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GIS-based planning support system for rural land-use allocation

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ABSTRACT

This article describes a planning support system for rural land-use allocation. The system is called RULES (RUral Land-use Exploration System) and is based on a geographic information system (GIS). Other software components have been incorporated into the GIS to link external analytical models to the system. These analytical techniques support three basic stages in a rural land-use planning model: land suitability evaluation, land-use area optimization, and spatial allocation of land uses. Land evaluation is carried out using multicriteria evaluation methods and the FAO framework. A multiobjective linear programming model has been designed for the optimization of land-use areas, where the objectives include economic, social, and environmental aspects. Suitability maps and land-use areas obtained in the two previous stages are used to design the final land-use map using three techniques: hierarchical optimization, ideal point analysis, and an algorithm based on simulated annealing. The system has been applied in Terra Chá (a region in NW Spain), thereby demonstrating its efficacy. The system enabled alternative land-use plans to be generated for this region according to different stakeholders' perspectives. This tool contributes to directing and supporting discussion throughout the planning process.

1. Introduction

Models, methods, and research in several disciplines have been developed for urban land-use planning. In contrast, rural planning has only been partially considered, and is almost always approached from the perspective of increased crop or forest production. The rural environment has undergone many changes in recent decades, including depopulation, deagriculturalization, the disappearance of the cultural landscape, and the appearance of new activities and prospects for the land. These changes require tools and "know-how" to support decision-making when linking activities to regions and vice versa.

In addition to land-use regulations, this process requires specific plans and initiatives to define the roles of different spaces. Rural land requires active management that enables the environment to develop appropriately. In addition, public participation in land-use planning processes is increasingly important. Given that such processes arouse the interest of an increasing number of individuals and groups (Jacobs, 1992),

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tools are required that can directly involve the stakeholders in the planning process and thereby identify the needs and objectives of the population.

The process of rural land-use planning involves different stages that require different kinds of studies (van Ittersum et al., 1998). The system described in the present paper includes three main stages in this process: (i) an evaluation of land suitability for each land-use type; (ii) the optimization of the different land-use areas; (iii) the spatial allocation of land uses.

The first IT applications designed for land-use planning only evaluated land suitability. Such applications include *ALES* (Rossiter, 1990), *MicroLEIS* (De la Rosa et al., 1992), and *ArcviewLESA* (Day et al., 2000). In addition, many systems have been designed to analyse the area assigned to each land use, including *GOAL-QUASI* (van Ittersum, 1995) and *ADELAIS* (Siskos et al., 1994). The only commercial GIS that includes tools for land evaluation and for the spatial allocation of land uses is *IDRISI* (Eastman et al., 1995). There are currently many methods and IT applications that deal with one or several land-use planning studies; however, only a few systems, such as *What-If* (Klosterman, 2001) and *SIRTPLAN* (FAO, 2000), incorporate all three of the aforementioned stages. *What-If* is an easily and widely used planning support system; however, it focuses on urban planning and lacks a firm theoretical basis (Klosterman, 1999). The *SIRTPLAN* system comprises a group of independent programmes that do not have a strictly defined methodology; instead, the system enables different techniques to be implemented at each stage of the planning process.

Most land-planning IT applications focus on urban planning; e.g., *CommunityViz* (Kwartler and Bernard, 2001), *UrbanSim* (Waddell, 2002), and *Smartplaces* (Croteau et al., 1997). Other systems are specifically designed for agroforestry uses, including *LADSS* (Matthews et al., 1999), *AEZWIN* (Fischer et al., 1998), *LUPAS* (Roetter et al., 2005), and *NELUP* (Watson and Wadsworth, 1996). *LADSS* includes stages of land evaluation, spatial allocation of land uses, and evaluation of environmental impact. *AEZWIN* and *LUPAS* include stages of land evaluation and area optimization, while *NELUP* includes area optimization, environmental evaluation, and a hydrological analysis.

Some of the above systems are commonly used in land-use plans, e.g., *What-If* has been applied to the development of land-use scenarios in Hervey Bay, Australia (Pettit, 2005), in Medina County, Ohio, USA (Klosterman et al., 2003), and Seoul, Korea (Kim, 2004), among other areas. The number of applications of *CommunityViz* is even more extensive than that for *What-If*; e.g., resource management plan in Lakeview (Oregon, USA), growth management plan in Eureka (Minnesota, USA), and the engagement of public participation in Verona (Wisconsin, USA; www.communityviz.com). *SIRTPLAN* has been used in several countries in South America. However, it is difficult to apply these systems to Spain. Some are not yet available (e.g., *LADSS*), and most of the commercial systems are adapted to the characteristics of North American land-use plans and focus on urban land uses. In addition, few of the remaining applications deal with the three stages mentioned above. For these reasons, we developed a new system that can be easily used in Spain, yet is sufficiently flexible to be applied in different contexts, and focused on agricultural and forestry land uses.

This paper describes a new planning support system for rural land-use allocation, termed RULES (RUral Land-use Exploration System). This system is innovative because three stages of the rural land-use planning process are incorporated into just one tool. To achieve this, several analytical models for each one of the three stages are included in one GIS. The three stages correspond to three system modules: (1) land evaluation, (2) area optimization, and (3) spatial allocation. The results of one module become the input for the others. This feedback between the modules enables the final result to be refined and improved. It also enables new factors involved in the planning process to be identified. The modelling process has been validated and discussed via its use in the Terra Chá region of NW Spain.

2. System architecture

Given that land-use planning is closely linked to the spatial component of data, the basis of RULES is a GIS (GeoMedia Professional®); this facilitates data management and analysis. Other tools have been integrated into the GIS by programming (see Fig. 1), including the LINDO API®, with libraries – a collection of subprograms to develop software – that were used to program a customized optimization application integrated in the GIS to solve linear programming models, and a heuristic algorithm that optimizes the spatial allocation of land uses.

The GIS and the other decision support tools are fully connected, as specific commands have been created for the application using Visual Basic and have been included in the existing GIS commands (Jankowski, 1995; Jun, 2000).

The GIS is used as a means of visualizing data and as a framework for analysis and modelling operations. Three new menus have been added to the GIS interface: one for each of the system's modules. These menus can be used to access the commands that execute the different methods of land evaluation, area optimization, and spatial allocation. Some of these commands establish links with other software components; however, the results of all operations are visualized in the GIS, thereby enabling total integration to be attained.

The land evaluation module has been programmed with the system's GIS component, using GIS programming objects to apply the reclassification, overlay, and map algebra techniques required to implement the land evaluation methods.

The area optimization module has been developed from LINDO® libraries. These were used to construct a customized optimization application that has been added to the system interface and thus integrated into the GIS environment.

The methods used in the spatial allocation module have been programmed using the spatial analysis and cartographic modelling tools provided by the GIS programming objects. A heuristic algorithm has also been developed, based on simulated annealing, and programmed in independent libraries that were subsequently integrated into the system.

The RULES interface is a customization of the GeoMedia® interface, which incorporates the specific commands of the system through three menus: *suitability*, *areas* and *allocation*. The *suitability* pull-down menu provides the options *weighted*

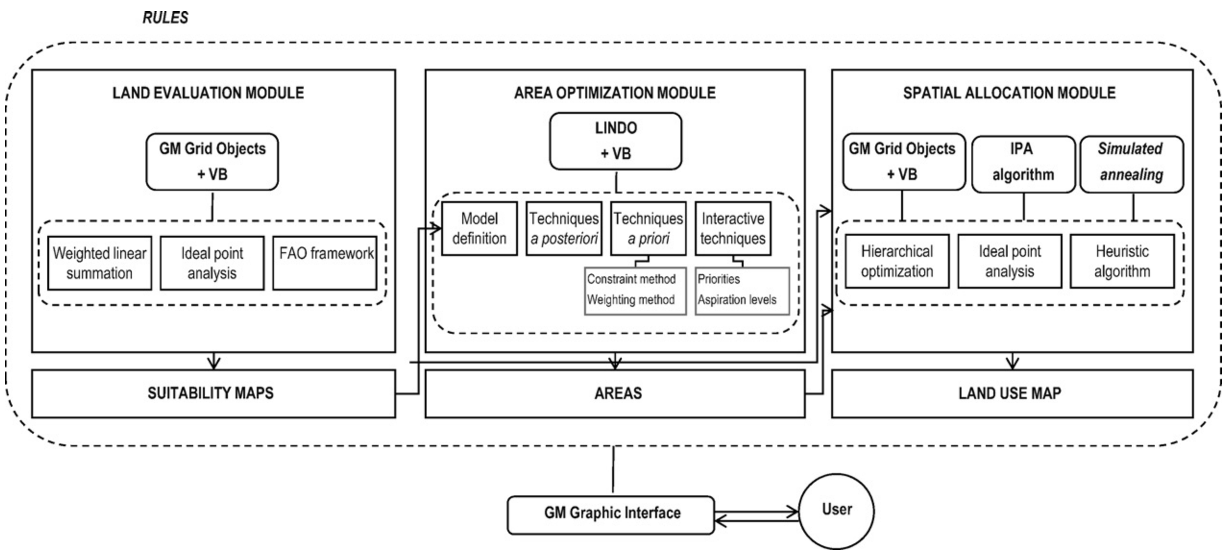

Fig. 1 – Structure of RULES: modules, commands, IT components, and results.

linear summation, *ideal point analysis* and *FAO framework*, which execute the methods of land evaluation. The options *Model definition*, '*a posteriori*' *assignment of priorities*, '*a priori*' *assignment of priorities* and *interactive assignment of priorities* are accessed from the *areas* menu. A sub-menu appears when we click on the menu '*a posteriori*' *assignment of priorities*, which allows us to choose between the *constraint method* and the *weighting method*, as well as in the menu *interactive assignment of priorities*, where a sub-menu enables us to select between the assignment of *priorities* or *aspiration levels*. The option *allocation* gives access to the menus *hierarchical optimization*, *ideal point analysis* and *simulated annealing*. All these methods are described in the following section.

