Journal of Hazardous Materials 185 (2011) 792–800

Contents lists available at ScienceDirect

Journal of Hazardous Materials

journal homepage: www.elsevier.com/locate/jhazmat

A risk-based decision tool for the management of organic waste in agriculture and farming activities (FARMERS)

Miguel Río[a], Amaya Franco-Uría[b], Emilio Abad[c], Enrique Roca[b,*]

[a] TIC Area, CIS D&T, A Cabana s/n – 15590 Ferrol, Spain
[b] Department of Chemical Engineering, University of Santiago de Compostela Lope Gómez de Marzoa s/n, 15782 Santiago de Compostela, Spain
[c] CESGA, Avenida de Vigo s/n, 15706 Santiago de Compostela, Spain

ARTICLE INFO

Article history:
Received 26 February 2010
Received in revised form
10 September 2010
Accepted 10 September 2010
Available online 23 October 2010

Keywords:
Cattle manure
Pastureland fertilising
Decision support tool
Metal accumulation
Risk assessment

ABSTRACT

Currently, specific management guidelines must be implemented for guaranteeing the safe reuse of organic waste in agriculture. With that aim, this work was focused on the development of a decision support tool for a safe and sustainable management of cattle manure as fertiliser in pastureland, to control and limit metal accumulation in soil and to reduce metal biotransfer from soil to other compartments. The system was developed on the basis of an environmental risk assessment multi-compartmental model. In contrast to other management tools, a long-term dynamic modelling approach was selected considering the persistence of metals in the environment. A detailed description of the underlying flow equations which accounts for distribution, human exposure and risk characterisation of metals in the assessed scenario was presented, as well as model parameterization. The tool was implemented in Visual C++ and is structured on a data base, where all required data is stored, the risk assessment model and a GIS module for the visualization of the scenario characteristics and the results obtained (risk indexes). The decision support system allows choosing among three estimation options, depending on the needs of the user, which provide information to both farmers and policy makers. The first option is useful for evaluating the adequacy of the current management practices of the different farms, and the remaining ones provides information on the measures that can be taken to carry out a fertilising plan without exceeding risk to human health. Among other results, maximum values of application rates of manure, maximum permissible metal content of manure and maximum application times in a particular scenario can be estimated by this system. To illustrate tool application, a real case study with data corresponding to different farms of a milk production cooperative was presented.

1. Introduction

The necessity of planning sustainable management strategies for biosolids (organic wastes) is urgent nowadays due to the important increase of the production of this kind of residues in the last decade. Organic waste is mainly derived from farming and agricultural activities (manure) and from biological wastewater treatment systems (sludge) [1]. Regarding manure, spreading as fertiliser in pasture and agriculture land has been and is the current management practice in rural environments of Spain, as well as in most European countries. On the other hand, the use of sludge as fertiliser in agriculture might also present several advantages in front of other management alternatives more currently used, since it leads to a decrease in the employment of artificial fertilisers and avoids its subsequent treatment and/or disposal [2,3]. However, organic waste may contain a high and varied quantity of both organic and inorganic pollutants like dioxins, PCBs, or heavy metals [4–6] that may be transferred to different environmental compartments and to humans. Thus, reusing of organic residues must be controlled for guaranteeing safe conditions.

Environmental Risk Assessment (ERA) methodology is applied to estimate the fate and exposure of several pollutants in the environment [7]. Under a multidisciplinary approach, ERA may be employed as a decision support technique in different fields and situations, like in restoration of contaminated sites, occupational exposure, or in the design and redesign of industrial processes for increasing inherent safety and minimising emissions. Promoting sustainable development is another application of environmental risk assessment, since it can be used to evaluate whether the reuse of waste is done under appropriate conditions, helping in the establishment of regulatory constrains in environmental policy. ERA process is constituted by four main steps: hazard identification, dose–response assessment, exposure assessment and risk characterisation [8]. Dose–response assessment identifies the rela-

---

* Corresponding author. Tel.: +34 981563100; fax: +34 981528050.
E-mail address: enrique.roca@usc.es (E. Roca).

0304-3894/$ – see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.jhazmat.2010.09.090

tionship between the received dose and the intensity or severity of the adverse effects produced on the exposed population. It is necessary to account for the duration and the intensity of doses in order to characterise the response of the receptor properly. An acute exposure involves high doses in a short period of time, while chronic exposures imply low received doses and a long-term duration. The adverse effects and toxicity in this last case are produced due to the slow accumulation of the substance in the receptors. Therefore, depending on the nature of exposure, acute or chronic recommended doses are established (Reference Doses, RfDs), below which no adverse health effect is produced, being widely available in reference data base of international organisations, like the Integrated Risk Information System, or IRIS data base [9] and the European chemical Substances Information System (ESIS) [10]. Exposure assessment consists of the quantitative estimation of the pollutant doses to which the receptor population is exposed. This environmental risk assessment phase may involve both fate and exposure estimation of a pollutant, since most of times, it is difficult, expensive and time-consuming to measure pollutant concentrations in each compartment of a particular scenario. However, knowing these concentrations is fundamental to evaluate the exposure of receptors. This is one of the main reasons why fate models are developed, i.e., to describe and estimate the distribution of pollutants in the environment. There are several software tools in the scientific literature for developing environmental risk assessment studies of a wide type of pollutants. EUSES (European Union System for the Evaluation of Substances) [11] and CalTOX [12] are two of the most representatives among them. Generally, these tools consist of a fate multicompartmental model linked to an exposure multipathway model. In these models, the user may select the adequate compartments and pathways for creating the desired scenario. However, they are thought to evaluate scenarios of great extension, generally at urban, country or even continental scale. The assessment of more specific scenarios, in which only a particular activity is responsible for the contamination of a reduced area, is not possible with this type of models. Therefore, more specific and simpler tools should be developed to carry out the risk assessment of activities which involve emission or release of pollutants in priority scenarios, like the reuse of biosolids as fertilising, a common practice in agriculture and farming that may release pollutants to the environment. To date, the spreading of manure and other fertilisers caused an important environmental problem, which is the contamination of water fluxes by nutrients (N and P) in rural zones [13]. Specific EU directives [14,15] were established to regulate the correct management of manure to avoid massive run-off and leaching of these nutrients away from the plough layer of soil to surface water and groundwater. In Spain, 70% of rural water in the NW was not drinkable in the last decade due to N and P contamination [16]. However, manure or sludge application can also result in the accumulation of persistent compounds (especially metals) in soils [17–19] in the future. With regards to this environmental problem of concern, application of solid waste (sludge and manure) in agricultural soils is nowadays only regulated by limit values of metal content in soil established by the Commission of European Communities [20], lacking, at least at regional/national scale, specific evaluation tools intended to estimate the possible accumulation of this type of persistent pollutants in soils and other compartments and to solve this environmental management problem.

The main objective of the present work is to develop a friendly risk-based system applied to the reuse of cattle manure as fertiliser in pastureland. This tool will help in the decision making process of waste reuse and management in cooperatives dedicated to farming activities, providing among other results, maximum values of manure application rates, maximum permissible metal content in manure and maximum application times of manure as fertiliser.

