.4.7.3 "Optimised (without side-effects)" strategy

According to the estimated merit functions of the two strategies, the strategy suggested by the optimisation process, without considering countermeasures' side-effects, was a slight improvement on the "Food restrictions" strategy (Table 5.20). The local and exported collective ingestion doses were 29% and 44% lower respectively, whilst the estimated cost of the strategy was €73m less. In addition, the local collective external dose was reduced by 23%.

Table 5.20 Summary results of the "Do nothing", "Food restrictions" and "Optimised (without side-effects)" strategies for Zaragoza.

	"Do nothing"	"Food restrictions"	"Optimised"
Local collective ingestion dose (man-Sv)	3,418	913	644
Local collective external dose (man-Sv)	843	843	648
Total local collective dose (man-Sv)	4,261	1,757	1,292
Exported collective ingestion dose (man-Sv)	7,537	361	200
Averted dose (man-Sv)	0	9,681	10,306
Implementation cost (€M)	0	193	120
Merit function (€M)	0	-38,361	-40,444

Although food restrictions still accounted for 58% of the total implementation costs for the optimised strategy (Table 5.21), this represents a reduction of €123m compared to the "Food restrictions" strategy. This reduction was achieved mainly by the deep ploughing of silage crops and the normal ploughing of pasture, which reduced the activity concentrations of lamb, beef and cow milk.

Table 5.21 Optimised countermeasures with associated costs and requirements for the Zaragozan case study.

Countermeasure implemented	Cost (€m)	Logistics
Food restrictions	70	n/a[1]
Deep plough (Silage crops)	26.3	433,000 hectares
Normal plough (Pasture)	13.1	73,000 hectares
Deep plough (Edible crops)	9.3	153,000 hectares
Urban lawn mowing	0.57	5,200 hectares
Dietary advice	0.48	n/a[1]
AFCF (Sheep)	0.15	2.9 million sheep
AFCF (Beef cows)	0.09	11,100 cows
Clean feed (Sheep)	0.04	n/a[1]
Clean feed (Beef cows)	0.04	n/a[1]
AFCF (Dairy cows)	0.03	1269 cow months

[1]Logistics not available

No reduction in the cost of the restrictions placed upon fruit and cereals was observed (Table 5.22), despite the recommended deep ploughing of edible crops. This is because ploughing was assumed to have taken place after the first harvest, and consequently had no effect on the activity concentrations of the food products requiring restrictions within the first year post-deposition. However, this countermeasure did reduce the ingestion doses arising from fruit, cereals, potatoes, leafy vegetables and root vegetables in subsequent years by 16, 28, 10, 20 and 38% respectively (Figures 5.19 and 5.20, page 168).

Table 5.22 Estimated cost of food restrictions, by food product, for the "Food restrictions" and "Optimised (without side-effects)" strategies in Zaragoza.

Food product	Cost of restriction (€m)	
	Food restrictions strategy	Optimised strategy
Beef	93	4.8
Lamb	35	0.9
Fruit	34.5	34.5
Pork	17	17
Cereals	10.9	10.9
Potatoes	1.6	1.6
Cow's milk	0.4	0.004

The reduction in the local collective external dose was due solely to the implementation of the urban lawn mowing countermeasure. As discussed previously, for this countermeasure to be fully effective it should be implemented soon after deposition, and before any significant rainfall. However, in this scenario it is estimated that 5,200 hectares of lawn would require mowing and again it is debatable whether this could be achieved with the required time-frame.

This strategy highlights several limitations to the way that certain fruit crops are simulated within the system: all edible crops are assumed to be ploughed and re-sown every year at specified dates; however, much of the fruit produced in Zaragoza is tree-borne (e.g. olives, grapes, peaches and oranges), and is neither sown nor ploughed routinely. To plough the soil around these crops, the trees would have to be removed and new ones replanted, after which it could take several years before they were fully productive again. In this strategy, it was suggested that all edible crops should be ploughed, however, the results of the "Food restrictions" strategy suggest that restrictions would only be required for fruit food products for the first year post-deposition. This makes the suggestion that tree-borne fruit should be ploughed even more questionable, as it would be more prudent to dispose of the first harvest post-deposition, rather than take the drastic action of excavating trees, and potentially reducing fruit production in subsequent years. A further limitation, in assuming that these crops are routinely ploughed, is that the model will tend to underestimate the activity concentration in the root zone of the soil, and hence also underestimate the activity concentrations in the plants and food products. Furthermore, because it is assumed that all edible crops are routinely ploughed, it is also assumed that there are no side-effects associated with the deep ploughing and skim and burial ploughing of these crops as they are merely extensions of the existing practices. However, there would almost certainly be a social impact associated with excavating the fruit trees within an area such as Zaragoza, not least of which would be the detriment to the landscape, of which they are an integral part. As a result of these limitations, there is considerable scope for improving the simulation of fruit production within the model.

5.4.7.4 "Optimised (with side-effects)" strategy

Including the social cost of countermeasures' side-effects when assessing strategies, resulted in a virtually identical scenario to that produced when side-effects were not considered (Table 5.23). The difference between the merit functions of the two strategies was almost entirely due to the inclusion of the side-effect costs, rather than any changes in the effectiveness of the countermeasure strategy, as the local and exported collective ingestion doses were increased by less than 1% and 5% respectively, and the implementation costs differed by less than €1m.

Table 5.23 Summary results of the "Optimised (without side-effects)" and "Optimised (with side-effects)" strategies for Zaragoza.

	Optimised (without side-effects)	Optimised (with side-effects)
Local collective ingestion dose (man-Sv)	644	644
Local collective external dose (man-Sv)	648	648
Total local collective dose (man-Sv)	1,292	1,292
Exported collective ingestion dose (man-Sv)	200	207
Averted dose (man-Sv)	10,306	10,300
Implementation cost (€M)	120	120
Side-effect cost (€M)	n/a	55
Merit function (€M)	-40,444	-40,388

The only differences between the countermeasures suggested for the two optimised strategies were that, when side-effects were considered, less administration of AFCF to dairy and beef cows, and clean-feeding of sheep and beef cows was suggested (Table 5.24). Including the cost of countermeasures' side-effects had little effect upon the output from the optimisation process because the main countermeasures suggested for this scenario were the deep ploughing of silage crops, the normal ploughing of pasture and the deep ploughing of edible crops. The two deep ploughing countermeasures did not incur any social cost as it was assumed that these are mere extensions of existing practices (i.e. it is assumed that silage and edible crops are ploughed routinely) and do not result in any additional environmental or social impact (Table 5.25). The normal ploughing of pasture countermeasure, however, is assumed to generate some side-effects, and accounts for 84% of the total social cost of this countermeasure strategy.

Table 5.24 Suggested countermeasures, with associated implementation costs, in the "Optimised (without side-effects)" and "Optimised (with side-effects)" strategies for Zaragoza.

	Implementation cost (€M)	
Countermeasure implemented	Optimised (without side-effects)	Optimised (with side-effects)
Food restrictions	70	70
Deep plough (silage crops)	26.3	26.3
Normal plough (pasture)	13.1	13.1
Deep plough (edible crops)	9.3	9.3
Urban lawn mowing	0.57	0.57
Dietary advice	0.48	0.48
AFCF (sheep)	0.15	0.15
AFCF (beef cows)	0.094	0.052
Clean feed (sheep)	0.043	0.037
Clean feed (beef cows)	0.044	0.030
AFCF (dairy cows)	0.025	0.024

Table 5.25 Estimated side-effect costs for each countermeasure in the "Optimised (with side-effects)" strategy in Zaragoza.

Countermeasure	Total social cost of side-effects (€M)
Normal plough (pasture)	46.5
Food restrictions	8.4
AFCF (beef cows)	0.14
AFCF (sheep)	0.09
Clean feed (beef cows)	0.07
Clean feed (sheep)	0.06
Deep plough (silage crops)	0
Deep plough (edible crops)	0
Urban lawn mowing	0
AFCF (dairy cows)	0

Despite the relatively large contribution to the social cost of the strategy, the extent of the implementation of normal ploughing was not altered when side-effects are considered during the optimisation process. This is because the countermeasure was so effective at reducing the activity concentrations of sheep and beef cows over the ten year period, and consequently reducing the amount of lamb and beef food products requiring restrictions, that no viable alternatives were available. Although deep ploughing and skim and burial ploughing of pasture would have incurred the same side-effect cost, and averted more dose, normal ploughing was estimated to be the most cost effective option in this scenario (Figure 5.22).

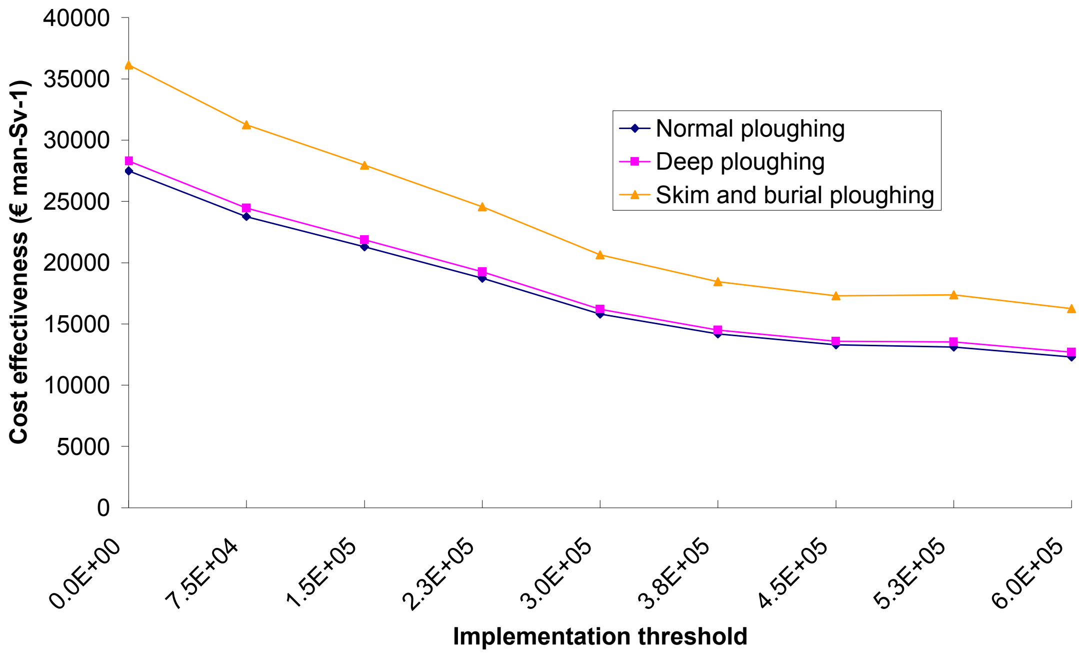

Figure 5.22 Cost effectiveness of normal, deep, and skim and burial ploughing at nine different implementation levels within Zaragoza. Interpolation is for illustrative purposes only.

5.5 SENSITIVITY ANALYSES

For each of the case studies, the limited sensitivity analyses, described in Chapter 4 and hereafter referred to as SA1 and SA2, were performed to investigate the variation of the merit function about the estimated optima. These analyses were only performed for the strategies produced when side-effects were not considered, as the optimum strategies suggested when side-effects *were* considered were not significantly different, and the work described here is computationally intensive.

For the SA1 procedure, the implementation thresholds of countermeasures were randomly sampled within defined percentages (1, 2, 5, 20, 50 and 100) of their optimum values, assuming uniform probability distributions, using a simple Monte-Carlo routine (n = 1000).

For the SA2 procedure, the implementation thresholds of the countermeasures suggested for implementation by the optimisation process were randomly sampled within the full range of each threshold, assuming uniform probability distributions (n = 10,000).

In both procedures, countermeasures which were mutually exclusive with those suggested for implementation by the optimisation process (e.g. normal and deep ploughing of pasture with skim and burial ploughing of pasture in the Cumbrian case study) were not included for the reasons cited in Chapter 4.

