Compilation of EU Dioxin Exposure and Health Data

Task 3 - Environmental Fate and Transport

Report produced for

European Commission DG Environment

UK Department of the Environment, Transport and the Regions (DETR)

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Executive Summary

An essential component in the development of policy to control and reduce human exposure to dioxins is a thorough understanding of how these compounds behave in the environment. This report critically evaluates the current state of knowledge and understanding, and examines the feasibility of developing models to predict how exposure might change into the future, as a consequence of reducing the amounts of dioxin released into the environment.

The average exposure of citizens in the EU Member States is already below the Tolerable Daily Intake (TDI) of 10 pg 2,3,7,8-TCDD/kg body weight per day, recommended by the World Health Organisation (WHO) in 1990, and is gradually declining. However, the WHO has recently proposed a new, lower TDI. It is essential to know whether the current level of exposure is likely to continue declining at a rate sufficient to bring it below the new TDI, within an acceptable timescale, or whether further policy measures will be required to achieve this.

This report concludes that it is currently not possible to make reliable projections of future average levels of human exposure to dioxins, as vital information is lacking in a number of important areas: the mechanisms and rates of key environmental transfer and degradation processes; the role played by reservoir sources in determining future levels of exposure; the pathways for exposure of citizens in Southern European Member States; validation of the output of existing environmental models. Hence, five key recommendations are made of work which should be undertaken in order to make this a feasible prospect for the future:

- A programme of work is required to improve the understanding and quantification of the fundamental transfer processes by which dioxins move between the different environmental media, particularly within the aquatic and terrestrial environments, and the degradation processes occurring within these media.
- The contribution to human exposure from reservoir sources, especially landfills, requires examination and, in particular, work to assess the behaviour and degradation processes of dioxins in these environments. Without this knowledge it will be impossible to predict the effect of regulatory controls on the future levels of human exposure.
- Policies aimed at further reducing human exposure to dioxins will have to be relevant and applicable across the EU. Most research work undertaken so far has been focused on the Northern Member States, although circumstances in Southern Member States might be very different. Further research is required to identify the important environmental pathways of dioxins in climates, agricultural systems and dietary regimes representative of Southern Europe.
- Measurement programmes across the Member States should be co-ordinated, in order to provide the data necessary for the validation of the key environmental models and to extend their current range of application. Some additional, targeted measurements may also be required.
- A dynamic (non-equilibrium) integrated model system should be developed, that would cover the majority of routes to human exposure. The components for this model system may well already be available, although they may require validation, and the output should

be probabilistic, in order to take account of the many uncertainties in the available input data and to avoid unrealistically extreme views of possible future levels of exposure.

Contents

1 Introduction

Dioxins[1] are ubiquitous in the environment at normally very low concentrations. They are formed as unwanted by-products during various industrial and combustion processes. While there are some natural sources of dioxin, for example forest fires, the magnitude of these sources is small in relation to anthropogenic ones. The relative importance of the anthropogenic sources has changed from the 1960s to the present day as a result of regulatory controls, firstly on chlorinated pesticides and then on industrial processes, principally incineration. During the 1980s and 1990s in the EU emissions from municipal solid waste incineration dominated emissions from industrial sources although, with greater regulatory controls on that sector since 1996, no one source now dominates.

An essential component in the development of policy to control and reduce human exposure to dioxins is a thorough understanding of how these compounds behave in the environment. This report critically evaluates the current state of knowledge and understanding, and examines the feasibility of developing models to predict how exposure might change into the future, as a consequence of reducing the amounts of dioxin released into the environment.

The average exposure of citizens in the EU Member States is already below the Tolerable Daily Intake (TDI) of 10 pg 2,3,7,8-TCDD/kg body weight per day, recommended by the World Health Organisation (WHO) in 1990, and is gradually declining. However, the WHO has recently proposed a new, lower TDI. It is essential to know whether the current level of exposure is likely to continue declining at a rate sufficient to bring it below the new TDI, within an acceptable timescale, or whether further policy measures will be required to achieve this. This position is illustrated schematically in Figure 1, below.