2. Methodology

2.1. Conceptual model

Several studies developing models and proposing tools of manure management for an efficient utilization and optimal balance of N and P requirements in agriculture, not only in terms of nutrients loss [21–23] but also considering social or economic factors as criteria [24,25] can be found in the literature. The STONE system [26] provides an advanced and integrated modelling approach, that allows evaluating the effects of changes in fertilisers input (including manure) and in policy measures on the leaching of N and P to surface and ground waters in The Netherlands, considering both past and future long-perspective scenarios.

However, it is necessary to consider the presence of other compounds usually present in the waste constituted by cattle droppings, which are heavy metals [27]. These pollutants come mainly from nutritional supplements of trace minerals aimed at improving health and productivity of animals [28] and can also be present in some animal fodder. Usually, these supplements are administered in excess, and the surplus is excreted by the animal through urine or faeces [29]. Therefore, metals end up in manure, reaching significant high concentrations [30]. Once applied as fertiliser in agricultural systems, metals contained in manure are slowly accumulated in soil. This may pose a serious problem in the near future, especially considering that some of them are strongly bound to organic matter. When organic matter is degraded, metals are released and may be transferred to soil solution or to groundwater and consequently, they can be absorbed by vegetation [27]. Afterwards, metals can be transferred from vegetation to cattle, and finally to humans. Concern about the past emissions of metals to soil not only due to manure or fertiliser application but also to other sources (atmospheric deposition, vehicle exhaust) has lead to the investigation and comparison of present metal concentrations in soils with critical metal concentrations [31,32]. Above these critical threshold concentrations, adverse effects on ecosystems can be produced. Therefore, adequate definition of these quality standards for chronic effects is required for reliable risk assessments [33]. With that aim, no observed effect concentrations (NOECs) data for the soil and groundwater organism or tolerable daily intakes (TDI) for grazing animals can be used [32]. Although evaluating the present soil quality in terms of metal concentration is necessary, considering that metals do not degrade, they can be accumulated in soil through long periods of time, and thus, it is also required to assess the future effects of long-term application of metals sources to soil, like manure [32].

Thus, dynamic models are needed to estimate the times involved in attaining a certain chemical state in response to input (deposition, fertilizers or manure) scenarios [34]. In that sense, Posch and de Vries [34] employed dynamic modelling to investigate important questions related to the time development of the soil chemical status under a constant future input of the metal: (i) the future metal concentration as a function of time (scenario analysis), (ii) the time when a prescribed chemical state is reached (delay times), and (iii) which future input (reduction) is needed to reach a prescribed chemical state within a prescribed time period (target loads). The developed decision support system uses a similar approach, since estimations are also based on dynamic modelling. However, the criterion employed in this case is not the metal content in soil, but the probability of adverse effects on human health, represented by risk indexes. These indexes are calculated according to the environmental risk assessment methodology and by means of a multiexposure model that considers all the relevant pathways of human exposure to metals. The tool can be applied in practice to calculate the risk index in a real scenario, as well as to determine other more useful parameters for the proper managing of this activity, like

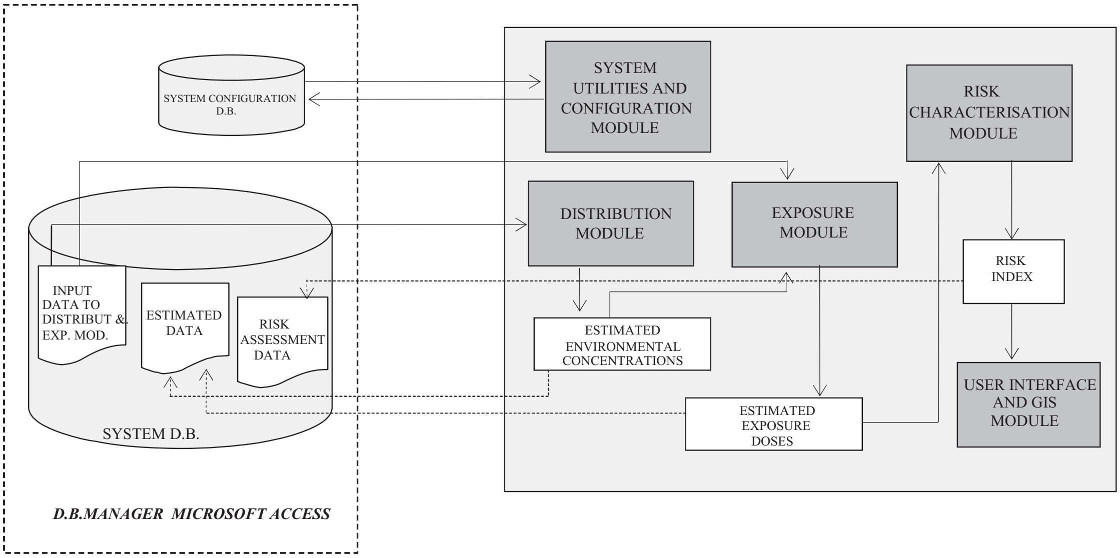


Fig. 1. Flowchart of the developed risk-based decision support tool.

maximum application rates of manure (input estimation) and maximum application duration (temporal horizon), ensuring that risk is maintained below critical limits.

2.2. General structure of the decision making system

Fertilising by Application and Reuse of Manure Environmental Risk Software (FARMERS) is a decision making system for organic solid waste reuse which was implemented in Visual C++ and it is constituted by a data base (MS Access®) (storage of parameters and results), a multicompartmental and multiexposure risk assessment model to calculate the risk index of heavy metal accumulation derived from cattle manure fertilising, and a GIS module for the visualisation of results.

The estimation process of the risk assessment model is based on the conceptual model and involves different modules associated in cascade: distribution (dynamic model), exposure (multipathway model) and risk characterisation. Each one will be described in detail in the following subsections.

2.2.1. Distribution module

Calculations set out from the distribution module (Fig. 1), where metal concentrations in soil, vegetation (in this case, pasture) and soil solution are determined. These concentrations are calculated within a temporal horizon chosen by the user, according to the case evaluated. However, taking into consideration that metals slowly accumulates in soil, and that the tool is intended to evaluate future threats due to this accumulation, temporal horizons higher than 5 years are recommended to perform simulations. Time considerations in this tool will be illustrated with a case study.

Accumulation of metals in soil is estimated by a dynamic mass balance applied to the system soil/vegetation/soil solution, according to the expression of Boekhold and van der Zee [35] and Moolenaar et al. [36]:

$$\frac{d(C_s)}{dt} = R_i - R_l - R_p \tag{1}$$

where C_s is the concentration of the metal in soil, R_i is the input rate of metal, R_l is the leaching rate to groundwater, and R_p is the uptake rate by plants. Taking into consideration the scenario evaluated in the present work, manure addition as fertiliser is considered as the only input rate of metals to soil, neglecting other possible inputs like aerial deposition or application of commercial fertilisers. Thus, R_i is calculated as the product of the application rate of cow manure (R_a) in $\mathrm{m^3\,ha^{-1}\,y^{-1}}$ by the metal concentration in manure (C_m) in $\mathrm{g\,m^{-3}}$. The leaching rate of metals from soil plough layer to deeper layers through soil solution mainly depends on the soil characteristics and the precipitation rate, and can be estimated by the equation [37]:

$$R_l = \frac{1000 \cdot F}{(k_d \cdot \rho \cdot d_p)} \tag{2}$$

where F is the precipitation excess ($\mathrm{m\,y^{-1}}$), calculated as the product of the infiltration factor in soil (F) by the precipitation rate (P) in $\mathrm{m\,y^{-1}}$, k_d is the metal soil–liquid partitioning coefficient ($\mathrm{L\,kg^{-1}}$), ρ is the soil bulk density ($\mathrm{kg\,m^{-3}}$) and d_p is depth of the plough layer (m). Finally, the metal uptake rate by plants (R_p) in $\mathrm{g\,ha^{-1}\,y^{-1}}$ is calculated by multiplying the plant content ($\mathrm{g\,kg^{-1}}$) and the average soil production rate of pasture ($\mathrm{kg\,ha^{-1}\,y^{-1}}$). Notice that the integrated form of Eq. (1) requires the units of R_l and R_p to be in $\mathrm{y^{-1}}$ [37], and thus, R_p must be referred to the initial metal concentration in soil. Furthermore, in order to estimate both metal leaching and plant uptake rates, it is necessary to know first soil–liquid partitioning coefficient (or the soil solution concentration), and the concentration in plants. In case that measured values of these concentrations were not available, constant soil–liquid partitioning coefficient and soil–plant uptake factor can be used [38], although uptake factors have been demonstrated to be dependant on the chemical concentration in soils and other soil characteristics [32,39]. Therefore, non-linear models could be more useful in risk assessment, and consequently, the tool can employ by default two multicorrelation empirical models based on soil properties and total metal concentrations in soil for calculating soil solution and plant metal contents. Metal concentrations in soil solution are estimated from the algorithms developed by Sauvé et al. [40], which involve soil pH, organic matter, and total metal concentration, except in case of Pb, being its soil–water partition coefficient only a function of pH and total Pb in soil. The equations present the form:

$$\log(C_{ss}) = a \cdot \mathrm{pH} + b \cdot \log(C_{tot}) + c \cdot \log(OM) + d \tag{3}$$

where C_{ss} is the metal concentration in soil solution ($\mathrm{\mu g\,L^{-1}}$), C_{tot} is the total metal concentration in soil ($\mathrm{mg\,kg^{-1}}$), OM is the soil organic matter (%C) and a, b, c and d are derived empirical coefficients. For the estimation of metal concentrations in plants, the selected models were those developed by Efroymson et al. [41]. These authors employed measurements of plant concentration in the growth form of above-ground tissue, predominantly herb and graminoid for the development of algorithms according to the equation:

$$\ln(C_p) = e + f \cdot \ln(C_{tot}) + g \cdot \mathrm{pH} \tag{4}$$

where C_p is the metal concentration in plant (mg kg^{-1}), C_{tot} is the total metal concentration in soil (mg kg^{-1}), and e, f and g are the corresponding empirical coefficients. These two non-linear algorithms were selected because they consider data corresponding to a wide variety of soils, plants and metals. Of course, these generic models should be employed with caution depending on the specific field of application [40], and in general, soil solution and vegetation models specifically developed for the study area are preferred, in order to provide a more reliable estimation of metal transfer between these compartments. Therefore, the coefficient values (and also the number of model regressors) can be modified in case more specific models were available. In fact, these models are being currently developed [42,43] for the area of study described in Section 3.

2.2.2. Exposure module

Next module in Fig. 1 evaluates metal exposure in two steps. First, concentrations in cattle milk and meat are estimated from the concentrations previously calculated in the distribution module. Afterwards, human exposure is determined as the sum of different exposure pathways.

Metals initially contained in manure are biotransferred from grass to cattle, although grass is not the only compartment involved in cattle exposure. Metal exposure to cattle is considered to be due to three exposure pathways: ingestion of grass, ingestion of soil and ingestion of water. Dermal and inhalation exposures routes to resuspended soil particles were not considered since they use to be not significant when compared with the ingestion route [44]. Although metals will be mainly accumulated in depuration organs like liver or kidney, the remaining compartments of the animal may also present significant concentrations. Attempting to evaluate human exposure, it is important to estimate metal content of edible parts, like meat and milk. These concentrations can be calculated by multiplying the concentrations in each exposure medium by their relative ingestion rates and by the contaminant-specific biotransfer factor (food-meat) [45]:

$$C_{ed} = (C_p \cdot PIR \cdot f + C_s \cdot SIR + C_w \cdot WIR) \cdot BTF \tag{5}$$

where C_{ed} is metal concentration in either meat and milk (mg kg^{-1}), C_p is metal concentration in plants (pasture), in mg kg^{-1}, PIR is pasture ingestion rate (kg day^{-1}), f is the fraction of food that comes from the area (pasture), C_s is the metal concentration in soil, SIR is the soil ingestion rate of cattle (kg day^{-1}), C_w is the metal concentration in water (mg L^{-1}), WIR is water ingestion of cattle (L day^{-1}) and BTF is the biotransfer factor for meat and milk (day kg^{-1}) depending on the concentration calculated, and which is specific for each metal. In the case that other metal source was provided to cattle, like for example diet supplements, the contribution to C_{ed} can be considered by adding a new term (product of metal concentration in the supplement or concentrate and the correspondent ingestion rate) to Eq. (5). It is necessary to distinguish between ingestion rates of cattle for meat or milk production. In general, cattle for meat production eat more pasture and drink a lower quantity of water than cattle for milk production. It is assumed that cattle are grazing in the area during the whole year, and that concentration of metals in water provided to cattle is the estimated in soil solution (no dilution factors are employed as part of a worst case evaluation).

When the concentration in cattle is known, human exposure can be quantitatively evaluated as the contribution of five exposure pathways: (1) ingestion of meat; (2) ingestion of milk; (3) dermal contact with soil particles; (4) ingestion of soil particles; and (5) inhalation of resuspended soil particles. The last three exposure pathways are included in the risk assessment because the potential receptors are inhabitants of rural areas, being an important fraction of them dedicated to dairy farm activities which might involve soil contact. However, previous simulations of the environmental risk assessment model showed a not significant contribution of these routes to total risk. For this reason, only equations describing meat and milk ingestion are described here. For more detailed information on soil contact exposure, see Franco et al. [46]. The average daily intake of metals from ingestion of meat and milk was estimated by multiplying the metal concentrations in cattle meat and milk (outcomes of Eq. (5)) by the daily amount of intake:

$$DDI = C_{ed} \cdot IR \cdot f \cdot \mathrm{BW}^{-1} \tag{6}$$

where DDI is the estimated daily dose of each metal due to either ingestion of meat and milk (mg kg^{-1} day^{-1}), C_{ed} is the metal concentration in meat and milk (mg kg^{-1}), IR is the ingestion rate of cattle meat and milk (kg day^{-1}), f is the fraction of meat and milk ingested that comes from the studied area, respectively (unitless) and BW is the body weight of each individual (kg).

2.2.3. Risk characterisation module

The last module is in charge of the risk characterisation process, in which daily doses at which human receptors are exposed (estimated in the previous exposure module) are compared to toxicological values obtained by the U.S.EPA Integrated Risk Information System (IRIS) [9] and from the WHO [47]. The quantification of potential non-carcinogenic risk was obtained by the determination of a unitless Hazard Quotient (HQ), which was calculated by dividing the individual doses of each metal by its correspondent Reference Dose, according to Eq. (7):

$$HQ_{ij} = \frac{DD_{ij}}{RfD_i} \tag{7}$$

where HQ_{ij} is the Hazard Quotient of metal i caused by the jth exposure pathway (among the 5 considered), DD_{ij} is the estimated daily dose of metal i by the jth exposure pathway, and RfD_i is the Reference Dose of metal i. Consequently, the sum of each HQ_{ij} will give the total HQ caused by metal i (HQ_{iT}).

