CAHIER DU LAMSADE

Laboratoire d'Analyse et Modélisation de Systèmes pour l'Aide à la Décision
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SORTING CROPPING SYSTEMS ON THE BASIS OF THEIR IMPACT ON GROUNDWATER QUALITY

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Résumé

Ce cahier présente la mise en œuvre d'une analyse multicritère en réponse à un problème posé par des chercheurs de l'INRA (Institut National de la Recherche Agronomique). Ces agronomes ont pour thématique générale de recherche l'évaluation environnementale des pratiques agricoles. Dans ce cadre, ils souhaitent disposer d'une méthode permettant de différencier des systèmes de culture en fonction de leur impact sur la qualité de l'eau. Pour mener à bien cette différenciation, des membres du LAMSADE (Laboratoire d'Analyse et Modélisation de Systèmes pour l'Aide à la Décision) proposent un tri des systèmes de culture à l'aide de la méthode ELECTRE TRI. Quatre catégories d'impact sont définies et trois familles de critères sont construites. La nature des critères constitue le débat central de l'étude : si des données de base sont utilisées, le nombre des critères est élevé ; si des données agrégées sont utilisées, les échanges d'information sont délicats. En dépit de ces difficultés, l'étude revêt un intérêt certain pour les chercheurs agronomes. Premièrement, en contribuant à donner aux agriculteurs des exemples concrets de systèmes de culture respectueux de la ressource en eau, elle permet aux chercheurs de coopérer avec des décideurs tels que l'Agence de l'Eau. Deuxièmement, la méthodologie multicritère semble être appropriée aux recherches de l'INRA. En effet, deux analyses similaires sont envisagées : l'une pour différencier des systèmes de culture en fonction de leur impact sur la faune sauvage et l'autre pour différencier des systèmes de culture en fonction de leur impact sur la qualité du paysage.

Mots clés

Agriculture ; Système de culture ; Impact environnemental ; Qualité de l'eau de profondeur ; Pesticides ; Azote ; Irrigation ; Méthodologie Multicritère d'Aide à la Décision

Sorting cropping systems
on the basis of their impact on groundwater quality

Abstract

In this paper the implementation of a multi-criteria analysis is described in order to answer a question of INRA (*'Institut National de la Recherche Agronomique', France*) researchers who assess the impact of agricultural practices on the environmental components. They were particularly interested in differentiating cropping systems as a function of their impact on groundwater quality. In order to give effect to this differentiation, LAMSADE (*'Laboratoire d'Analyse et Modélisation de Systèmes pour l'Aide à la Décision', France*) members proposed a way of sorting cropping systems using the ELECTRE TRI method. Four categories of impact were defined and three families of criteria were built up. The main debate was about the nature of criteria: if basic data are used, the number of the criteria is high; if aggregated data are used, exchanges of information are tedious. Despite these difficulties, the study has been of important value for the agronomic researchers. Firstly, it helps them to work with decision-makers, such as the Water Agency: it allows farmers to be given concrete examples of cropping systems which preserve groundwater quality. Secondly, the multi-criteria methodology used seems to fit their research: they are indeed now using the same approach to differentiate cropping systems on the basis of their impact on wild fauna or landscape quality.

Keywords

Agriculture; Cropping system; Environmental impact; Groundwater quality; Pesticides; Nitrogen; Irrigation; Multi-criteria methodology for decision aiding

1 Introduction

This paper deals with agriculture and its impact on the environment. For fifty years in western countries land has been exclusively considered as a generator of produce and has been cultivated in order to guarantee food security. There has been a great pressure on farmers to increase agricultural productivity. They succeeded in so doing thanks to progress in mechanization and to chemical treatments (fertilisers and pesticides). As a consequence we have seen increasing pollution of natural sites and impoverishment of biodiversity. To give just one example, the excess of nitrogen spread on arable lands is found almost everywhere in the drinking water supply.

In 1987 the Sustainable Development concept was defined by members of the United Nations Organisation. This concept aims at harmonizing economic development with respect to the environment. All economic areas are covered by this concept. Among them is agriculture. Nowadays farmers have to follow three different objectives at the same time: profitability (the 'oldest' one), quality and ecology. There is also now a new great pressure on them to respect the environment. They have to implement new cropping systems which are both productive and harmless to the environmental components.

European and national agricultural or environmental organisations are all working on the implementation of the concept of Sustainable Development. In France the National Institute of Agronomic Research (INRA) develops integrated arable cropping systems[1]; agencies, such as the Water Agency (*'Agence de l'Eau'*), give to farmers financial subsidies or other incentives so as to modify their agricultural practices towards environmentally and economically viable alternative agricultural systems.

In this new agricultural context this paper presents a case study. The second section, 'the client's problem', explains the research field of INRA, the problem which the agronomic researchers met and why they called on LAMSADE to help them to solve it. The third section is devoted to the choice of the data: which agricultural techniques should be taken into account to describe a cropping system? Which variables describing the agricultural techniques should be used? The fourth section presents the solution proposed by LAMSADE members to answer

[1] A cropping system is defined as a sequence, on a given plot of land, of crops and the associated agricultural practices.

INRA's problem. It gives arguments about the choice of the multi-criteria methodology and the ELECTRE TRI method; the implementation of the analysis and notably the construction of three families of criteria are described; finally, the analysis is discussed from a methodological point of view. The fifth section sets out the client's comments: the suitability of the resolution of the problem and further applications. Concluding remarks follow this last section.

2 The client's problem

The research field of the INRA agronomic laboratory is related to sustainable agriculture and specifically to the assessment of the environmental impact of arable cropping systems. This laboratory connects the agricultural techniques involved in a cropping system with the agro-system and its environment. The relations 'agricultural techniques - environment' are presented in table 1.

Table 1
Relations 'agricultural techniques - environment'

	Agricultural techniques									
Environmental targets	Nitrogen management	Phosphorus management	Pesticide management	Irrigation	Organic matter	Energy	Crop diversity	Mechanical operations	Soil cover	Ecological structures
Protection of:										
Groundwater quality	X		X	X						
Surface water quality		X	X							X
Air quality	X		X							
Soil quality		X	X		X			X	X	
Wild fauna			X	X			X	X	X	X
Landscape quality							X		X	X

Derived from BOCKSTALLER *et al.* (1997)

A mathematical relationship (marked X in table 1) is developed whenever a technical decision of the farmer has an influence on an environmental target. It is based on the available scientific knowledge and / or expert judgements [BOCKSTALLER *et al.* (1997)] and constitutes an 'evaluation module'. Each evaluation module [agricultural technique x * environmental target y] summarizes the impact of x on y and is established from basic information recorded by the farmer (example: quantity of fertiliser spread) and from stable characteristics (example: human toxicity of a product).

For example, the evaluation module [*irrigation* * *groundwater quality*], M_{igw}, is calculated as follows:

$M_{igw} = 7 + \Sigma\, bi / 20 + \Sigma\, ki$ $\qquad\qquad$ $0 < M_{igw} < 10$

$\Sigma\, bi$: sum of the positive *bi* for all irrigations;

$\Sigma\, ki$: sum of bonus

The calculation of *bi* is based on a simplified water balance at the field level for each irrigation:

bi = State of soil water capacity + Precipitations + Irrigations + Evapotranspiration

One point of the evaluation module corresponds to 20 mm of water.