5.5.1 Cumbria SA1

The ranges of the normalised expenditures (i.e. where the maximum possible expenditure on a countermeasure = 1), due to the specified variations about the optimum implementation thresholds of each countermeasure in the Cumbrian case study, are shown in Figure 5.23. Within 5% of the optimum implementation thresholds there was little variation in the extents of the countermeasures' implementations. However, when the thresholds were varied by up to 10, 20 and 50%, marked increases in the ranges of expenditures on food restrictions, clean-feeding of sheep, administration of AFCF to sheep and, to a lesser extent, clean-feeding of cattle were observed. With the thresholds varied by up to 100% about the optimum, the expenditures on clean-feeding and administration of AFCF to dairy cows, beef cows and sheep, and the potassium fertiliser countermeasures covered almost the entire range of implementation levels for these countermeasures, while the expenditure on food restrictions varied over nearly half of its potential range. There was little or no change in the expenditures of the ploughing, urban lawn mowing or clean-feeding and administration of AFCF to chickens and pigs countermeasures for any of the variations. This was because the optimal implementation thresholds for these countermeasures were either at the maximum or minimum values possible, where the "flat" regions, caused by the time intervals between calculations and the raster based representation of the affected area, are generally more extensive.

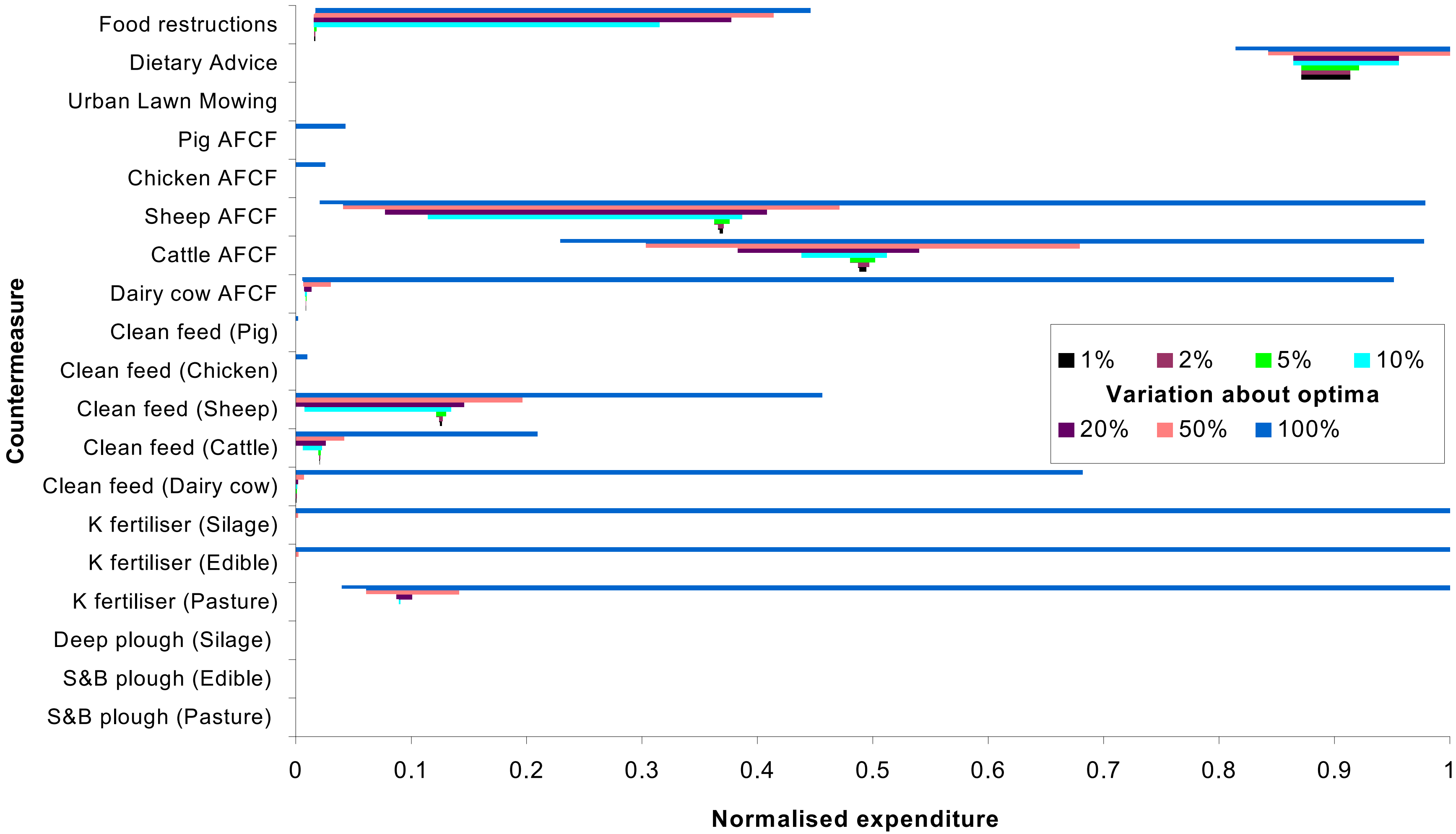

Figure 5.23 Ranges in the normalised expenditures of countermeasures resulting from the defined variations about the optimum implementation thresholds for the Cumbrian case study by the SA1 procedure.

Within 5% of the optimum implementation thresholds, the value of the merit function varied by less than 1% (Figure 5.24). The principal reason for this relatively insignificant variation was the small ranges of the countermeasures' implementation levels covered within the variations about the optimum implementation thresholds, as described above. However, when the optimum thresholds were allowed to vary by up to 10% or more, there was a significant increase in the range of values of the merit function, with the maximum value increasing from -£507M with thresholds varied by up to 5%, to +£132M, +£269M, +£357M and +£838M for the 10, 20, 50 and 100% variations about the optimum, respectively. Within these variations about the optimum implementation thresholds, the merit function shows strong negative correlations with the expenditure on the clean-feeding sheep and administration of AFCF to sheep countermeasures, and a strong positive correlation with the expenditure on food restrictions (Table 5.26).

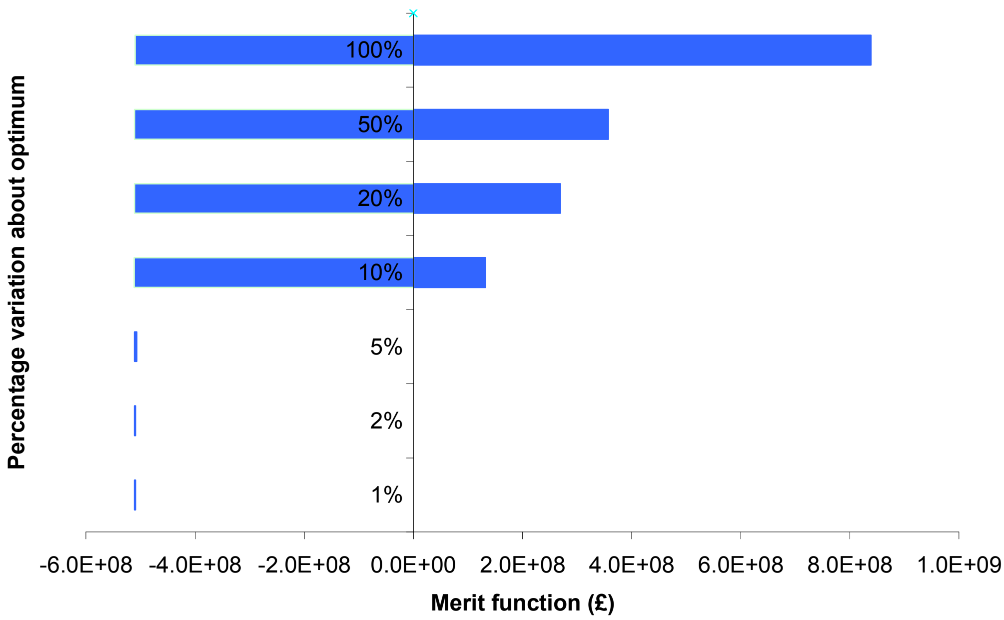

Figure 5.24 Variation in the value of the merit function within 1, 2, 5, 10, 20, 50 and 100% of the optimum implementation thresholds of the countermeasures suggested in the "Optimised (without side-effects) strategy for Cumbria .

Table 5.26 Significant correlations ($p < 0.001$) within 10% of the optimum implementation thresholds for the Cumbrian case study.

	Clean-feeding sheep[a]	AFCF to sheep[a]	Food restrictions[a]
Food restrictions[a]	-0.97	-0.98	1
Averted dose	-0.88	-0.92	0.94
Overall costs	-0.97	-0.97	0.99
Merit function	-0.97	-0.97	0.99

[a] Correlation relates to the expenditure on these countermeasures.

The strong negative correlations of the expenditures on the sheep countermeasures with the expenditure on food restrictions, confirms that the variation in the merit function around the optimum is due to the ability of the sheep countermeasures to reduce the need for restrictions on the sale of lamb food products. Interestingly, however, both countermeasures also show a strong negative correlation with the level of averted dose. This is because these countermeasures reduce the activity concentrations of sheep food products to below the implementation threshold for food restrictions, resulting in the entry of contaminated food products (albeit below the statutory limits for food restrictions) into the food chain, and consequently doses for consumers which would have been avoided if the sale of the food product had been restricted.

5.5.2 Cumbria SA2

The value of the merit functions, arranged in ascending order, of the 10,000 strategies generated during the SA2 procedure are shown in Figure 5.25. The lowest value found during this procedure was -£477m. This compares to the optimum value of -£511m, obtained by optimisation, which took approximately 1000 iterations.

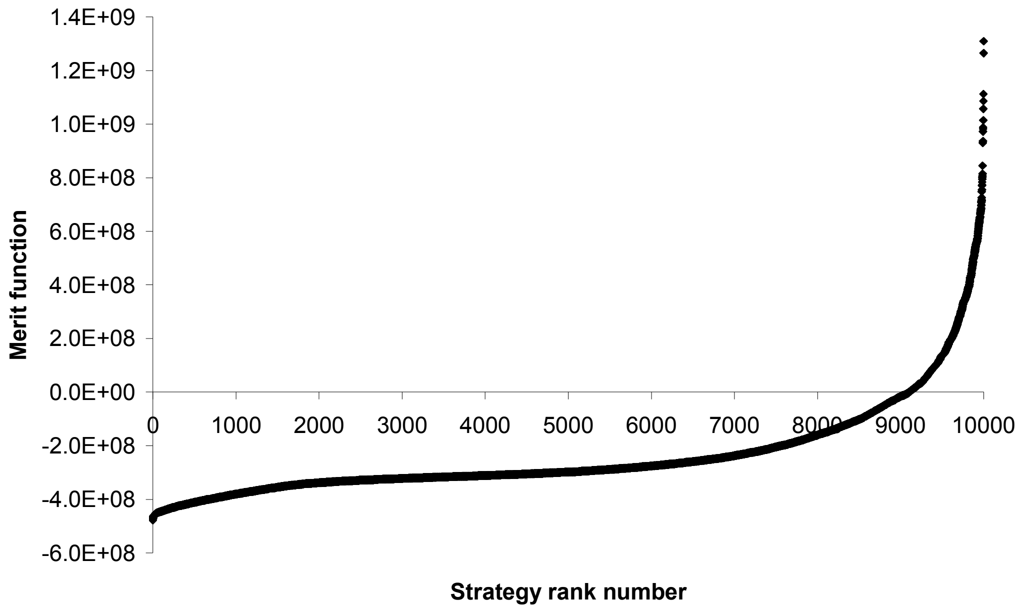

Figure 5.25 Strategies generated by the SA2 procedure for the Cumbrian case study, ranked according to the value of the merit function (£).

As would be expected, optimisation is more efficient than the random sampling of countermeasure implementation thresholds, and, furthermore, is able to locate countermeasure strategies with lower merit functions. Approximately 9% of the strategies created were deemed to be "bad" (i.e. with positive merit functions), while many of the justified strategies (i.e. those with negative merit functions) were of similar merit. However, the "dip" at the lower end of the distribution indicates that there was a small fraction (~10%) of strategies which were "better" than the majority of the justified strategies.

In this scenario, the merit function is more strongly correlated with the overall implementation costs of strategies than the level of averted dose, and the implementation costs are most strongly correlated with the expenditure on food restrictions; suggesting that the driving force for the optimisation procedure in this scenario is the reduction of the expenditure on food restrictions (Table 5.27).

Table 5.27 Significant correlations within the strategies created by the SA2 procedure for the Cumbrian case study.

	Skim and burial (Pasture)[a]	Clean feed (Dairy cows)[a]	Food restrictions[a]	Merit function	Averted dose
Clean feed (Beef cows)[a]	-0.427*	-	-	-	-
Clean feed (Sheep)[a]	-0.425*	-	-	-	-
Food restrictions[a]	-	-	1	-	-
Merit function	-	0.575**	0.74**	1	-
Averted dose	0.55**	-	0.46*	0.43*	1
Overall costs	-	0.564**	0.75*	0.99**	0.50*

*$p < 0.05$; **$p < 0.01$. [a] Correlation relates to the expenditure on these countermeasures.