This report summarises the work undertaken to examine the feasibility of projecting future levels of exposure on the basis of current knowledge and understanding; a more detailed account of the work is given in the Technical Annex to this report. There are, essentially, four main issues, which are listed below, and each one has been thoroughly reviewed through extensive literature research and consultation with international experts from across the EU and elsewhere. The issues are as follows:

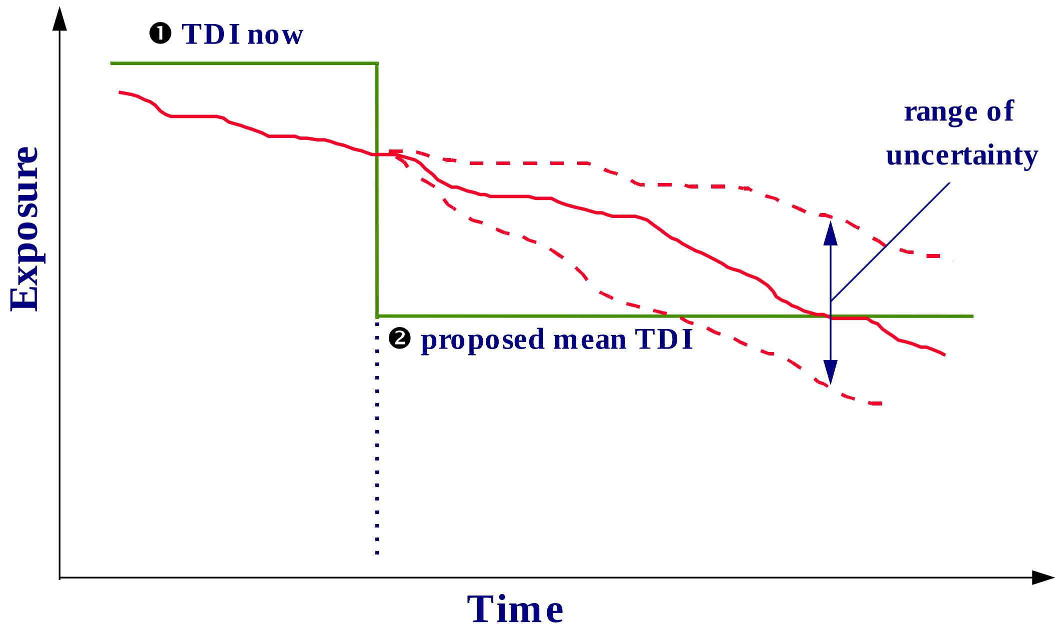
- how do dioxins move through the environment and what are the main pathways to exposure;
- to what extent are the parameters governing these processes understood and quantified;
- are appropriate tools available to model these processes and pathways;
- to what extent have existing models been used for dioxins and have they been validated against data from appropriate monitoring programmes?

Having addressed these issues, an assessment has been made of what further work is required, in order to make the modelling and prediction of future exposure to dioxins within the EU Member States a feasible prospect for the future. This assessment is

[1] The class of compounds made up of the polychlorinated dibenzo-*p*-dioxins (PCDD) and polychlorinated dibenzofurans (PCDF) is collectively termed ‘dioxins’ throughout this report.

presented under three headings: the overall Conclusions of the analysis; Recommendations for specific actions required; a compilation of the detailed Topics for Further Research.

Figure 1. *Hypothetical projection of future exposure and implications for further policy measures*



2 Fate and transport of dioxins in the environment

This section summarises the processes by which dioxins move through the environment, the main pathways leading to human exposure and the extent to which the parameters governing these processes are understood and quantified. It also considers long range transport of dioxins, reservoir sources and environmental sinks.

