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Ana Passuello

Marta Schuhmacher

Vikas Kumar

M. Nadal

J. L. Domingo

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An integrated multimedia model and multicriteria analysis approach to managing sewage sludge application on agricultural soils: framework and methodology

A. C. Passuello[a], **M. Schuhmacher**[a,b], **V. Kumar**[a,c], **M. Nadal** [b], **J. L. Domingo**[b]

[a] *School of Chemical and Process Engineering, ''Rovira i Virgili'' University, Av. Paıses Catalanes 26, 43007 Tarragona, Spain*
[b] *Laboratory of Toxicology and Environmental Health, School of Medicine, ''Rovira i Virgili'' University, San Lorenzo 21, 43201 Reus, Spain*
[c] *Catchment Science Centre, University of Sheffield, S3 7HQ, Sheffield, UK*
(ana.passuello@urv.cat)

Abstract: Sludge application to agricultural soils is a managing practice of increasing use, because of its benefits to soil and crops. The Council Directive 86/278/CEE regulates concentrations of heavy metals for sludge application, but has no restrictions related to organic compounds contamination. The Decision Support System (DSS) presented here, integrates a multimedia risk model of persistent organic pollutants (POPs) to human and ecosystem (P), a model concern to areas' vulnerability to nitrogen (N), and also an economical model (E), to indicate the best decision management for sludge application on agricultural soils. The three dimensional representation of the model allows a simple visualization of the multicriteria analysis, permitting transparency on decision making.

Keywords: Decision Support System (DSS), Sludge Final Disposal, Diffusive Transport Model, Risk Assessment.

1. INTRODUCTION

The application of sewage sludge to agricultural soils is a widely extended practice, and that is progressively increasing with the years. The number and capacity of wastewater treatment plants has increased in the last few years in Spain, resulting in an enlargement of 47% on sludge production between the years 1997 and 2003 [Applus, 2007]. The sludge from wastewater treatment plants is a residue that must be properly disposed, in order to protect the environment. Its increasing use on agriculture soils without proper treatment makes it a topic of concern. However with careful management, the application of sludge to land is clearly beneficial to agricultural soils and crops. The main benefit for agricultural proposes is the increase of the nutrients as well as the organic carbon content in soil, which improves the crops production.

The Council Directive 86/278/CEE determines values for concentrations of heavy metals in soils to which sludge is applied, concentrations of heavy metals on sludge and the maximum annual quantities of such heavy metals which may be introduced into soil intended for agriculture. However, in Spain, there are no legally enforceable restrictions related to organic compounds which may be present in sludge.

An extensive and diverse range of organic compounds are known to exist in sewage sludge [Katsoyiannis and Samara, 2005], many of which become transferred to sludge-amended agricultural soils [Wild and Jones, 1992]. These polluting agents move through the different compartments, and they accumulate throughout the food chain. As is, a multicompartimental model is used as a tool for predicting pollutants distribution on the environmental compartments (air, water, soil, crops), and evaluate its risk for the population as well as the ecosystem, through exposition and risk assessment models.

Another point of concern is that sludge application on soils may lead to groundwater nitrification, as a result of nitrogen movement through the lixiviate. The nutrients content of sludge is a variable related to application dose. Studies have been proved that sludge application improves soil fertility along the years [Fuentes et al., 2008]. On the other hand, care must be taken on areas that are vulnerable to nitrogen pollution, as recommended on EC Nitrate Directive 91/676.

Economically, sludge application improves soil fertility and exempt fertilizers use to correct the soil. Also, the crop production is increased because of the nutrients content of the sludges.

In order to determine the best scenarios for sludge application on agricultural soils for crops production in Spain, a decision support system (DSS) that integrates economical and environmental issues is presented. The objective of this DSS is to minimize the environmental risks (to human and ecosystems) and maximise the economic return, considering the characteristics of the different sites that sludge may be applied. The DSS is presented in Figure 1.