This is confirmed by analyses of the differences between the estimated averted doses and implementation costs in the best and worst 10% of the ranked strategies (Table 5.28), which show that the strategies with the lowest merit functions are associated with a significantly lower levels ($p < 0.001$ using Mann-Whitney test) of averted dose and implementation costs.

Table 5.28 Mean averted doses and implementation costs for the best and worst 10% of the strategies generated by the SA2 procedure.

Sub-population of strategies	Mean averted dose (man-Sv)	Mean implementation costs (£M)
Best 10%	32,368	249.8
Worst 10%	33,893	901.2

These results raise the question of whether the preference for the aversion of implementation costs rather than dose in this scenario would be ethically defensible. However, the purpose of these case studies was to investigate the applicability of the system to different environmental, agricultural and social conditions, and to demonstrate that the optimisation procedure efficiently identifies optimal remediation strategies which are consistent with the preferences of decision makers. If, in a real situation, decision makers, or other stakeholders, were to find the strategies suggested by the system unacceptable on radiological or ethical grounds, the driving forces for the optimisation procedure could be altered via the values defined for the base cost of the unit of collective dose or the level of aversion to high individual doses.

In terms of averted dose, the most significant countermeasure in this scenario, apart from food restrictions, was skim and burial ploughing of pasture, which was also moderately correlated with the reduction of clean feeding cattle and sheep. These appear to be reasonable findings as, although skim and burial ploughing is a “one-off” countermeasure, its effectiveness at reducing the activity concentration of pasture grass, which in turn affects the activity concentrations of dairy cows, beef cows and sheep, is experienced continuously after its initial implementation, thus producing high levels of averted dose. In addition, because it reduces the activity concentration of the pasture grass on which animals are grazed, and itself incorporates a limited clean feeding regime while grass is reseeded, it also reduces the expenditure on the clean-feeding of sheep and beef cows countermeasures.

Surprisingly, however, there is no correlation found between skim and burial ploughing and the merit function, even though the skim and burial ploughing countermeasure was the cornerstone of the optimum strategy. In fact, further investigation reveals that significantly less is spent on skim and burial ploughing in the best 10% of the strategies generated than in the worst 10% (Table 5.29); seemingly in contradiction to the optimum strategy, in which skim and burial ploughing was fully implemented.

Table 5.29 Mean expenditure on skim and burial ploughing in the best and worst 10% of the strategies created by the SA2 procedure for the Cumbrian case study.

Sub-population of strategies	Mean expenditure on skim and burial ploughing (£M)
Best 10%	7.8***
Worst 10%	20.5***

*** $p < 0.001$ using Mann-Whitney test

This seemingly anomalous behaviour is due to the assumption of uniform probability distributions for the countermeasures' implementation thresholds and the particular relationships between the skim and burial ploughing of pasture and the administration of clean feed and AFCF to sheep countermeasures. In the optimal strategy it was suggested that skim and burial ploughing should be implemented wherever deposition had occurred and where ploughing was feasible, and that clean feed and AFCF should be administered to sheep where ploughing was not possible. Accordingly, the implementation threshold for skim and burial ploughing was set close to its minimum value, while the optimum threshold for the clean-feeding of sheep countermeasure was close to its maximum value. However, because the probability distributions of the implementation thresholds used by the Monte-Carlo routine were assumed to be uniform, the majority of the values selected for the implementation threshold of skim and burial ploughing were above the optimal value (corresponding to implementation in fewer cells), and those selected for the clean-feeding of sheep were below the optimal value (corresponding to implementation in more cells) (Figure 5.26).

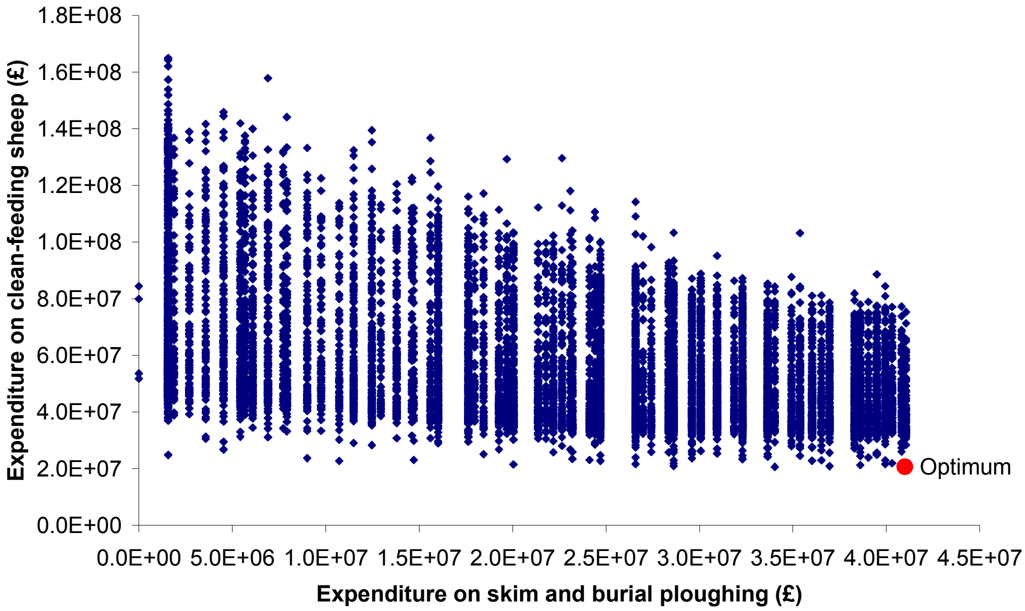

Figure 5.26 Corresponding expenditures on clean-feeding of sheep and skim and burial ploughing pasture within the strategies generated during SA2 for Cumbria.

Consequently, in most of the strategies created by the Monte-Carlo routine, the spatial extent of the implementation of clean-feeding sheep was greater than in the optimum strategy, particularly in those areas where skim and burial was the preferred option, while skim and burial ploughing was generally suggested in fewer cells than in the optimum strategy. Furthermore, on the relatively few occasions when the selected expenditure on skim and burial ploughing was at its maximum, this always coincided with the clean-feeding of sheep being implemented more extensively than in the optimal strategy, due to the reason stated above (Figure 5.26). These effects led to both countermeasures being implemented in some of the cells in most of the strategies, which was unfavourable, in terms of the merit function, in this scenario. Thus, whenever the Monte-Carlo routine selected implementation thresholds which corresponded to the full implementation of skim and burial ploughing, the strategies produced tended to have relatively high merit functions. This limitation in the use of Monte-Carlo methods in this situation further highlights the need for an appropriate optimisation procedure for locating optimal remediation strategies.

5.5.3 Zaragoza SA1

With the implementation thresholds of countermeasures randomly sampled from within 50% of their optimum values, there was little variation in the value of the merit function (Figure 5.27).

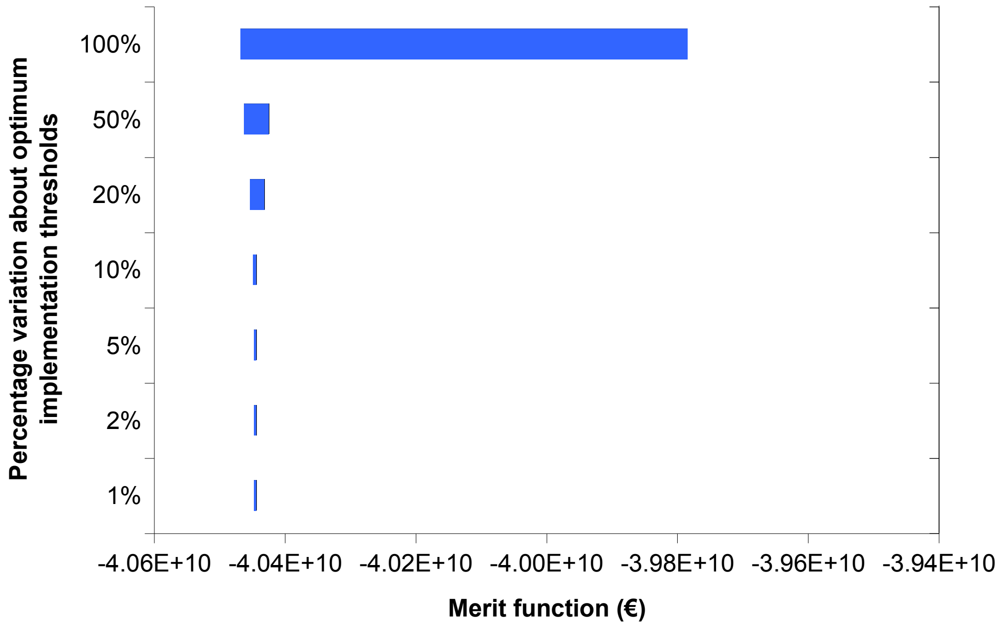

Figure 5.27 Variation in the value of the merit function (€) within 1, 2, 5, 10, 20, 50 and 100% of the optimum implementation thresholds for the Zaragozan case study .

This was mainly due to the small variation in their implementation levels (Figure 5.28), caused by the non-linearity of implementation thresholds with implementation levels, as described previously. However, when implementation thresholds were randomly selected from within 100% of their optimum values, there was more variation in the implementation levels of most countermeasures, and a more significant variation in the value of the merit function did occur, with the maximum value increasing from -40,000M € within 50% of the optimum values to -39,800M €. This increase was associated with increased expenditure levels on the addition of potassium fertiliser to pasture and silage crops, confirming that these countermeasures are not cost-effective in this scenario, and therefore, should not be implemented (Table 5.30).

Table 5.30 Significant correlations ($p < 0.01$) within 100% of the optimum implementation thresholds.

	K fertiliser (Pasture)[a]	K fertiliser (Silage)[a]	Merit function
Overall Costs	0.66	0.74	0.99
Merit function	0.66	0.74	1

[a] Correlation relates to the expenditure on these countermeasures.

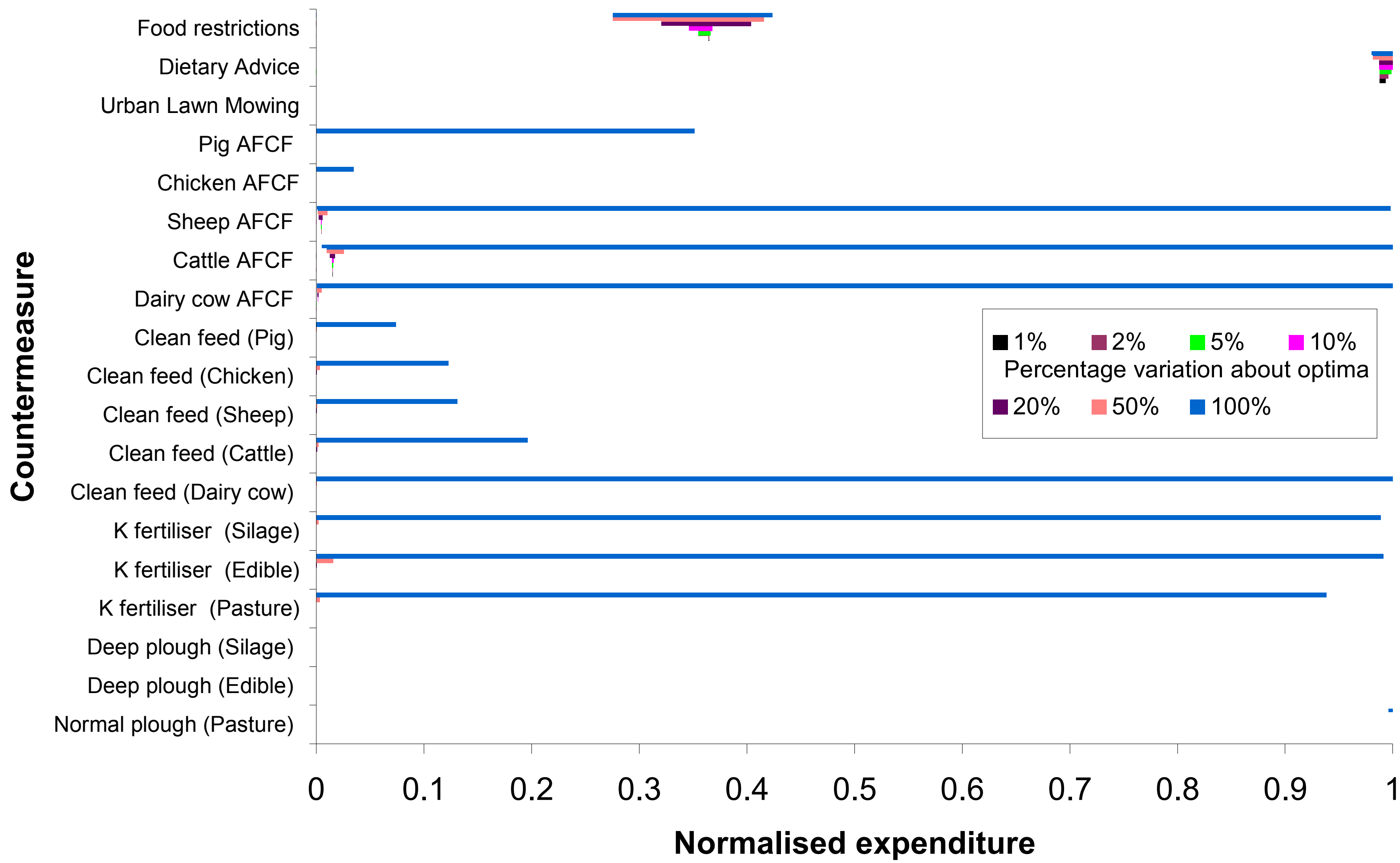

Figure 5.28 Ranges in the normalised expenditures of countermeasures resulting from the defined variations about the optimum implementation thresholds in the SA1 procedure for the Zaragozan case study.

