EVALUATING THE IMPACT OF SEWAGE SLUDGE APPLICATION ON AGRICULTURAL SOILS

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Abstract

Sewage sludge application on agricultural soils is recommended by governments in order to recycle nutrients and organic matter. However, this practice may lead to ecological and human risks. In this paper, a decision support system for helping in the management of sewage sludge is presented. The system integrates different methodologies. In the first stage, fuzzy expert systems are used to assess the partial utility of the alternatives with respect to some complex criteria. This is combined with the use of classical piecewise linear functions for simple criteria. In the second stage, utilities are aggregated with conjunctive/disjunctive operators. The results obtained in a case study with real data are presented.

Keywords: Fuzzy expert systems, Aggregation operators, Decision Making, Environmental applications, Sewage sludge management.

1 INTRODUCTION

This paper addresses the problem of recycling sewage sludge produced at wastewater treatment plants (WWTP). This sludge can be used as fertilizer in agricultural soils, helping to the sustainability of the water life cycle. Although this process has many advantages, it must be carefully decided where to send each type of sludge, because sludge contains contaminants (metals and organic compounds) that may impact humans and ecosystems. For this reason, it is interesting to have tools to evaluate the suitability of applying a certain sewage sludge on a particular soil.

Nowadays, there is only one regulation indicating the maximum metal content permitted in sewage sludge that is going to be used as fertilizer. In this work we have

developed a sophisticated decision support system that integrates the experts' knowledge about the impact on the human health and the environment, in relation to the different characteristics of the sewage sludge and the soil. This system is expected to be used by the manager that decides the best place to send the sewage sludge of each of the different WWTPs in a region [6]. From a technological point of view, the system developed is particularly interesting because the solution proposed integrates fuzzy expert systems into a traditional multiattribute aggregation model.

The paper is organized as follows. Section 2 introduces the problem of management of sewage sludge (i.e. biosolids). Section 3 presents the decision support system designed to evaluate the suitability of applying some sludge into a certain agricultural soil. Section 4 shows the first part of the process, consisting in evaluating partial utilities with respect to low level criteria. Then, section 5 is devoted to present an aggregation model of the partial utilities in order to obtain the global utility. Section 6 shows a real case study and the results obtained. Finally, some conclusions and future work is outlined in section 7.

2 BIOSOLID MANAGEMENT

Biosolids, also referred as sewage sludge, are residues generated at WWTPs, obtained from solids removal on various parts of the treatment system. In Spain the production of biosolids increased in a 39% from 1997 to 2005 [5]. The legislation requires building new plants in towns with a population higher than 2000 inhabitants, so more than 1000 WWTP have been build in all Spain.

Once treated, sludge can be recycled or disposed using three main routes: disposal on agricultural soil, incineration and landfill. Any of these three scenarios leads to different impacts to humans and ecosystems. In this work we focus on the study of biosolids disposal in agricultural soils. This study is part of some Spanish funded research projects.

Sewage sludge application on soil improves fertility and exempt fertilizers use. Furthermore the transfer of nutrients and organic matter to the soil increases crop production. For these reasons, the Spanish government wants that at least 70% of the WWTP sludge is applied into agricultural soils. In 2005 the recycling of sewage sludge to agriculture represented a 65% of the total disposal of biosolids [5]. However, it should be studied how this percentage may be increased. Some studies have proven that sewage sludge application improves soil fertility along the years [4]. Even so, sewage sludge application on soils may lead to groundwater nitrification as a result of nitrogen movement through lixiviate. The nitrates content of sewage sludge is a variable related to application dose. Special care must be taken on areas that are vulnerable to nitrogen pollution, as recommended on EC Nitrate Directive 91/676.

In addition to these issues, the impacts to humans and ecosystems must be considered, such as the exposition to organic contaminants through different routes (inhalation, ingestion and dermal contact), the lifecycle, and the field properties.

3 ARCHITECTURE OF THE DECISION SUPPORT SYSTEM

To design this decision support system, a Multi-Attribute Utility approach has been taken [3]. This approach considers that the different alternatives that are analysed in the decision process can be evaluated by a set of criteria *G*. Criteria are built on the basis of the alternatives' properties. Each criterion is a function g_i , where $g_i(a_i)$ is regarded as a partial utility (i.e. preference) from the decision maker point of view. The partial utility value denotes the degree to which the value of some property a_i satisfies a specific requirement of the user. It can also be called a preference or suitability degree.