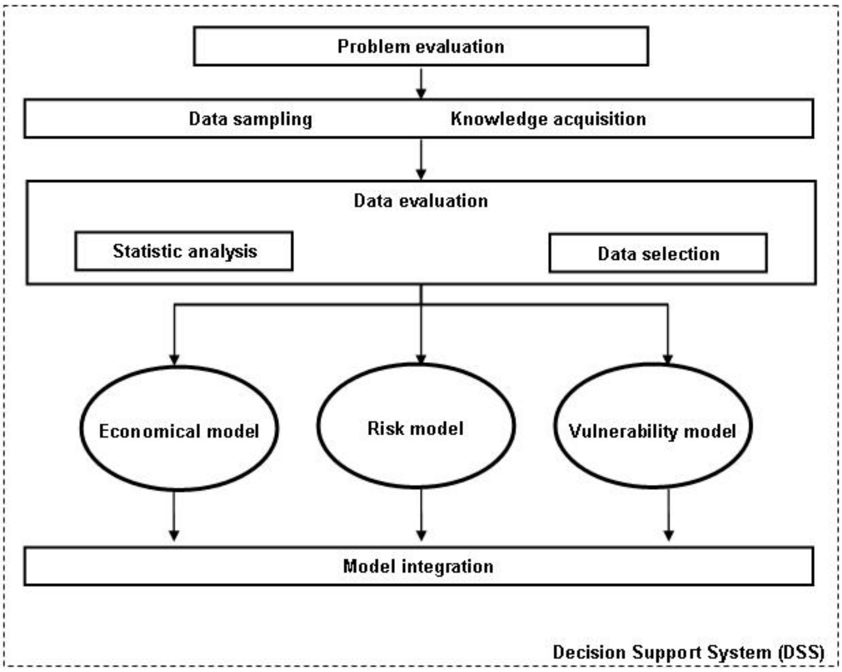

Figure 1 Phases of the decision support system (DSS)

The DSS presented here allows analysing different scenarios, according to economical and environmental criteria. For that, three models are used: one related to risk impacts of persistent organic pollutants (POPs) to human and ecosystem (P), another related to vulnerability to nitrogen (N), and also an economical model (E). The models will be applied to different scenarios, according to local site and sludge characteristics. The development of these models is presented in the following section.

2. MULTICRITERIA ANALYSIS

2.1 Risk model

Persistent organic pollutants (POPs) constitute a class of man-made chemicals with a pronounced persistence against chemical/biological degradation, environmental mobility, a tendency for bioaccumulation in human and animal tissue, and significant impacts on human health and the environment, even at extremely low concentrations [Katsoyiannis and Samara, 2005]. In a previous study, several samples of sludge were collected and characterized. The sludge analysis defined the POPs to be evaluated (PAHs, PCBs, PBDEs, PCNs, Nonilfenol, PFOS and PFOAS).

The fate model considers the rates of POPs' release because of sludge application and its fate through soil, air, crops, soil invertebrates and soil-dwelling mammals. Vegetation and soil have been treated separately, as their characteristics of exchange with the atmosphere are different [Wania et al., 2006].

The model is based on Level IV fugacity models [Webster and Mackay, 2007], which is most useful for estimating recovery times of a contaminated system that is experiencing reduced emissions [Mackay, 2001]. That's the case of sludge amended soils, which receive an amount of sludge once a year.

Physical chemical properties data and concentrations in sludge are used to calculate the concentrations in the compartments, and uptake into vegetation, soil invertebrates and soil-dwelling mammals. The soil component of the model allows different layer of soil to be defined. The model is dynamic and allows seasonally variable environmental parameters, since the seasonal and multi-year time scale is of most interest for POPs [Wania et al., 2006].

The parameters used to develop the model are: sludge characteristics and application dose, soils characteristics (porosity, hydraulic conductivity, bulk density, field area, density of organic matter and mineral matter, bioavailability factor, layer depth, volume fraction of air and water), kind of crop, temperature, and pollutant properties (solubility, K_{OW}, vapour pressure, H, persistency, half life in soil and toxicity).

The parameters considered to estimate crop contamination are biosolids properties (K_{OW}, K_{OA}), contaminant concentration, and crop properties, for two types of cereals: corn and wheat. Also, the climatology is considered, as the crops are cultivated at separate seasons. For invertebrates and mammals, the volume, density, volume fractions of lipid and water are taken into account.

The key processes considered are those who could lead to loss of chemical during the transport, at the two layers of soils (Figure **2**).