2.1 PROCESSES DESCRIBING ENVIRONMENTAL TRANSPORT

The generalised environmental processes by which dioxins move through the environment are reasonably well known; they have been studied not only for dioxins but also for other pollutants, such as PCBs and radionuclides. As a result, the processes governing the behaviour of, for example, particles in the atmosphere, or particle transport in rivers, are well understood. What is not so well understood is the aspects of environmental transfers which are specific to dioxins.

Dioxins are multimedia pollutants and, once released to the environment, become distributed between environmental compartments. They follow a range of familiar routes and the three figures in the following sections illustrate the fate and transport processes for dioxins in the atmospheric, terrestrial and aquatic environments although, clearly, these systems are not mutually exclusive.

2.1.1 Atmospheric Environment

Figure 2 illustrates the major processes involved as dioxins are transported through the atmosphere and deposit to terrestrial surfaces. The distances of travel before deposition depend upon factors including the height of release, temperature, prevailing meteorological conditions and particle size.

Dioxins are semivolatile compounds and, in the atmosphere, can exist in both the gaseous phase and bound to particles, depending upon the environmental conditions. Two particularly important variables are the temperature and the total suspended particle loading of the air. There is continual exchange between the particle and vapour phase and during the summer months, when temperatures are high, the less chlorinated dioxin congeners tend to be found predominantly in the vapour phase; in the winter months they are split between the particulate and vapour phases. Dioxins in the vapour phase can undergo photochemical transformation to less toxic compounds, although the rates of these reactions are not well quantified. Dioxins attached to particulate matter are probably most resistant to degradation.

The main pathway by which dioxins move from the atmospheric to the terrestrial environment is deposition to soil, vegetation and water bodies by wet and dry processes, or in mist (occult deposition). Vapour and particle phase deposition occurs, although there are relatively few measurements by which to quantify the relative importance of these two processes. Small amounts of dioxin can be returned to the atmosphere by the resuspension of previously deposited material, or revolatilisation of the less chlorinated congeners.

Figure 2. *Fate and transport in the atmospheric environment*

2.1.2 Terrestrial environment

Figure 3 illustrates the fate and transport of dioxins in the terrestrial environment. Plant and soil surfaces receive inputs of dioxin through wet and dry deposition from the atmosphere, although the rates of deposition are not well quantified. For agricultural systems an additional source of dioxins can be the application to soil of sewage sludge. Because of their chemical characteristics and very low solubility dioxins accumulate in most soil types, with very little water leaching. Very gradual processes of degradation may transform dioxins into less toxic compounds within the soil. Levels in vegetation tend to reflect recent exposure to dioxins, as vegetation is only exposed for a relatively short time, with new growth replacing old and crops being harvested. For agricultural leaf crops the main source of contamination is direct deposition from the atmosphere and soil splash; for root crops soil contamination and binding of dioxins to the lipids in cell walls. However, the significance of root uptake from the soil requires further investigation, as there appear to be large differences between plant species. Grazing animals are exposed to dioxins by ingesting contaminated pasture crops and dioxins are found to accumulate primarily in the fatty tissues and milk.

An important point to note is that in the 1960s and early 1970s, the application of chlorinated pesticides containing dioxins (for example 2,3,7,8-TCDD in the pesticide 2,4,5-T) may have been a more important source than emissions from combustion. Dioxins from these sources may have accumulated in the soil and could continue to influence exposure levels long after their application has ceased.

Figure 3. *Fate and transport in the terrestrial environment*

2.1.3 Aquatic environment

Figure 4 illustrates the fate and transport of dioxins in the aquatic environment. Here, the major inputs to water bodies are via wet and dry deposition, although direct inputs from industrial effluent and run-off from soil may also be important. Dioxins partition quickly to organic matter and so accumulate in sediments. Dioxins accumulate in aquatic fauna as a result of the ingestion of contaminated organic matter. The concentration of dioxins in fish tissue is found to increase up the food chain (biomagnification) as a result of the progressive ingestion of contaminated prey, although the processes by which this occurs are not well quantified.