In this problem, an alternative is the combination of a certain type of biosolid coming from some concrete WWTP into a certain agricultural soil. The number of features describing sewage sludge is 6 and 8 for characterizing the soil and landscape. Additionally 8 properties have been also included in the alternative's description, which are mainly related to economic issues and to the sensible population that might be affected.

Partial utility values of all the criteria are obtained from evaluating the features of the alternative with the corresponding utility function. Then, those partial utilities are aggregated to find a global utility value for each alternative. Afterwards, these ratings are rank ordered.

Finally, parameter uncertainty has been addressed. A sensitivity analysis tool has been implemented to

understand the effects of the parameter variations on the results. Sensitivity analysis can help to explain the results and make the recommendations with confidence [8].

Figure 1 shows the architecture of the decision support system developed. First the input data coming from the analysis of the chemical and physical properties of the sewage sludge and soils are evaluated using the utility functions. Then, the global utility value is calculated using the Logic Scoring of Preference model (LSP) [1]. Finally, the tool ranks the alternatives according to their global utility and performs a sensitivity analysis on the weights given to the different operators of LSP.

For the utility assessment, two different methodologies are used [7]: fuzzy expert systems to evaluate the utility of composite criteria and traditional linear functions for simple criteria. This is explained in more detail in the next section.



Figure 1: Decision support system architecture.

To organize the set of criteria, a hierarchical structure has been defined together with the experts. In the first level, three main types of criteria are distinguished: economical, environmental and social. Each of these classes of preference criteria represents a different aspect of the problem regarding different points of view. The hierarchy of criteria is shown in Figure 2. Simple and Composite criteria are denoted by (S) and (C), respectively.



Figure 2: Family of criteria.

4 PREFERENCE ASSESMENT

Partial utility functions are built from the knowledge of the domain experts. Utility functions must give a preference score to each possible value in the reference domain of a certain feature of the alternatives. During this process we found that some of the criteria do not depend on a single feature but on the interactions among combinations of features, usually a combination of soil and sludge properties. Therefore, the characterization of the utility functions in this environmental problem was not straightforward. First of all, the interactions between those features have been studied in order to find which are the groups of variables that should be modelled together to define the preference criteria. Then, two types of criteria have been distinguished, which have been called: Simple criteria, S, and Composite criteria, C. In both cases, a preference scale from 0 to 10 has been selected, for expert's convenience.

Definition 1. Simple criteria $S \subset G$ are criteria of the form $g: \mathcal{R} \rightarrow [0..10]$

Definition 2. Composite criteria $C \subset G$ are criteria of the form $g: \mathcal{R} \times \mathcal{R} \times ... \times \mathcal{R} \rightarrow [0..10]$

In Figure 2, the two types of criteria are indicated: (S) refers to Simple criteria and (C) corresponds to Composite criteria. For simple criteria, the classical value functions can be applied because a single feature must be considered. However, for composite criteria, the definition of the preference function depends on the combination of soil and sludge properties and, sometimes, also other variables. In this case, fuzzy rule-based systems have been proposed to model the interactions.

4.1. LINEAR UTILITY FUNCTIONS

In the family of criteria there are 9 simple criteria. They are related to the economical and social aspects of the problem. Those criteria do not have dependences with sludge properties, so that they can be directly evaluated from a single feature.

For this type of criteria, classical utility functions have been defined [3]. Each utility function is obtained by a linear interpolation between the utility scores that the experts have given to certain reference values.



Figure 3: Utility function for the Temperature criterion.

Figure 3 shows the utility function for the Temperature criterion. This function takes as reference the average temperature is represented in Celsius degrees. The utility is an ascending function because high temperatures produce a high degradation of the organic matter and, thus, plant contamination decreases.

4.2. FUZZY EXPERT SYSTEMS

In order to represent the utilities in composite criteria, the use of fuzzy rules has been proposed [7]. Rules permit to model the interactions between the physical and chemical properties of the sewage sludge and the soil. Each rule premise represents a combination of values and the conclusion establishes the corresponding utility value (i.e. measuring the positive impact degree). In addition, this fuzzy approach permits to handle the uncertainty, naturally present in this kind of environmental problem.