3. System description

RULES is a planning support tool focused on rural land use, with the objective of automating the processes and operations needed for the design of land-use plans, according to the decision-maker's preferences and opinions. The system generates the optimal land-use scenario for the conditions specified by the user. These scenarios are represented as land-use maps.

The first step in drawing up these land-use maps using RULES is to obtain a raster-based GIS coverage for each land suitability evaluation factor. These coverages represent the input information needed to obtain suitability maps for each land use. Such maps are generated by one of the three methods in the land evaluation module: weighted linear summation, ideal point analysis, or the FAO framework. The next step is to determine the area of each land use by employing the area optimization module. In this module, users can establish their priorities *a posteriori*, *a priori*, or in an interactive way, using different multiobjective linear programming techniques. Finally, the suitability maps and the areas of each land use obtained in the two aforementioned modules are used as input data for the spatial allocation module. This module has three methods for obtaining the final land-use map: hierarchical optimization, used when the priorities of land uses are known; ideal point analysis, used when a numerical weight can be assigned to each land use; and the heuristic algorithm, used when spatial requirements are considered.

In addition to automating the operations required for these three stages, RULES enables the user to express his/her preferences and opinions in each phase of the planning process, as well as to visualize the results and consequences in the form of land-use scenarios. The interactivity of the system enables scientific methods to be integrated with the knowledge and experience of planners or other agents.

A detailed description of the system's three modules is given below. Each module can be used independently. A brief description of the theoretical bases and the procedures used to apply each method is also provided.

3.1. *Land evaluation module*

Land evaluation is the degree of achievement of the land-use requirements provided by the land. The determination of the suitability level for each land use and spatial unit is the basis for subsequent land planning and management. Land evaluation is a basic part of the land-use planning process (FAO, 1976).

There are many methods available for the evaluation of land suitability. Of these, three methods have been selected for use in the present system. Two of these are multicriteria analysis methods: weighted linear summation and ideal point analysis. The third method is the FAO framework (FAO, 1976) with the limitation scoring system (Triantafilis et al., 2001). These three methods enable physical and socioeconomic criteria to be included in the analysis. They also generate suitability maps made up of continuous numerical values. Continuous maps are necessary in this approach, as the methods employed in assigning land uses in the spatial allocation module require this type of map as input data.

3.1.1. *Weighted linear summation*

Weighted linear summation is the multicriteria evaluation procedure most frequently used to obtain suitability maps for a particular activity (see Bojorquez-Tapia et al., 2001; Eastman et al., 1998; Engelen et al., 1999; Mendoza, 1997; Ridgley and Heil, 1998; Weerakoon, 2002). In addition, this procedure is easily implemented in a raster GIS (Eastman et al., 1995). In the weighted linear summation, each evaluation factor is given a weight, and the results are added according to the following equation:

$$a_{ij} = \sum_{k=1}^{K} w_k x_{ijk} \tag{1}$$

where a_{ij} is the suitability of cell in the row i and column j of the raster map, that is, the cell (i, j), w_k is the weight assigned to factor k, and x_{ijk} is the value of factor k in cell (i, j). To apply this method in the system, the raster layers corresponding to the evaluation factors must be standardized to a common scale. The sum of the weights assigned to the factors should be equal to 1.

3.1.2. *Ideal point analysis*

Ideal point analysis is based on calculating each alternative's (cell's) distance from the ideal point (Barredo, 1996). The ideal point is the best possible alternative; in this case, it would be a cell with the highest value in every criteria. Therefore in a standardized factor between 0 and 1 the ideal point is 1. Cells with a shorter distance to the ideal point will have higher suitability for the considered land use. This method calculates suitability according to the following equations:

$$a_{ij} = \frac{L_{max} - L_{ij}}{L_{max} - L_{min}} \tag{2}$$

$$L_{ij} = \left[\sum_{k=1}^{K} w_k |x_{ijk} - 1|^p \right]^{1/p} \tag{3}$$

where a_{ij} is the suitability of cell (i, j), L_{max} is the maximum distance value, L_{min} is the minimum value, L_{ij} is the distance from cell (i, j) to the ideal point, w_k is the weight assigned to factor k, x_{ijk} is the standardized value (between 0 and 1) of factor k in cell (i, j), and p is the metric for the distance calculation.

The user should introduce those raster layers corresponding to the evaluation factors. Layers must be in a standardized scale between 0 and 1. The weight of the factors should also be introduced and should add up to 1 (Fig. 2). In addition, the degree of risk that the decision-maker is willing to accept can be altered by varying the value of the parameter p. This parameter indicates the degree of compensation between the factors; i.e., the degree to which factors with a low score can be compensated for by more positive factors. The result is a continuous suitability map with values between 0 and 1.

3.1.3. *FAO framework*

The FAO framework for land evaluation (FAO, 1976) matches the land qualities of each cartographic unit with the requirements of each land utilization type. From this, matching land units are classified into the following suitability classes: S1, highly suitable; S2, suitable; S3, marginally suitable; N1, currently not suitable; N2, permanently not suitable. To apply

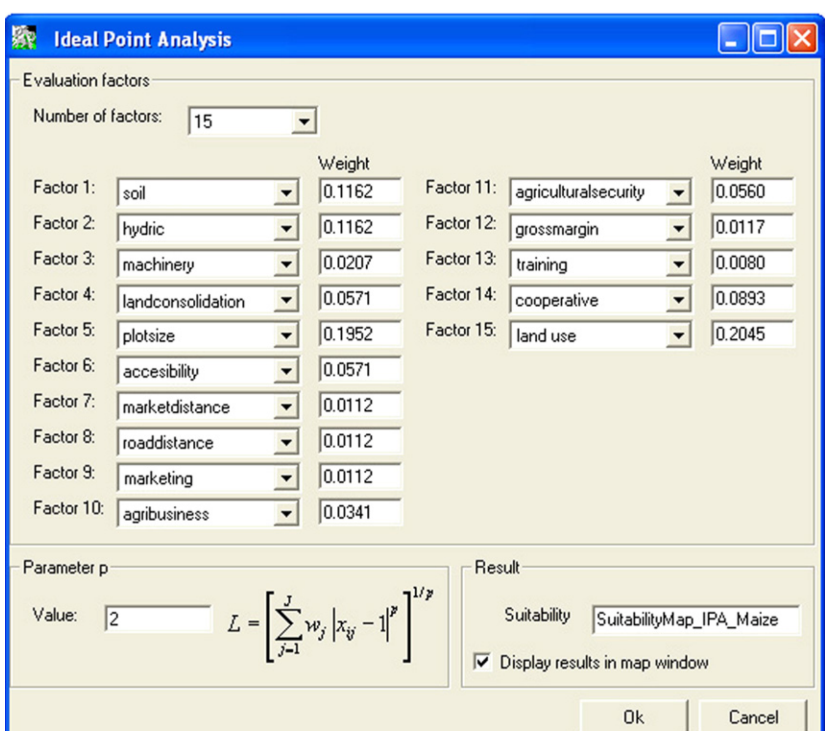

Fig. 2 – RULES window for obtaining suitability maps using ideal point analysis.