Figure 4. *Fate and transport in the aquatic environment*

2.2 RESERVOIRS

The greatest quantities of dioxin are associated with soils and sediments, and these are regarded as ‘reservoirs’ of dioxin, which can be gradually released or transferred to other media. Landfill sites are also thought to be important reservoirs, as a result of the disposal of incinerator ash and chemical wastes containing relatively high concentrations of dioxin. However, the contribution of these reservoirs to human exposure is presently thought to be slight. Nevertheless, as other inputs into the environment decline, their contribution may become increasingly important in limiting the rate of decline of human exposure.

2.3 SINKS

There is a limited range of mechanisms for the environmental degradation of dioxins to less harmful compounds. These include degradation by sunlight and, to a lesser extent, by microbially secreted enzymes. However the importance of these sinks is not well understood. Degradation takes place extremely slowly in soils and sediments. In the atmosphere the vapour phase undergoes degradation, but the importance of this, given the small fraction of dioxins in the vapour phase, is not well understood.

2.4 LONG RANGE TRANSPORT

There is a limited number of environmental measurements relating to the long range transport (over 100s of kilometres) of dioxins. This is primarily because of the difficulty of measurement in remote locations and the rarity of such programmes. Dioxins occur in areas with no local sources, such as the remote regions of the Arctic and Antarctic, and this suggests that, despite the vapour phase degradation processes, dioxins are available for long range transport.

2.5 PARAMETERS CONTROLLING FATE AND TRANSPORT

There are 210 dioxin congeners which possess a range of chemical and physical properties. Seventeen of these are of interest for their potential effect on humans. Knowledge of the values of a number of parameters representing the properties of individual dioxins is necessary in order to predict the behaviour of the mixtures found in the environment. The physical and chemical properties which are measures of, or control the behaviour of dioxins are:

- their low vapour pressure;
- their extremely low solubility in water;
- their solubility in organic matrices;
- their preference to bind to organic matter in soil and sediments.

Combinations of these properties are measured to develop a range of parameters, which are used in the many models to predict the environmental fate of dioxins.

The vapour pressure controls the partitioning of the individual dioxins between the vapour and the particle phase. Dioxins are generally present in the atmosphere associated with particles. The strength of this association varies, depending on the amount and nature of particles present in the atmosphere, the air temperature and the level of dioxin chlorination.

In environmental modelling octanol is often used as a surrogate for biological systems. Hence, the ability of dioxins to partition between air or water and octanol is used as a measure of their ability to bioconcentrate to plants, animals and fish. These parameters are described as the octanol water or octanol air partition coefficients (K_{ow} and K_{oa} respectively) although, for many congeners, there is substantial uncertainty in their value.

Dioxins will associate with the organic matter present in soils and sediments. This association is represented by the organic carbon water partition coefficient (K_{oc}). However, the nature of this association is poorly understood.

Because of the differences in environmental behaviour between congeners the composition of the dioxin mixtures alter between environmental media and this has important implications for predicting human toxicity. The ‘toxic equivalent’ (TEQ) concept was designed to assess the potential toxicity of a mixture of 2,3,7,8-substituted dioxins in exposed organisms. However, it is now routinely applied to environmental matrices (such as soil and sewage sludges), to emissions (such as the discharges from incinerators) and as the basis for legislative controls. Using TEQs to predict the toxicity of environmental matrices makes important assumptions about the relative rates of transfer of the different 2,3,7,8-substituted dioxins from the environmental matrix into the exposed organism, which are often not valid.

3 Modelling of dioxin transport in the environment

This section summarises the concepts that are important in attempting to model the processes and pathways by which dioxins move through the environment. It considers which models are appropriate for various situations and the limitations of the models that have been used.