5.5.4 Zaragoza SA2

In contrast to the Cumbrian scenario, all 10,000 of the strategies generated by sampling from within the full range of countermeasures' implementation thresholds were associated with negative merit functions, suggesting that all of the combinations of countermeasures generated would be justified in this scenario (Figure 5.29). This is as expected because the implementation threshold for the food restrictions countermeasure was maintained at the constant value defined within the case study; an action which was deemed to be justified on its own in this scenario (with a merit function of –27,200M €). Consequently, any implementation of additional countermeasures, which should reduce the expenditure on food restrictions, should also be justified, and consequently reduce the merit function further.

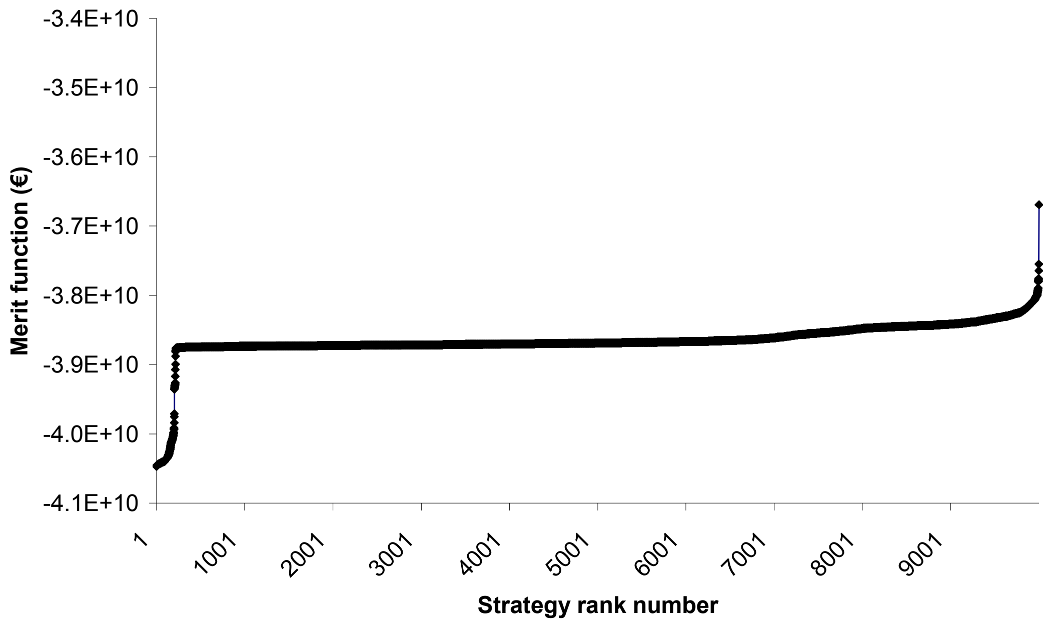

Figure 5.29 Strategies generated by the SA2 procedure for the Zaragozan case study, ranked according to the value of the merit function (€).

The steep gradient in the value of the merit function amongst the best strategies in Figure 5.29 corresponds to the 225 strategies in which there was some expenditure on dietary advice. The reason that there are so few strategies with some expenditure on dietary advice is due to the limitation, highlighted previously, that the optimum implementation threshold of the countermeasure was found to be close to its minimum value. Hence the Monte-Carlo routine selected values greater than the optimum more frequently than values at or below it. In this instance, this problem was compounded by the fact that the maximum implementation threshold of dietary advice was calculated including the predicted activity concentrations of semi-natural food products, which were assumed to not be consumed by the population in this scenario. This countermeasure is only implemented if a food product is consumed, and therefore the maximum implementation threshold was artificially high due to the activity concentrations of the semi-natural food products. Consequently, a large portion of the range in the countermeasure's implementation threshold corresponded to dietary advice not being implemented.

The significant correlations within the SA2 generated strategies indicate that dietary advice is the most cost-effective countermeasure in this scenario (Table 5.31). This is plausible as the implementation costs for dietary advice are relatively low, but the potential for dose reduction is large, particularly in the Zaragozan case study where a significant proportion of the population's diet was assumed to consist of home-grown fruit and vegetables. The countermeasures most strongly correlated with the level of averted dose in this scenario were urban lawn mowing and the deep ploughing of edible crops.

Table 5.31 Significant correlations within the strategies generated for Zaragoza by the SA2 procedure.

	Normal plough (Pasture)[1]	Deep plough (Edible)[1]	K fertiliser (Pasture)[1]	K fertiliser (Silage)[1]	Urban lawn mowing[1]	Dietary advice[1]
Food restrictions[1]	-0.91**					
Averted dose		0.45*			0.76**	
Overall costs			0.60**	0.73**		
Merit function						-0.84**

* $p < 0.05$; ** $p < 0.01$. [1] Correlation relates to the expenditure on these countermeasures.

Again, these appear to be reasonable findings as urban lawn mowing is particularly effective at reducing external doses, provided that it is implemented before any significant rainfall, and in Zaragoza, where rainfall levels are relatively low, this assumption may not be too unreasonable. Deep ploughing of edible crops results in particularly high levels of averted dose in this scenario due to the large quantities of locally and regionally produced fruit and vegetables assumed to be consumed by the local population, and because these crops are the main exports from the region.

Overall, these results indicate that, provided that food restrictions are implemented at the recommended CFILs, any combination of additional countermeasures would be justified in this scenario. However, strategies in which the dietary advice countermeasure was implemented were associated with significantly lower values of the merit function than those in which it was not, and, therefore, it would appear that the implementation of this countermeasure should be a priority for decision makers. In terms of dose reduction, the deep ploughing of edible crops and urban lawn mowing countermeasures appear to be the most effective in this scenario.

5.6 CASE STUDIES COMPARISON

The two sites selected for the case studies presented here were deliberately chosen to be as dissimilar as possible within a European context, in order to assess the applicability and adaptability of the system to different environments. The main differences between the two sites, and the populations residing within them, are summarised below (Table 5.32). The two scenarios generated for each site were broadly similar with comparable maximum deposition levels (~0.5 MBq ^{137}Cs m^{-2}), however, in the Zaragozan scenario the deposition was spread over 11,885 km^2 as opposed to 4,800 km^2 in Cumbria.

Table 5.32 Major differences between Cumbria and Zaragoza and their resident populations.

Attribute	Cumbria	Zaragoza
Typical soil properties	High % organic matter, low pH, low % clay, low K^+	Low % organic matter, neutral pH, high % clay, high K^+
Agricultural output	Focussed mainly on animal derived food products (Total output = 1.04 M tonnes)	Focussed mainly on arable crop production (Total output = 1.02 M tonnes)
Population	418,587 Widely distributed	843,462 Localised around Zaragoza city
Food product consumption	High intake of meat and dairy products, low intake of fruit and vegetables	High intake of fruit and vegetables, low intake of meat and dairy products
Sourcing of food products	Mainly from outside of the region	A large proportion of fruit and vegetables sourced from within the region
Activity profiles	Most people live in semi-detached houses	Most people live in flats in urban areas
Social preferences	Landscape>Animal welfare> Normal daily life> Water quality	Landscape>Water quality>Normal daily life

5.6.1 "Do nothing" strategies

In the Cumbrian case study, the system predicts that the main source of dose of the local population would be exposure to external radiation, whereas in Zaragoza, ingestion was predicted to be the major exposure pathway for the resident population. The main reason for this difference was the dissimilar geographical origins of the food products assumed for the two populations. The Cumbrian population's diet was assumed to be sourced from outside of the region, and consequently was assumed to be uncontaminated. In contrast, on average, 70% of the Zaragozan population's fruit and vegetable intake was assumed to be sourced from within the region (either as home-grown produce, or from other local or regional sources), and, therefore, a large proportion of the population's intake of this food group was predicted to be contaminated. Consequently, the collective ingestion dose received within Zaragoza was estimated to be more than ten times that received by the Cumbrian population. This highlights the importance of determining the geographical origins of a population's diet when estimating collective ingestion doses. If it had been assumed that, in the Cumbrian case study, all of the food product groups consumed by residents of the region were sourced locally, this would have led to a predicted local collective ingestion dose of 1,552 man-Sv in the "Do nothing" strategy (compared with 245 man-Sv when other geographical origins were considered). In a decision making situation, this overestimation could lead the competent authorities to implement an overly drastic remediation strategy, resulting in unnecessary environmental and social impacts.

Although the total deposition, and the resultant local collective ingestion dose, in Cumbria was less than that in Zaragoza, more than three times as much dose was produced via food products in Cumbria than Zaragoza. This was largely due to the elevated long-term bioavailability of radiocaesium in Cumbria, caused by nutrient poor soil with high levels of organic matter. In contrast, the soil in Zaragoza is characterised as having low organic matter content and high clay and nutrient status, resulting in low long-term bioavailability of radiocaesium. The effect of the typical soil characteristics of the two regions on the long-term bioavailability of radiocaesium can be seen in Figure 5.30, which shows the temporal variation of the predicted activity concentration of pasture for one cell in each of the regions. The depositions in each of the cells was approximately 520,000 Bq m^{-2} ^{137}Cs, however, after ten years the activity concentration of the pasture grass in the Cumbrian cell is predicted to be above 50,000 Bq kg^{-1} DW, whereas in the Zaragozan cell, the predicted activity is below 200 Bq kg^{-1} DW.

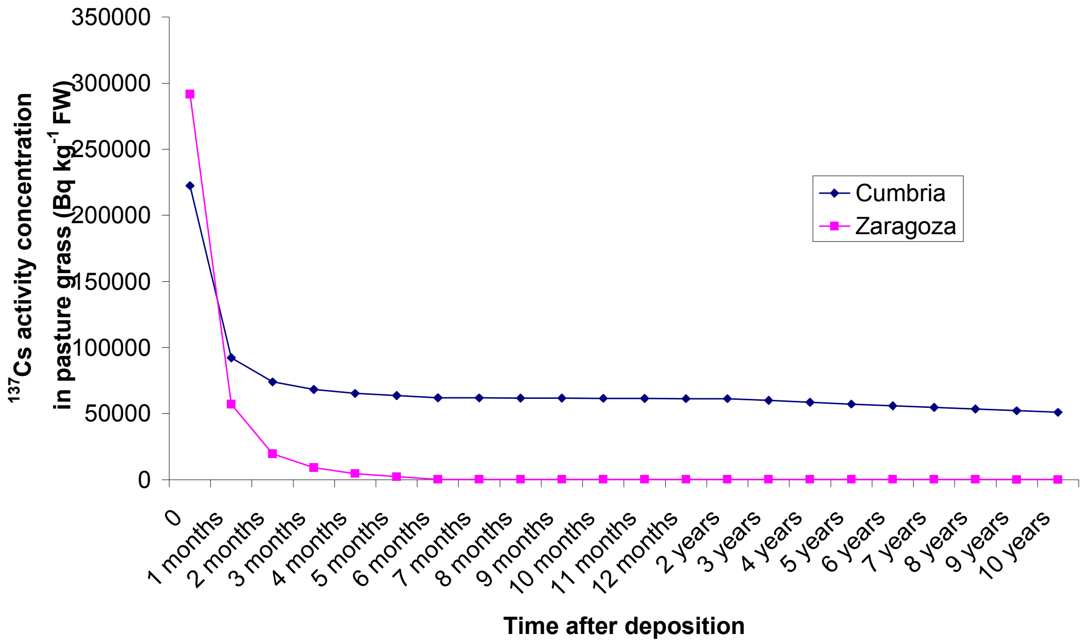

Figure 5.30 Temporal variation in the ^{137}Cs activity concentration of pasture grass (Bq kg^{-1} FW) for cells with similar deposition levels in Cumbria and Zaragoza.