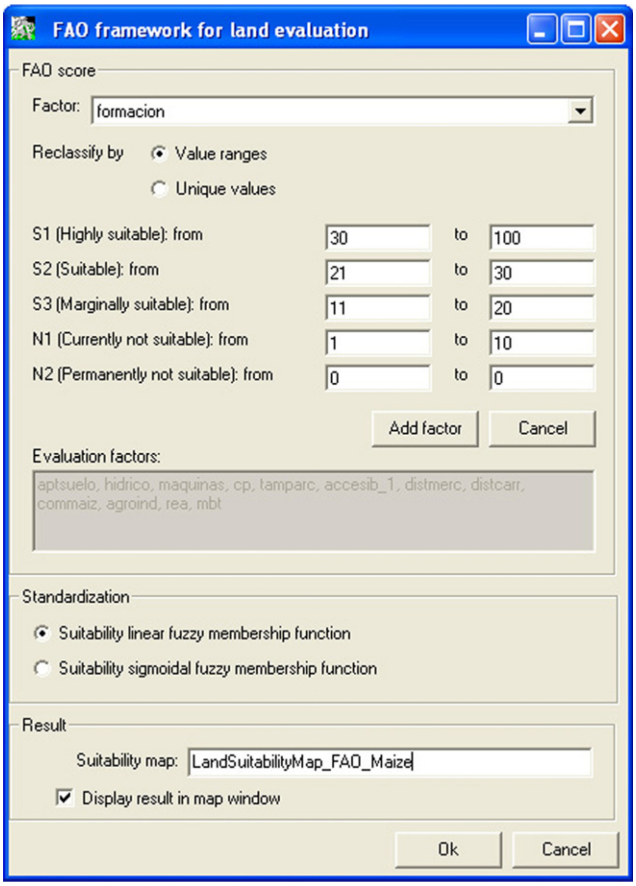

Fig. 3 – RULES window for obtaining suitability maps using the FAO framework.

the FAO framework with limitation scoring (Triantafilis et al., 2001), the user should reclassify the values (which are not necessarily standardized) of each evaluation factor into these suitability classes (Fig. 3). This reclassification can be carried out using single values for discrete factors, by assigning each individual value of a factor to a suitability class, or using ranges for continuous factors by assigning a value range to each suitability class. The programme will assign a limitation score to each value of a factor, in accordance with its suitability class. The limitation scores are as follows: 0 points for S1, 1 point for S2, 3 points for S3, 9 points for N1, and 27 points for N2 (Triantafilis et al., 2001). The sum of the limitation scores of the introduced factors gives the "accumulated limitation score". Finally, the user should select a linear (Eq. (4)) or sigmoidal (Eq. (5)) function to obtain the suitability by standardizing the accumulated limitation score:

$$a_{ij} = \frac{l_{max} - l_{ij}}{l_{max} - l_{min}} \qquad (4)$$

$$a_{ij} = \cos^2\left(\frac{l_{ij} - l_{min}}{l_{max} - l_{min}} \times \frac{\pi}{2}\right) \qquad (5)$$

where a_{ij} is the suitability of cell (i, j), l_{max} is the maximum accumulated limitation value, l_{min} is the minimum value, and l_{ij} is the accumulated limitation in cell (i, j). The result is a continuous suitability map with values between 0 and 1.

3.2. *Area optimization module*

Most methods for the optimization of spatial land-use allocation require the area demanded for each land use as external input data (i.e., Eastman et al., 1998; Aerts and Heuvelink, 2002; Stewart et al., 2004). Some systems, i.e., *What-If*, obtain these areas from population growth predictions and forecasts about demands for each activity. In other cases, minimum and maximum thresholds, between which land-use areas can vary, are defined (Stewart et al., 2004), or final areas are established directly by the decision-maker (van der Merwe, 1997; Aerts and Heuvelink, 2002). However, linear programming is the technique most frequently used for this purpose, especially for agroforestry land uses (Chuvieco, 1993; Ridgley and Heil, 1998; Zander and Kächele, 1999; Lu et al., 2004).

Santé and Crecente (2007) designed a multiobjective linear programming model in which the decision variables correspond to land uses and the objectives include economic, social, and environmental aspects. This model enables the different land-use options to be examined in terms of the area assigned to each land use and according to the priorities or aspiration levels that the decision-maker assigns to each objective. This module includes various multiobjective linear programming techniques to solve the model. The aim of all the techniques is to design, examine, and evaluate the different land-use options. These techniques have been implemented in an interactive way, such that there is an exchange of information between the analyst and the system. This information exchange is carried out via a series of dialogue stages in which the planner establishes his/her priorities, and calculation stages in which new solutions are calculated on the basis of the planner's instructions. This approach aids understanding of the consequences of the decisions taken throughout the planning process, and of the relation between the model's different economic, social, and environmental objectives. The parameters introduced into the model help the planner to reflect on the perspectives of the different interest groups involved in the planning process.

First, the user should execute the command "Model definition" to adjust the model's parameters. In this command, the user selects the objectives and land uses, and introduces the technical coefficients and the right-hand side of land availability (maximum area available) and demand constraints for each land use (Fig. 4). The user can select from six objectives: maximization of gross margin, minimization of production costs, maximization of rural employment, maximization of agricultural land, minimization of the use of agrochemicals, and maximization of the naturalness of land use. The user can then select between techniques that assign priorities *a posteriori*, *a priori*, or in an interactive way.

3.2.1. *'A posteriori' assignment of priorities*

The system includes commands for two generating techniques: the constraint method and the weighting method. These techniques provide the group of efficient solutions from which the planner will select the definitive solution *a posteriori*. The constraint method (Goicoechea et al., 1982) is based on optimizing one objective function and treating the other functions as constraints. This generates a group of efficient solutions via parametric variation of the right-hand side of

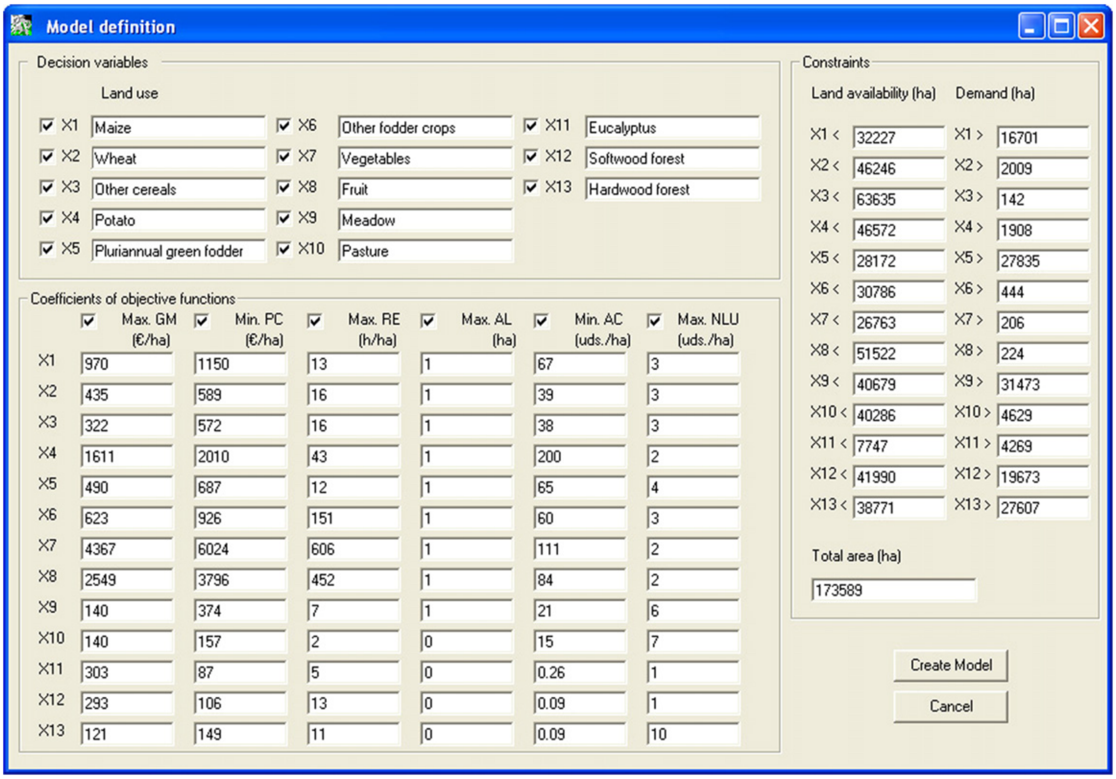

Fig. 4 – Form for introducing the parameters (land uses, objective functions, technical coefficients, land constraints) of the area optimization model.

these constraints. The weighting method (Cohon, 1978) consists of assigning a weight to each one of the objective functions, which are then combined into one objective function.

In the command for executing the constraint method, the user should select the objective that is to be the objective function. The remaining objectives are transformed into constraints by introducing the value *r*: the number of different values of right-hand sides of the constrained objectives. In the weighting method, a group of weights are assigned to each objective. The minimum weight, maximum weight, and weight interval must be entered for each objective. For both commands, the model's solutions for all combinations of right-hand sides or weights are given in a report whose content can be exported to a text file (Fig. 5).