The bonus can be taken into account only if there is no leaching more than 10 mm. A bonus can be obtained if the first water supply is less than 20 mm (bonus = 0,5), or if the soil water capacity is not fully filled after the water supply (i.e., bonus = 1,5 if the soil water reserve is filled less than 15 mm of the maximum soil water capacity).

The value of the evaluation module M_{igw} is 7 when the risks of leaching are low (the soil water reserve is exactly or not totally filled).

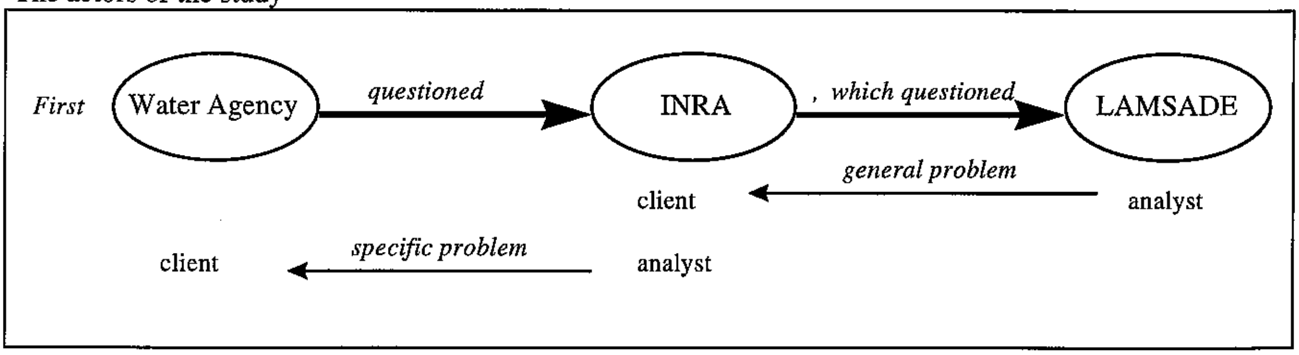
Table 1 can be interpreted either down the columns or across the rows. The interpretation down the columns was already done by INRA researchers [BOCKSTALLER *et al.* (1997), GIRARDIN *et al.* (1998)] to help the farmer to assess the impact of each of his cultivation practices on the agrosystem and its environment (i. e., all the environmental targets). In this way, he can evaluate the weak points of his farm management, and, year after year, the evolution of his practices.

INRA was motivated by interpreting the table across the rows. Indeed, this second kind of interpretation gives the impact of all agricultural practices on one environmental target. It would be of special interest to organisations, institutions, agencies or associations whose main activity is the protection of a specific environmental component (water quality, soil conservation, biodiversity, landscape preservation, etc.). The Water Agency which focuses on the component 'water' is one such organisation. It aims to guarantee the quality of aquatic areas and drinking water supplies.

According to table 1 (first row) and as explained in section 3, three agricultural techniques among those involved in a cropping system have an impact on groundwater quality: the application of nitrogen and the application of pesticides and irrigation. INRA researchers and Water Agency experts agreed on how to differentiate cropping systems, through these three techniques, as a function of their groundwater quality impact. Indeed, this differentiation would help Water Agency technicians to make more easily recommendations to farmers. The agronomic laboratory had all the relevant data to give effect to this study, but it did not have the methodology to handle this information. Considering the multiple attributes that had to be analysed simultaneously (many agricultural techniques), INRA thought that multi-criteria methodology for decision aiding could provide a feasible set of tools and asked LAMSADE to work with them.

As shown in figure 1, there were also two problems, two kinds of clients and two kinds of analysts:

Figure 1
The actors of the study



- A specific problem was that of the Water Agency. This agency aims to provide accurate advice to farmers. In order to do this, it needed the help of INRA to differentiate cropping systems as a function of their impact on groundwater quality. For this problem, the client was the Water Agency and the analyst was INRA.

- The second was a general problem, that of INRA. In order to answer the specific problem of the Water Agency, INRA needed an appropriate methodology to analyse multiple and various data. LAMSADE members could help it to find this methodology. For this second problem, the client was INRA and the analyst was LAMSADE. Let us note that LAMSADE experts had direct relations with Water Agency members, as these members represented the final client.

The study took place from February to September 1996.

3 The data

3. 1 The cropping systems in the study

The data relative to cropping systems came from the farm network of INRA. This network included seventeen commercial arable farms of the Rhine plain in France and Germany and was created in 1993. All the farmers are involved in the network on a voluntary basis. At the farm level there are several possible ways of cultivating maize (so called 'cropping systems'). INRA's technicians meet farmers yearly and collect all the data on the maize cropping systems in each farm from the farmer's 'log book', without resorting to field measurements. Among all the cropping systems used in the network, thirty-three were selected for the study because of their diversity rather than of their representativeness.

3. 2 The agricultural techniques

Table 1 shows that groundwater quality is highly influenced by three agricultural techniques: nitrogen management, pesticide management and water management (irrigation).

Nitrogen management takes into account the nitrogen supplied by fertilisers (amount, date and number of applications), the ploughing in of straw, the introduction of catch crops during winter time (or other improving techniques). Nitrate leaching is mainly due to an inappropriate balance between nitrate availability and the amount of nitrate required by the crops. Nitrate pollution is related to leaching, and it can be avoided by a well-adapted nitrogen fertiliser supply and by good management of cover crops during the winter which catch the nitrate still available in the soil.

Pesticide management is described in terms of the amount applied, the chemical and physical characteristics of the active ingredient (field half-life, mobility, human toxicity), the location of application (in the soil, on bare soil or on the crop) and the date of application (season). In order to reduce pesticide pollution of groundwater, it is important that the farmer uses active ingredients which are as less soluble and as little toxic to humans as possible.

Irrigation management consists of determining the hydric balance and the amount of water applied. Irrigation interferes with nitrogen and pesticide leaching. Inadequate management of irrigation often produces an excess of water which will induce an almost direct leaching.

The other agricultural practices (phosphorus or potassium management, crop diversity, soil management, etc.) are considered as techniques which have not any significant direct or indirect effects on groundwater quality.

4 The solution proposed

4. 1 Choice of the multi-criteria method

Cropping systems can be harmful to groundwater quality through three agricultural practices. From the multi-criteria methodology point of view [ROY and BOUYSSOU (1993b)], the *action* (or *alternative*) 'cropping system' (CS) is characterized by three dimensions (nitrogen, pesticides and water management). These three dimensions are not compensatory: a water source, no matter how low the nitrate concentration, is not potable if its pesticides content is high. This consideration led us to synthesize the three dimensions by outranking in a partial order (or *outranking with incomparabilities* [ROY (1996)]).

The sorting (the assignment to some predefined categories) of CS provides a good display of the results for developing recommendations. Indeed, INRA aims at differentiating cropping systems by grouping, for example, into a first category those that are helpful to groundwater quality and into a second category those that are harmful to it, ... Let us note that INRA and the Water Agency are able to define *a priori* some categories (categories will be *predefined*). The problem formulation chosen is of β type [ROY and BOUYSSOU (1993b), ROY (1996)]. Sorting is preferred to selecting (problem formulation α [ROY and BOUYSSOU (1993b)]) or ranking (problem formulation γ [ROY and BOUYSSOU (1993b)]) because:

- The notion of category is close to the notion of norm (a common expression of quality). Sorting avoids a comparison of the CS: each CS is judged by itself, independently of the others; it is only compared to the reference CS, real or fictitious, for example a legal norm. The number of CS may be extremely high; moreover a CS already sorted can be deleted from its category and new ones can be added to the sorting process without re-considering all the CS already analysed.