In Cumbria, lamb and beef food products were predicted to contribute 34% and 89% to the local and exported collective ingestion doses respectively, as a significant proportion of the sheep and beef cow herds were assumed to be grazed on upland pastures, where long-term bioavailability of radiocaesium is particularly pronounced, and because the production rates for these products were relatively high. However, in Zaragoza, animal derived food products contributed less than 1% to the local collective ingestion dose and only 7% to the exported collective ingestion dose. In this scenario, fruit and cereals were the food products predicted to be responsible for 89% of the local collective ingestion dose and 86% of the exported ingestion dose. In the case of fruit, this was due to harvesting occurring just two months after deposition, and because approximately 70% of the population's intake of fruit was assumed to have been sourced from within the region.

The predicted collective external doses within each region were comparable (764 man-Sv in Cumbria compared with 843 man-Sv in Zaragoza), despite 70% of the Zaragozan population living in and around the urban areas of Zaragoza city, and the Cumbrian population being more evenly distributed around the county. This was because, although the predicted average external dose received over the ten year study period in Cumbria was higher than in Zaragoza (1.8 mSv compared to 1.0 mSv), the total population in Cumbria is only 49% of that in Zaragoza.

5.6.2 "Food restrictions" strategies

In the Cumbrian case study, simply implementing food restrictions was predicted to avert approximately 33,000 man-Sv, compared to just 10,000 man-Sv in Zaragoza. However, although this strategy was predicted to avert more than three times as

much dose in Cumbria as in Zaragoza, the estimated implementation cost in Cumbria was approximately 17 times that in Zaragoza. This difference is because the system suggested that food restrictions would be required in Cumbria throughout the study period, whereas in Zaragoza it suggested they would only be required during the first year post-deposition. In addition, the food products which were placed under restrictions in Cumbria were predominantly lamb and beef, which resulted in the costly disposal of nearly 5.4 million carcasses. In contrast, the food products which were placed under restrictions in Zaragoza were mainly fruit and cereals, whose disposal costs were assumed to be far cheaper than that of lamb and beef products.
Consequently, despite this strategy averting more dose in Cumbria than in Zaragoza, it was deemed unjustifiable in the former scenario because the benefit derived from it was far outweighed by the scale of the resources required to implement it (as evidenced by the large positive value of the merit function). In contrast, the comparable strategy was deemed justifiable in Zaragoza.

5.6.3 Optimised (without side-effects) strategies

In both case studies, the optimisation procedure suggested strategies which were, according to the respective merit functions, improvements upon the "Food restrictions" strategies. Not only were the total collective doses reduced (by 15% and 30% in Cumbria and Zaragoza respectively), but the implementation costs of the countermeasure strategies were also significantly reduced (by £2,123M and €73M respectively). The focus of the optimised countermeasure strategy for Cumbria was the reduction of the activity concentrations in lamb and beef, which was achieved by implementing countermeasures which either acted directly upon the animals (clean-feeding or AFCF administration), or upon their feeds (skim and burial ploughing of pasture and the addition of potassium fertiliser to pasture). In the Zaragozan case study, the majority of the expenditure was also focussed upon reducing the activity concentrations of lamb and beef food products (by normal ploughing of pasture and deep ploughing of silage crops), despite food products derived from edible crops contributing the most to both the local and exported collective ingestion doses. These countermeasures, whose implementations were only suggested for five months post-deposition, reduced the expenditure on food restrictions for lamb and beef products by €122M. In contrast, there was no reduction in the restrictions placed upon fruit and vegetable food products, as the deposition event took place during the growing season of these crops and no countermeasures were considered that could actively reduce contamination prior to harvesting. Consequently, the only option was for the food products derived from the first harvest post-deposition of these crops to be restricted. However, after the first harvest, the deep ploughing of edible crops was suggested by the system, which reduced the activity concentrations of the crops in subsequent years.

In each of the case studies urban lawn mowing and urban topsoil removal were the only urban or industrial countermeasures found to be effective enough to warrant inclusion within the list of countermeasures to be optimised, even though exposure to external radiation was estimated to contribute the most to the local collective dose in the Cumbrian scenario. This was because the costs associated with implementing many of the urban countermeasures were not compensated for by the doses that they averted in these scenarios. To illustrate this point, the averted doses and costs associated with the full implementation (i.e. implemented in every cell where permitted and feasible) of selected countermeasures in the Cumbrian case study are given in Table 5.33.

Table 5.33 Averted doses and implementation costs resulting from the full implementation of selected countermeasures in the Cumbrian case study.

Countermeasure	Averted dose (man-Sv)	Implementation cost (£M)	Cost-effectiveness (£ Man-Sv^{-1})
Skim and burial ploughing (Pasture)	11,538	41.0	3553
AFCF (sheep)	15,843	32.3	2038
Urban lawn mowing	268	0.3	893
Urban roof hosing	101	12.4	122,772
Urban triple digging	357	69.0	193,277

In this scenario, the costs of skim and burial ploughing and administration of AFCF to sheep are of the same order of magnitude as the costs of urban roof hosing and triple digging. However, these two agricultural countermeasures avert between 40 and 150 times more dose than the two urban countermeasures. Consequently, the cost of averting each man-sievert is less for the two agricultural countermeasures than the two urban countermeasures. Indeed, the values for the former countermeasures are below the lowest value of the unit of collective dose used in the model (£20,000 man-Sv^{-1}), and are therefore likely to be of benefit in this scenario. In contrast, the costs of averting each person-sievert with the two urban countermeasures are well above this value, and this is the reason that these countermeasures were not selected for this case study. The only urban countermeasure that was deemed to be worth implementing in these case studies was urban lawn mowing. Although this countermeasure does not avert any more dose than the other urban countermeasures, it is relatively cheap to implement (estimated to cost just £300,000 for the whole deposition area in Cumbria), and thus its cost-effectiveness is below that of the lowest value of the person-sievert used. However, as highlighted previously, to be effective lawn mowing would have to be performed in the first few weeks after the deposition, and before any significant rainfall. In this time, it is debatable whether it would be possible to mow the predicted amount of lawn area required in either case study.

One reason that many of the urban and industrial countermeasures were not deemed effective in these case studies may be that they were assumed to only reduce the dose of the local population, in contrast to the agricultural countermeasures, which also reduced the ingestion doses received by people living outside of the region, as a consequence of the reduced activity concentrations in exported food products.

In both case studies, most of the food products produced from within the regions were assumed to be exported elsewhere, and as a result, the agricultural and food-based countermeasures suggested by the system, tended to reduce more ingestion dose through exported food products than through those consumed locally. Consequently, although the people living within the case study areas were predicted to receive the highest doses from the contamination, the countermeasure strategies were focussed on reducing the ingestion doses of people living outside the affected regions, whose total doses were assumed to be negligible in comparison. Whether the strategies suggested here are "fair" could therefore be questioned (i.e. whether the distributions of the individual doses received, or the benefits of the restoration strategies are equitable).

However, these strategies were developed using a value of α (the monetary value of the unit of collective dose), which was related to the level of individual dose, as described by Lochard et al. (1994). Therefore the system could be made to place more emphasis on reducing the dose of the resident population by adjusting the values used for determining the monetary value of the unit of collective dose. This could be achieved either by increasing the aversion coefficient, so that there was more disparity in the costs incurred by higher and lower doses, or by reducing the dose threshold above which the aversion coefficient is considered (provided that it was still assumed that the doses of non-residents were below this threshold). In these case studies the latter method would be more likely to have the desired effect, due to the relatively low levels of individual dose within the affected areas.

Alternatively, it could be argued that, as agricultural production is important to the economies of both regions, reducing the activity concentrations in the exported food products benefits the local population, whose livelihoods depend upon it. However, following this line of argument highlights a further limitation to the approach taken during these case studies. In Cumbria, tourism is a major source of income, which would undoubtedly be adversely affected following a deposition of radionuclides within the region. The potential loss of revenue from tourism may even be greater than the loss from the agricultural industry. For example, following the Foot and Mouth Disease (FMD) epidemic in the UK in 2001, the estimated cost to the tourist industry between 2001 and 2005 was approximately £5,000m, whereas the cost for the agricultural sector was only estimated to be around £600m (Anderson, 2002).

Consequently, if the revenue associated with tourism was included within the model, and it was possible to estimate how this would be affected by radioactive contamination of the region, the optimisation process would be more likely to produce restoration strategies that focussed on allowing the tourist industry to function as normal, rather than maintaining the food production industry in the area.

5.6.4 Optimised (with side-effects) strategies

Including the social costs of countermeasures' side-effects in the assessment of restoration strategies had little impact upon the output from the optimisation procedure in both case studies: resulting in the suggestion of similar restoration strategies to those produced when side-effects were not considered. The estimated value of the social costs was higher in Cumbria than in Zaragoza (£165.8M compared with €55M (£39M) respectively), reflecting the protracted length of time over which countermeasure implementation was estimated to be required within the region.

The reason for the relative insignificance of the social costs of countermeasures' side-effects seems to be that, in both case studies, the ploughing countermeasures formed an integral part of the suggested strategies, and these were so effective at reducing the transfer of radionuclides through the food chain that, even though they were often associated with relatively large social costs, there was limited potential for the optimisation process to suggest alternative countermeasures without a substantial reduction in the levels of averted dose. As a result, the system could only reduce the social costs of the strategies by reducing the implementation of other, less extensively implemented, countermeasures, whose social and environmental impacts were significantly less than that of the ploughing countermeasures. It should be remembered, however, that in these case studies, only a limited number of countermeasure side-effects were considered, and it may be the case that the inclusion of other side-effects would have resulted in the suggestion of alternative strategies. Furthermore, it is also likely that the social costs of countermeasures' side-effects would be of more consequence in scenarios with lower levels of deposition, as they would not be greatly outweighed by the monetary value of the averted doses.

5.6.5 Sensitivity

The results of the sensitivity analyses show that within 5% of the optimum implementation thresholds there was little variation in the value of the merit function in the Cumbrian scenario. However, this was mainly due to the relatively small variations in the implementation levels of the countermeasures over these ranges, caused by the non-linearity of the implementation thresholds with the extents of countermeasures' implementations. When the variation about the optimum implementation thresholds did lead to changes in the extents of countermeasures' implementations, the merit function was most sensitive to the implementation levels of the clean-feeding of sheep and administration of AFCF to sheep countermeasures, which greatly reduce the expenditure required for the restriction of lamb. However, because of non-linearity, no variation was seen in the implementation levels of some countermeasures within any of the defined ranges, most notably that of skim and burial ploughing of pasture. It is possible, therefore, that the merit function about the optimum may also be sensitive the implementation levels of other countermeasures, particularly that of skim and burial ploughing of pasture, which was the countermeasure most strongly correlated with averted dose.

The SA2 procedure suggested that the main driving force for the optimisation procedure was the reduction in the expenditure on food restrictions, rather than the aversion of dose. The most effective countermeasure in terms of averted dose was the skim and burial of pasture countermeasure which also reduced the amount of clean-feeding of sheep and beef cows required.

In the Zaragozan scenario, there was little variation in the value of the merit function within any of the defined ranges about the optimum, suggesting that there were many potential strategies of similar merit. This was confirmed by the SA2 procedure, which indicated that, provided that food restrictions were implemented at the recommended CFILs, any combination of the other selected countermeasures would be justified.

5.7 SUMMARY

The main findings of these case study investigations were:

- In the Cumbrian case study, the major source of dose to the local population was predicted to be exposure to external radiation, whereas in the Zaragozan case study, ingestion was predicted to be the major exposure pathway. The maximum individual doses over the ten year period were estimated to be 75 mSv and 29 mSv respectively.