In the initial stage, a group of environmental and toxicological experts identified which interactions between features are relevant for each composite criterion. Then, appropriate rules were defined by the experts with the help of knowledge engineers. For each composite criterion a hierarchical fuzzy expert system has been implemented. The construction process is the following one:

- 1. Define a fuzzy linguistic variable for each numerical feature that interacts with another one in some composite criterion.
- 2. Define a linguistic variable for giving utility values to the composite criteria. A variable with 11 fuzzy numbers (from 0 to 10) has been defined.
- 3. Design the rule blocks that are needed in each composite criterion and their interrelations.
- Define the set of rules for each combination of interacting features. The conclusions of the rules are fuzzy preference values from the domain defined in the previous step.
- 5. Link the rule blocks according to the structure defined at step 3.

An example of the structure of the fuzzy expert system corresponding to the composite criterion "Groundwater Vulnerability" is shown in Figure 4.

Step 4 is the more difficult and time-consuming one, because the domain experts must be careful in considering all the combinations of values of different soil and sludge properties and give the appropriate utility value for them. However, in step 3, where experts choose the subsets of variables that should be evaluated together, we have been able to identify small groups of variables interacting at the same time. This reduces the complexity of the rule definition and reduces the risk of introducing errors or contradictions in the rules, which is one of the main problems in rule-based systems.



Figure 4: Expert System for Groundwater Vulnerability.

Figure 5 shows an example of the rules that are included in the RB_DR_TT rule block (Figure 4), which evaluates the suitability of an alternative with respect to the sludge treatment type (TT) and the groundwater nitrification test (DR - DRASTIC). The conclusion of the rules is a fuzzy number. DoS stands for Degree of Support of the rule.

IF		THEN	
Sludge_TT	Soil_DR	DoS	U_DR_TT
Mechanical	low	1.00	_7_
Mechanical	medium_low	1.00	_5_
Mechanical	medium_high	1.00	_3_
Mechanical	high	1.00	_1_
Thermal	low	1.00	_9_
Thermal	medium_low	1.00	_7_
Thermal	medium_high	1.00	_5_
Thermal	high	1.00	_3_
Compost	low	1.00	_10_
Compost	medium_low	1.00	_9_
Compost	medium_high	1.00	_7_
Compost	high	1.00	_4_

Figure 5: Fuzzy rules considering the sludge treatment type (TT) with respect to the Soil nitrification (DR).

5 PREFERENCE AGGREGATION

Once the impact on a soil has been evaluated with respect to a particular sludge, the numerical utility evaluations obtained for each simple and composite criterion have to be aggregated to calculate the global preference score of this alternative.

Because the criteria have been organized in a hierarchical classification with very clear groups regarding to different aspects of the problem, it is needed to select an aggregation method that permits to take into account this classification of criteria. After considering different aggregation approaches (Torra and Narukawa, 2005), we propose to apply the LSP method (Dujmovic and Hagashima, 2006). LSP (Logical Scoring of Preferences)

uses generalized conjunction/disjunction operators for combining the values taking into consideration the different levels in the hierarchy of criteria and the user weights and constraints over those criteria.

LSP method consists in logically aggregating the values of small sets of attributes in a compositional way. Thus, the result of the aggregation at the lower level criteria is aggregated again, in the next higher level, using the same type of logical operators. Those aggregation levels are defined by the structure of the hierarchy of criteria. In addition, the LSP aggregation method also permits to give adjustable levels of relative importance to criteria.

This family of operators permits to model situations in which some subsets of criteria must be fulfilled simultaneously while other ones are optional (replaceable). For modelling simultaneity, conjunctive operators must be selected, because they are representing the andness concept, whereas, for replaceability (orness) some kind of disjunctive operator must be used.

In the problem of sludge disposal management, experts agreed in the need of distinguishing between conjunctive and disjunctive groups of criteria. This is the reason why it is convenient to make the evaluation using the LSP method.