- Choosing (selecting a certain number of CS) does not allow an exhaustive analysis of CS: some CS are not taken into account although they may be interesting. For example, the selection of those CS which are less harmful to groundwater is interesting but unfortunately this is insufficient: the selection of the most dangerous CS may also be worthwhile.

- Ranking (ordering the CS as a function of their increasing or decreasing intensity of harmfulness) would be interesting but its use would be subjective: at which rank does a CS become damaging for groundwater?

All these considerations justified the choice of the ELECTRE TRI method [ROY (1996), ROY and BOUYSSOU (1993a)]. Appendix 1 gives a short presentation of this multi-criteria assignment method.

4. 2 Definition of categories

CS categories were determined by experts of the Water Agency. They defined four categories as shown in table 2. The number of categories was a compromise between accuracy (two categories would have given little information) and ease of management (five categories would have been too detailed).

Table 2
The four categories of cropping systems used in maize production

Category	C_1	C_2	C_3	C_4
Definition	*CS with a very high environmental risk level*	*CS resulting in environmental problems*	*CS aimed at preserving the environment*	*CS respecting the environment*
Comments	Risks caused by an error of practice	Conventional CS, common agricultural practices	Reference methods, use of improved methods	Important involvement of the farmer for protecting the environment
Which recommendations for farmers ?	CS that must be rejected	CS that have to be improved	CS that should be implemented	Ideal CS

Category C_3 corresponds to a recommended cropping system which could still be improved. In this cropping system nitrate, pesticides and water management are well balanced. As an example, a cropping system is put in category C_3 if the first nitrogen application is less than 50 kgN ha^{-1}, if nitrogen supply is split into three applications, if the calculation of the total nitrogen quantity follows the recommended local rules, and if the second and third applications of nitrogen are localised along the maize rows. A CS is included in category C_4 if the farmer uses innovative and improved techniques such as the use of a cover crop to catch the residual soil nitrogen, the measurement of the mineral residue of nitrogen before sowing, etc.

With regard to pesticide management, the cropping system could be placed in category C_3 if the farmer uses specific active ingredients. For example, for weeding he must apply 'sulfonylurea' instead of 'alachlore' and 'atrazin', and systematically substitute a mechanical treatment for a chemical one. For irrigation management, if the quantity of the water applied does not exceed the soil water reserve, the cropping system will fall into category C_3. A soil water reserve filled to only 90% will correspond to category C_4. Category C_1 includes cropping systems which have been managed with significant agronomical mistakes (a high excess of nitrogen or water, a too high dose of pesticides which have a high toxicity to human beings, etc.). The cropping systems of category C_2 are managed without agronomical and / or environmental considerations: the only one objective of the technical decisions is in general the highest yield.

4. 3 Assigning actions to categories

For nitrogen, water and pesticides management, the available information could be either the basic data obtained directly from the farmer (see section 3) or the evaluation modules built by INRA researchers [GIRARDIN *et al.* (1998)] (the 'X' in table 1, see section 2). According to this type of information, three families of criteria were constructed.

4. 3. 1 The first criterion family: three 'criteria - evaluation modules'

This first criterion family uses most intensively the research results of INRA. The agronomic laboratory is used to synthesize all the basic data for one given agricultural practice in an evaluation module. This module is based on agronomic knowledge [ARONDEL and

GIRARDIN (1997), BOCKSTALLER *et al.* (1997)]. Each criterion from this first family is also built from an evaluation module: the criterion 'nitrogen' g_N is derived from the evaluation module [nitrogen * groundwater], the criterion 'pesticides' g_{pest} from the evaluation module [pesticides * groundwater] and the criterion 'irrigation' g_{irri} from the evaluation module [irrigation * groundwater].

Because of the inaccuracy and the vagueness of the data, the reasoning on each criterion takes place on interval orders. The discrimination power of each criterion is reduced; therefore a strict preference threshold '*p*' [ROY (1996)] was defined for each of them. For example the inaccuracy of 'nitrogen' information is due to the extent of control of mechanical spreading (speed of the tractor, etc.). As a consequence, the amount of nitrogen actually spread can differ from the required amount. This and the other two thresholds were established with the help of agronomic researchers, who had developed the evaluation modules.

The help of the experts of Water Agency (*Agence de l'Eau Rhin - Meuse*) was necessary to weight the criteria. They could indeed better appreciate the relative impact on groundwater quality of each agricultural practice. Moreover, two members of the 'Haut-Rhin' General Council (*Conseil Général du Haut-Rhin*) took part in the definition of the weights. This organisation also gives financial support for initiatives of groundwater protection in the French part of the Rhine plain. The revised 'weighting with cards' method, initially proposed by SIMOS [SCHÄRLIG (1996), SIMOS (1990)] was used. Six experts were questioned; their answers gave five different weight sets (two experts gave exactly the same answers). The five weight sets (let us note 'k_i' the weight of the criterion 'i', see table 3) underline the major role of pesticide management ($k_{pest} \geq 0.5$), the minor importance of irrigation ($k_{irri} \leq 0.13$) and the importance of nitrogen management ($k_N \geq 0.35$, except for the fifth set). The order of importance of the criteria was kept in the different weight sets.

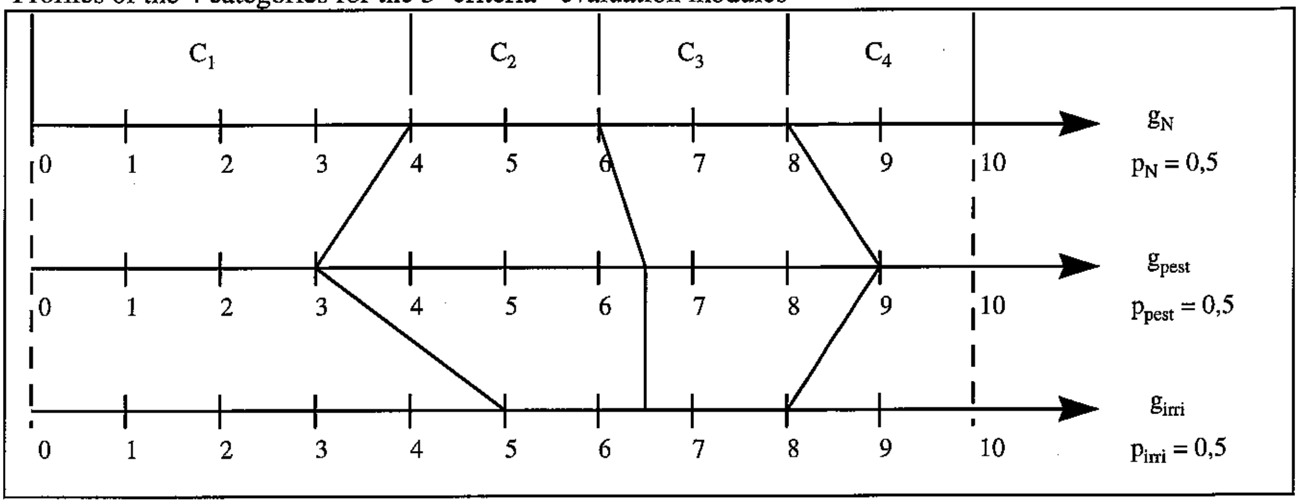
The evaluation (or *performances*) of the thirty-three CS on the three criteria are presented in table 3.