- Cumbria was estimated to produce more than three times as much dose via food products than Zaragoza, largely because of the long-term bioavailability of radiocaesium, caused by the soil characteristics within the region.
- The food products estimated to contribute the most to the local collective ingestion dose were potatoes, lamb and beef in Cumbria, and fruit and cereals in Zaragoza. The majority of the dose exported via food products from Cumbria was due to lamb and beef; in Zaragoza this was due to fruit and cereals.
- Considering the geographical origins of food products reduces the estimate of the local collective ingestion dose. Consequently, a more appropriate scale of countermeasure implementation may be suggested, resulting in less environmental and social disruption.
- The "Food restrictions" strategy would be unjustified in Cumbria, but justified in Zaragoza according to ICRP principles. Restrictions on the sale of lamb and beef food products would still be required in a large proportion of Cumbria 10 years post-deposition. Food restrictions would not be required in Zaragoza after the first year post-deposition.
- In both case studies the optimised strategies were significant improvements upon the corresponding "Food restrictions" strategies, with increased levels of averted dose and lower implementation costs. In the Cumbrian scenario, this was mainly achieved by the skim and burial ploughing of pasture and the administration of clean-feed and AFCF to sheep and beef cows. In Zaragoza, the normal ploughing of pasture, the deep ploughing of edible and silage crops and the dietary advice countermeasures were the most widely implemented.

- The ploughing countermeasures are the most cost-effective countermeasures due to their high efficacy at reducing the plant uptake of radionuclides over long time periods.
- The modelling of tree-borne fruit could be improved, to account for the different cultivation practices associated with them. In particular, the assumption that these crops are routinely sown or ploughed should be revised.
- The inclusion of the social costs of a limited number of side-effects had little impact upon the countermeasure strategy suggested by the optimisation process. This was mainly due to the ploughing countermeasures being so effective at reducing dose that no viable alternatives were available.
- There is significant room for improving the procedures used to perform the sensitivity analyses. In particular, the non-linearity of countermeasures' implementation thresholds with their implementation levels limits the power of the analyses. However, the remedy for this limitation may require the complete restructuring of the system.
- Discount rates applied to costs and benefits had little effect on the optimisation process in either case study. This may be due to the effectiveness of the ploughing countermeasures in these scenarios. As previously stated, the ploughing countermeasures are preferentially selected on the basis of their effectiveness at dose reduction. Changing the discount rate for costs has no effect upon the estimated implementation costs for these countermeasures because they are implemented in the first year post-deposition; before the discount rate has any effect upon the estimated costs of services, materials, etc. For this reason, and because there are no viable alternatives in these scenarios,

the ploughing countermeasures are still preferentially selected when positive discount rates are used, leaving little potential for the optimisation process to suggest significantly different countermeasure strategies.

In general, the system performed well during these case study investigations: it was flexible enough to accommodate two very dissimilar environments, populations and agricultural practices, and it successfully produced strategies which were significant improvements upon simple “Food restrictions” strategies.

CHAPTER 6: GENERAL DISCUSSION

In this Chapter the major achievements accomplished during the development of the system are described, together with some of the limitations and suggestions for further work.

As stated in Chapter 1, the primary objective of this work was to develop a system to assist the design of sustainable long-term strategies for the remediation of radioactively contaminated land. To achieve this aim several secondary objectives were defined, which included:

- the incorporation of the simulation of radiological countermeasures, including the estimation of their environmental and social side-effects, into existing radionuclide transfer models, and the combination of these with a raster-based GIS database to allow the spatial variation in system inputs and outputs to be represented.
- the development of a new method for the simulation of human populations. In particular, giving consideration to the geographical origins of consumed food products, in order to improve the estimation of the level of collective dose, and the distribution of individual doses in a scenario.
- the development of a methodology to assist the selection of appropriate countermeasure strategies for a given scenario, including the facility to optimise those strategies according to the preferences of decision makers and other stakeholders.

On a technical level, all of the secondary objectives have been achieved; however, the ultimate test of whether the primary objective has been met is whether the system would be useful to decision makers when designing long-term remediation strategies. To assess the success of the system at achieving this goal, two widely differing case studies were devised, which allowed the applicability of the system to be tested. With the exception of the modelling of tree-borne fruit, the system was generally successful at accommodating the two contrasting environments, populations and agricultural systems of the selected sites. Furthermore, for each case study, the system identified optimal remediation strategies which were significant improvements upon simple food restrictions strategies, which constitute the statutory minimum actions following the contamination of the human food chain.

In addition, the system has been used in two mock nuclear emergency exercises involving potential end-users. In the first exercise, decision makers were presented with the predictions for the Cumbrian case study described here, and asked to comment on, and refine the strategies proposed by the optimisation procedure. Feedback from the end-users regarding the usefulness of the system was generally positive and, in particular, it was remarked that the system provided a good level of detail for decision makers, and that the suggested optimised strategies provided a good starting point for the design of a long-term remediation strategy. However, the end-users also remarked that some estimation of the uncertainty involved in the predictions would have been useful. In the second exercise, the system was used to predict the consequences of a hypothetical small-scale accident at the Sellafield reprocessing plant in

Cumbria, as part of the OSCAR 7 recovery exercise undertaken by British Nuclear Fuels Limited, in conjunction with the relevant authorities (e.g. The Food Standards Agency, The Environment Agency and Cumbria county council). Again, the feedback from end-users was positive with the representatives from the Food Standards Agency showing particular interest in the outputs from the system.

It should be noted that a systematic validation of the radiological predictions made by the system has not been performed, although the predictions of the underlying plant uptake and food-chain models used have been tested previously (Crout et al., 1999; Absalom et al., 2001; Müller et al., 1993; Köhler, Peterson and Hoffman, 1991; IAEA, 1995). In each of these studies, only the ability of the models to predict the activity concentrations in food products was tested, and as the prediction of the ingestion doses resulting from contaminated food products is also dependent upon the simulation of human behaviour, it cannot, therefore, be inferred that this system accurately predicts the levels of individual or collective dose for a given scenario. However, during the development of the system described here, data for the radioactive deposition in Cumbria resulting from the Chernobyl incident was collated, and calculations performed for a one year period post-deposition. The resulting predictions were 16.5 μSv and 61 μSv for the average and maximum annual individual doses received by residents of Cumbria in the first year after the Chernobyl deposition, respectively. These are similar to the 27 μSv and 64 μSv as estimated by Sanchez *et al.* (1999), who reconstructed the doses of Cumbrian residents using previously published data regarding dietary habits and activity concentrations within the region, one month after the Chernobyl incident.

6.1 MAJOR ACHIEVEMENTS

6.1.1 Human population modelling

The method developed for the creation and simulation of human populations represents a significant advance within radiological DSS. The stochastic generation of representative individuals (the number of which is only limited by computational constraints), using population level data, allows the variations seen between individuals in human populations to be represented, and for behavioural characteristics which lead to high levels of exposure to ionising radiation to be identified. Furthermore, by considering the geographical origins of consumed food products more realistic predictions of the levels of individual and collective dose for a given scenario can be made, which in turn will lead to the suggestion of remediation strategies whose economic and social impacts are more appropriate to the levels of dose received. As far as the author is aware, with the exception of the RESTORE DSS (Voigt and Semiosckina, 1999), all other DSS use radiological models which assume that all consumed food products are locally produced, and therefore tend to over-predict dose levels in areas where significant deposition has occurred, and under-predict where there is little or no deposition, as evidenced in a systematic review of radioecological models (IAEA, 1995). In the context of designing remediation strategies these effects may have serious consequences, as over-predictions of dose levels may lead to the suggestion of overly drastic strategies, resulting in unnecessary environmental damage and social disruption. Perhaps more worryingly, under-prediction may lead to the suggestion of inadequate strategies which could leave some individuals exposed to unacceptably high levels of dose.

To illustrate this point, the “Do nothing” strategy in the Cumbrian case study was repeated using populations with almost identical habits data, the only exception being that all food products were assumed to be sourced locally rather than from a variety of locations. The resulting local collective ingestion dose was estimated to be 1,552 man-Sv; over 6 times the 245 man-Sv value predicted for the case study. Although, in this system, the increase in the level of the local collective ingestion dose corresponds to an equivalent reduction in the exported ingestion dose (because food products which are not consumed locally are assumed to be exported), the monetary value of the dose may be higher, as the residents of a contaminated area are more likely to receive doses above the defined dose aversion threshold than individuals living outside of the affected area, whose doses are assumed to be below the threshold. Consequently, when all food products are assumed to be sourced locally, countermeasures appear to be more effective in terms of the merit function, which could potentially alter the output from the optimisation procedure. This example demonstrates that the origins of food products consumed by affected populations are key factors, which, although difficult to define, must be considered if the benefits of remediation strategies are to be appropriately balanced against their implementation costs and detrimental side-effects.

6.1.2 The consideration of countermeasures' side-effects.

Although the need to consider the social aspects of radiation protection was first formalised by the ICRP in 1965 with the precursor to the ALARA principle that "any unnecessary exposure be avoided and that all doses be kept as low as readily achievable, economic and social considerations being taken into account" (ICRP, 1965), generally the non-radiological effects and indirect costs of countermeasure strategies have received little explicit attention within DSS. More recently, a limited number of attempts have been made to quantify the side-effects of countermeasures' implementations, most notably within the CESER DSS (Salt and Dunsmore, 2000). However, this DSS does not consider the doses received within an area, and consequently cannot compare the benefits of countermeasures' implementations with the associated detriments, and thereby identify optimal remediation strategies. To date the only DSS that includes the social and environmental impacts of countermeasures within the assessment and optimisation of remediation strategies is the MOIRA DSS (Insua et al., 2000), however, this system is focussed upon aquatic environments which do not generally contribute significantly to individual or collective doses following an atmospheric release of radionuclides. Although, as discussed below, there is significant room for improvement in the number, and quantification of the side-effects considered within the system described here, this represents the first serious attempt to explicitly incorporate these factors into the assessment and optimisation of terrestrial based remediation strategies.

6.1.3 A methodology for the selection and optimisation of long-term remediation strategies

Previously, the focus of radiological DSS has been short-term, acute-phase responses to nuclear emergencies such as evacuation, sheltering and the administration of prophylactic iodine. Where long-term countermeasures have been included, the usefulness of the systems in assisting the design of long-term remediation strategies has been limited, either due the restricted number of countermeasures considered (e.g. RESTORE (Voigt and Semioschkina, 1999); Papazoglou et al., 1997; Perny and Vanderpooten, 1998), the limited consideration for the spatial variability of model inputs and outputs (TEMAS, Montero et al., 2001), or the inability of the system to automatically generate and optimise long-term remediation strategies (RODOS (Papamichail and French, 2000) and PRANA (Yatsalo et al., 1997)). The system described here, therefore, represents the first off-site nuclear emergency DSS which has numerous, practical long-term countermeasures incorporated into spatially implemented radiological models, and which allows the interactive assessment and optimisation of remediation strategies. The case studies presented in Chapter 5 demonstrate that the system is flexible enough to cope with widely varying agricultural and social conditions, and can successfully, and efficiently, identify optimal remediation strategies which are consistent with the preferences of decision makers and other stakeholders.

6.2 LIMITATIONS AND SUGGESTED FURTHER WORK

Due to the complex and variable nature of radionuclide transfer in the environment, agricultural systems, urban environments and human behaviour, all radiological DSS contain rationalisations and assumptions which affect their output. It is imperative that these limitations are made explicit to decision makers, to ensure that they are aware of the boundaries within which the systems are designed to operate.

Given below are the major limitations of the system developed here, potential solutions and suggestions for the future development of the system. Although many of the suggested improvements could improve the predictive capability of the system, and increase the level of detail available to decision makers, a parsimonious approach should be taken to the future development of the system, as any additional functionalities must be balanced with the usability and computational requirements of the system.

6.2.1 Crop modelling

The model used to describe the cultivation of crops was adapted from the SAVE system (Gillett et al., 2001) and is subject to several limitations. The growing period for each crop considered within the system is defined by single sow and harvest dates, and, therefore, contaminated food products and feedstuffs derived from crops are assumed not to enter the food chain until the first harvest after deposition. However, in reality, many crops (e.g. potatoes, leafy vegetables and root vegetables) are harvested at various times during the year. Consequently, the system may underestimate the activity concentrations of food products derived from crops harvested before the defined harvest date, and overestimate those derived from crops harvested after the defined date. A potential remedy for this problem would be to allow ranges for the sow and harvest dates of crops to be defined, rather than single dates, and to assume a distribution of harvesting within these defined dates. However, to perform this modification, the modelling of crop growth, which is dependent upon the specified sow and harvest dates, would also have to be altered.