3.1 WHAT IS A MODEL?

A model can be defined as a simplified version of the 'real system' that approximately simulates the response of the real system. In terms of the transport and fate of dioxins, the real system is normally very complicated, and simplification is introduced in the form of a set of assumptions that express the scientific community's understanding of the nature of the system and its behaviour. When models are developed, assumptions are introduced which are only as good as the understanding of the mechanisms operating in the modelled system. Because the model is a simplified version of the real system, there is no unique model for a given system. Different sets of simplifying assumptions will result in different models, each approximating the 'real system' in a different way.

Many models that are used are deterministic, that is, the input parameters for the models consist of fixed values and the output is a single estimate. This often leads to the misconception that the output value is 'the value' to be expected under a given set of conditions, implying an accuracy which does not exist. Some of the dioxin transport and fate models use parameters derived from data which are often scarce or show a wide range of possible values. Predictions that are based on such imprecise data will also be inherently imprecise.

Probabilistic or stochastic modelling takes account of the uncertainty in the values of input parameters, and involves using statistical methods, applied to large amounts of data, to generate empirical relationships between the various properties of a system and its behaviour. The objective of a stochastic model is that, given a specified input, the model will generate an output with a specified variability.

3.2 MODELLING DIOXIN FATE AND TRANSPORT

There is a wide range of models available with varying structures. Models can be created to consider the whole system, or some detailed component process within the larger whole. Some models which have been used for PCBs can be used for dioxins with modifications. Descriptions of the types of models that have been used are given in the Technical Annex to this report.

Dioxin fate and transport has often been modelled to:

- predict movement from one environmental compartment to another (e.g. air to land) or from one part of an environmental compartment to another (e.g. water to sediment) often with the aim of predicting the media that are likely to accumulate the highest concentrations and to predict the concentration in those media;
- predict human exposure from specific sources (e.g. waste incinerators) which has involved using multi-media models of varying complexity.

The current environmental models tend to split into two classes; those that describe the equilibrium behaviour of the compounds and those which describe the transport properties. The former are of use in assessing the dioxin exposure of the population as a whole. The latter are of most benefit when assessing the effects of a particular release.

3.2.1 Models to predict impacts of specific sources

Combustion sources such as municipal solid waste incinerators (MSWIs), certainly in the past, have represented important local sources of dioxin. Advances in combustion technology have substantially reduced emissions from new plant. Dioxins emitted from these sources can deposit on to land surrounding the MSWI which might be used for agriculture, and this pathway represents a starting point for the route by which dioxins may enter the human food chain. Since the food chain is often the pathway which provides the highest intake of dioxins for humans, resources have been invested to model this environmental pathway and to validate models through environmental measurements. A range of models has been developed in various countries and this diversity of approach might suggest that even this pathway is incompletely understood. Other environmental transfer pathways have received comparatively little attention.

These multimedia models vary substantially in their complexity. For example, one approach simply calculates the concentrations of dioxin in milk based on the volume of air that a pasture scavenges, with factors to account for absorption from the stomach and the rate of milk production. The model has no expressions to represent the mechanisms of any of these processes but, interestingly, or perhaps fortuitously, predicts the concentrations in milk to within 50%. When tested against other more detailed models, this simple approach predicted most closely the concentrations measured.

The most complex models include sophisticated plume dispersion sub-models to predict the downwind transport of dioxins from their source and deposition to pasture, interception sub-models to predict the contamination of pasture and pharmokinetic sub-models to predict the absorption of dioxins by cattle and their excretion into milk. These complex models incorporate mechanistic description of fate and transfer processes, and with appropriate parameters, provide reasonably accurate predictions of the levels of dioxins transferred to milk from cattle grazing pasture in a wide range of environmental conditions. However, although the models describe in depth the fate and transport, the values of the necessary input parameters are often uncertain.