Table 3
Performance table of 33 cropping systems (CS) on 3 criteria

Criteria → **CS ↓**	g_N	g_{pest}	g_{irri}
1	6.47	6.33	5.46
2	5.5	4.55	5.46
3	1.92	4.55	5.46
4	6	4.55	5.46
5	4.46	5.26	5.8
6	6.48	5.26	4.75
7	6	7.19	5.46
8	4.43	0.88	5.38
9	5.78	0.88	5.38
10	5.92	2.90	5.23
11	4.03	2.14	5.13
12	6.53	2.14	3.69
13	4.67	6.87	10
14	4.37	2.92	10
15	5.32	6.87	10
16	5.65	3.87	7.58
17	4.93	6.07	7
18	5.86	6.07	10
19	5.45	5.18	6
20	3.64	3.49	10
21	3.53	2.11	10
22	4.53	4.51	10
23	5.25	2.05	10
24	4.87	4.59	10
25	3.77	7.16	10
26	3.5	9.35	10
27	5.17	7.45	7.37
28	6.22	7.45	7
29	6.27	8.64	7.55
30	6.07	6.96	10
31	5.9	8.65	10
32	7.07	8.65	10
33	6.43	6.95	10
Thresholds	*0.5*	*0.25*	*0.25*
	k_N	k_{pest}	k_{irri}
Weight set 1	0.4	0.5	0.1
Weight set 2	0.35	0.52	0.13
Weight set 3	0.38	0.5	0.12
Weight set 4	0.38	0.52	0.1
Weight set 5	0.19	0.7	0.11

The 'boundaries' of the four categories were determined by agronomic researchers through the category profiles [ROY (1996), YU (1992)]. The performances of the profiles were defined from the evaluation modules. Figure 2 presents the 'boundaries' of the four categories on the three 'criteria - evaluation modules'.

Figure 2
Profiles of the 4 categories for the 3 'criteria - evaluation modules'



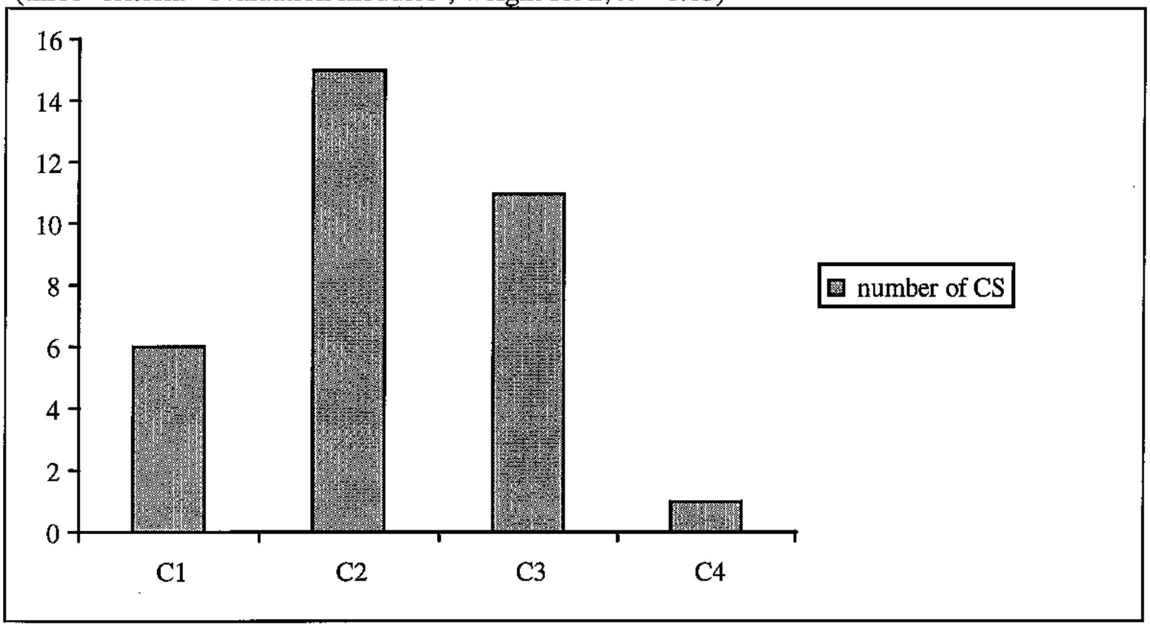
The ELECTRE TRI method (see appendix 1) was applied using the software ELECTRE TRI [YU (1992)] (a new implementation is now available, see [MOUSSEAU *et al.* (1998)]). This software uses two sorting processes: an optimistic one (disjunctive logic: the best ranked criterion determines the assignment) and a pessimistic one (conjunctive logic: the worst ranked criterion determines the assignment). In this case, as usual in the field of quality, the process is rather conjunctive. Therefore, only pessimistic sorting processes were used. The strictness of the assignment procedure can be adjusted by the parameter λ (see appendix 1): three λ values were used: 0.65, 0.75 and 0.85.

No fixed value of λ was used and this was deliberate. This choice was linked with the sense in which the study was carried out. The aim was neither not to rediscover 'elements known from other sources', nor to confirm results obtained by other scientific procedures. The reasoning was also 'voluntarist'. By talking about the problem formulation P.β [ROY and BOÜYSSOU (1993b)], the significance of the λ parameter was explained to the actors. From this point of view, no λ value was better than another: the point was only to know with which severity level the CS should be sorted. This is why the display of results had to present carefully the 'stable' and 'unstable' CS across the different λ values and the different weight sets, keeping in mind that, for one λ value and for one weight set, all the CS are put into one category or into another.

As a result of this approach, the CS are allocated to the three first categories: six (from the total number of thirty-three) are assigned to C_1 (18%), eleven to C_2 (33%), seven to C_3

(21%), and nine are considered unstable (28%). In view of the definition of the C_4 category, it is not surprising to observe no 'stable' CS in this category. Except for one CS (CS 26) which is sometimes assigned to C_1 and sometimes to C_4, the 'unstable' CS (with respect to the weight sets and λ values) move between two (or three) neighbouring categories. Figure 3 gives an assignment example, for one weight set (weight set 2) and one λ value ($\lambda = 0.65$).

Figure 3
Sorting of the 33 CS into the 4 categories
(three 'criteria - evaluation modules'; weight set 2; $\lambda = 0.65$)



This first criterion family allows INRA's problem to be answered. However, this approach has an important disadvantage: the construction (based on the computational procedure) of the evaluation modules is not transparent to those unfamiliar with INRA research. This lack of a clear understanding of the meaning of the evaluation modules adversely affected communication between the different members involved and made information exchanges very tense.

4. 3. 2 The second criterion family: the thirteen 'criteria - basic data'

The aim of this second approach was to improve the discussion with the actors by using criteria which were easy for everybody to understand. With the help of INRA researchers, thirteen new criteria, called 'criteria - basic data', were constructed from the data explaining each of the three agricultural techniques (see section 3.). In this approach, nitrogen management is described by five criteria: criterion 'amount' g_{Na}, 'balance of nitrogen' g_{bal}, 'date of application'

g_{Nda}, 'splitting up' g_{split}, 'improving techniques' g_{tech}. Pesticide management is described by six criteria: 'amount' g_{Pa}, 'half-life of active ingredient' g_{hl}, 'mobility' g_m, 'toxicity' g_{tox}, 'location of application' g_{loc}, 'date of application' g_{Pda}. Irrigation management is described by two criteria: 'hydric balance' g_{hb}, 'amount of first apply' g_{Ia} (see table 4, appendix 2).