3.2.2. *'A priori' assignment of priorities*

The user can formulate his/her priorities *a priori* using the weights assigned to each objective in the goal programming application. In goal programming, the analyst must specify an aspiration level for each objective function; the preferred solution is that which minimizes the difference between the value attained and the aspiration level for each goal (Goicoechea et al., 1982). The same form shows the model's solution, i.e., the land-use areas, and each objective's value and achievement rate.

3.2.3. *Interactive assignment of priorities*

The interactive assignation of priorities can be carried out using two commands. In the first command, the user's priorities are formulated by establishing priorities between the different objectives. This is done according to the technique described by Lu et al. (2004). In the second command, which implements the STEP method (Cohon, 1978), the priorities are formulated by fixing aspiration levels for each objective.

In the interactive assignation of priorities, the user should select the highest priority objective to obtain, in the same form, the model's solution and each objective's value and achievement rate. After observing the achievement rates, the user should select the next-highest priority objective and introduce the permitted variation in the previous objective. This will again produce the model's solution and the value of the objectives. The process continues until the priorities and the permitted variations have been established for each of the objectives.

To apply the STEP method, after observing the achievement rates attained for each objective the user should select an objective whose achievement rate he/she is willing to reduce. The user should then introduce the maximum allowed decrease in the value of this objective (Fig. 6). The process ends when the allowed decrease for each objective has been established or when the user considers that the achievement rate for all of the objectives is appropriate.

3.3. *Spatial allocation module*

Land-use planning may be defined as the process of allocating different uses to specific units of area within a region (Stewart et al., 2004). This allocation of land uses is based on the land performance when used for these purposes (FAO, 1976); that is, on land suitability for each

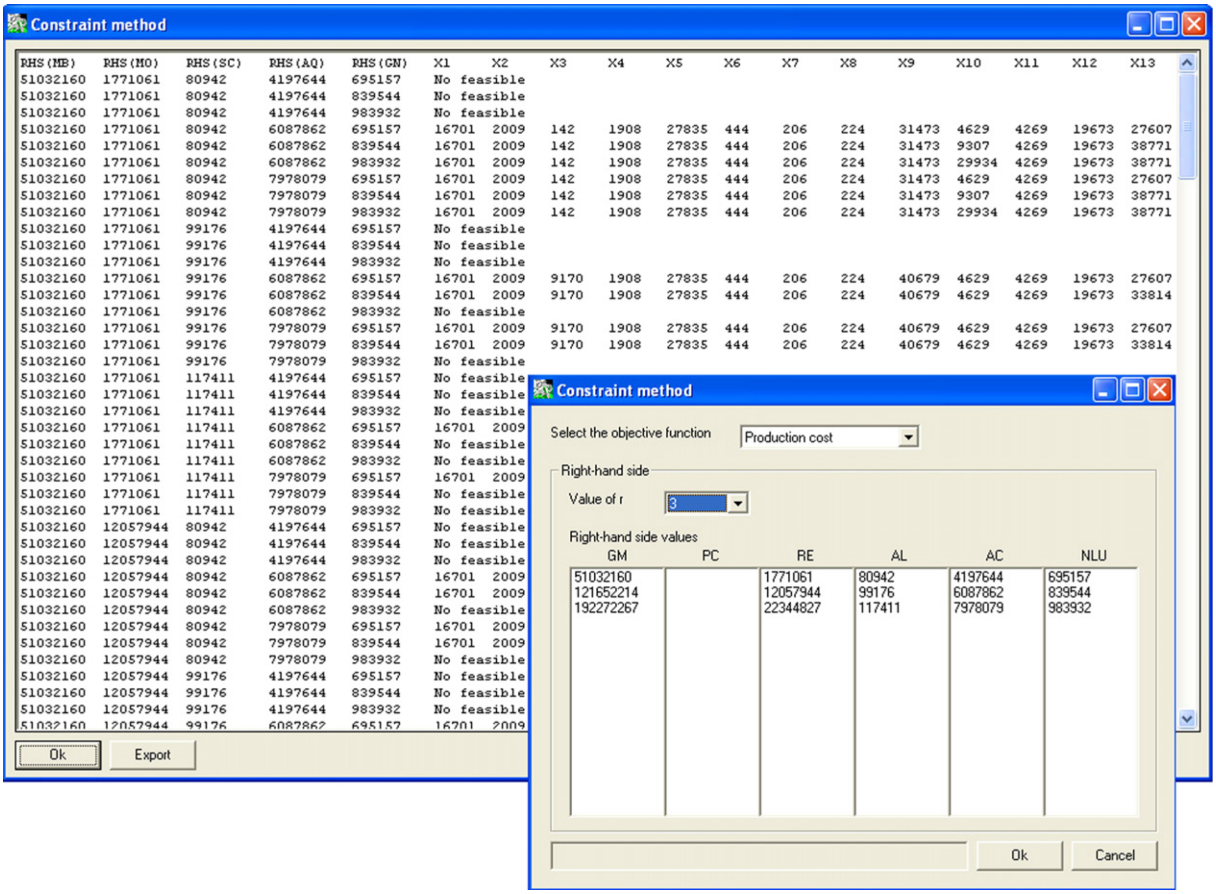

Fig. 5 – RULES window for application of the constraint method and the result of its application.

use. Many optimization techniques have been proposed to select optimal sites for a single land use. However, this problem is more complex when multiple conflicting objectives are considered (Eastman et al., 1995). Only a few techniques have been developed to deal with this multiobjective problem, which are based fundamentally on multicriteria evaluation methodologies or on heuristic algorithms.

The aim of this third module is to design the final land-use map by using the suitability maps and the optimum area for each land use as input data. These data are obtained from the two previous modules. To achieve this, RULES includes two multicriteria evaluation methods: hierarchical optimization and the ideal point analysis (Barredo, 1996). In addition, a new heuristic algorithm has been designed to optimize the spatial allocation of uses. Hierarchical optimization is applicable when the priorities of the uses are known. To apply the ideal point analysis, a numerical weight has to be assigned to each use. Hierarchical optimization and ideal point analysis base land-use allocation exclusively on the suitability of each land unit (cell of the raster map) for the different uses. In contrast, the algorithm helps us to consider the compactness of the zones assigned to each land use. Compactness is included in many spatial allocation models (e.g., Aerts et al., 2003; Nalle et al., 2002), as an irregular allocation of uses in small, scattered, unconnected areas is undesirable.

3.3.1. *Hierarchical optimization*

Hierarchical optimization consists of allocating the most suitable areas for the highest priority use until the required surface area for this use has been attained. The process continues by allocating land to the use that has the second-highest priority. The process is repeated until the whole area is allocated (Carver, 1991).

To execute this command, the user should introduce the suitability maps for each land use in the order of greatest priority to least priority. The user should also input the area required for each use, expressed in terms of number of raster map cells.

3.3.2. *Ideal point analysis*

The ideal point analysis was proposed by Barredo (1996) as a method for the spatial allocation of conflicting land uses. The approach consists of maximizing the suitability for one land use while minimizing the suitability for the remaining uses. Calculation of the distance from the ideal point is carried out as follows:

$$L_{ijm} = \left[\left(\sum_{k=1}^{K} w_k |x_{ijk} - 0|^p \right) + (w_m |x_{ijm} - 1|^p) \right]^{1/p} \qquad (6)$$

where L_{ijm} is the distance between cell (i, j) and the ideal point for use m, p is the metric (Euclidean distance: $p = 2$), w_k is the

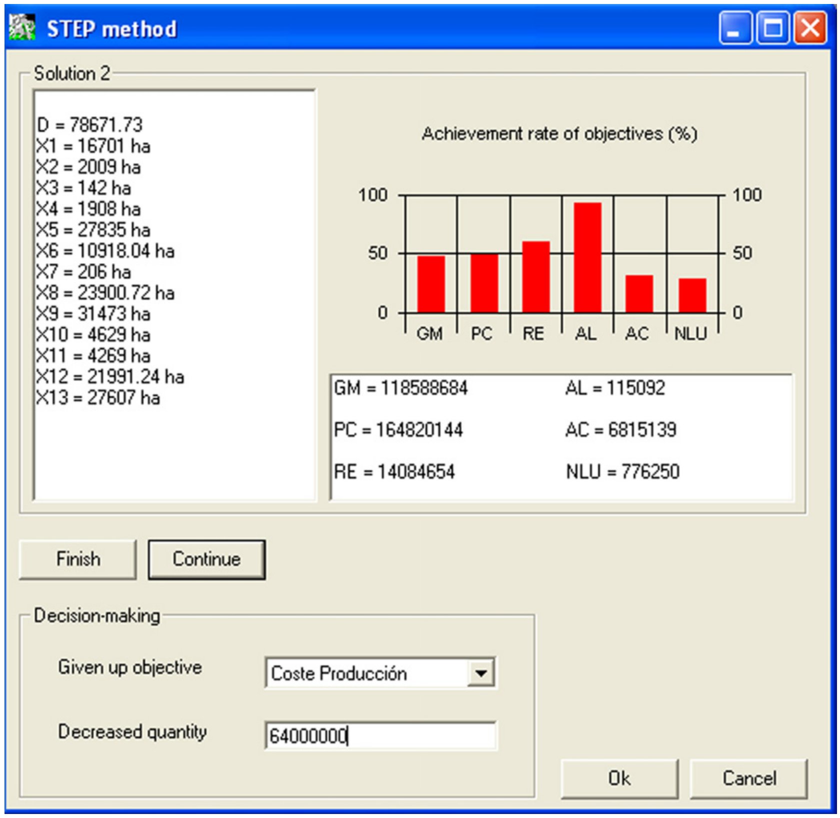

Fig. 6 – RULES window for application of the STEP method.

weight of use k, x_{ijk} is the standardized suitability value of cell (i, j) for use k, x_{ijm} is the standardized suitability value of cell (i, j) for use m, 1 is the value of the ideal point, and 0 is the minimum value for suitability maps standardized between 0 and 1.