Although the level of simultaneity/replaceability can be adjusted to any degree, we have simplified the scenario considering only two degrees of conjunction, two degrees of disjunction and the average operator (which compensates both). As explained in [2], the parametric Weighted Power Mean is the best function to implement this aggregation model (eq. 1). The parameter r permits to adjust the degree of andness/orness. In addition, different weights can be given to each input, subject to adding up to 1.

$$U(a) = \left(w_1(g_1(a))^r + w_2(g_2(a))^r + \dots + w_n(g_n(a))^r\right)^{\frac{1}{r}}$$
(1)

Table 1 has an example of the results with two input criteria g_1 and g_2 and the different operators (r values) considered in this work. The weights have been established in 0.5 for both. It can be seen that when r=1 the average between the two values (0.4 and 0.9) is obtained. The higher the value of r the more disjunctive is the operator, giving more importance to the fulfilment of at least one input. Whereas, if the smaller the r value, the more conjunctive is the operator, penalizing the low values in the inputs.

Table 1: Example of LSP aggregation

		D++	DA A		CA	C++	
$g_{l}(a)$	$g_2(a)$	<i>r</i> =20	<i>r</i> =4	<i>r</i> =1	<i>r</i> =-0.7	r=-9	
0.4	0.9	0.87	0.76	0.65	0.57	0.43	



Figure 6: Aggregation model.

Following the hierarchical structure of the family of criteria (Figure 2), the LSP method has been used to aggregate the values according to this structure. At each aggregation point the most suitable aggregation operator has been selected, according with the knowledge of the environmental experts in the project. Notice that both conjunctive and disjunctive operators have been chosen. Experts have also defined the weights of each input. The aggregation model is represented in Figure 6.

At the execution step, before applying the aggregation function (Eq. 1), all the partial utility values are put into the [0..1] interval.

6 TESTING AND ANALYSIS

No previous data sets exist for this problem and this has been an additional handicap for this study. The domain experts participating in this project have work hard to prepare a case study with real data. At the moment, 4 samples of different types of sludge coming from different Catalan WWTP have been collected. These plants receive waters coming from industrial and/or residential areas. In addition, we have 6 samples of different types of agricultural soils in Catalonia. The sludge and soil samples collected have been analyzed in different laboratories (toxicology, chemistry, etc.) in order to extract the values of the properties required. The soils sampled cover a wide range of situations, such as acid and alkaline soils, different textures and different levels of organic matter. Thus, the case study includes 24 alternatives (denoted as T#) that are used to study the performance of the decision support system developed.

Table 2 shows the position of each alternative in the partial rankings in each of the intermediate nodes of the model (see Figure 6: 1 is the best position, 24 the worst one). Each column corresponds to one node, being **'a'** the right most one (the global utility or suitability), and continuing from right to left and up to down. Although

there are changes in the positions depending on the node evaluated, few alternatives are at the best positions for all the partial aggregations (f.i. T5, T23), while others are always placed at the worst positions (f.i. T12, T16, T18).

Table 2 : Ranking position at each aggregation point

	а	b	С	d	е	f	g	h	i	j	k	I
T1	17	24	5	19	5	6	22	9	3	8	4	5
T2	7	24	2	11	1	2	18	21	1	20	2	3
Т3	12	13	3	18	4	5	23	17	1	16	2	3
Т4	10	13	11	9	9	10	17	17	7	16	8	9
Т5	9	13	1	17	2	3	21	5	2	4	3	4
Т6	18	24	12	21	10	11	24	25	7	24	8	9
T7	19	21	19	15	17	18	14	9	16	8	17	18
Т8	6	21	9	5	6	7	9	21	8	20	9	10
Т9	8	9	10	9	8	9	17	17	5	16	6	7
T10	20	9	22	16	21	22	7	17	21	16	22	23
T11	5	9	6	7	3	4	12	5	4	4	5	6
T12	21	21	21	20	20	21	20	25	21	24	22	23
T13	22	10	20	23	22	23	14	9	19	8	20	21
T14	11	21	15	6	14	15	9	21	14	20	15	16
T15	16	21	16	13	16	17	17	17	15	16	16	17
T16	23	21	23	22	23	24	7	17	23	16	24	25
T17	15	21	13	14	13	14	12	5	12	4	13	14
T18	24	21	24	24	24	25	20	25	23	24	24	25
T19	4	1	14	4	15	16	3	9	13	8	14	15
T20	1	3	7	1	11	12	4	21	9	20	10	11
T21	3	6	8	2	12	13	7	17	11	16	12	13
T22	13	6	18	10	19	20	1	17	18	16	19	20
T23	2	6	4	3	7	8	2	5	10	4	11	12
T24	14	3	17	12	18	19	10	25	18	24	19	20

