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LUSE, a decision support system for exploration of rural land use allocation: Application to the Terra Chá district of Galicia (N.W. Spain)

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Abstract

This article describes LUSE, a system for exploration of rural land use allocations (total area devoted to each kind of use) by multiobjective linear programming methods. The objectives pursued are maximization of gross margin, employment in agriculture, land use naturalness and traditional rural landscape, and minimization of production costs and use of agrochemicals. The constraints on the areas devoted to the land uses considered in addition to those imposed by their joint and individual availabilities, are that they must reach levels considered to satisfy existing demand for those uses or their products, and that the areas devoted to maize and fodder must be sufficient for maintenance of dairy farm production. The program generates comprehensive samples of the Pareto-optimal set, and also allows interactive convergence on a solution that is satisfactory to the decision-maker or interactive exploration of the Pareto-optimal set. The system is currently parameterized for use in an area of Galicia (N.W. Spain), but is easily adaptable to other geographic locations.

Keywords: Rural land use planning; Land use allocation; Multiobjective linear programming

1. Introduction

Like many other rural areas of Europe, Galicia (N.W. Spain) is undergoing rapid changes involving depopulation, reduction of agricultural activity, scattered house building, the destruction of the traditional landscape, and the reservation of land for recreational or conservational roles. In this context, there is an increasing demand for land use planning tools that are flexible enough to contribute usefully to the task of allocating land use in a way that reconciles, as much as possible, such frequently conflicting objectives as economic viability, maintenance of social structure, and environmental conservation. Formal multiobjective programming techniques allow the planner to gain pre-decision insight into the problem by examination of the advantages and disadvantages of potential allocation schemes and the consequences of giving priority to one or another objective (van Ittersum et al., 1998).

Most applications of mathematical programming to rural land use allocation have employed linear models. Examples of the use of single-objective linear programming models include that of Chuvieco (1993), designed to minimize rural unemployment by maximizing the area devoted to labour-intensive uses; and that of Campbell et al. (1992), designed to balance local production and imports in Antigua in such a way as to minimize overall cost while satisfying demand. In some models, the decision variables have not been the areas devoted to each kind of land use, but rather the areas that are to undergo a change of use (Shukla et al., 2003).

The increasing complexity involved in agricultural land planning makes multiobjective models increasingly necessary. When multiple objectives must be taken into account (total production, gross value, net profit, cost minimization,

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prevention of erosion, self-sufficiency, etc), single-objective models are of limited help to the land use planner. Multiobjective linear programming and related techniques provide a methodology for analyzing the relationships and conflicts among these objectives. Although there is extensive literature available on linear programming applied to farm planning, models designed for optimization of rural land use areas in a multiobjective context are less common. One of the most widely employed multiobjective methods developed to tackle such situations is goal programming. This approach has been used, for example, by Ive and Cocks (1983) in Australia; by Giupponi and Rosato (1998), who considered the choice of land use and farming system in the Venice Lagoon Basin given the joint objectives of profit maximization and risk avoidance; by Oliveira et al. (2003) for management of a Brazilian estate combining forestry, buffalo breeding and tourism; and by Zander and Kächele (1999), whose overall concern was sustainable development. Multiobjective methods other than goal programming that have been employed include the generation of a comprehensive sample of the Pareto-optimal set by the weighting method (Shakya and Leuschner, 1990) or by the constraint method (van Leeuwen et al., 2001).