This command implements the algorithm in Fig. 7, which describes the following procedure: (i) calculate the distance from the ideal point for each land use using Eq. (6); (ii) allocate to each cell the use that has the least distance from the ideal point; (iii) calculate the area allocated to each use; (iv) if this area is greater than the required area, allocate the most suitable cells to this use (those that have the least distance to the ideal point) until the area introduced by the user is covered; (v) if there are uses whose goals have not been covered, the area of the previously allocated uses will be excluded and the process repeated from step (ii).

To apply this method, the user needs to introduce the suitability maps, the weight and area of each land use, and the value of the parameter p.

3.3.3. *Simulated annealing*

We selected an optimization algorithm based on simulated annealing (Kirkpatrick et al., 1983), as it has a demonstrated suitability for multiobjective land-use allocation problems (Aerts and Heuvelink, 2002).

To execute this algorithm, the user can alter the values of two groups of parameters (Fig. 8): parameters for altering the energy function, and parameters corresponding to the cooling schedule. The first group includes the weighting factors (α_1, α_2)

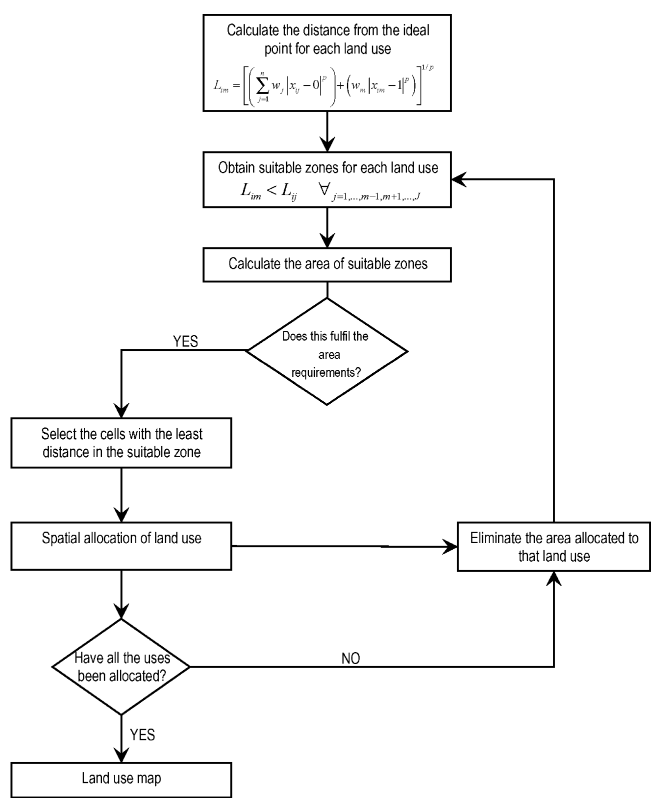

Fig. 7 – Flow chart showing the algorithm for implementing ideal point analysis with conflicting objectives.

for the two terms in the following objective function (F):

$$F = \alpha_1 \sum_{i=1}^{I} \sum_{j=1}^{J} w_n A_{ijn} + \alpha_2 \sum_{n=1}^{N} \sum_{r_n=1}^{R_n} P_{r_n}$$

where A_{ijn} is the suitability of cell (i, j) for use n, w_n is the weight of use n, I is the number of rows in the grid, J is the number of columns in the grid, and P_{rn} is the perimeter of the r_nth zone of the R_n zones with use n, measured as the number of axes of the cells of r_n that are adjacent to a cell with a different use to that of n.

The values of the parameters used to define the cooling schedule can be altered by the user to influence the process' characteristics. If not, the default values can be accepted, as the algorithm has already been validated for these values. The variable parameters include the initial value of T, the number of iterations for a value of T, the minimum number of temperatures (stop condition), and a parameter to control the reduction in T. The initial temperature marks the degree of freedom to change the initial solution. Thus, the higher this value, the more time is required to calculate the algorithm, but the more reliable the final solution. Likewise, the higher the number of iterations in a temperature, the higher the number of temperatures; the closer to 1 the control parameter, the greater the probability of obtaining a solution that is closer to optimal, and the longer the processing time required for the algorithm.

4. Case study

Terra Chá is a region in NW Spain that covers an area of 1832 km^2. Fifty-three percent of this area is given over to agricultural activity. The overall breakdown of the region's land use is as follows: crops, 25.7%; pasture, 27.5%; scrubland, 26.6%; forestry, 18.7% (INE, 2002).

Existing land uses in the region, as given in the 2001 Agricultural Statistics, were taken as the basis for identifying different uses for land-use planning. The following uses were considered: maize, wheat, other cereals, potatoes, pluriannual green fodder, other fodder crops, vegetables, fruit, meadows, pasture, eucalyptus, softwood forest, and hardwood forest. Each land use requires different agronomic, socioeconomic, and management conditions for sustainable exploitation. From all the requirements initially identified for an optimal land evaluation according to the FAO framework (1976), those which could be obtained from the available information were selected (Table 1). The selected factors were weighted (Table 2) and introduced into the system as raster coverages with 539 × 569 cells of 100 m × 100 m each. Subsequently, these factors were standardized to a range of values between 0 and 1. The weights for each factor were established using the analytic hierarchy process (AHP) (Saaty, 1980).

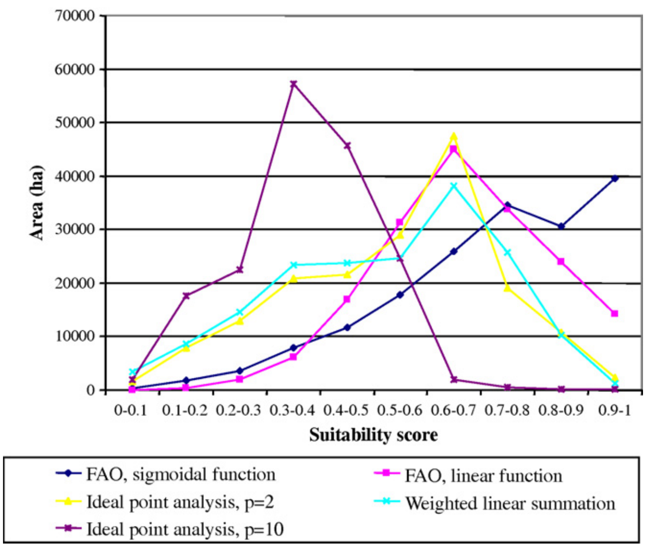

Fig. 9 – Suitability of the land for maize, as obtained using different techniques.

The methods employed in the land evaluation module produced continuous suitability maps for the 13 land uses. We selected the suitability maps obtained using ideal point analysis for $p = 2$ (see Fig. 9 for an example), as this option provides

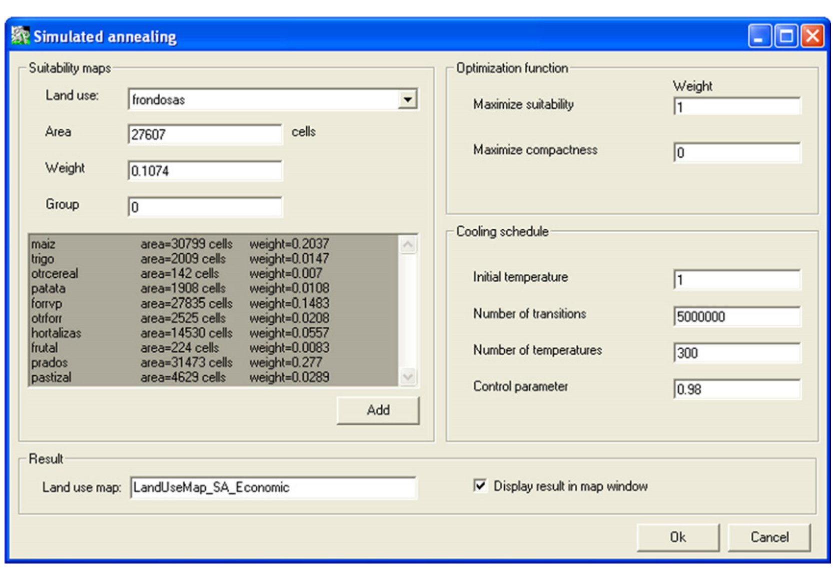

Fig. 8 – Form for the spatial allocation of land uses using 'simulated annealing'.