In case one or more of the metals evaluated were considered to cause carcinogenic effects on human health by any of the three main routes of exposure, the Individual Excess Lifetime Cancer Risk (IELCR) can be calculated by multiplying a Slope Factor (SF) in (mg kg^{-1} day^{-1})$^{-1}$ by the estimated dose (mg kg^{-1} day^{-1}). The Hazard Index, or the value of global non-carcinogenic risk, is calculated by the sum of the HQ_T of each metal contained in manure, according to the specific case evaluated (an example will be presented in Section 3). The maximum allowed value of HI must be indicated to perform the risk evaluation. This value is of main importance, since it is the criterion used by the decision making system to determine maximum parameter values (either application rates or fertilising duration) for manure management.

According to environmental risk assessment methodology, values of the Hazard Index and Cancer Risk (CR) must not exceed the safety limits of HI > 1 and CR < 10,000. However, the decision making system is evaluating only one of the several activities which may cause metal exposure in human receptors, i.e., it is estimating an incremental risk. Therefore, the value of either HI or CR, which are employed as criteria for optimising results, could be reduced as a prevention measure, considering that other pathways of metal exposure might exist in the area of study.

2.2.4. Parameters

In the database of the decision making system all the required parameters by the environmental risk assessment model are stored. Parameters needed by the distribution module equations comprise manure, soil and climate characteristics. Manure is defined by metal concentrations (any number of metals) and the application rate per area and per unit of time (m^3 ha^{-1} y^{-1}). Soil characteristics include data on soil composition (metal background concentration and percentage of organic matter), environmental factors (pH, exchange capacity, and soil infiltration capacity) and the pasture production rate. Climate is defined by the precipitation rate, which plays a key role in metal leaching. All the parameters of the distribution module are specific of the scenario evaluated, and therefore, their numerical values will vary according to the case study and must be introduced by the user. However, the parameters required by the exposure module equations are included by default in the database of the decision support tool. These parameters are related with cattle and human exposure data, and are shown in the Appendix in Tables A1 and A2, respectively. Toxicological limit values for each metal (RfD and SF) are also stored by default in the database. Values of these factors for some of the metals most commonly contained in manure (Cu, Cd, Ni, Pb and Zn) and presenting different levels of toxicity can also be seen in the Appendix in Table A3. To illustrate differences of meat and milk BTFs among these metals, their correspondent BTF values are also shown in Table A1. Furthermore, Table A2. shows the parameter values stored in the tool database for estimating human exposure through the soil pathways. It is important to remark that the decision making system allows adapting and changing both cattle and physiological human parameters depending on the characteristics of the assessed population, in order to account for natural variability. Values of metal RfDs and SF can also be modified if more updated values were available.

In case current measured metal concentrations in vegetation (pasture), water and milk were available, they can also be stored in the database associated to the corresponding land plot. Each sample belongs to a specific point which is assigned to geographical coordinates. These coordinates will allow the results derived from each sample to be exported to a GIS application, that is, the results can be visualised directly on maps corresponding to the area of study according to the different land plots or fields. Different layers allow representing the initial metal content of manure and the results (Hazard Indexes, maximum manure application rates, etc.) associated to each field.

2.3. Optimisation of managing parameters

FARMERS decision system can provide different results according to the needs of the case study. By default, HI and metal HQ are calculated, and can be visualised conventionally (number) or employing a Geographical Information System (GIS), which relates risk indexes with their correspondent land plot or farm. Direct estimate of the risk index corresponds to an evaluation case characterised by specific properties of the scenario (pH, organic matter, among others) and specific values of application rate and metal content of manure. Thus, the HI value will indicate whether cattle manure in terms of metal content and application duration (years) are appropriate for the fertilisation of the considered area. The results of this evaluation case comprise not only risk indexes (HI, metal-specific and exposure pathway-specific HQ) but also the intermediate results needed to finally calculate them. These intermediate values are the estimated metal contents after years of application in soil, soil solution, vegetation, and cattle milk and meat. In case the HI exceeds recommended safety limits, the decision support system indicates some recommendations to keep the risk index within acceptable levels.

Besides the direct estimate of risk indexes in a scenario characterised by specific manure and pastureland, the decision support system offers two additional estimation options. These options are oriented to improve in the practice the management of pastureland fertilising under health risk criteria. In a real situation, farmers and breeders are not able to modify the characteristics of the manure produced by their cattle. In this case, the correct protocol is to know which characteristics (background metal content, pH, etc.) a pastureland should have for fulfilling the criterion HI < 1. Thus, HI value is in this case an input parameter, together with metal concentrations of manure, the preferred application rate according to the farmer needs, and the expected years of duration of this application. Notice that the system requires an average annual rate, although fertilisation is carried out throughout the year in several discrete events (normally three). As main result, the decision making system indicates the metal concentration in soil below which the fertilising plan is feasible in terms of health risk. In addition, it may select among soils of different locations stored in the data base, the ones which fulfil the metal content criteria calculated.

On the other hand, the opposite situation can be produced, although it is less frequent. In this third evaluation case, a farmer plans a specific fertilising protocol for his land plot, but maybe the manure produced by cattle is not suitable in terms of metal content (exceeds HI criterion). In that case, the system estimates either the optimum value of the application rate or the maximum metal content that manure might have for the specific temporal horizon established by the fertilising protocol. Thus, required input parameters are soil characteristics (background metal concentrations) and the HI value. In summary, optimum values of different parameters are calculated depending on the case. The system may find a best solution by searching the adequate manure of soil sample on the data base according to the situation. This latter is only possible if farmers are associated in a cooperative and information of their land plots are stored in the system data base. Furthermore, a protocol of sharing and mixing the manure produced in different farms for obtaining an appropriate product can be easily established by using this system. Another application is the management of manure surplus produced in some farms, which usually ends up in water streams or in the proper soil, causing groundwater pollution by leaching of N and P and metal accumulation in soil.