Comprehensive sampling of the Pareto-optimal set, the classical way of presenting the decision-maker with a panorama of candidate solutions, tends to generate a bewilderingly large amount of information. It is often more helpful to impose some scheme for combining the multiple objectives into one single objective, and then explore the consequences of varying the relative weights or priorities given to the various objectives within this scheme. This kind of procedure amounts to sampling only those regions of the Pareto-optimal set that correspond to a set of diverse management philosophies regarding the relative importance of different objectives, and is becoming increasingly useful with the growing involvement of stakeholders with conflicting interests in land use planning (van Ittersum et al., 2004). It can be especially enlightening when the exploration can proceed interactively, so that there is an exchange of information between the decision-maker and the system. This allows the decision-maker's preferred solution to be provided using implicit information supplied by him/her. This could be, for example, answers to questions such as "which objectives can be relaxed to improve others?" or "which solution is preferred in this group?". The particular approach known as Interactive Multiple Goal Linear Programming (IMGLP) has been used in this way for land use planning (Suhaedi et al., 2002), analysis of agricultural development policies (De Wit et al., 1988), evaluation of land use strategies (Lu et al., 2004), and has been even implemented in an application called GOAL-QUASI to explore future land use options in the European Union (van Ittersum, 1995). Another approach, Aspiration/Reservation-Based Decision Support (Fischer and Makowski, 1996), has been implemented in a tool called AEZWIN (Fischer et al., 1998) to expand FAO's Agro-Ecological Zoning (AEZ). The AEZ and a multiobjective linear programming model were used by Agrell et al. (2004) to develop a decision support system for exploration of crop areas. The ADELAIS multiobjective linear programming software has been applied by Siskos et al. (1994) to cropping pattern planning.

In this paper we describe LUSE, a system that allows the exploration of rural land use allocations by a variety of multiobjective linear programming methods. The objectives pursued are maximization of gross margin, employment in agriculture, land use naturalness and traditional rural landscape, and minimization of production costs and use of agrochemicals. The constraints on the areas devoted to the land uses considered, in addition to those imposed by their joint and individual availabilities, are that they must reach levels considered to satisfy existing demand for those uses or their products, and that the areas devoted to maize and fodder must be sufficient for maintenance of dairy farm production. LUSE is currently parameterized for use in the Terra Chá area of Galicia (N.W. Spain), but is easily adaptable to other geographic locations. We illustrate its use here by comparing the results afforded by the various methods it implements when three different objective-type priority philosophies are imposed: economic > social > environmental; social > economic > environmental; and environmental > social > economic.

2. The LUSE model

2.1. The study area

For better appreciation of the objectives and constraints incorporated in the model, it is perhaps helpful to be familiar with the general characteristics of the area to be analysed in Section 4, which is fairly representative of numerous other areas of Galicia and other regions of Spain. The 1832 km^2 of Terra Chá (Fig. 1) are distributed between a broad southern plain in which the main towns and most farming activity are located, and a more hilly northern area devoted predominantly to forestry and environmental protection. The farms of the southern plain are mostly dairy farms with their farmland devoted to fodder crops.

2.2. The decision variables

The decision variables handled by LUSE are the areas X_i devoted to the thirteen main agroforestry crops, products or uses registered in Terra Chá in 2001: maize, wheat, other cereals (rye, barley, oats), potatoes, perennial green fodder, other fodder crops (beet, turnip), vegetables, fruit, meadow, pasture, eucalyptus, softwoods, and hardwoods.

2.3. The objectives of the model

The LUSE model incorporates two objectives of each of three kinds: economic, social and environmental.

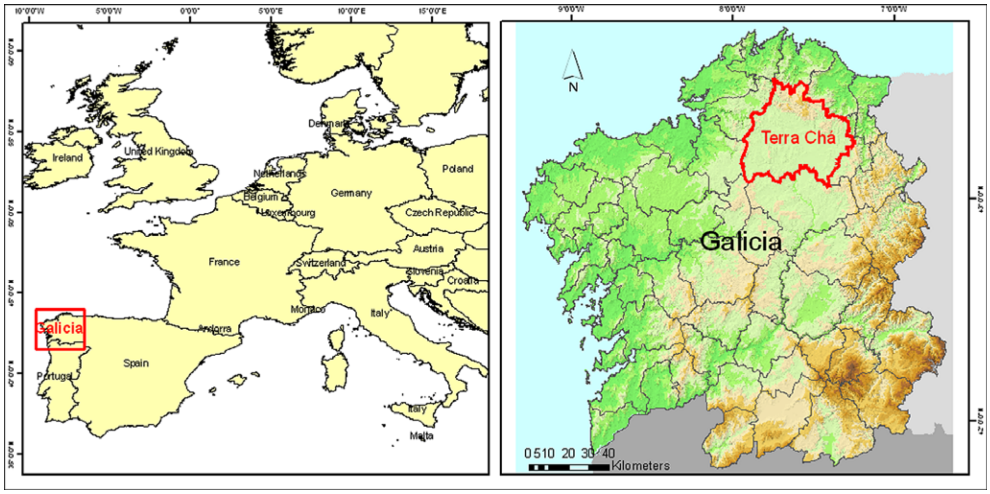

Fig. 1. Location of the study area.