Table 1 – Factors for land suitability evaluation

Land-use requirements		Factors
Initial	Available	
Agronomic requirements		
Temperature regime	Bioclimatology	Free bioclimatic intensity (Carballeira et al., 1983)
Radiation regime		
Capacity to put down roots	Suitability for mechanisation, root penetration, and erosion risk	Productive capacity (Díaz-Fierros and Gil, 1984)
Fertility		
Flood tolerance		
Frost tolerance		
Water availability	Water regime	Water regime (Díaz-Fierros and Gil, 1984)
Oxygen availability		
Salinity, sodicity, toxicity		
Management requirements		
Suitability for mechanisation	Suitability for mechanisation, root penetration, and erosion risk	Productive capacity (Díaz-Fierros and Gil, 1984)
Technological level/mechanisation	Number of machines	No. of machines per farm in the municipality (INE, 2002)
Structural requirements	Land consolidation	Land consolidation area in the parish (Miranda, 2002)
Farm's area	Plot area	Size of the plot
Location	Location	Accesibility Distance to the road network Distance to markets
Marketing	Marketing	No. of farms that market their produce/km^2 (INE, 2002)
Agroforestry businesses	Presence of agroforestry business	No. of agricultural and forestry businesses in the municipality (INE, 2002)
Reforestations	Presence of reforestations	Reforested area in the municipality (Miranda, 2002)
Socioeconomic requirements		
Labour intensity	No. of farmers	Members of the special agricultural social security scheme per parish area/population
Capital intensity	Gross margin	Average gross margin of the farms in the municipality (INE, 2002)
Technical education level	Education level	Farmers with theoretical training in the municipality (INE, 2002)
Association level	Association level	No. of cooperative members in the parish
Attitude		
Environmental requirements		
Environmental impact	Protected areas	Areas protected by the 2001 Nature Network
Landscape impact	Protected areas	Areas protected by the 2001 Nature Network
Current land use	Current land use	Current land-use map Spanish forest map

an intermediate degree of compensation between the values of the suitability evaluation factors, and consequently, a medium risk level in decision-making (Santé and Crecente, 2005), as explained in Section 3.1.2. From these suitability maps, we obtained the land availability constraints for the linear programming model implemented in the area optimization module. An available area for each use was taken as that which had a suitability score higher than 0.7. This value was determined through trial and error, attempting to assign to each land use the best area for it but taking into account that this area should be greater than the actual area of each use.

The first step in determining the optimal areas for each land use was to adjust the parameters of the linear programming model. Each one of the 13 land uses was assigned a decision variable. Technical coefficients were introduced for each use. The values of the coefficients for gross margin were obtained from the Spanish Agricultural Census, the coefficients for production cost, labour and use of agrochemicals were extracted from an unpublished study of agricultural productive planning in 17 regions of Galicia, and the coefficients for the degree of naturalness were determined according to the scale put forward by Géhu and Géhu-Franck (1979), which

Table 2 – Factors and weights used in land-suitability evaluation for each land use

	Maize	Wheat	Other cereals	Potato	Pluriannual fodder	Other fodder	Vegetables	Fruit	Meadow	Pasture	Eucalyptus	Softwood forest	Hardwood forest
Productive capacity	0.1162	0.1160	0.1432	0.1151	0.0784	0.0958	0.0380	0.1440	0.1066	0.1149	0.0591	0.0264	0.4593
Free bioclimatic intensity											0.1188	0.1846	0.0951
Water regime	0.1162	0.1160	0.1432	0.1151	0.0387	0.0440	0.0380	0.1440	0.1774	0.1149			
No. of machines per farm in the municipality	0.0207	0.0147	0.0344	0.0320	0.0226	0.0253	0.0116	0.0291	0.0300	0.0439			
Land consolidation area in the parish	0.0571	0.0623	0.0579	0.0727	0.1291	0.0958	0.0083	0.0645	0.0559	0.0660			
Size of the plot	0.1952	0.1766	0.1432	0.1995	0.2065	0.1712	0.0083	0.1064	0.1057	0.1851	0.1188	0.0342	
Accessibility (m. road network/m^2)	0.0571	0.0623	0.0878	0.0744	0.1291	0.0958	0.0750	0.0402	0.0559	0.0660	0.0323	0.0204	
Distance to markets	0.0112	0.0190	0.0115	0.0170	0.0104	0.0119	0.1253	0.0686	0.0107	0.0110			
Distance to the road network	0.0112	0.0190	0.0115	0.0255	0.0104	0.0119	0.1253	0.0686	0.0107	0.0110			
No. of farms that market their produce/km^2	0.0112	0.0393	0.0115	0.0544	0.0153	0.0140	0.1890		0.0179	0.0191			
No. of agribusinesses in the municipality	0.0341	0.0190	0.0228	0.0143	0.0227	0.0252	0.0750	0.0321	0.0300	0.0191			
No. of forestry businesses in the municipality											0.0177	0.0543	
Reforested area in the municipality											0.0177	0.0543	
Members of the special agricultural social security scheme per parish area/population	0.0560	0.0623	0.0484	0.0272	0.0524	0.0599	0.0190	0.0163	0.0559	0.0324			
Average gross margin of the farms in the municipality	0.0117	0.0105	0.0170	0.0104	0.0170	0.0186	0.0190	0.0099	0.0107	0.0110			
Farmers with theoretical training in the municipality	0.0080	0.0080	0.0085	0.0080	0.0075	0.0078	0.0169	0.0099	0.0079	0.0078			
No. of cooperative members in the parish	0.0893	0.0283	0.0228	0.0367	0.0533	0.0608	0.0289	0.0163	0.0559	0.0377			
Current distribution of land uses	0.2045	0.2465	0.2365	0.1978	0.2065	0.2619	0.2221	0.2501	0.2687	0.2600	0.2584	0.2578	0.1928
Spanish forest map											0.2584	0.2578	0.1928
Areas protected by the 2001 Nature Network											0.1188	0.1103	0.0599

Table 3 – Outline of the objective priorities for the linear programming model in the three planning scenarios

Scenario	Option	Objective priority[a]						Objective weights						Aspiration levels (%) of objectives					
		GM	PC	RE	AL	AC	NLU	GM	PC	RE	AL	AC	NLU	GM	PC	RE	AL	AC	NLU
Economic	1	1°	2°	3°	4°	5°	6°	25	20	15	10	5	1	100	95	90	85	80	75
	2	1°	2°	3°	4°	6°	5°	25	20	15	10	1	5	100	95	90	85	75	80
	3	1°	2°	4°	3°	5°	6°	25	20	10	15	5	1	100	95	85	90	80	75
	4	1°	2°	4°	3°	6°	5°	25	20	10	15	1	5	100	95	85	90	75	80
	5	2°	1°	3°	4°	5°	6°	20	25	15	10	5	1	95	100	90	85	80	75
	6	2°	1°	3°	4°	6°	5°	20	25	15	10	1	5	95	100	90	85	75	80
	7	2°	1°	4°	3°	5°	6°	20	25	10	15	5	1	95	100	85	90	80	75
	8	2°	1°	4°	3°	6°	5°	20	25	10	15	1	5	95	100	85	90	75	80
Social	1	3°	4°	1°	2°	5°	6°	15	10	25	20	5	1	90	85	100	95	80	75
	2	3°	4°	1°	2°	6°	5°	15	10	25	20	1	5	90	85	100	95	75	80
	3	4°	3°	1°	2°	5°	6°	10	15	25	20	5	1	85	90	100	95	80	75
	4	4°	3°	1°	2°	6°	5°	10	15	25	20	1	5	85	90	100	95	75	80
	5	3°	4°	2°	1°	5°	6°	15	10	20	25	5	1	90	85	95	100	80	75
	6	3°	4°	2°	1°	6°	5°	15	10	20	25	1	5	90	85	95	100	75	80
	7	4°	3°	2°	1°	5°	6°	10	15	20	25	5	1	85	90	95	100	80	75
	8	4°	3°	2°	1°	6°	5°	10	15	20	25	1	5	85	90	95	100	75	80
Environmental	1	5°	6°	3°	4°	1°	2°	5	1	15	10	25	20	80	75	90	85	100	95
	2	6°	5°	3°	4°	1°	2°	1	5	15	10	25	20	75	80	90	85	100	95
	3	5°	6°	4°	3°	1°	2°	5	1	10	15	25	20	80	75	85	90	100	95
	4	6°	5°	4°	3°	1°	2°	1	5	10	15	25	20	75	80	85	90	100	95
	5	5°	6°	3°	4°	2°	1°	5	1	15	10	20	25	80	75	90	85	95	100
	6	6°	5°	3°	4°	2°	1°	1	5	15	10	20	25	75	80	90	85	95	100
	7	5°	6°	4°	3°	2°	1°	5	1	10	15	20	25	80	75	85	90	95	100
	8	6°	5°	4°	3°	2°	1°	1	5	10	15	20	25	75	80	85	90	95	100

[a] GM, gross margin; PC, production costs; RE, rural employment; AL, agricultural land; AC, use of agrochemicals; NLU, naturalness of land use.