3. Application of the decision system: case study

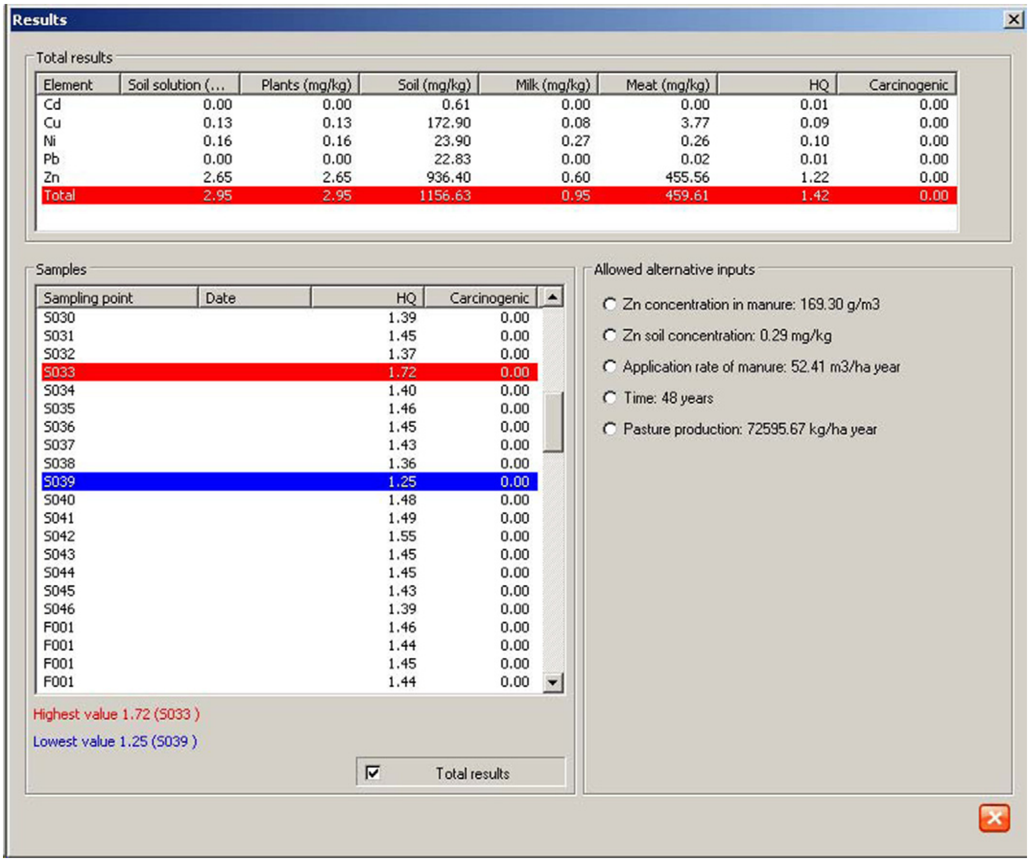
The developed system can be applied to different scenarios, although the default scenario describes areas in Galicia (NW Spain) of intensive farming of cattle for milk production, which is one of the most important economic activities. This region presents a particular meteorology, characterised by abundant rainfall all over the year. Soils are characterised by acid pH and high organic matter contents. These particular characteristics may favour metal mobility in soil and therefore, its bioavailability. Notice that FARMERS system is mainly oriented to manure reuse, although it can be applied for the management of another type of biosolids, as long as the required parameters were available. For illustration purposes, a case study dealing with manure application is presented. The study area is sited in A Pastoriza (Galicia, NW Spain), and corresponded to an extension of 2250 ha of pastureland surrounding river Magdalena basin in the Lugo province, which are grouped within a farming cooperative for milk production. The origin of soil metal concentrations in this area was previously investigated by multivariate statistical analysis, specifically Principal Component Analysis (PCA), Cluster Analysis (CA) and Correlation Matrix (CM). It was found that soil levels of metals like Cd, Cu and Zn were mainly due to continuous application of cattle manure as fertiliser [48]. Thus, the necessity of developing this assessment was completely justified, considering the preexisting conditions in the area. The decision making system was applied to the whole zone, represented by manure and soil samples of the different farms integrating the cooperative. An exhaustive sampling campaign was carried out by the Dept. of Soil Science and Agricultural Chemistry

Table 1
Average values of soil and manure metal concentrations in the area of study.

Parameter	Units	Value
Cd_{soil}	mg kg^{-1}	0.35
Cu_{soil}	mg kg^{-1}	22.2
Ni_{soil}	mg kg^{-1}	27.1
Pb_{soil}	mg kg^{-1}	11.7
Zn_{soil}	mg kg^{-1}	89.3
Cd_{manure}	g m^{-3}	0.17
Cu_{manure}	g m^{-3}	50.2
Ni_{manure}	g m^{-3}	4.5
Pb_{manure}	g m^{-3}	3.5
Zn_{manure}	g m^{-3}	317.4

of the University of Santiago de Compostela through all the cooperative extension. Cylindrical 8-cm diameter Auger probes were employed to collect samples of both soil and manure. In soil, representative samples of the different fields were constituted by several random sub-samples (20-cm depth) collected in zigzag throughout the field area (the number of sub-samples varying between 5 and 10 according to the field extension). Representative samples of manure were obtained by taking several sub-samples at different depths in the manure tank. The average values of 46 representative samples for metal concentrations in manure and soil properties can be seen in Table 1. It is remarkable the high average concentration of Zn in the manure (317.4 g m^{-3}), which is caused by different sources [48]. Manure was applied by farmers at rates ranging between 25 and 207 m^3 ha^{-1} y^{-1}. A representative average value of 90 m^3 ha^{-1} y^{-1} was selected to perform calculations for estimating HI. The results provided by the decision making system are shown in Fig. 2. The sum of each metal HQ or HI is equal to 1.42, indicating that human receptors can be at risk in the future if the current management practices are maintained. Specifically, the accumulation of the oligoelement Zn in soil and subsequent biotransfer to pasture, meat and milk is the main origin of potential adverse health effects, while other much more toxic metals (Cd and Pb) do not almost contribute to the hazard index. An individual evaluation of HI in each land plot is also performed, indicating that none of them are suitable neither for the average manure application rates nor the manure metal content produced in the area, since the minimum HI value obtained was 1.25. These results (HI of each land plot of the cooperative) can be seen in a GIS map (Fig. 3), providing a much more comprehensive information to farmers about the future situation of their exploitations if their current management practices were applied in the coming years. In Fig. 2, suggested maximum allowed values for fulfilling the imposed criterion of HI < 1 are provided for Zn concentrations in manure (170 g m^{-3}) and soil (0.29 mg kg^{-1}), as well as for the application rate (52 m^3 ha^{-1} y^{-1}) and duration of the fertilising period (48 y). On the other hand, suggested values for some of these parameters (application rate and Zn concentration in manure) are within the range of those that can be found in each individual parcel of land. Thus, this overall evaluation does not mean that in some farms correct management practices were applied.

Although the estimation of the HI for a single farm is useful since it supplies knowledge about the adequacy of the practices currently used by a farmer in his own property, the other two above-mentioned options (knowing either which manure to apply on his fields, or which fields are adequate for applying his manure) are more useful for the management of a single farm. For instance, the farm represented by the soil sample 8 and with a fertilising plan of 200 m^3 manure ha^{-1} y^{-1} during 20 years, should only applied manure produced in 6 of the 46 farming installations of the cooperative. It has to be remarked that a previous estimation of the application rate based on soil nutrient requirements is essential.



Element	Soil solution (...	Plants (mg/kg)	Soil (mg/kg)	Milk (mg/kg)	Meat (mg/kg)	HQ	Carcinogenic
Cd	0.00	0.00	0.61	0.00	0.00	0.01	0.00
Cu	0.13	0.13	172.90	0.08	3.77	0.09	0.00
Ni	0.16	0.16	23.90	0.27	0.26	0.10	0.00
Pb	0.00	0.00	22.83	0.00	0.02	0.01	0.00
Zn	2.65	2.65	936.40	0.60	455.56	1.22	0.00
Total	2.95	2.95	1156.63	0.95	459.61	1.42	0.00

Sampling point	Date	HQ	Carcinogenic
S030		1.39	0.00
S031		1.45	0.00
S032		1.37	0.00
S033		1.72	0.00
S034		1.40	0.00
S035		1.46	0.00
S036		1.45	0.00
S037		1.43	0.00
S038		1.36	0.00
S039		1.25	0.00
S040		1.48	0.00
S041		1.49	0.00
S042		1.55	0.00
S043		1.45	0.00
S044		1.45	0.00
S045		1.43	0.00
S046		1.39	0.00
F001		1.46	0.00
F001		1.44	0.00
F001		1.45	0.00
F001		1.44	0.00

Highest value 1.72 (S033)

Lowest value 1.25 (S039)

☑ Total results

○ Zn concentration in manure: 169.30 g/m3
○ Zn soil concentration: 0.29 mg/kg
○ Application rate of manure: 52.41 m3/ha year
○ Time: 48 years
○ Pasture production: 72595.67 kg/ha year

Fig. 2. General results dialog box.