For the determination of the weights (SIMOS' method), only three experts were questioned. The pesticide data have the largest weights, irrigation has always a very small relative importance (see table 4).

The set of pesticide data (amount, half-life, solubility, toxicity, location and date of application) corresponds to applications of active ingredients. In the studied CS sample, the number of applications per CS varies from two to six. In this second approach, it was necessary to combine, by CS, the data from the different applications. The sum or the mean of amounts, half-life, etc. has no agronomic significance. As a pessimistic or conjunctive process was adopted for the study, the performance chosen for the CS for each of these criteria was the least adequate for each of the applications. Thus, the highest value of the amount, of the half-life, of the mobility, the lowest value of the toxicity, of the location (referring to coding) and of the date (referring to coding) were chosen. Let us note that there was no methodological problem at this level in the first approach because the evaluation module already combined the applications by a set of fuzzy decision rules [BOCKSTALLER *et al.* (1997)]. The expert system allows the giving of a global value for each pesticide application.

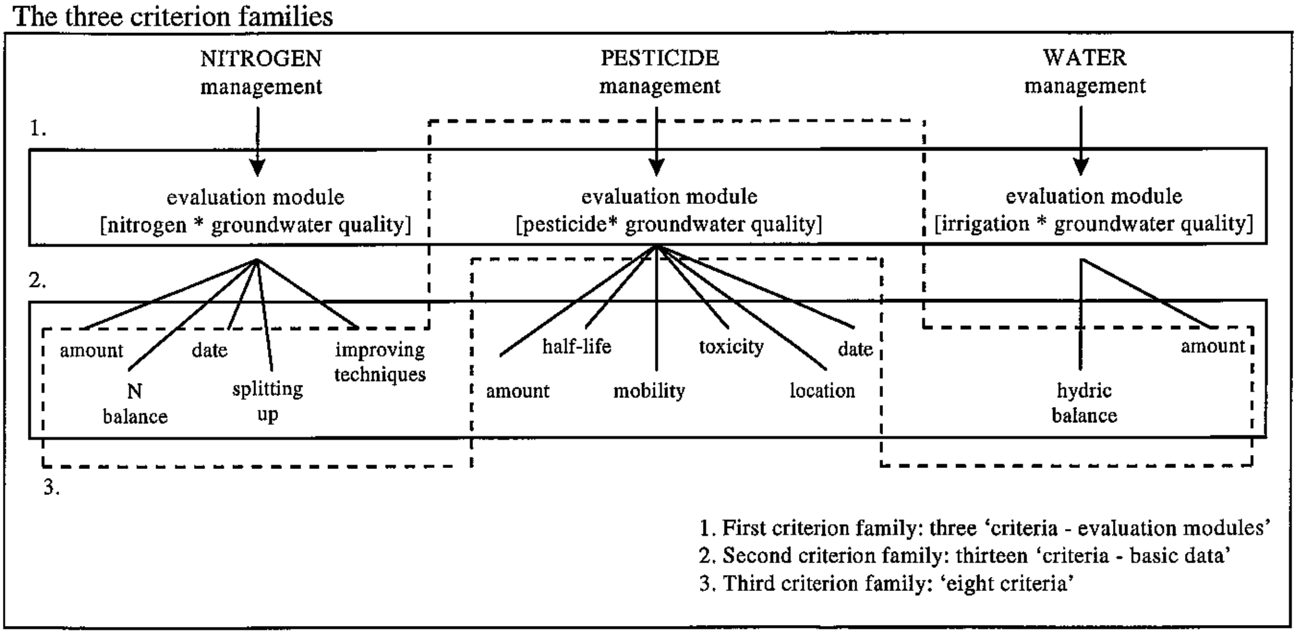
The categories were delimited with INRA researchers by determining the profiles. As a result, the distribution of the CS is 'narrow' (only between C_1 and C_2). Only one third of the CS is stable across the three weight sets and the three λ values, five in C_1 and six in C_2. All the others are unstable between C_1 and C_2.

This CS distribution is disappointing: it does not allow INRA's question to be answered. The two highest categories are useless, although they were defined by the Water Agency experts. The assignments seem strict compared to the first approach. This can be explained by the bad or extremely bad performances of the thirty-three CS on the six pesticide criteria. As the global weight of these six criteria is nearly 60%, it is not surprising to find all the stable CS in the lowest categories. The way performances have been selected (the worst value of the amount, half-life, etc.) is a too drastic decision. Another way was investigated: after discussion with a Water Agency expert, it appeared that 'half-life' was the most important pesticide characteristic from his point of view. The data of the active ingredients which had the highest half-life value were selected. In this case, only one application per CS was taken into account. Even so, the results were also disappointing (all the CS assigned to C_1 and C_2 categories). To solve this difficulty was time consuming. Therefore, it was decided to proceed with the study by using a part of the aggregation proposed by the INRA researchers.

4. 3. 3 The third criterion family: the 'eight criteria'

This last approach accepts the aggregation of pesticide data in a 'criterion - evaluation module' (as done in the first approach) and uses the primary data of nitrogen information and irrigation information (as done in the second approach) (figure 4).

Figure 4
The three criterion families



From a methodological point of view, this third criterion family is questionable: all the criteria do not have the same hierarchical nature (see figure 4). Nevertheless it was constructed in an 'explicative' way. It provides indeed an opportunity to compare the two sorting processes of the first and the third approaches. In both these cases, the best weighted criterion is the same (g_{pest}) and the lower weighted criteria are different: in one case two evaluation modules (g_N and g_{irri}), in the other case the basic data (g_{Na}, g_{bal}, g_{Nda}, g_{split}, g_{tech}, and g_{hb}, g_{Ia}). This comparison was valuable and interesting to the client (INRA researchers). This last approach was performed exclusively by INRA and LAMSADE members, because the required data were all deducible from the data of the two first approaches (see table 5, appendix 3).

The thresholds of the eight criteria are the same as the thresholds defined during the first two approaches. The weights were established from those of the thirteen 'criteria - basic data' (with $k_{pest} = k_{Pa} + k_{hl} + k_m + k_{tox} + k_{loc} + k_{Pda}$). The categories were delimited from the previous approaches.

Then, the assignment is 'wide' from C_1 to C_3, and even C_4. The results are very close to those obtained in the first approach. The best weighted criterion g_{pest} used in the two approaches largely explains these similarities. The two sorting processes assign some CS differently. This difference results from the performances of these CS on the seven 'criteria - basic data', corresponding to nitrogen and irrigation management. In that way, it is possible to compare the two evaluation modules [nitrogen * groundwater] and [irrigation * groundwater] used in the first approach, with the basic data from which they are derived used in the third approach. For agronomic researchers, this result validates, to a certain extend, the method of aggregation they use to elaborate these two evaluation modules.

This approach is 'artificial' because of the hybrid aspect of its criteria. However, it was implemented only in order to compare it with the first approach. The comparison of the different assignments between the first and the third approaches is valid only if the weight sets were the same. This is why the first approach was again adopted with three new weight sets:

$$k_N = k_{Na} + k_{bal} + k_{Nda} + k_{split} + k_{tech}$$

$$k_{irri} = k_{hb} + k_{Ia}$$

and $k_{pest} = k_{pest}$ of the third approach.

The results are the same as in the first approach with the initial weight sets.