Table 4 – Areas and weights assigned to the land uses in each scenario

	Economic scenario		Social scenario		Environmental scenario	
	Area (ha—no. of cells)	Weight	Area (ha—no. of cells)	Weight	Area (ha—no. of cells)	Weight
Maize	30,799	0.2037	16,701	0.0557	16 701	0.0557
Wheat	2,009	0.0147	2,009	0.0147	2009	0.0289
Other cereals	142	0.0070	142	0.0070	142	0.0070
Potato	1,908	0.0108	1,908	0.0108	1908	0.0208
Pluriannual fodder	27,835	0.1483	27,835	0.1483	27 835	0.1483
Other fodder crops	2,525	0.0208	3,571	0.0208	444	0.0147
Vegetables	14,530	0.0557	206	0.0083	206	0.0083
Fruit	224	0.0083	33,566	0.2770	224	0.0108
Meadow	31,473	0.2770	31,473	0.2037	40 679	0.2770
Pasture	4,629	0.0289	4,629	0.0401	20 728	0.1074
Eucalyptus	7,747	0.0401	4,269	0.0289	4269	0.0401
Softwood forest	22,161	0.0773	19,673	0.0773	19 673	0.0773
Hardwood forest	27,607	0.1074	27,607	0.1074	38 771	0.2037

assigns a naturalness index between 0 (urban systems) and 10 (natural and indigenous complex structures) to the landscape according to the type of vegetation, the degree of modification of the soil, and human intervention. The values of the right-hand side were also introduced: land availability and demand for each use and total area.

Three types of decision-makers were then considered to reflect on the different priorities of the agents involved in the process: farmers, environmentalists, and the local community. The farmers give priority to productivity and the economic profit of the land use (economic scenario). Environmental associations give priority to naturalness and the low use of agrochemicals in the land uses (environmental scenario). The rest of the local community were interested in boosting rural employment (social scenario). These scenarios are expressed in the different weights, priorities, or aspiration levels assigned to each objective (Table 3). Once the model and the planning scenarios had been defined, the system's dif-

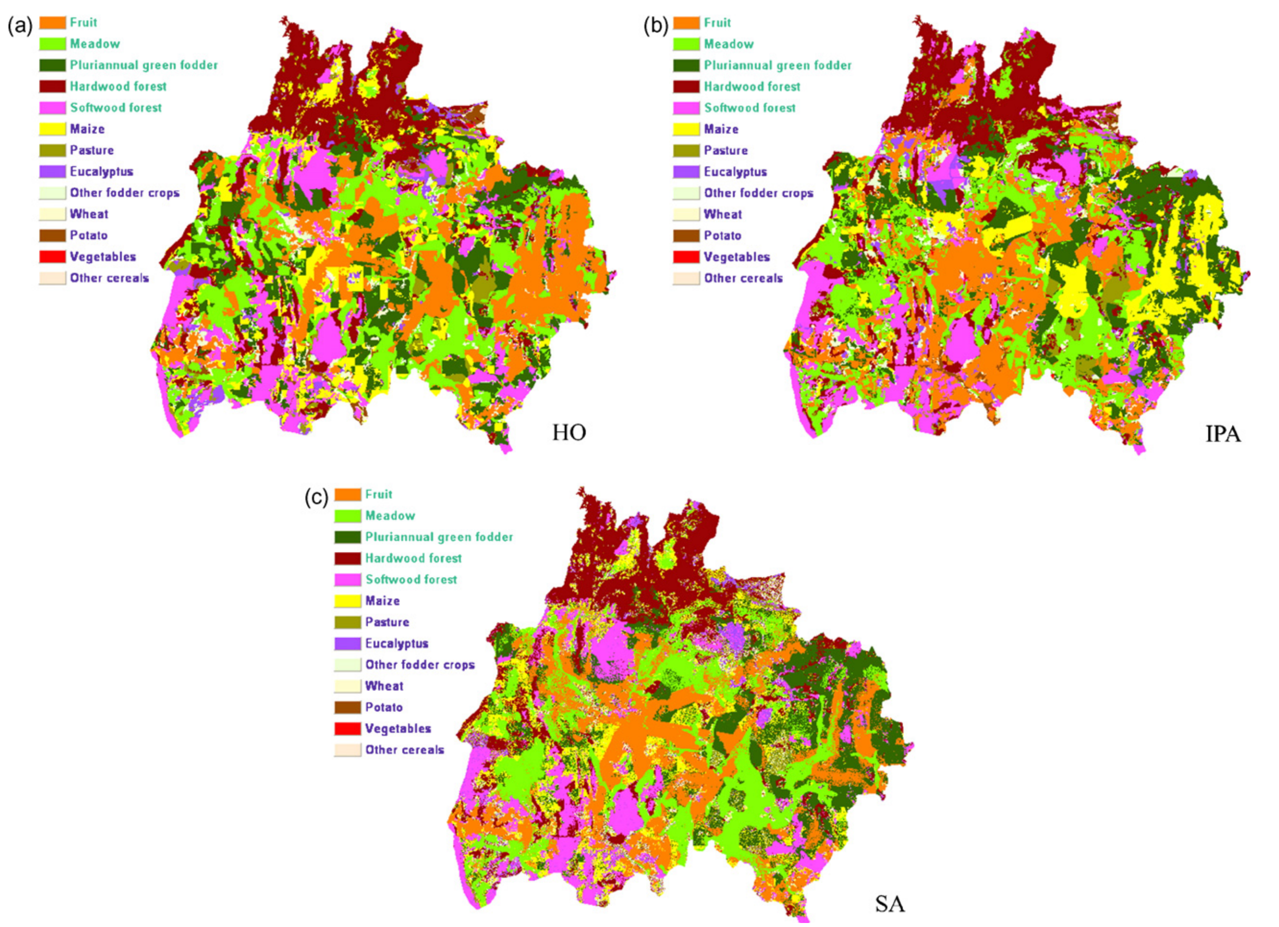

Fig. 10 – Land-use maps obtained for the social scenario using: (a) hierarchical optimization (HO), (b) ideal point analysis (IPA), and (c) simulated annealing (SA).

Table 5 – Evaluation of the land-use maps obtained using the three spatial allocation methods installed in RULES

	Hierarchical optimization	Ideal point analysis	Simulated annealing ($\alpha_1 = 1$, $\alpha_2 = 0$)
Economic scenario			
Suitability	122,726	125,146	128,705
Average area (ha)	25.33	22.94	14.86
Zone perimeter (km)	13779.6	14879.6	16184.8
No zones	7352	8195	12,674
Largest zone (ha)	19,680	17,548	18,511
Smallest zone (ha)	1	1	1
Calculation time	5 min	19 min	4 h 57 min
Social scenario			
Suitability	124,354	126,369	127,979
Average area (ha)	27.10	23.21	6.58
Zone perimeters (km)	13310.8	14381.8	24187.0
No. of zones	6872	8071	28,529
Largest zone (ha)	17,254	18,720	17,155
Smallest zone (ha)	1	1	1
Calculation time	5 min	19 min	4 h 56 min
Environmental scenario			
Suitability	122,867	126,277	126,887
Average area (ha)	25.70	24.08	7.69
Zone perimeter (km)	13378.8	13911.0	21991.0
No. of zones	7221	7812	24,444
Largest zone (ha)	22,244	20,969	21,012
Smallest zone (ha)	1	1	1
Calculation time	5 min	19 min	4 h 56 min

ferent multiobjective techniques were applied to resolve the model (Santé and Crecente, 2007).