3.2.2 Models that predict the fate of dioxins on a continental or global scale

On a wider scale, the media and geographical locations where dioxins accumulate can be predicted well, along with qualitative to semi-quantitative estimates of the likely concentrations of the dioxins. The types of models that are currently often used in these situations are fugacity models and box models. They are less suitable for use on smaller scales. There are various levels of sophistication of fugacity model; the most sophisticated are capable of predicting the long-term partitioning of dioxins between various media and can account for non-steady state fluxes of dioxins and non-equilibrium systems (which is the real situation). These models predict that long range transport of dioxins to cooler environments may occur but there have been relatively few environmental measurements to support this prediction.

3.2.3 Modelling individual air, water and terrestrial systems

The level of modelling effort invested in assessing the transport and fate in these environments reflects the general importance of the individual pathways for human exposure. Therefore, most resources have been invested in assessing the air-grass-cow-human pathway. Even in this pathway, certain steps are incompletely modelled. The sections below very briefly cover the current status of modelling in each of these systems and outline the main weaknesses in the models or supporting data.

Air

Although the models that predict the dispersion of dioxins in the atmosphere are well developed, the model capabilities are probably more sophisticated than the input data available. Relatively few models can account for the ability of dioxins to partition between the vapour and particle phases.

Terrestrial

The terrestrial environment is inherently more complex to model than the atmospheric environment; there are more media to consider and a wider range of transfer pathways between the media. Some transfer pathways can be considered unimportant in comparison to others. For example, dioxins accumulate in plants mainly by atmospheric deposition and soil splash and not from root uptake, although the various processes involved in each of these pathways is not well understood. For dioxin intake to humans, the air→leaf→cattle→milk and dairy products pathway is often the most important to model.

Aquatic

Dioxins will bind very strongly to sediment and organic matter in aquatic environments and these will represent reservoir sources for dioxins in these environments. Therefore, models which quantitatively predict this are important, although the water column/sediment partitioning process is not well understood, nor is the stability of dioxins in sediments. In general, the mechanisms of surface water transport and fresh water lake systems are fairly well understood, although few models have been specifically developed or used for dioxins. Groundwater models have not been considered because dioxins are very insoluble, although they could be mobilised if dissolved in solvents.

3.2.4 Exposure assessment models

This type of model is often used to predict the dioxin exposure of a population. Many exposure assessment models for dioxins make conservative (or worst case) assumptions to compensate for uncertainties, to ensure that the exposure of the population remains below acceptable threshold limits. The problem with this approach is that many conservative assumptions may be combined in a model to produce an overly pessimistic prediction of the likely exposure. This approach does not help policy makers decide which of a range of options would be most useful to limit the exposure of populations to dioxins. One solution to this is to use probabilistic models which produce a distribution of possible values rather than a single value.

For risk assessment, it may be a waste of resources to plan an exposure assessment orders of magnitude more accurate than the toxicological data with which it will be combined.

4 Conclusions

The following points summarise the overall findings of this task.

- Dioxins are multimedia pollutants and once released to the environment become distributed between environmental compartments. They follow a range of familiar routes: in the atmosphere they exist in both the gaseous phase and bound to particles, depending on the environmental conditions, and are deposited on soil, vegetation and water bodies by wet and dry deposition or in mist. Soil run-off can transfer dioxins from land to water. In water bodies dioxins rapidly adsorb to organic matter and subsequently settle out in sediments.
- Once associated with soils and sediments dioxins degrade slowly and may persist for many years. In the atmosphere the vapour phase undergoes degradation, but the importance of this, given the small fraction of dioxins normally in the vapour phase, is not well quantified.
- The greatest reservoirs of dioxins are soils and sediments, from which they may be released by both natural and anthropogenic processes over extended timescales. Landfill sites are also thought to be important reservoirs, since some contain incinerator ash and chemical wastes containing relatively high concentrations of dioxin in comparison to other media.
- Dioxins have been measured in areas with no local sources and thus are available for long range transport over a scale of 1000s of kilometres.
- Dioxins are lipophilic and accumulate in fatty tissues. Some are metabolised slowly and, thus, can biomagnify in the food chain.
- The major routes of human exposure are those relating to food stuffs. Hence, in Northern Europe (e.g. United Kingdom, Netherlands and Germany), research interest has focused on the air-grass-cow exposure pathway, although consumption of seafood is also important (e.g. in Scandinavia). Other pathways representative of Southern European climates, agricultural practices and dietary regimes have not been studied to the same extent.
- Dioxin fate and transport has often been modelled:
  - to predict movement between environmental compartments (e.g. air to land) or from one part of an environmental compartment to another (e.g. water to sediment), often with the aim of predicting the media that are likely to accumulate the highest concentrations and to predict the concentration in those media;
  - to predict human exposure from specific sources (e.g. waste incinerators) which has involved using multi-media models of varying complexity.
- Although human exposure models have been produced, they are predominantly of the non-dynamic type and fully dynamic ones (that model mechanics and kinetics) have yet to be developed. Some scenarios are better modelled that others, for example human exposure from waste incineration, while others have received little attention, for example potential exposure from landfills.