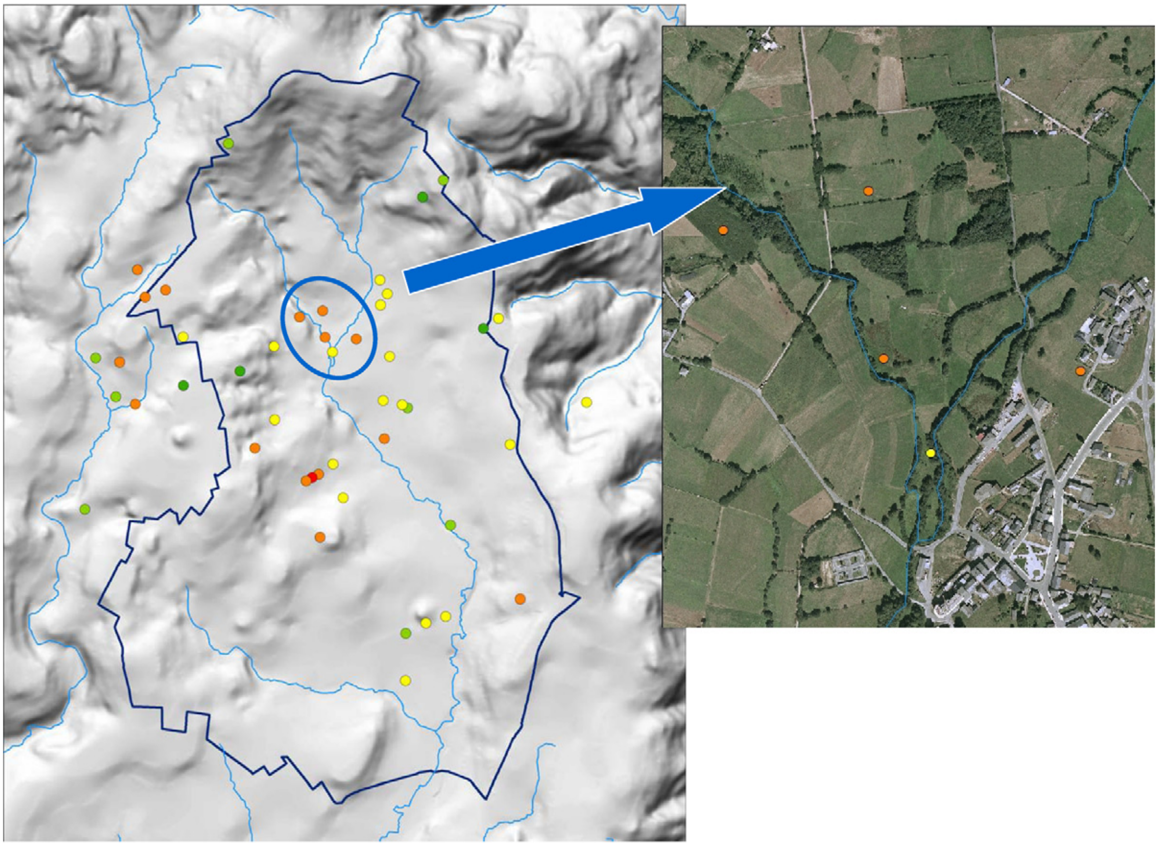


Fig. 3. GIS visualisation of the study area with Hazard Indexes of each parcel (zoom in the right figure). Colour code of HI values: dark green (1.24–1.32); light green (1.33–1.38); yellow (1.39–1.43); orange (1.44–1.55); red (1.56–1.72).

For that reason, FARMERS system provides optimum results when linked to a management tool for calculating N and P requirements [49].

The remaining evaluation case indicates that only 4 parcels (10, 12, 18 and 39) among 46 are suitable for performing the previous fertilising plan, with manure produced in farm 8. This option is very useful to safely manage the annual manure surplus of a particular farm.

These last two estimation options could very useful for implementing an exchange protocol between the farmers of a milk production cooperative. The decision system can identify gaps or surpluses and find the adequate properties that manure or soil must have for fulfilling safety and sustainable management criteria. Another important parameter that can be optimised by the proposed system is the maximum duration of a specific fertilising plan. It was demonstrated by the HI higher than 1 obtained in all the land plots (Fig. 3) that current application practices would result in a significant metal accumulation in soil and consequent health risk. Although the temporal horizon employed for HI calculation was high (100 years), future land use policy should be oriented not only to a reduction of pollutant concentration in manure, but also to a modification of fertilising practices in order to guarantee a safe agricultural and farming environment to future generations.

4. Conclusions

The risk-based decision support system was developed to be used by a cooperative instead of being used by a single farmer. The idea is to share the knowledge of all farmers in the cooperative. Knowing the characteristics of each farm (production, metal content and application rates of manure, soil properties, etc.) will be useful for identifying gaps or surplus in the fertilising of different land plots of the cooperative. It has to be remarked that a correct parameterisation of the decision making system according to the scenario evaluated is crucial in order to obtain adequate results. The system is oriented to intensive-farming areas for milk production constituted by pastureland for cattle grazing. Reusing the high manure volume produced in this type of installations to fertilise soil seems to be the best management measure. However, most of times the manure application rates are subjected to space restrictions rather than to a real necessity of nutrients by soil. Consequently, metal accumulation in soil and biotransfer to vegetation, cattle and humans are produced soon or later. This can be limited by the proposed decision support system, which gives useful information about the risk of reusing manure, indicating different protocols according to the specific needs of the evaluated case. Remark that this system is thought to be linked with a program calculating macronutrient requirements of soil, in order to provide a more complete and comprehensive guide of manure reuse as fertiliser in pastureland.

Acknowledgements

This work was supported by the Dirección Xeral de I+D+I (Xunta de Galicia) through the project FARIA (PGDIT05TAM00201CT).

Appendix A.

Tables A1–A3 are included in the Appendix, providing model parameter values.

Table A1
Value of parameters required for estimating metal concentration in cattle meat and milk.

Parameter	Units	Value
Cd BTF$_{meat}$	day kg^{-1}	4.0E−04
Cu BTF$_{meat}$	day kg^{-1}	9.0E−03
Ni BTF$_{meat}$	day kg^{-1}	5.0E−03
Pb BTF$_{meat}$	day kg^{-1}	4.0E−04
Zn BTF$_{meat}$	day kg^{-1}	1.0E−01
PIR$_{meat}$	kg day^{-1}	16.1
SIR$_{meat}$	kg day^{-1}	1.0
WIR$_{meat}$	L day^{-1}	50
Cd BTF$_{milk}$	day kg^{-1}	1.0E−03
Cu BTF$_{milk}$	day kg^{-1}	1.5E−03
Ni BTF$_{milk}$	day kg^{-1}	1.6E−02
Pb BTF$_{milk}$	day kg^{-1}	3.0E−04
Zn BTF$_{milk}$	day kg^{-1}	1.0E−02
PIR$_{milk}$	kg day^{-1}	1.3
SIR$_{milk}$	kg day^{-1}	0.13
WIR$_{milk}$	kg day^{-1}	75
f, fraction of pasture from area	Unitless	80

Values from [44].