Table 3 : Ranking of soils with respect to WWTP sludge

	Best soil	Next options in the ranking	Worst soil
WWTP1	L2 (0.606)	L5 (0.592) L4 (0.588)	L6 (0.514)
WWTP2	L5 (0.619)	L2 (0.609) L3 (0.604)	L6 (0.454)
WWTP3	L2 (0.578)	L5 (0.557) L3 (0.551)	L6 (0.418)
WWTP4	L2 (0.682)	L5 (0.680) L3 (0.672)	L6 (0.566)

Table 3 presents the global utility values and ranking obtained at the end of the process. For each WWTP the ranking and utility degree of the soils is presented. This information is very useful for the decision maker that has to manage the sewage sludge application on those soils.

Considering that a single soil must be assigned to unique sludge, a reasonable decision could be the next one:

• WWTP1 sludge is sent to L4, because it permits a degree of suitability of 0.588, only slightly inferior to the best possibility for this sludge.

- WWTP2 sludge is sent to L5, because it is the best option, with a utility value of 0.619.
- WWTP3 sludge is sent to L2, because this is the best option for this sludge, reaching a value of 0.578,
- WWTP4 sludge is sent to L3, because this is the sludge that produces better evaluations with all the soils, and the three best options have all very good ratings. This option is evaluated with 0.672.

2.1. SENSITIVITY ANALYSIS ON THE WEIGHTS

The sensitivity analysis performed studies the effect of the parameters of the LSP method in the results, which are the weights w_i and the degree of andness/orness, r. Since the determination of weights has been quite difficult for the experts, we have concentrated on this parameter.

The sensitivity analysis has been performed converting the static weights, w, into a normal probability distribution, W, with a deviation of 10%, in the form W=N(w,0.1w).

 Table. 4: Number of different positions

	а	b	С	d	е	f	g	h	i	j	k	I
T 2 3	2	1	2	1	4	1	2	1	1	1	1	1
Τ8	3	1	2	2	1	4	1	2	2	1	1	1
T13	1	1	1	1	1	1	1	4	2	1	1	1
Αv	2.1	1	1.2	1.7	1.4	1.7	1.3	3	1.5	1	1	1
MAx	5	1	2	4	4	4	3	6	3	1	1	1

The 3 first rows in Table 4 show an example of the sensitivity of 3 alternatives with respect to the weights. The forth row indicates the average in the number of different positions for each node, considering the 24 alternatives. Notice that last aggregation node **'a'** is the most sensitive to the weights. In general, they are quite robust, with an average difference below 2 positions. Last row shows the maximum number of different positions that an alternative has suffered due to the weights change.

7 CONCLUSIONS AND FUTURE WORK

We have presented a decision support system for assisting the managers of biosolids produced at WWTP in finding the best distribution into agricultural soils.

The tool designed and developed follows the traditional MAUT approach, where two stages are considered: rating and ranking. The rating of the alternatives is achieved by means of the aggregation of partial utility values. In this case, we propose the use of a parametric operator that permits to model simultaneity and replaceability. In addition, fuzzy rules have been used to build a model for the utility evaluation in composite criteria. This is a novel approach to utility representation. From our experience,

fuzzy rules are suitable for implementing utility functions in composite criteria, because they are able to represent the expert knowledge about the behaviour of combinations of different variables in a particular domain that could not be modelled otherwise.

It is also worth to note that the results obtained by the system have been satisfactory. After an initial evaluation of these results, the experts affirm that the expected results were correlated to the results obtained. More tests with new samples of real data is going to be done. With more data, it will be possible to make a tuning of the parameters with machine learning techniques.

Now this model will be extended to the consideration of other destinations for biosolids, such as incineration in cement plants or disposal at landfill. Another future line consists in representing the data in geo-referenced maps.

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