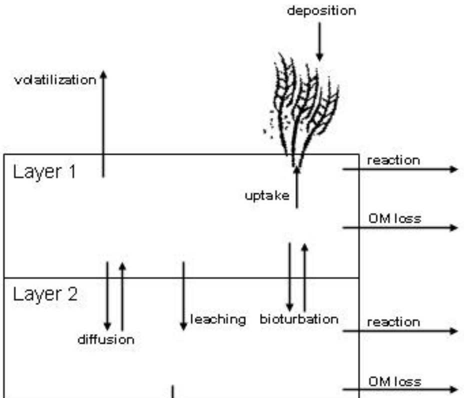

Figure 2 Transfer processes considered on the different environmental compartments. Adapted from Webster and Mackay [2007].

The environmental compartments are linked by inter-compartmental transfer processes. The first layer soil loses chemical by five processes: volatilization to the air above the soil compartment, leaching to the second layer, sorbed phase transport (bioturbation) to the second layer, diffusion in pore air and pore water to the second layer, and degrading reactions. The second layer loses chemical by sorbed phase transport and diffusion to the first layer, by leaching, and by degrading reactions. Chemical is lost from the entire soil system by degradation in each layer, by volatilization from the top layer, and by leaching from the lower layer [Webster and Mackay, 2007].

A fugacity approach is used in order to estimate the mechanisms of volatilization, diffusion, leaching, reaction, bioturbation and loss of organic matter. A sensibility analysis is assessed with the aim of defining the most relevant parameters.

For model validation, the analysis of collected samples of sludge and soils where the sludge is applied will be used. Also, an experiment on field scale is being developed, in order to quantify toxicological impacts and pollutants movement. In this experiment, the different types of soils and climate will be assessed, considering two cereal types: corn and wheat.

Organic contaminants may impact humans and ecosystem through different pathways [Schowanek, et al., 2004]. The exposure and risk model considers ecosystem and human exposure to polluted soil, food and air, with the different routes of contamination: air pollution due to volatilization, vegetal pollution through soil and polluted air, dermal absorption by contact with soil, ingestion of contaminated soil and crops, inhalation of re-suspended soil particles.

The Risk Assessment Analysis is based on CEC [2003]. Risks for adverse human health effects are estimated assuming to be carcinogens or non-carcinogens [Schuhmacher et al., 2001]:

- Non-carcinogenic risk: To determine if the contaminant poses a risk to human health, daily intake is compared with the reference dose (RfD) for chronic exposure. The tolerable daily intake (TDI) established by the WHO was here used.

- Carcinogenic risk: It is calculated by multiplying the estimated dose by the carcinogenic potency factor. The predicted carcinogenic risk is an upper-bound estimate of the potential risk associated with the exposure.

The risks to the ecosystem are calculated using the PECs for all environmental compartments, as described in the EU Technical Guidance Document [CEC, 2003].

Chemical properties may be highly uncertain due to difficulty in measurement, while landscape data are highly variable at spatial scales [Bennett et al., 1999]. Therefore, it is very important to present clearly the propagation of parameter variances into model outputs that reflect environmental persistence of chemicals [Luo and Yang, 2007]. For that, the Fuzzy Latin Hypercube Sampling (FLHS), a technique that allows characterization of both uncertainty and variability in the input variables, will be applied as described by Kumar et al. [2008].

2.2 Vulnerability model

To determine the areas that are vulnerable to nitrogen, the lixiviate movement through groundwater is assessed; considering the geographic boundaries, the biosolid's contaminant concentration, the kind of agricultural application, soil and pollutant properties.

The transport of nutrients to groundwater will be based on an improved version of DRASTIC [Rupert, 1999], which calibrates the point rating scheme to measured nitrite plus nitrate as nitrogen ($NO_2 + NO_3$ - N).

DRASTIC index is a numerical ranking system developed by Aller et al. [1987] to assess groundwater pollution potential in various hydrogeologic settings. In the DRASTIC methodology, groundwater pollution potential is evaluated by seven factors: D – depth to water; R – net recharge; A – aquifer media; S – soil media; T – topography (slope); I – impact of the vadose zone media; and C – hydraulic conductivity of the aquifer. Each of the DRASTIC factors is assigned a relative weight ranging from 1 to 5. The most significant factor has a weight of 5 and the least significant has a weight of 1.