4. 3. 4 Comments about the implementation of the multi-criteria methodology for decision aiding

The first and the second approaches underline the fact that criteria are more than tools across which the different actions are evaluated. They are the basis of the actors' communication between each other. The eventual difficulties in understanding them were observed at each analysis step. On this point, the first approach is questionable, since the three 'criteria - evaluation modules' were not easily readable by people who are not aware of the INRA method. The Water Agency and General Council experts confirmed the choice of the agricultural practices which are 'dangerous' for groundwater quality, but at each actors' meeting, it was necessary to spend time for explaining the content of the criteria.

The delimitation of the categories emphasized the 'weak points' of the three 'criteria - evaluation modules'. The elaboration of profiles was impossible with the Water Agency experts, because they expressed the data as direct units (essentially in concentrations) instead of indices, which are pure indirect data, and it was very difficult (especially with the criterion g_{pest}) for the INRA researchers. However, in the second approach, the profiles were developed quickly and easily referring to data from existing literature (mobility, half-life, toxicity, etc.). In this approach, the profiles could be developed by anybody who has some knowledge in this topic.

The revised method of 'weighting with cards' was effective. The actors who, at first, were surprised by the direct involvement of each of them, agreed on the method both because of its simplicity and because it made use of their own opinions. The subsidiary question ('which is the balance of importance between the first and the last cards'?) seemed to them unnecessary because they assimilate this balance to the number of cards separating the extreme cards [SCHÄRLIG (1996)]. Some experts simply counted the cards, others timidly suggested a value for this balance.

It is interesting to compare the weighting given by the same three actors (the three General Council members) to both the three 'criteria - evaluation modules' and the thirteen 'criteria - basic data'. Except in one case, the sum of the weights of the split criteria was not equal to the weight of the corresponding aggregated criterion (see tables 3 and 4). In contrast to the usually observed behaviour [EISENFUHR *et al.* (1988)], no participant weighted systematically the set of split criteria more than the aggregated criterion. Let us note that the criteria of irrigation management show again the subsidiary importance of this agricultural practice for the interviewed actors.

The difficulty encountered in the second approach (about 'pesticide management' information) is a real problem. This is particularly unfortunate, because this information is dominant: it represents at least 50% of the total weight of the information describing the three given agricultural practices. For the six 'pesticide' criteria (g_{Pa}, g_{hl}, g_m, g_{tox}, g_{loc} and g_{Pda}), the available information refers to an application of an active ingredient, although for the other seven criteria it refers to a CS (that is to say, a set of several pesticides). How can we convert the 'pesticide management' information? How can we aggregate it at the 'CS' level with respect to the different active ingredient applications? More generally, how can we decide the performances of an action on *n* criteria, when only the performances of its components (*sub-actions*) are known? The aggregated criterion (evaluation module) gives a real advantage compared to the basic data: it allows us to take into account several treatments (applications of active ingredients). This important question should be also central in a study where *actions* (or *alternatives*) should not be the CS anymore but all the CS of a farm (maize, sugar beet, wheat, etc.) which constitute what is called a 'Farming System' by researchers in agronomy. In this case, in order to obtain global indicators (at the farm level), INRA researchers calculated the weighted sum of the specific indicators as a function of the CS areas.

5 The client's comments

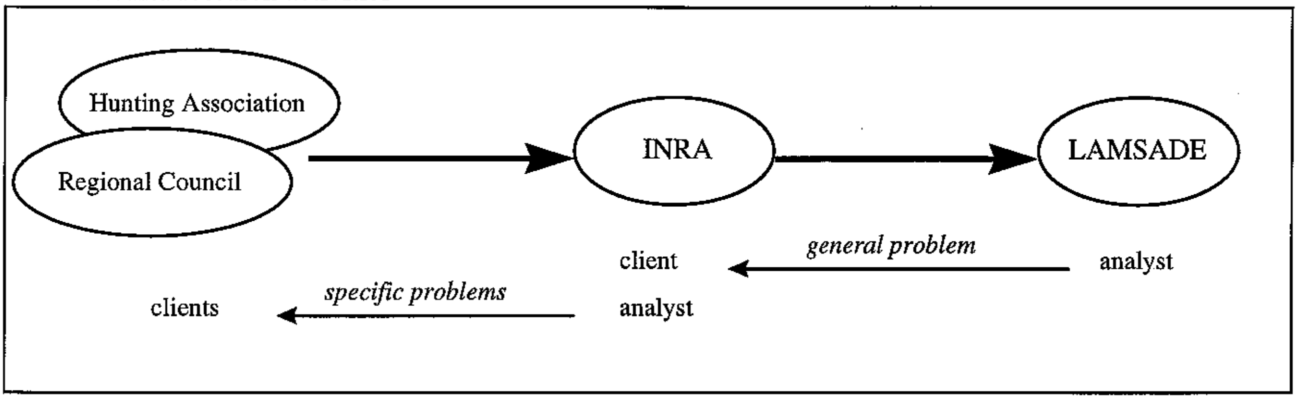
As far as the INRA researchers were concerned, the multiple criteria method implemented has made it possible: a) to make the best possible use of the aggregation of the basic information into a more synthetic form - the evaluation modules, b) to demonstrate that it is easy for researchers in agronomy to take over such a method, c) to demonstrate that it is feasible for the ELECTRE TRI sorting method to answer the questions of the end users; but it is also possible to point out some difficulties: a) the presentation of the multi-criteria approach to the 'clients' needs time to be taken so as to be sure they will be able to give an accurate value to the weighting factors, b) the degree of aggregation of the basic information is difficult to choose.

The methodology presented in this study is relevant for organisations which focus their activities on one environmental component. As the end user, the Water Agency was interested in the results given by the method developed jointly by the specialists in multi-criteria methodology and the researchers in agronomy. The construction of criteria associated with the problem formulation P.β [ROY and BOUYSSOU (1993b)] allows one to identify cropping systems which can be recommended according to their impact on groundwater quality, to follow the evolution of agricultural practices, and to assess the impact of its agro-environmental policy.

Moreover, this methodology allows us to appreciate how decision-maker's strategies influence the analysis. In our case, the important weights of 'pesticides' criteria lay stress on the Water Agency's current measures, that is to say, the protection of ground and surface water against pesticides residues. If this study had taken place five years ago, we think that the highly weighted criteria would have been those concerned with 'nitrogen' information. In France indeed, in 1992, the main interest in water protection was nitrogen pollution.

The best demonstration of the relevance of such a multi-criteria analysis assessing the impact of a cropping system on the environment, is certainly that INRA researchers are implementing it again for two other research activities (figure 5).

Figure 5
INRA's other research activities



First, a regional hunting association wishes to give financial support to farmers who manage their land with positive benefits for small game, and it has asked the researchers to help them to choose such a farming system. Indeed, a new study is starting using the same multi-criteria method to choose criteria which have an impact on small game, as it was done in the present study to choose criteria which characterize the impact of agricultural techniques on groundwater quality. In this case, the cropping systems will be sorted taking into account the impact of pesticides, irrigation, soil covering, soil tillage, cropping plan and non-productive elements (e.g., edges, field margins, etc.) as presented along the fifth row of table 1. Secondly, the same approach is also being used to answer the question of a Regional Council which is interested in the impact of cultivation practices on landscape quality, for example, how to identify cropping systems which have a beneficial impact on the landscape. The problem is more complex than the previous ones because of the difference of spatial scale, but it could be solved by using the same methodology (sixth row, table 1).