In the economic scenario, we selected the areas obtained using the STEP method, as this was the method that produced the best compensation between the achievement rates for the two conflicting economic objectives. The results of option 4 were used, as they had the highest average achievement rate for the economic objectives. The STEP method was also used in the social scenario, as it simultaneously provided a higher achievement rate for the two social objectives. In this case, option 1 was selected, as it had the highest average achievement rate for the social objectives. In the environmental scenario, the goal programming method simultaneously produced a higher achievement rate for the two environmental objectives. There was no difference in the solution produced by the various options. Table 4 summarizes the areas and weights assigned to each land use in the three planning scenarios. The weights, needed for spatial allocation methods, were calculated by means of the AHP on the basis of comparing pairs of land uses according to their economic and environmental importance and their effect on rural employment.

To obtain the spatial allocation of land uses, we first used the hierarchical optimization process. We only indicated the order of priority of land uses, according to the weights in Table 4. The weights obtained using AHP were then used in the ideal point analysis. A value of 2 was used for the parameter p. Finally, the heuristic algorithm was applied to maximize both the suitability and compactness of the areas for each land use. In the first application of this algorithm, we only considered the member of the cost function that maximizes suitability; in this way, the results could be compared with those obtained in the two previous methods (see Fig. 10 as an example).

In the three scenarios, the simulated annealing technique produced the best overall suitability for the land-use map, at the expense of a reduction in the compactness of the land-use regions (Table 5). Simulated annealing provided a suitability that was between 2.91 and 4.87% higher than that obtained using hierarchical optimization, and between 0.48 and 2.84% higher than that obtained using ideal point analysis; however, the greatest compactness of the land-use zones was obtained using the hierarchical optimization method. This method produced an average zone area that was between 6.73 and 16.76% larger than that obtained with ideal point analysis, and between 70.46 and 311.85% larger than that obtained using simulated annealing. The method also produced a perimeter that was between 3.83 and 7.44% shorter than that produced using the ideal point analysis, and between 14.86 and 44.97% shorter than that obtained using simulated annealing.

Simulated annealing was then applied by assigning a weight of 0.5 to both the suitability maximization and the perimeter minimization (Fig. 11). These weights provided the best trade-off between the suitability and the spatial characteristics of the land-use map in previous analysis (Santé et al., 2008). The consideration of compactness in the energy function of the heuristic algorithm helped to notably improve the spatial distribution of the land-use zones (the perimeter was reduced by between 54.10 and 62.47%; the average area increased by between approximately 2 and 4 times). These improvements were made at the expense of a small reduction in the suitability of between 2.07 and 3.74% (Table 6); accordingly, in this case simulated annealing produced lower suitability than that obtained using hierarchical optimization and ideal point analysis. The only exception to this finding was the economic scenario, in which simulated annealing continued to provide greater suitability than the other techniques.

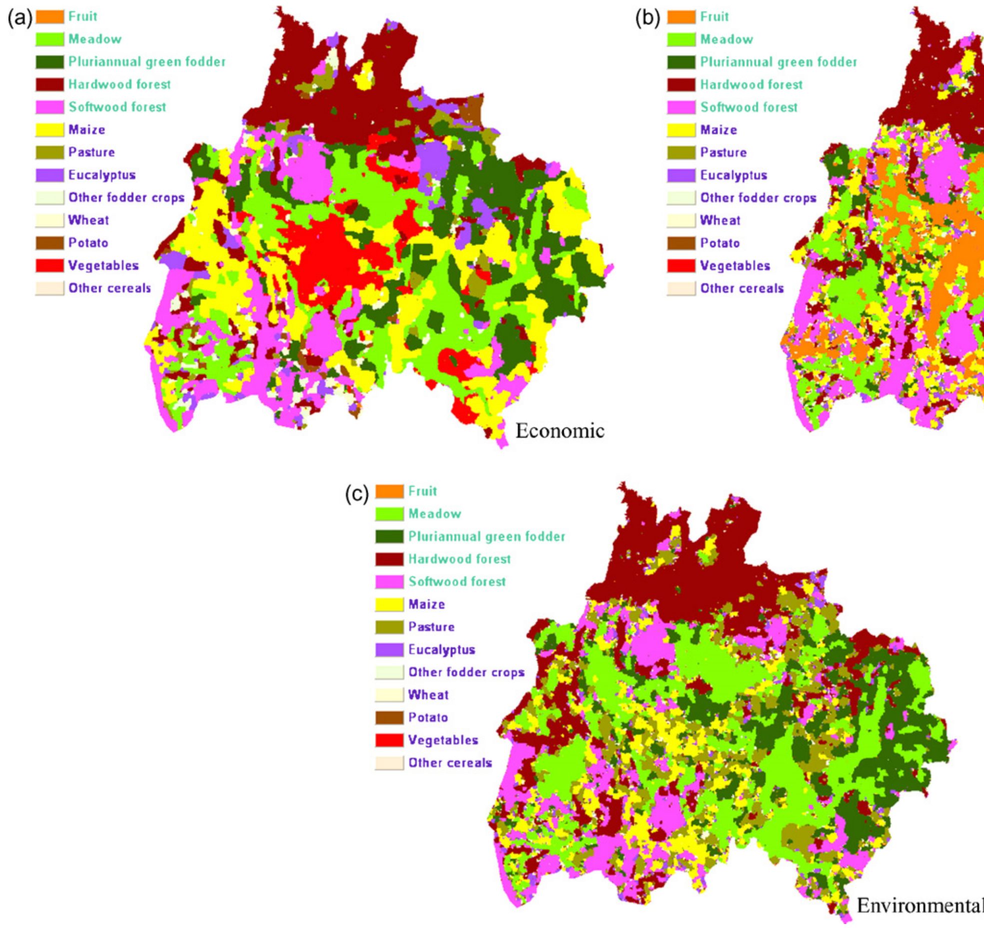

Fig. 11 – Land-use maps obtained using simulated annealing with a weight of 0.5 in the two terms of the cost function for the (a) economic, (b) social, and (c) environmental scenarios.

Table 6 – Indicators for evaluating the land-use maps obtained using simulated annealing

	Economic scenario	Social scenario	Environmental scenario
Suitability	126,037	123,528	122,316
Average area (ha)	80.99	25.12	28.20
Perimeter length (km)	6073.8	10660.2	10094.8
No. of zones	2284	7297	6524
Largest zone (ha)	21,649	20,301	22,673
Smallest zone (ha)	1	1	1

The same weight is given to suitability and compactness.

The values of compactness indicators for simulated annealing are better than those for hierarchical optimization and ideal point analysis, except in the case of the average area and the number of zones generated by hierarchical optimization in the social scenario. Therefore, we can state that this option produces the most compact spatial distribution of the zones in the land-use map.

The availability of a technique that enables the consideration of spatial constraints compensates the additional requirements of simulated annealing, such as the higher computer demand. Despite the long processing time, this approach remains faster than manually defining the limits of the land uses by means of the traditional process. Over a period of several days, technicians can generate several alternative land-use plans that can be used subsequently in public workshops to show the community the consequences of different decisions in terms of the land-use scenario.

5. Conclusions

This paper presents a support tool for rural land-use planning. The tool achieves an appropriate balance between scientific precision and applicability under the constraints of time, information, and expert personnel. The proposed system manages complex problems in which many factors need to be considered and a large amount of data handled, as well as enabling users to reflect on different and conflicting interests. The system explores land-use alternatives and the consequences of certain technical, socioeconomic, or environmental decisions. This type of analysis is useful in political and social debates on future land uses, and in the design of strategic land-use policies.

We demonstrated RULES' potential in generating alternative scenarios that reflect the different objectives and perspectives of the agents involved in a land-use planning process. These scenarios are defined by the user by modifying the evaluation factors, the weights assigned to the land uses, and the plan objectives; the inclusion or exclusion of certain uses; and the characteristics of the agroforestry uses (e.g., the requirements, technical coefficients, and demand), among others.

The system was applied in the Terra Chá region of NW Spain to illustrate its potential as a decision support tool and its effectiveness in resolving large-scale problems (306,691 cells) that involve the analysis of a large amount of spatial data. In this application the strengths and weaknesses of the system could be identified.

The first ones include its flexibility in dealing with any group of data, its interactivity with the user, and the way it can be adapted to the different planning strategies and perspectives of the agents involved in the planning process. Despite the complexity of the operational and IT aspects, the structure of RULES is easy for the user to assimilate, as it is organised into three stages that the planners are familiar with. Another advantage is the availability within each module of a group of different techniques. This permits two possibilities; all methods can be tried and the best or preferred solution selected, or the user can select "a priori" the most appropriate technique for each situation according to his/her experience. Generally, the first option will be more interesting for inexpert users or for group decision-making, and the second one for experienced planners. The modular design of the tool, which uses standard programming languages and methodologies, facilitates maintenance and future broadening of its scope of application.

On the other hand, although RULES is an interactive tool that promotes debate between the different interest groups, one of its main limitations is that it lacks a mathematical model that enables different users' opinion to be considered simultaneously. There is also a lack of a scenario evaluation module, which would speed up feedback in the process. We are currently working on this.

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