Table A2
Value of parameters required for calculating human exposure to metals through the different pathways.

Parameter	Units	Value
Meat and milk ingestion pathways		
IR$_{meat}$ [50]	g day^{-1}	53.2
IR$_{milk}$ [51]	g day^{-1}	436
BW [52]	kg	67.52
f_{meat}	Unitless	1
f_{milk}	Unitless	1
Soil ingestion, inhalation and dermal contact pathways		
IR$_{Soil}$ [53]	mg day^{-1}	25
Ratio of skin surface area/body weight [54]	cm^2 kg^{-1}	248
Contact time [45]	h day^{-1}	1.5
Adherence factor [54]	mg cm^2	0.52
Dermal absorption factor [55]	Unitless	0.001
Fraction of skin exposed	Unitless	0.15
Fraction of resuspended soil particles [56]	Unitless	1.0E−02
Inhalation rate [57]	m^3 d^{-1}	11.4
Particle concentration in air [58]	mg m^{-3}	0.1
Fraction retained in the lung	Unitless	0.5

Table A3
Toxicity values: Reference Doses (RfDs) and Slope Factors (SF) for non-carcinogenic and carcinogenic effects, respectively.

Metal	*RfD* (mg kg^{-1} day^{-1})	SF (kg day mg^{-1})	Source
Cadmium	1.00E−03	6.3E+00 (inhalation)	[9]
Copper	4.00E−02	–	[9]
Nickel	2.00E−02	–	[9]
Lead	3.60E−03	–	[47]
Zinc	3.00E−01	–	[9]

References

[1] M. Mahamud, A. Gutiérrez, H. Sastre, Biosolids management in Spain: a case study, Waste Manage. 17 (1998) 463–472.
[2] J.C. Hargreaves, M.S. Adl, P.R. Warman, A review of the use of composted municipal solid waste in agriculture, Agric. Ecosyst. Environ. 123 (2008) 1–14.
[3] M.A. Qazi, M. Akram, N. Ahmad, J.F. Artiola, M. Tuller, Economical and environmental implications of solid waste compost applications to agricultural fields in Punjab, Pakistan, Waste Manage. 29 (2009) 2437–2445.
[4] R.E. Alcock, J. Bacon, R.D. Bardget, A.J. Beck, P.M. Haygarth, R.G.M. Lee, C.A. Parker, K.C. Jones, Persistence and fate of polychlorinated biphenyls (PCBs) in sewage sludge-amended agricultural soils, Environ. Pollut. 93 (1996) 83–92.
[5] M.D. Perez-Murcia, R. Moral, J. Moreno-Caselles, A. Perez-Espinosa, C. Paredes, Use of composted sewage sludge in growth media for broccoli, Bioresour. Technol. 97 (2006) 123–130.
[6] I. Walter, F. Martínez, V. Cala, Heavy metal speciation and phytotoxic effects of three representative sewage sludges for agricultural uses, Environ. Pollut. 139 (2006) 507–514.
[7] C.J. van Leeuwen, T.G. Vermeire (Eds.), Risk Assessment of Chemicals: An Introduction, 2nd ed., Springer, 2007.
[8] NRC (National Research Council), Issues on Risk Assessment. Committee on Risk Assessment Methodology, National Academy Press, 1993.
[9] U.S.EPA, Integrated Risk Information System (IRIS), http://www.epa.gov/iris/ (Accessed October 2009).
[10] EC (European Commission), European chemical Substances Information System (ESIS). Institute for Health and Consumer Protection, http://ecb.jrc.ec.europa.eu/esis/ (Accessed October 2009).
[11] ECB (European Chemical Bureau), EUSES Documentation – The European Union System for the Evaluation of Substances, The Netherlands: RIVM, National Institute of Public Health and Environment, 1997, available from European Chemical Bureau (EC/DGXI), Ispra, Italy.
[12] T.E. McKone, CalTOX, A Multimedia Total Exposure Model for Hazardous-waste Sites Parts I–IV. Report UCRL-CR-111456PtI-IV, Lawrence Livermore National Laboratory, Livermore, CA, 1993.
[13] S.M. Eldridge, K.Y. Chan, I. Barchia, P.K. Pengelly, S. Katupitiya, J.M. Davis, A comparison of surface applied granulated biosolids and poultry litter in terms of risk to runoff water quality on turf farms in Western Sydney, Australia, Agric. Ecosyst. Environ. 134 (2009) 243–250.
[14] EC (European Commission), Council Directive 91/676/EEC of 12 December 1991 concerning the protection of waters against pollution caused by nitrates from agricultural sources, Brussels, European Council, 1991.
[15] EC (European Commission), Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy (further amended by Directive 2008/105/EC), Brussels, European Council, 2000.
[16] M. Araujo, R. Sueiro, M. Garrido, Contaminación biótica. In: As augas de Galicia. Consello da Cultura Galega, 1996 (in Spanish).
[17] F. Madrid, R. López, F. Cabrera, Metal accumulation in soil after application of municipal solid waste compost under intensive farming conditions, Agric. Ecosyst. Environ. 119 (2007) 249–256.
[18] S.L. Lipoth, J.J. Schoenau, Copper, zinc, and cadmium accumulation in two prairie soils and crops as influenced by repeated applications of manure, J. Plant Nutr. Soil Sc. 170 (2007) 378–386.
[19] J.O. Azeez, I.O. Adekunle, O.O. Atiku, K.B. Akande, S.O. Jamiu-Azeez, Effect of nine years of animal waste deposition on profile distribution of heavy metals in Abeokuta, south-western Nigeria and its implication for environmental quality, Waste Manage. 29 (2009) 2582–2586.
[20] EC (European Commission), Council Directive 86/278/EEC of 12 June 1986 on the protection of the environment, and in particular of the soil, when sewage sludge is used in agriculture as amended by Council Directive 91/692/EEC (further amended by Council Regulation 1882/2003/EC), and Council Regulation 807/2003/EC, Brussels, European Council, 1986.
[21] J.J. Schröder, H.F.M. Aarts, J.C. van Middelkoop, R.L.M. Schils, G.L. Velthof, B. Fraters, W.J. Willems, Permissible manure and fertilizer use in dairy farming systems on sandy soils in The Netherlands to comply with the nitrates directive target, Eur. J. Agronomy 27 (2007) 102–114.
[22] M. Bechmann, P. Stålnacke, S. Kværnø, H.O. Eggestad, L. Øygarden, Integrated tool for risk assessment in agricultural management of soil erosion and losses of phosphorus and nitrogen, Sci. Total Environ. 407 (2009) 749–759.
[23] R. De Jong, C.F. Drury, J.Y. Yang, C.A. Campbell, Risk of water contamination by nitrogen in Canada as estimated by the IROWC-N model, J. Environ. Manage. 90 (2009) 3169–3181.
[24] C.G. Sørensen, B.H. Jacobsen, S.G. Sommer, An assessment tool applied to manure management systems using innovative technologies, Biosyst. Eng. 86 (2003) 315–325.
[25] S. Karmakar, M. NKetia, C. Laguë, J. Agnew, Development of expert system modeling based decision support system for swine manure management, Comput. Electron. Agric. 71 (2010) 88–95.
[26] J. Wolf, A.H.W. Beusen, P. Groenendijk, T. Kroon, R. Rötter, H. van Zeijts, The integrated modeling system STONE for calculating nutrient emissions from agriculture in the Netherlands, Environ. Modell. Softw. 18 (2003) 597–617.
[27] N.S. Bolan, D.C. Adriano, S. Mahimairaja, Distribution and bioavailability of trace elements in livestock and poultry manure by-products, Crit. Rev. Environ. Sci. Tec. 34 (2004) 291–338.
[28] F.A. Nicholson, B.J. Chambers, J.R. Williams, R.J. Unwin, Heavy metal contents of livestock feeds and animal manures in England and Wales, Bioresour. Technol. 70 (1999) 23–31.
[29] E.T. Kornegay, J.D. Hedges, D.C. Martens, C.Y. Kramer, Effect of soil and plant mineral levels following application of manures of different copper levels, Plant Soil 45 (1976) 151–162.
[30] R. Moral, M.D. Perez-Murcia, A. Perez-Espinosa, J. Moreno-Caselles, C. Paredes, B. Rufete, Salinity, organic content, micronutrients and heavy metals next term in pig slurries from South-eastern Spain, Waste Manage. 28 (2008) 367–371.
[31] D.J. Brus, J.J. de Gruijter, D.J.J. Walvoort, F. de Vries, J.J.B. Bronswijk, P.F.A.M. Römkens, W. de Vries, Mapping the probability of exceeding critical thresholds for cadmium concentrations in soils in The Netherlands, J. Environ. Qual. 31 (2002) 1875–1884.
[32] W. de Vries, P.F.A.M. Römkens, L.T.C. Bonten, Spatially explicit integrated risk assessment of present soil concentrations of cadmium, lead, copper and zinc in The Netherlands, Water Air Soil Pollut. 191 (2008) 199–215.
[33] S. Lofts, D.J. Spurgeon, C. Svendsen, E. Tipping, Deriving soil critical limits for Cu, Zn, Cd, and Pb: a method based on free ion concentrations, Environ. Sci. Technol. 38 (2004) 3623–3631.