6 Conclusion

This study took place in the course of research into Sustainable Agriculture and more specifically into the assessment of the impact of cropping systems on environmental components. It was generated by a request of INRA researchers, who wanted to differentiate cropping systems on the basis of their impact on groundwater quality. This differentiation was done thanks to multi-criteria analysis: the action is the cropping system, the criteria describe the agricultural techniques harmful to groundwater quality (nitrogen, pesticide and water management) and the problem formulation chosen is the sorting of cropping systems into four categories. Three criterion families have been built. The comparison of them stresses the importance of the nature of the data used for criteria elaboration.

From a methodological point of view this work underlines the relevance of the multi-criteria methodology for decision aiding for environmental issues. In this area indeed: a) data are multiple and various (criteria are tools which respect to this diversity); b) there are different stakeholders such as researchers and decision-makers (the weighting of criteria is a tool which takes account of their own opinions).

From the point of view of applications, this work is useful, a) for INRA's researchers: they appreciate the methodology, which helps them to solve some of their research problems, b) for the Water Agency, as the end user: this organization can indeed take advantage of this work by giving farmers some concrete examples of cropping systems which preserve the qualities of the groundwater.

Acknowledgements

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Appendices

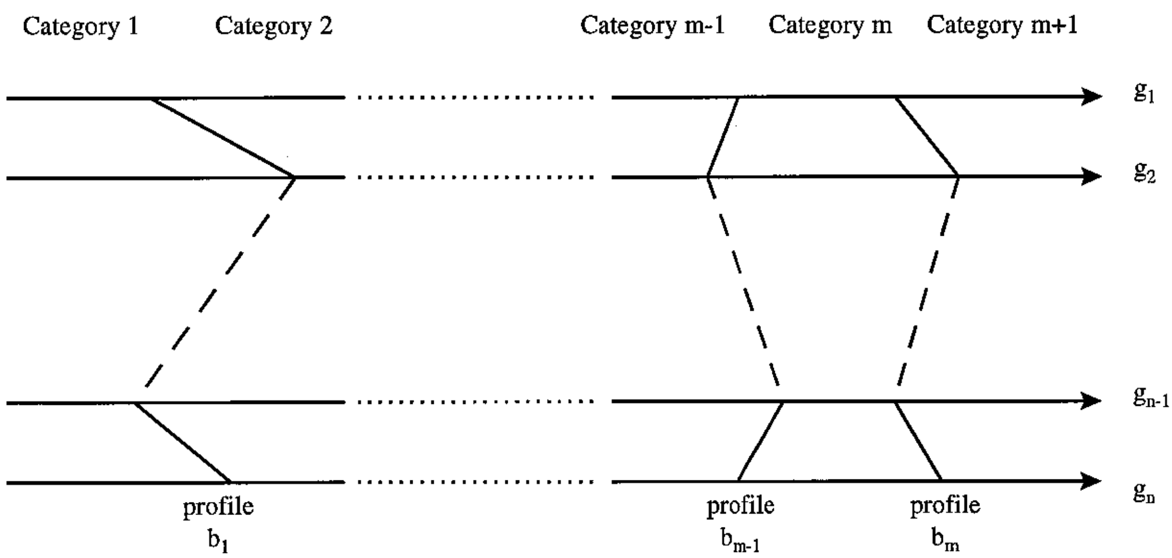
Appendix 1

Principle of the ELECTRE TRI method

(for further details see [ROY and BOUYSSOU (1993a)], [MOUSSEAU and SLOWINSKI (1998)], [YU (1992)])

ELECTRE TRI is a multiple criteria assignment method: it allows the assignment of actions (or alternatives) to some predefined ordered categories.

The following figure presents the different criteria ('g' is the criterion, 'n' the number of criteria) and the different categories; one assumes that preferences increase with the value on each criterion.



The limit between two consecutive categories is formalized by a profile (or 'reference action'). Each category is defined by two profiles: a lower profile and an upper profile (for example, category 'C_m' is defined by the lower profile 'b_{m-1}' and the upper profile 'b_m').

Categories are exclusive of each other: one action cannot be assigned to different categories. In order to assign each action to one category, the action is compared with the profiles. The ELECTRE TRI method proceeds in two consecutive steps:

1. construction of an 'outranking' relation S;
2. exploitation of S in order to assign actions to categories.

1. Construction of an 'outranking' relation S

Let a be the action and b_h be the upper profile of category C_h (and also the lower profile of category C_{h+1}). ELECTRE TRI uses an outranking relation S [ROY (1991)], i.e., validates or invalidates the assertion aSb_h (and b_hSa), whose meaning is 'a is at least as good as b_h'. In order to validate the assertion aSb_h (or b_hSa), two conditions should be verified:

- concordance: for an outranking aSb_h (or b_hSa) to be accepted, a 'sufficient' majority of criteria should be in favour of this assertion (the weights k of the criteria represent voting power),
- non-discordance: when the concordance condition holds, none of the criteria in the minority should oppose the assertion aSb_h (or b_hSa) in a 'too strong way' (the veto thresholds account for this discordance concept).

Technically, an index $\sigma(a, b_h)$ ($\sigma(b_h, a)$, respectively; $\sigma \in [0, 1]$) is built [ROY (1991)] and represents the degree of credibility of the fuzzy outranking relation assertion aSb_h (or b_hSa, respectively). In order to obtain a crisp relation S, a cutting level λ is introduced ($\lambda \in [0.5, 1]$) [ROY (1991)]. The assertion aSb_h (or b_hSa, respectively) is considered to be valid if $\sigma(a, b_h) \geq \lambda$ ($\sigma(b_h, a) \geq \lambda$, respectively).

The values of $\sigma(a, b_h)$, $\sigma(b_h, a)$ and λ determine the preference situation between a and b_h:

- $\sigma(a, b_h) \geq \lambda$ and $\sigma(b_h, a) \geq \lambda \Rightarrow aSb_h$ and $b_hSa \Rightarrow aIb_h$, i.e., a is indifferent to b_h,
- $\sigma(a, b_h) \geq \lambda$ and $\sigma(b_h, a) < \lambda \Rightarrow aSb_h$ and not $b_hSa \Rightarrow aPb_h$ or aQb_h, i.e., a is preferred to b_h (strongly or weakly),
- $\sigma(a, b_h) < \lambda$ and $\sigma(b_h, a) \geq \lambda \Rightarrow$ not aSb_h and $b_hSa \Rightarrow b_hPa$ or b_hQa, i.e., b_h is preferred to a (strongly or weakly),
- $\sigma(a, b_h) < \lambda$ and $\sigma(b_h, a) < \lambda \Rightarrow$ not aSb_h and not $b_hSa \Rightarrow aRb_h$, i.e., a is incomparable to b_h.

2. Exploitation of S in order to assign actions to categories

Two assignment procedures are then available (the role of these exploitation procedures is then to analyse the way in which an action a is compared to the profiles so as to determine the category to which a should be assigned):

Pessimistic (or conjunctive) procedure:

a) compare a successively to b_i, for $i = m, m-1, ..., 0$,

b) b_h being the first profile such that aSb_h, assign a to category C_{h+1} $(a \rightarrow C_{h+1})$.

Optimistic (or disjunctive) procedure:

a) compare a successively to b_i, for $i = 1, 2, ..., m$,

b) b_h being the first profile such that b_hPa or b_hQa, assign a to category C_h $(a \rightarrow C_h)$.