2.3.1. Economic objectives

Economic objectives include the maximization of profit (Shukla et al., 2003; Suhaedi et al., 2002; van Leeuwen et al., 2001), of gross margin (Rehman and Romero, 1993; Siskos et al., 1994), and of total net agricultural return, calculated as the difference between gross production value and total costs (Lu et al., 2004). In LUSE the first of our economic objectives, O_1, is maximization of gross margin (Eq. (1))

$$O_1 = \mathrm{TGM} = \sum_i \mathrm{GM}_i X_i \quad (1)$$

where GM_i is the gross margin per hectare of land use i. The values of the coefficients GM_i in the model as currently parameterized for Terra Chá were obtained from the Spanish Agricultural Census or, in the case of forestry uses, from an unpublished study of 17 areas of Galicia carried out in collaboration with the agricultural engineering company Eido Galicia S. L. (hereinafter "the 17-area study"); these are listed in Table 1. The Spanish Agricultural Census defines the gross margin (Margen Bruto Estándar) as the balance between the monetary value of gross production and the value of certain direct costs inherent in that production. This concept does not include machinery costs or waged labour. For this reason we also sought to minimize total production costs (Eq. (2))

$$O_2 = \mathrm{TPC} = \sum_i \mathrm{PC}_i X_i \quad (2)$$

where PC_i is the production cost per hectare of land use i determined in the 17-area study (Table 1). These two economic objectives are considered simultaneously in other agricultural land use models (i.e. Dogliotti et al., 2004; Lu et al., 2004), as occasionally capital availability and therefore production costs place limits on production independently of the subsequent profit.

2.3.2. Social objectives

Our broad social aims are the conservation of rural landscape and the maintenance of rural population. They

Table 1
Land use technical data required by the objective functions of LUSE[a]

Decision variable	Land use	Gross margin (€/ha)	Production costs (€/ha)	Labour needs (h/ha)	Fertilizer needs (kg/ha)	Biocide needs (treatments/ha)	Naturalness
X_1	Maize	970	1150	13	445	2	3
X_2	Wheat	435	589	16	125	2	3
X_3	Other cereals	322	572	16	114	2	3
X_4	Potato	1611	2010	43	1165	7	2
X_5	Perennial green fodder	490	687	12	425	2	4
X_6	Other fodder crops	623	926	151	365	2	3
X_7	Vegetables	4367	6024	606	698	3.6	2
X_8	Fruit	2549	3796	452	394	3.5	2
X_9	Meadow	140	374	7	250	0	6
X_{10}	Pasture	140	157	2	179	0	7
X_{11}	Eucalyptus	303	87	5	3	0	1
X_{12}	Softwoods	293	106	13	1	0	1
X_{13}	Hardwoods	121	149	11	1	0	10

[a] Data refer to a one-year, one-crop cycle.

are closely connected, since rural landscape means farmland, and farmland must be worked. LUSE operationalizes these concerns through two specific objectives. The first is the maximization of the total area of land (Eq. (3)) devoted to agricultural uses (maize, wheat, other cereals, potato, perennial green fodder, other fodder crops, vegetables, fruit and meadow)

$$O_3 = \text{TAL} = \sum\nolimits_{i \in \text{AU}} X_i \tag{3}$$

where AU is the set of agricultural uses. The second is the maximization of the total number of man–hours per year (Eq. (4)) employed in the land uses considered

$$O_4 = \text{TMH} = \sum\nolimits_i \text{MH}_i X_i \tag{4}$$

where MH_i is the number of man–hours required per year per hectare by land use i, as determined in the 17-area study (Table 1). Chuvieco (1993) sought to minimize rural unemployment by maximizing the area devoted to labour-intensive land uses, while Shukla et al. (2003, 1994); Lu et al. (2004) and Suhaedi et al. (2002) maximized the total number of workers required for all uses or, almost equivalently, the total number of man–days of labour required. By contrast, van Leeuwen et al. (2001) sought to limit labour requirements by minimizing the number of man–days per year and Siskos et al. (1994) did so by minimizing seasonal jobs.