[34] M. Posch, W. de Vries, Dynamic modelling of metals—time scales and target loads, Environ. Modell. Softw. 24 (2009) 86–95.
[35] A.E. Boekhold, S.E.A.T.M. van der Zee, Long term effects of soil heterogeneity on cadmium behaviour in soil, J. Contam. Hydrol. 7 (1991) 371–390.
[36] S. Moolenaar, S.E.A.T.M. van der Zee, T.M. Lexmond, Indicators of the sustainability of heavy-metal management in agro-ecosystems, Sci. Total Environ. 201 (1997) 155–169.
[37] C. de Meeûs, G.H. Eduljee, M. Hutton, Assessment and management of risks arising from exposure to cadmium in fertilisers, I, Sci. Total Environ. 291 (2002) 167–187.
[38] C.F.I. Baes, R.D. Sharp, A.L. Sjoreen, R.W. Shor, A Review and Analysis of Parameters for Assessing Transport of Environmentally Released Radionuclides Through Agriculture, ORNL-5786, Oak Ridge National Laboratory, Oak Ridge, TN, USA, 1984.
[39] ORNL, Empirical models for the uptake of chemical from soil by plants. ES/ER/TM-198, Oak Ridge National Laboratory, Oak Ridge, TN, USA, 1998.
[40] S. Sauvé, W.H. Hendershot, H.E. Allen, Solid-solution partitioning of metals in contaminated soils: dependence on pH, total metal burden and organic matter, Environ. Sci. Technol. 34 (2000) 1125–1131.
[41] R.A. Efroymson, B.A. Sample, G.W. Suter II, Uptake of inorganic chemicals from soil by plant leaves: regressions of field data, Environ. Toxicol. Chem. 20 (2001) 2561–2571.
[42] C. Lopes, M. Herva, A. Franco, M.L. Fernández-Marcos, E. Roca, Modelling of heavy metal transfer from soil to vegetation in a cattle manure application scenario, in: ICCE 2009: 12th EuCheMS International Conference on Chemistry and the Environment, Stockholm, 2009.
[43] M. Herva, A. Franco, M.L. Fernández-Marcos, E. Roca, Multicorrelation models for the estimation of bioavailable metal concentration in soil fertilised with cattle manure, in: ICCE 2009: 12th EuCheMS International Conference on Chemistry and the Environment, Stockholm, 2009.
[44] ORNL, Guidance for Conducting Risk Assessments and Related Risk Activities for the DOE-ORO Environmental Management Program, BJC/OR-271. Oak Ridge National Laboratory, Oak Ridge, TN, USA, 2004.
[45] U.S.EPA, Exposure Assessment Methods Handbook, EPA/600, Exposure Assessment Group, Office of Health and Environmental Assessment, Washington, DC, 1989.
[46] A. Franco, M. Schuhmacher, E. Roca, J.L. Domingo, Application of cattle manure as fertiliser in pastureland: Estimating the incremental risk due to metal accumulation employing a multicompartment model, Environ. Int. 32 (2006) 724–732.
[47] WHO, Lead in drinking water. Background document for development of WHO Guidelines for Drinking-water Quality. http://www.who.int/water_sanitation_health/dwq/chemicals/lead.pdf, 2003.
[48] A. Franco-Uría, C. López-Mateo, E. Roca, M.L. Fernández-Marcos, Source identification of heavy metals in pastureland by multivariate analysis in NW Spain, J. Hazard. Mater. 165 (2009) 1008–1015.
[49] M.R. Teira-Esmatges, X. Flotats, A method for livestock waste management planning in NE Spain, Waste Manage. 23 (2003) 917–932.
[50] M. López Alonso, J.L. Benedito, M. Miranda, C. Castillo, J. Hernández, R.F. Shore, Contribution of cattle products to dietary intake of trace and toxic elements in Galicia, Spain, Food Addit. Contam. 19 (2002) 533–541.
[51] Estudio Nacional de Nutrición y Alimentación (ENNA 91), Spanish National Institute of Statistics (INE), 1991 (in Spanish).
[52] M. Schuhmacher, M. Meneses, A. Xifró, J.L. Domingo, The use of Monte-Carlo simulation techniques for risk assessment: study of a municipal waste incinerator, Chemosphere 43 (2001) 787–799.
[53] P.K. LaGoy, Estimated soil ingestion rates for use in risk assessment, Risk Anal. 7 (1987) 355–359.
[54] B. Finley, D. Proctor, P. Scott, D. Mayhall, Development of a standard soil-to-skin adherence probability density function for use in Monte Carlo analysis of dermal exposure, Risk Anal. 14 (1994) 555–569.
[55] ORNL, Risk Assessment Information System (RAIS), Oak Ridge, TN, USA: Oak Ridge National Laboratory.
[56] J.K. Hawley, Assessment of health risk from exposure to contaminated soil, Risk Anal. 5 (1985) 289–302.
[57] B. Finley, D. Proctor, P. Scott, N. Harrington, D. Paustenbach, P. Price, Recommended distributions for exposure factors frequently used in health risk assessment, Risk Anal. 14 (1994) 533–553.
[58] MeteoGalicia, Consellería de Medio Ambiente, Xunta de Galicia, Spain. http://www.meteogalicia.es.