- Some of the dioxin transport and fate models use parameters derived from data which are often scarce or show a wide range of possible values. Predictions that are based on such imprecise data will also be inherently imprecise. In this case, stochastic models are most suitable since the model will generate an output with a specified variability.

5 Recommendations

This report concludes that it is currently not possible to make reliable projections of future average levels of human exposure to dioxins, as vital information is lacking in a number of important areas: the mechanisms and rates of key environmental transfer and degradation processes; the role played by reservoir sources in determining future levels of exposure; the pathways for exposure of citizens in Southern European Member States; validation of the output of existing environmental models. Hence, five key recommendations are made of work which should be undertaken in order to make this a feasible prospect for the future:

- A programme of work is required to improve the understanding and quantification of the fundamental transfer processes by which dioxins move between the different environmental media, particularly within the aquatic and terrestrial environments, and the degradation processes occurring within these media.
- The contribution to human exposure from reservoir sources, especially landfills, requires examination, and in particular work to assess the behaviour and degradation processes of dioxins in these environments. Without this knowledge it will be impossible to predict the effect of regulatory controls on the future levels of human exposure.
- Policies aimed at further reducing human exposure to dioxins will have to be relevant and applicable across the EU. Most research work undertaken so far has been focused on the Northern Member States, although circumstances in Southern Member States might be very different. Further research is required to identify the important environmental pathways of dioxins in climates, agricultural systems and dietary regimes representative of Southern Europe.
- Measurement programmes across the Member States should be co-ordinated, in order to provide the data necessary for the validation of the key environmental models and to extend their current range of application. Some additional, targeted measurements may also be required.
- A dynamic (non-equilibrium) integrated model system should be developed, that would cover the majority of routes to human exposure. The components for this model system may well already be available, although they may require validation, and the output should be probabilistic, in order to take account of the many uncertainties in the available input data and to avoid unrealistically extreme views of possible future levels of exposure.

6 Topics for further research

This section summarises areas of uncertainty in the fate, transport and modelling of dioxins where further research is required. Topics have been grouped according to the environmental medium to which they relate: atmospheric, terrestrial or aquatic, with topics relating specifically to modelling listed separately. This section has been collated from the more detailed information in the technical annex.

6.1 ATMOSPHERIC ENVIRONMENT

The atmosphere is nowadays the most important medium through which dioxins are transported, and it is essential to understand the atmospheric behaviour of dioxins thoroughly. Atmospheric modelling is a well developed discipline and sophisticated models are available. However, specific data for dioxins is lacking.

- The vapour/particle partitioning of individual dioxin congeners needs further study, particularly in conditions more typical of Southern Europe.
- Particle size distribution data is needed for dioxins associated with particles.
- Measurements of wet and dry (vapour and particulate) deposition rates to a range of surfaces are needed.
- Deposition velocities for individual congeners are required, and the scavenging coefficients of vapour and adsorbed material by rain, snow and fog.
- Quantification of the rate of the degradation mechanisms for individual dioxin congeners are required to enable the rate of decline of environmental levels to be calculated.