Once the DRASTIC Index has been computed, it is possible to identify areas, which are more likely to be susceptible to GW contamination relative to others. The higher the DRASTIC Index, the greater is the GW pollution potential.

2.3 Economical model

For the economic evaluation, the costs and benefits of the sludge application are calculated. The costs considered on this evaluation are transport, storage and sludge application on land. Thus, the main economical variables are the distance between the agricultural area and the treatment plant, the amount of sludge produced and the nitrogen content of sludge, which is related to the application dose.

The organic matter content of soil is improved with the sludge application, fact that is not observed on fertilisers application on soil [Fuentes et al., 2008]. For this reason, the agricultural productivity of the alternative sites (scenarios) where sludge is applied is estimated as described by Koo and O'Connell [2006]. The agronomic model is based on nitrogen response curves and the crops' price. The yield (in t/ha/year) is a function of nitrogen application (kg N/ha/year), and the price is estimated by the crops market value (€/t).

3. AGGREGATION

In order to define the normalization indexes, different scenarios will be applied for each of the models. The normalization values are defined through a linear function [Afgan and Carvalho, 2004].

Then, the models are integrated considering the normalized values aggregated as a three dimensional vector (Figure 3). For that, weighting values may be defined by the decision maker. The best option is, thus, the one who gets closer to an optimum value.

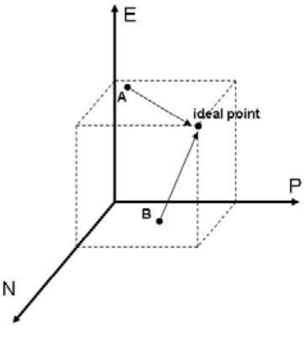

Figure 3 Representation of two scenarios as three dimensional vectors: risk impacts of persistent organic pollutants (POPs) to human and ecosystem (P), vulnerability to nitrogen (N), and economical model (E).

It may be noted in Figure 3, that the point A represents an alternative viable economically, but with low concern on environmental problems. On the other hand, point B is not interesting on economical point of view, but has a major concern on the environmental issue than point A. In order to calculate which point is closer to an "ideal scenario", the following equation is suggested:

$$d_{ij} = \sqrt{\lambda_P^2 \left(u_j - u_i\right)^2 + \lambda_N^2 \left(v_j - v_i\right)^2 + \lambda_E^2 \left(w_j - w_i\right)^2} \quad (1)$$

Where d_{ij} is the distance between the selected scenario *i* and the optimal point *j*, λ_P, λ_N, and λ_E, are the weighting values for the scenarios P, N and E; u_i and u_j are the vector P values for the scenario *i* and the optimal point *j,* v_i and v_j are the vector N values for the scenario *i* and the optimal point *j,* and w_i and w_j are the vector E values for the scenario *i* and the optimal point *j.*

4. CONCLUSIONS

At present, the Spain's legal regulation regarding sludge application on agricultural soils only concerns about metal levels. Several works have shown that the existence of vulnerable areas, as well as the impacts of the POPs present in sludge are issues of concern.

The DSS presented here consists in a simple way of aggregating different criteria. It permits using models based on different evaluation techniques, as well as on decision maker's experience. It represents a first screening of the main parameters to be considered on a DSS of sludge application on agricultural soils, and will be applied to a reduced number of scenarios. Then, a site specific evaluation must be done, with the aim of assessing the uncertainty of the selected variables.

The economic evaluation is significant, as it consists on main criteria for the decision maker. In this study, not only direct cost, but long range estimation was considered, in order to define the best scenario along a larger period. Besides, because of the tendency of water resources shortage, avoiding the groundwater nitrification leads to a prevention of future environmental, and consequently, economical problems.

Moreover, this article presents an innovative way to assess the risk of POP's exposure to humans and ecosystem, evaluating the fate of these contaminant, followed by a exposure and risk analysis.

The three dimensional representation allows viewing the contribution of each of the selected criteria (economical, vulnerability and risk) on the final result. The weighting factor applied by the decision maker may be clearly observed, as well as the individual contribution of the models, enhancing the transparency and reliability of the method.

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