An important limitation in the modelling of fruit crops was highlighted by the Zaragozan case study. The fruit crop simulated in the model is assumed to be representative of soft fruit (e.g. strawberries) which are sown and ploughed annually. However, in Zaragoza, and many other regions in Europe, many of the fruits cultivated are tree-borne (e.g olives and oranges), and are not sown or ploughed annually, if at all. Consequently, the system may underestimate the activity concentration of tree-borne fruit, as the simulated routine ploughing of these crops is assumed to reduce the plant uptake of radionuclides. In addition, the system will greatly underestimate the implementation costs associated with ploughing these crops, which would require the removal and re-planting of trees, with a potential loss in production in subsequent years, either while existing trees recovered, or while new trees matured. Furthermore, there would also be a significant social impact associated with removing fruit trees in regions where they form an integral part of the landscape.

A solution to this limitation would be to introduce a new crop type into the system, representing tree-borne fruit, where routine sowing and ploughing were not assumed, and the implementation cost of the ploughing countermeasures was adjusted accordingly. In addition, side-effects could be associated with the ploughing countermeasures for this crop type. However, the benefits of improving the modelling of tree-borne fruit crops would have to be weighed against the potential increase in computational effort required to estimate the activity concentrations of an additional crop type.

6.2.2 Human population modelling.

Although, when compared to other DSS, the method developed for the simulation of human populations in this system is relatively sophisticated, there is still significant room for improvement. For example, currently, the doses to all individual types simulated are calculated using the same dose conversion factor, so that, in effect, all individuals are assumed to be of the same age group. To resolve this, dose conversion factors could be defined for different age groups, together with the proportion of the population within each group: which would allow the Monte-Carlo routine to create the appropriate number of individual types for each age group. Furthermore, due to the models used to estimate external doses, all sub-populations are assumed to spend most of their time in and around the building types considered. This may be a reasonable assumption for “urban” individuals, however, “rural” individuals (e.g. farmers) generally spend more time outdoors away from the shielding effects of buildings (Stewart et al., 1990), and consequently may be more exposed to external radiation. However, comparison of the estimated average external dose received by the population in a cell with a deposition level of 690,000 Bq m^{-2} ^{137}Cs using the model described here with the dose estimated for an individual continually exposed 1m above a well mixed soil by a simple model (Attwood et al., 1998) shows that the former model actually predicts a higher level of external dose than the latter (1.5 mSv a^{-1} c.f. 1.3 mSv a^{-1} in the first year after deposition), which may be a result of the fixation of radiocaesium to urban surfaces assumed in the model. It is unlikely, therefore, that the system would underestimate the external dose to "rural" individuals.

In addition, for simplicity, a normal probability distribution was assigned to each of the attributes used to describe the habits of populations, and these were assumed to be independent. However, many of the attributes are unlikely to be normally distributed, and correlations usually exist between attributes (e.g. individuals who consume relatively large quantities of leafy vegetables may be more likely to also consume relatively large quantities of other vegetables (MAFF, 1994)). Therefore, allowing different types of probability distributions to be defined for attributes, and correlations to exist between attributes, may lead to a more realistic reflection of the types of individuals observed in real populations.

Further limitations in the simulation of human populations are that i) the relative proportions of each defined sub-population are spatially constant, and ii) the attributes used to describe them are temporally constant. In principle, the relative proportion of each individual type could be allowed to vary on a cell by cell basis according to some predefined criteria. For example, the relative proportion of "urban" individuals (e.g. people who live in flats) could be designated as being higher in areas of high population density. However, for this function to be of benefit, detailed information about the relationships between behavioural attributes and spatial statistics would be required.

In a long-term DSS, the assumption that the attributes describing the human population are temporally constant may have a significant effect upon the output from the system, as behaviours and attitudes may change markedly within a relatively short time-span, especially following a major event such as a nuclear accident (Grande et al., 1999). Predicting such changes is extremely problematic, if not impossible, and for this reason this has not been attempted here; however, allowing decision makers to investigate the effects of hypothetical temporal changes in population attributes could be a useful addition to future long-term DSS.

6.2.3 The simulation of countermeasures

As stated previously, only those countermeasures deemed the most likely to be implemented were included within the system. However, many more countermeasures could be incorporated, which would increase the options available to decision makers and may lead to the identification of remediation strategies with lower merit functions. Furthermore, for each of the countermeasures considered, only one method of waste disposal has been included. However, in different scenarios, other methods of waste disposal may be more appropriate, and, therefore, the inclusion of these alternatives would further enhance the options available for investigation by decision makers and the optimisation procedure. Another potential enhancement of the simulation of countermeasures would be the inclusion of a greater number of countermeasure side-effects. These were limited during this work as the objective was to develop a methodology for their inclusion within a decision making framework, rather than an attempt to identify and consider all of the relevant side-effects associated with the countermeasures and scenarios considered. The side-effects which were included had little effect in either of the case studies presented; however, it may be that other side-effects, such as the impact on tourism, would have had greater influence on the outcomes of the optimisation procedure. Moreover, countermeasures' side-effect costs are likely to be of greater significance for smaller incidents.

A further limitation associated with the simulation of countermeasures was that, due to the use of trigger variables and implementation thresholds to determine if countermeasures are implemented in a cell or not, their implementation within a region may not be contiguous. Although in a radiological or economic context this may be the most appropriate use of resources, it may be publicly unacceptable for a countermeasure not be implemented in a cell while being implemented in the cells adjacent to it. This situation could be remedied by the creation of a simple rule that specified that a particular countermeasure should be implemented in a cell, regardless of the value of the trigger variable within it, if the countermeasure had been implemented in at least, say, three of the neighbouring cells.

6.2.4 Other limitations/further improvements.

When presented with the output from a DSS, a key consideration for decision makers will be the uncertainties attached to the predictions made. In an attempt to address this issue, a facility has been incorporated into this system, which allows a limited assessment of the sensitivity of the merit function for a particular scenario to the implementation levels of the selected countermeasures. However, the uncertainties associated with other model and system inputs are not considered. A possible improvement to the system, therefore, would be to take a more stochastic approach to the radionuclide transfer and dose modelling, by allowing probability distributions to be defined for inputs, and subsequently running the system in an iterative manner using input parameters randomly sampled from within the distributions. The uncertainties associated with model predictions could then be made explicit to decision makers, enhancing their confidence in the outputs of the system. However, without a significant enhancement of the computational efficiency of the program, or a considerable increase in computer processor speeds, this would be an extremely computationally intensive procedure for a system of this size and complexity, which would increase the length of time for the system to complete simulations, and severely compromise the interactivity of the system. It is possible that this problem could be overcome by the use of a gaussian process emulator that can describe complex models with greater computational efficiency (Kennedy and O'Hagan, 2000).

Due to the focus of this work being the development of *long-term* remediation strategies, short-term responses and doses received during the acute phase immediately following an accident have not been considered. However, actions taken in the immediate aftermath of an accident may have significant consequences on the efficacy of any future remediation strategy. For example, in areas which have been evacuated it may not be possible to perform some countermeasures before their effectiveness is diminished (e.g. to be fully effective lawn mowing must be performed before any significant rainfall event). Furthermore, any doses received during the acute phase (e.g. from inhalation during the passing of a contaminated plume), may constitute a significant proportion of an individual's total dose. Consequently, the monetary value of the collective dose would be greater, potentially allowing more extensive implementation of long-term countermeasures to be justified.

6.3 CONCLUSIONS

Previously, radiological DSS have generally focussed upon short-term, acute phase responses to nuclear emergencies, and only considered the direct radiological and economic consequences of those actions in the assessment of potential remediation strategies. The system described in this thesis is the first radiological DSS to specifically address the design of long-term remediation strategies, and to explicitly consider the environmental and social impacts of agricultural and urban countermeasures. The simulation of numerous commonly implemented countermeasures have been incorporated into existing radiological models which, in turn, have been combined with a raster-based GIS database to account for the spatial variation in system inputs and outputs. In addition, a novel method for the creation and simulation of human populations has been developed, using Monte-Carlo sampling of statistically defined attributes, which include the geographical origins of consumed food products. Furthermore, a methodology for the selection and optimisation of remediation strategies has been developed, which has the ability to incorporate a limited number of environmental and social side-effects caused by the implementation of countermeasures into the assessment of remediation strategies.

As demonstrated in Chapter 5, the system is flexible enough to cope with widely differing agricultural, urban and social conditions, and can successfully identify optimal remediation strategies, using a range of agricultural and urban countermeasures, according to the preferences of decision makers and the general public.

Moreover, the system has been used in two end-user exercises, receiving positive feedback in both cases, and is currently being adapted for operational use by the Norwegian Radiation Protection Authority.

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APPENDICES

Appendix A

Table A1. Attribute coefficients for countermeasure side-effects.

Countermeasure	Attribute				
	Landscape/ biodiversity	Water	Animal welfare	Heritage	Daily life
Normal ploughing (pasture)	1	0.3	0.2	0/1[c]	0
Deep ploughing (pasture)	1	0.3	0.2	0/1 [c]	0
S&B ploughing (pasture)	1	0.3	0.2	0/1 [c]	0
K fertiliser	0.2	0.2	0	0	0
Liming	0.3	0	0	0	0
AFCF	0	0	0/0.1[a]	0	0
Clean feeding	0.4	0.3	0/0.1/0.2[b]	0	0
Roof hosing	0	0	0	0.05	0.1
Wall washing	0	0	0	0.05	0.1
Triple digging	1	0	0	0.05	1
Topsoil removal	1	0	0	0.05	1
Street sweeping	0	0	0	0	0
Lawn mowing	0	0	0	0	0.05
Tree pruning	0.4	0	0	0.05	0.05
Food restrictions (Milk products)	0.1	0.3	0	0.3	0.2
Food restrictions (Chicken/eggs)	0.05	0.05	0	0.3	0.2
Food restrictions (Other meat)	0.05	0.05	0	0.3	0.2
Food restrictions (Crops)	0.05	0.1	0	0	0.2

[a] Values are for the administration of concentrates and boli respectively.
[b] Values are for chickens and pigs/dairy cows/ beef cows, sheep and goats respectively.
[c] Values are for pasture in cells not designated as ESAs and cells designated as ESAs respectively.

Appendix B

Table B1 Parameters used to simulate the growth, management and contamination of crops in the Cumbrian case study.

Parameter	Crop						
	Pasture	Cereals	Maize	Potatoes	Leafy Veg.	Root Veg.	Fruit
Minimum biomass (kg FW m^{-2})	0.216	0.013	0.015	0.087	0.045	0.085	0.015
Sow day (day of year)	-	274	91	105	91	213	60
Dry matter fraction	0.2	0.85	0.24	0.21	0.08	0.08	0.16
Harvest day (day of year)	-	217	248	288	274	288	213
Harvest index	1	0.43	0.5	0.55	0.9	0.55	0.5
Yield (kg FW m^{-2})	4.323	0.671	0.748	4.342	2.27	4.225	0.728
Day of maximum pasture biomass (day of year)	181	-	-	-	-	-	-
Day of minimum pasture biomass (day of year)	304	-	-	-	-	-	-
K fertilizer day (day of year)	90	90	90	90	90	90	90
Root zone depth (cm) (for Sr, Pu, Am)	10	25	25	25	25	25	25
Initial Cs distribution depth (cm)	2.5	2.5	2.5	2.5	2.5	2.5	2.5

Table B2 Data used to simulate the feeding of livestock animals in the Cumbrian case study.