6.2 TERRESTRIAL ENVIRONMENT

Human exposure to dioxins is mainly from the consumption of foodstuffs and the soil acts as a reservoir for dioxins. Therefore, it is important to understand the behaviour of dioxins in terrestrial ecosystems and, particularly, in a wide range of agricultural ecosystems including those of Southern Europe. The terrestrial environment is complex and there are, therefore, more areas where further research is required.

- Review of data indicates that for congeners with log K_{ow}>5.5 there is substantial uncertainty in the values of K_{ow}. Further work is needed to confirm the magnitude of this parameter for these congeners.
- Models assume a linear relationship between K_{oc} and K_{ow}. For some dioxin congeners this may not be appropriate. Further measurements of these parameters are required.
- Further measurements are needed of vapour to leaf transfer for a wider range of species, particularly food and fuel crops, to assess the relative importance of the various deposition mechanisms to vegetation.
- Further work is needed to define the rates of transport and degradation in soils with very low organic matter contents.
- The bioavailability of dioxins in vegetation and soil is not well known.
- The effect of climate and different agricultural practices are not well understood and could be important in view of the wide range in the European environment.

- The significance of root uptake needs to be investigated for a wider range of species as a few species appear to have unusually large soil to plant transfer of dioxins.
- Dioxin transfer to plants via soil splash and animal trampling should be accounted for in models, but currently rarely is.
- Biotransfer factors for animals other than cattle need to be quantified.
- Differences in animal husbandry practices need to be taken in to account by the models (for example feeding silage to cattle and feedlot fattening). This implies that models developed for one country may not be applicable in another.
- The pharmokinetics of dioxins in animals are not well known.
- The behaviour of dioxins in animals other than cattle and chickens is not well understood and needs to be examined.
- More measurements of background concentrations of dioxins in vegetation and animal tissue are required.
- Knowledge of the fate and transport of dioxins in landfills needs considerable research attention since these can contain relatively large quantities of dioxins.
- Studies on the levels of dioxin associated with PCP treated wood are needed, and the potential for dioxins to recycle in the environment from this source.
- Studies are needed on the levels and sources of dioxins in composted material and the environmental fate of the dioxins in the composted material.

6.3 AQUATIC ENVIRONMENT

For some critical groups, consumption of seafood may be the main source of dioxin exposure and sediments are an important reservoir source of dioxins.

- The input of dioxins from runoff in soil from catchment areas needs to be quantified.
- Further work on the partitioning of dioxins between the particulate and dissolved organic phases in the water column is needed; experimental work should be applied to field situations.
- The importance of dioxins attached to dissolved carbon and in colloids is not well understood.
- Little is known about the stability/mobility of organic carbon-associated dioxins in sediments.
- Further information is needed about the stability of dioxins in sediments under different redox environments.
- Standardised sampling strategies are needed for determining dioxin concentrations in fish and sediments.
- Photolysis and biomagnification are not well parameterised in the aquatic environment.
- Modelling studies of dioxin behaviour in the aquatic environment and the food chain are limited and more are required.

6.4 MODELLING

In addition to the topics listed above, a number of general problems currently limit the modelling of dioxins in the environment.

- Models are limited by inaccurate physicochemical parameters e.g. H, solubility, K_{ow}. Models need to predict congener specific information, and not just as I-TEQs.

- Model validation currently restricts most assessment applications of models to screening calculations. The availability of more extensive environmental data sets for model validation would facilitate their broader application.
- Sensitivities and uncertainties of models need to be assessed to focus model development in the most important areas.
- Stochastic models need to be developed which provide a most likely answer with a range of possibilities.
- Model intercomparisons need to be carried out to identify the most accurate models for specific applications.