If b_{h-1} and b_h denote the lower and upper profiles of the category C_h, the pessimistic (or conjunctive) procedure assigns the action a to the highest category C_h such as a outranks b_{h-1}, i.e., aSb_{h-1}. When using this procedure with $\lambda = 1$, an action a can be assigned to category C_h only if $g_j(a)$ equals or exceeds $g_j(b_h)$ (up to a threshold) for each criterion (conjunctive rule).

The optimistic (or disjunctive) procedure assigns a to the lowest category C_h for which the lower profile b_h is preferred to a, i.e., b_hPa or b_hQa. When using this procedure with $\lambda = 1$, an action a can be assigned to category C_h when $g_j(b_h)$ exceeds $g_j(a)$ (up to a threshold) at least for one criterion (disjunctive rule). When λ decreases, the conjunctive and disjunctive characters of these rules are weakened.

Appendix 2

Table 4
Performance table (33 CS; 13 criteria)

Criteria → preference order	g_{Na} decr.	g_{bal} decr.	g_{Nda} incr.	g_{split} incr.	g_{tech} incr.	g_{Pa} decr.	g_{hl} decr.	g_{m} decr.	g_{tox} incr.	g_{loc} incr.	g_{Pda} incr.	g_{hb} decr.	g_{la} decr.
C S ↓													
1	-5	21	1	0.67	0	2.4	60	3.556	0.0005	2	2	21	35
2	7	45	1	1	0	2.4	60	3.556	0.0005	2	2	21	35
3	127	21	1	1	0	2.4	60	3.556	0.0005	2	2	21	35
4	7	60	1	2	0	2.4	60	3.556	0.0005	2	2	21	15
5	34	42	0	1	1	0.75	91	4.515	0.0005	1	2	24.1	27
6	15.8	25.5	0	0.67	1	0.75	91	4.515	0.0005	1	2	45.1	3
7	0	24	0	0.67	1	1.575	91	2.543	0.0005	2	2	21	15
8	40	37	0	1.5	1	1.05	1278	6.213	0.0005	1	2	32.4	12
9	8.5	37	0	1	1	1.05	1278	6.213	0.0005	1	2	32.4	12
10	8.5	24	0	1	1	1.799	90	4.515	0.0005	1	2	35.4	12
11	49	48	0	3	1	1.05	90	4.515	0.0005	1	2	37.4	25
12	21	24	0	1	1	1.05	90	4.515	0.0005	1	2	66.3	25
13	45	42	0	2	1	0.85	91	5.446	0.0005	3	2	-70	0
14	57	39	0	2	1	0.85	91	5.446	0.0005	1	2	-70	0
15	42	24	0	1	1	0.85	91	5.446	0.0005	3	2	-70	0
16	5	25.5	-1	0.67	0	2.4	1278	6.213	0.0005	1	2	-11.6	20
17	20	42	0	1	0	0.585	60	4.239	0.0005	3	2	0	12
18	-8	42	-1	2	0	0.585	60	4.239	0.0005	3	2	-70	0
19	63	25.5	-2	0.67	0	2.88	60	3.556	0.0005	2	2	20.1	25
20	58	42	-1	2	0	2.88	60	4.515	0.0005	1	2	-70	0
21	58	48	0	2	0	2.88	1278	6.213	0.0005	1	2	-70	0
22	26	48	0	2	0	2.88	60	4.515	0.0005	1	2	-70	0
23	10	42	0	2	0	2.88	1278	6.213	0.0005	1	2	-70	0
24	22	42	1	1	0	1.225	60	4.515	0.0005	1	2	-70	0
25	52	45	1	1	0	1.25	60	3.556	0.0005	2	2	-70	0
26	70	35	1	1	0	0.36	30	2.699	0.05	3	2	-70	0
27	33	29	0	3	1	0.24	49	4.239	0.01	3	2	2.2	30
28	14	14	-2.5	1	1	0.24	49	4.239	0.01	3	2	0	30
29	2	29	-2.5	3	1	0.3	49	3.314	0.01	3	2	-11.1	30
30	23	6	0	1	1	2.88	90	2.543	0.0005	1	2	-70	0
31	18	15	0	1	1	0.3	91	3.314	0.01	1	2	-70	0
32	1	27	0	2	1	0.3	91	3.314	0.01	1	2	-70	0
33	-4	42	0	2	1	1.5	91	3.320	0.01	1	2	-70	0
Thresholds	*5*	*5*	*0.5*	*0*	*0*	*10%*	*25%*	*15%*	*25%*	*0*	*0*	*5*	*5*
Weight set 1	0.1	0.06	0.1	0.07	0.04	0.11	0.11	0.11	0.11	0.08	0.08	0.02	0.03
Weight set 2	0.06	0.07	0.06	0.07	0.06	0.11	0.11	0.11	0.11	0.1	0.02	0.05	0.06
Weight set 3	0.1	0.03	0.08	0.05	0.03	0.1	0.13	0.13	0.13	0.05	0.08	0.03	0.05

Appendix 3

Table 5
Performance table (33 CS; 8 criteria)

Criteria → preference order	g_{Na} decr.	g_{bal} decr.	g_{Nda} incr.	g_{split} incr.	g_{tech} incr.	g_{pest} incr.	g_{hb} decr.	g_{Ia} decr.
C S ↓								
1	-5	21	1	0.67	0	6.33	21	35
2	7	45	1	1	0	4.55	21	35
3	127	21	1	1	0	4.55	21	35
4	7	60	1	2	0	4.55	21	15
5	34	42	0	1	1	5.26	24.1	27
6	15.8	25.5	0	0.67	1	5.26	45.1	3
7	0	24	0	0.67	1	7.19	21	15
8	40	37	0	1.5	1	0.88	32.4	12
9	8.5	37	0	1	1	0.88	32.4	12
10	8.5	24	0	1	1	2.90	35.4	12
11	49	48	0	3	1	2.14	37.4	25
12	21	24	0	1	1	2.14	66.3	25
13	45	42	0	2	1	6.87	-70	0
14	57	39	0	2	1	2.92	-70	0
15	42	24	0	1	1	6.87	-70	0
16	5	25.5	-1	0.67	0	3.87	-11.6	20
17	20	42	0	1	0	6.07	0	12
18	-8	42	-1	2	0	6.07	-70	0
19	63	25.5	-2	0.67	0	5.18	20.1	25
20	58	42	-1	2	0	3.49	-70	0
21	58	48	0	2	0	2.11	-70	0
22	26	48	0	2	0	4.51	-70	0
23	10	42	0	2	0	2.05	-70	0
24	22	42	1	1	0	4.59	-70	0
25	52	45	1	1	0	7.16	-70	0
26	70	35	1	1	0	9.35	-70	0
27	33	29	0	3	1	7.45	2.2	30
28	14	14	-2.5	1	1	7.45	0	30
29	2	29	-2.5	3	1	8.64	-11.1	30
30	23	6	0	1	1	6.96	-70	0
31	18	15	0	1	1	8.65	-70	0
32	1	27	0	2	1	8.65	-70	0
33	-4	42	0	2	1	6.95	-70	0
Thresholds	*5*	*5*	*0.5*	*0*	*0*	*0.25*	*5*	*5*
Weight set 1	0.1	0.06	0.1	0.07	0.04	0.6	0.02	0.03
Weight set 2	0.06	0.07	0.06	0.07	0.06	0.56	0.05	0.06
Weight set 3	0.05	0.03	0.08	0.05	0.03	0.62	0.03	0.05