	Animal[1]					
Parameter	DC	BC	S	G	C	P
Pasture DMI[2] (Jan-Feb) (kg d^{-1})	0	0	1	0	0	0
Pasture DMI (Mar-Apr) (kg d^{-1})	1.5	12	1.25	0	0	0
Pasture DMI (May-Jun) (kg d^{-1})	12	12	1.25	1	0	0
Pasture DMI (Jul-Aug) (kg d^{-1})	12	12	1.25	1	0	0
Pasture DMI (Sep-Oct) (kg d^{-1})	1.5	12	1.25	0	0	0
Pasture DMI (Nov-Dec) (kg d^{-1})	0	0	1	0	0	0
Stored grass DMI (Jan-Feb) (kg d^{-1})	9.75	12	0.25	2.3	0	0
Stored grass DMI (Mar-Apr) (kg d^{-1})	7.5	0	0	2.3	0	0
Stored grass DMI (May-Jun) (kg d^{-1})	0	0	0	1.3	0	0
Stored grass DMI (Jul-Aug) (kg d^{-1})	0	0	0	1.3	0	0
Stored grass DMI (Sep-Oct) (kg d^{-1})	7.5	0	0	2.3	0	0
Stored grass DMI (Nov-Dec) (kg d^{-1})	9.75	12	0.25	2.3	0	0
Maize silage DMI (Jan-Feb) (kg d^{-1})	0	0	0	0	0	0
Maize silage DMI (Mar-Apr) (kg d^{-1})	0	0	0	0	0	0
Maize silage DMI (May-Jun) (kg d^{-1})	0	0	0	0	0	0
Maize silage DMI (Jul-Aug) (kg d^{-1})	0	0	0	0	0	0
Maize silage DMI (Sep-Oct) (kg d^{-1})	0	0	0	0	0	0
Maize silage DMI (Nov-Dec) (kg d^{-1})	0	0	0	0	0	0
Cereal concentrates DMI (Jan-Feb) (kg d^{-1})	9	4	0.25	1.4	0.08	2.4
Cereal concentrates DMI (Mar-Apr) (kg d^{-1})	9	4	0.25	1.4	0.08	2.4
Cereal concentrates DMI (May-Jun) (kg d^{-1})	6	4	0.25	1.4	0.08	2.4
Cereal concentrates DMI (Jul-Aug) (kg d^{-1})	6	4	0.25	1.4	0.08	2.4
Cereal concentrates DMI (Sep-Oct) (kg d^{-1})	9	4	0.25	1.4	0.08	2.4
Cereal concentrates DMI (Nov-Dec) (kg d^{-1})	9	4	0.25	1.4	0.08	2.4

[1]DC = Dairy Cows, BC = Beef Cows, S = Sheep, C = Chickens, P = Pigs
[2] DMI = Dry Matter Intake

Table B3 Dietary consumption data used to generate sub- populations in the Cumbrian case study.

Food product	% consumers	Mean consumption rate (kg yr^{-1})	Standard deviation (kg yr^{-1})
Cow's milk	98	177	94.8
Goat's milk	0	0	0
Sheep milk	0	0	0
Cream	45	6.8	9.4
Butter	62	4.1	3.6
Cow cheese	80	7.2	6.0
Goat cheese	0	0	0
Sheep cheese	0	0	0
Chicken	70	21	15.8
Eggs	80	10.4	8.0
Pork	42	8.32	8.0
Lamb	32	10.1	12.4
Beef	76	17.7	12.8
Cereals	90	41	15
Potatoes	95	64.4	44.5
Leafy vegetables	62	9.3	6.5
Fruit	60	34	29.5
Fish	0	0	0
Roe deer	0	0	0
Red deer	0	0	0
Reindeer	0	0	0
Moose	0	0	0
Wild fowl	0	0	0
Wild boar	0	0	0
Fungi	0	0	0
Berries	0	0	0
Root vegetables	90	22.6	17

Table B4. Parameter values used to characterise the geographical origins of food products consumed by sub-populations in the Cumbrian case study.

	Origin of food product											
	Home-grown			Local			Regional			External		
Food group	% Consumers	Mean % of total	Std Dev	% Consumers	Mean % of total	Std Dev	% Consumers	Mean % of total	Std Dev	% Consumers	Mean % of total	Std Dev
Dairy	n/a	n/a	n/a	1	80	10	100	15	10	100	85	10
Meat	n/a	n/a	n/a	1	50	10	100	15	10	100	85	10
Fruit and vegetables	25	10	10	20	20	10	100	10	10	100	80	10
Cereals	n/a	n/a	n/a	0	0	0	100	10	10	100	90	10
Semi-natural	n/a	n/a	n/a	0	0	0	0	0	0	0	0	0

Table B5. Parameter values used to generate the activity profiles of sub-populations in the Cumbrian case study.

Parameter	%	Std Dev
Individuals living in semi-detached houses	60.75[a]	n/a
Individuals living in terraced houses	32[a]	n/a
Individuals living in flats	7.25[a]	n/a
Time spent in the urban environment	77	10
Time spent in the industrial environment	23	10
Semi-detached (ground floor) residency	25[c]	5
Semi-detached (1st floor) residency	60 [c]	10
Semi-detached (attic) residency	5 [c]	3
Semi-detached (outside) residency	10 [c]	5
Terraced (ground floor) residency	25 [c]	5
Terraced (1st floor) residency	60 [c]	10
Terraced (attic) residency	5 [c]	3
Terraced (outside) residency	10 [c]	5
Flats (inside)	95 [c]	3
Flats (outside)	5 [c]	3
Individuals working in factories	30[a]	n/a
Individuals working in offices	70[a]	n/a
Factory middle residency	60 [c]	5
Factory office residency	30 [c]	10
Factory outside residency	5 [c]	3
Office inside residency	95 [c]	5
Office outside residency	5 [c]	3
Compliance[d]	80[a]	n/a

[a] As a percentage of the whole population.
[b] These parameter values only refers to individuals who reside the appropriate building type.
[c] Values are the percentage of the total time an individual spends within the building.
[d] Corresponds to the percentage of the population who are assumed to comply with the dietary advice countermeasure.

Appendix C

Table C1 Parameters used to simulate the growth, management and contamination of crops in the Zaragozan case study.

Parameter	Crop						
	Pasture	Cereals	Maize	Potatoes	Leafy Veg.	Root Veg.	Fruit
Minimum biomass (kg FW m^{-2})	0.089	0.006	0.018	0.005	0.056	0.092	0.066
Sow day (day of year)	-	305	32	74	60	182	32
Dry matter fraction	0.2	0.85	0.24	0.21	0.08	0.08	0.16
Harvest day (day of year)	-	186	186	258	244	258	182
Harvest index	1	0.43	0.5	0.55	0.9	0.55	0.5
Yield (kg FW m^{-2})	1.785	0.277	0.912	0.259	2.819	4.615	3.299
Day of maximum pasture biomass (day of year)	151	-	-	-	-	-	-
Day of minimum pasture biomass (day of year)	304	-	-	-	-	-	-
K fertilizer day (day of year)	90	90	90	90	90	90	90
Root zone depth (cm) (for Sr, Pu, Am)	10	25	25	25	25	25	25
Initial Cs distribution depth (cm)	2.5	2.5	2.5	2.5	2.5	2.5	2.5

Table C2 Data used to simulate the feeding of livestock animals in the Zaragozan case study.

	Animal[1]					
Parameter	DC	BC	S	G	C	P
Pasture DMI[2] (Jan-Feb) (kg d^{-1})	0	0	0.51	0	0	0
Pasture DMI (Mar-Apr) (kg d^{-1})	9.1	11.1	0.51	0.12	0	0
Pasture DMI (May-Jun) (kg d^{-1})	9.1	11.1	0.51	0.12	0	0
Pasture DMI (Jul-Aug) (kg d^{-1})	9.1	11.1	0.51	0.12	0	0
Pasture DMI (Sep-Oct) (kg d^{-1})	0	11.1	0.51	0.12	0	0
Pasture DMI (Nov-Dec) (kg d^{-1})	0	0	0.51	0	0	0
Stored grass DMI (Jan-Feb) (kg d^{-1})	2.8	9.5	0	0.24	0	0
Stored grass DMI (Mar-Apr) (kg d^{-1})	0	0	0	0.12	0	0
Stored grass DMI (May-Jun) (kg d^{-1})	0	0	0	0.12	0	0
Stored grass DMI (Jul-Aug) (kg d^{-1})	0	0	0	0.12	0	0
Stored grass DMI (Sep-Oct) (kg d^{-1})	0	0	0	0.12	0	0
Stored grass DMI (Nov-Dec) (kg d^{-1})	0	9.5	0	0.24	0	0
Maize silage DMI (Jan-Feb) (kg d^{-1})	9.1	0	0	0	0	0
Maize silage DMI (Mar-Apr) (kg d^{-1})	4.9	0	0	0	0	0
Maize silage DMI (May-Jun) (kg d^{-1})	4.9	0	0	0	0	0
Maize silage DMI (Jul-Aug) (kg d^{-1})	4.9	0	0	0	0	0
Maize silage DMI (Sep-Oct) (kg d^{-1})	9.1	0	0	0	0	0
Maize silage DMI (Nov-Dec) (kg d^{-1})	9.1	0	0	0	0	0
Cereal concentrates DMI (Jan-Feb) (kg d^{-1})	2.1	3.1	0.09	0.36	0.08	2.6
Cereal concentrates DMI (Mar-Apr) (kg d^{-1})	0	1.5	0.09	0.36	0.08	2.6
Cereal concentrates DMI (May-Jun) (kg d^{-1})	0	1.5	0.09	0.36	0.08	2.6
Cereal concentrates DMI (Jul-Aug) (kg d^{-1})	0	1.5	0.09	0.36	0.08	2.6
Cereal concentrates DMI (Sep-Oct) (kg d^{-1})	2.1	1.5	0.09	0.36	0.08	2.6
Cereal concentrates DMI (Nov-Dec) (kg d^{-1})	2.1	3.1	0.09	0.36	0.08	2.6

[1]DC = Dairy Cows, BC = Beef Cows, S = Sheep, C = Chickens, P = Pigs
[2] DMI = Dry Matter Intake

Table C3 Dietary consumption data used to generate sub- populations in the Zaragozan case study.

Food product	% consumers	Mean consumption rate (kg yr^{-1})	Standard deviation (kg yr^{-1})
Cow's milk	98	78.9	42.2
Goat's milk	0	0	0
Sheep milk	0	0	0
Cream	45	1.63	2.23
Butter	62	0.33	0.29
Cow cheese	80	1.8	1.5
Goat cheese	0	0	0
Sheep cheese	0	0	0
Chicken	70	24.9	18.7
Eggs	80	14.4	11.1
Pork	42	54.2	52.0
Lamb	32	6.5	7.9
Beef	76	13	9.4
Cereals	90	83.4	30.5
Potatoes	95	51.3	35.3
Leafy vegetables	62	107.4	74.66
Fruit	60	103	89.3
Fish	0	0	0
Roe deer	0	0	0
Red deer	0	0	0
Reindeer	0	0	0
Moose	0	0	0
Wild fowl	0	0	0
Wild boar	0	0	0
Fungi	0	0	0
Berries	0	0	0
Root vegetables	90	19	14.2

Table C4. Parameter values used to characterise the geographical origins of food products consumed by sub-populations in the Zaragozan case study.

	Origin of food product											
	Home-grown			Local			Regional			External		
Food group	% Consumers	Mean % of total	Std Dev	% Consumers	Mean % of total	Std Dev	% Consumers	Mean % of total	Std Dev	% Consumers	Mean % of total	Std Dev
Dairy	n/a	n/a	n/a	1	80	10	100	10	10	100	10	10
Meat	n/a	n/a	n/a	1	50	10	100	10	10	100	10	10
Fruit and vegetables	60	15	10	40	30	10	100	50	10	100	30	10
Cereals	n/a	n/a	n/a	0	0	0	100	35	10	100	65	10
Semi-natural	n/a	n/a	n/a	0	0	0	0	0	0	0	0	0

Table C5. Parameter values used to generate the activity profiles of sub-populations in the Zaragozan case study.

Parameter	%	Std Dev
Individuals living in semi-detached houses	60.75[a]	n/a
Individuals living in terraced houses	32[a]	n/a
Individuals living in flats	7.25[a]	n/a
Time spent in the urban environment	77	10
Time spent in the industrial environment	23	10
Semi-detached (ground floor) residency	25[c]	5
Semi-detached (1st floor) residency	60 [c]	10
Semi-detached (attic) residency	5 [c]	3
Semi-detached (outside) residency	10 [c]	5
Terraced (ground floor) residency	25 [c]	5
Terraced (1st floor) residency	60 [c]	10
Terraced (attic) residency	5 [c]	3
Terraced (outside) residency	10 [c]	5
Flats (inside)	95 [c]	3
Flats (outside)	5 [c]	3
Individuals working in factories	30[a]	n/a
Individuals working in offices	70[a]	n/a
Factory middle residency	60 [c]	5
Factory office residency	30 [c]	10
Factory outside residency	5 [c]	3
Office inside residency	95 [c]	5
Office outside residency	5 [c]	3
Compliance[d]	80[a]	n/a

[a] As a percentage of the whole population.
[b] These parameter values only refers to individuals who reside the appropriate building type.
[c] Values are the percentage of the total time an individual spends within the building.
[d] Corresponds to the percentage of the population who are assumed to comply with the dietary advice countermeasure.