2.3.3. Environmental objectives

Environmental objectives play a leading role in the systems developed by Suhaedi et al. (2002), who sought to minimize erosion, and by Lu et al. (2004), who sought to minimize soil loss, cropped land, nitrogenated fertilizer use, biocide use, and nitrogen losses. With a different kind of target region, Chuvieco (1993) incorporated ecological concerns by means of a constraint requiring the conservation of at least 75% of natural vegetation. Two environmental objectives were established in LUSE: the minimization of the total use of agrochemicals (Eq. (5)) and the maximization of the naturalness of land uses (Eq. (6)). The first objective, TAC, is considered because the level of use of agrochemical products is a good indicator of land use intensity (Wascher, 2000), whereas the naturalness of land use, NLU is an indicator of the state of habitat conservation

$$O_5 = \text{TAC} = \sum\nolimits_i \text{AC}_i X_i \tag{5}$$

$$O_6 = \text{NLU} = \sum\nolimits_i N_i X_i \tag{6}$$

where N_i is the naturalness of land use i as quantified according to the scale put forward by Géhu and Géhu-Franck (1979). This scale assigns a naturalness index between 0 (urban systems) and 10 (natural and indigenous complex structures which have not undergone soil modification or human exploitation) to the landscape according to the structure of the vegetation, the characteristics of the flora and the degree of modification of the soil and human intervention. AC_i is a coefficient calculated by the Eq. (7) that, under the assumption that crops will be harvested just once a year, combines the fertilizer and biocide requirements of land use i that were determined in the 17-area study (Table 1)

$$\text{AC}_i = (B_i - B_{\min})/(B_{\max} - B_{\min}) + (F_i - F_{\min})/(F_{\max} - F_{\min}) \tag{7}$$

where B_i and F_i are respectively the number of biocide applications and the quantity of fertilizer (kg/ha) required per year by land use i, and the subscripts max and min indicate the maximum and minimum values of these parameters in Table 1.

2.4. Constraints

2.4.1. General constraints

The land use areas X_i are each subject to the constraint that X_i cannot exceed the total area of land in the study area that will sustain land use i, which for the purposes of this study was taken to be land with a suitability value of 0.7 or greater for use i in the land suitability maps calculated in Santé and Crecente (2005), $S_{i,0.7}$

$$X_i \leqslant S_{i,0.7} \quad (i = 1, \ldots, 13)$$

Also, of course, the sum of the X_i cannot exceed ST, the total area of land in the study area that will sustain any of the uses considered (i.e. that has a suitability of 0.7 or greater for any of these uses)

$$\sum\nolimits_i X_i \leqslant \text{ST}$$

In addition to these upper bounds, LUSE also imposes on X_i the lower bound that it cannot be less than the area dedicated to that land use by farms according to the Agricultural Census (2001)

$$X_i \geqslant X_{i,2001}$$

The purpose of this lower bound is to ensure satisfaction of current demand for the use, as it is the area required to maintain the current structure of farms and implements an ecological requirement for conservation of 100% of current hardwood forest. The total area of all land uses in 2001 does not coincide with the total area available in the region as there is a large area with scrub-forest which could be dedicated to agricultural or forestry uses and in addition there are agricultural and forestry areas that are not included in the Agricultural Census.

2.4.2. Special constraints

Two of the land uses handled by LUSE are subjected to further constraints. In order to prevent the dependence of dairy farmers on expensive industrial concentrates, the areas of land devoted to maize (X_1) and perennial green fodder (X_5) must be sufficient to maintain the number of dairy cows in the study area, VL

$$X_1 \geqslant 0.3\text{VL}$$

$$X_5 \geqslant 0.5\text{VL}$$

where the coefficients 0.3 and 0.5 have been derived from the dairy cow fodder requirements published by López (1997).

3. The analytical tools of LUSE

The overall structure of the LUSE system is shown in Fig. 2. It comprises the model described in the previous section; an analysis module capable of analysing this model by means of various multiobjective methods afforded by three submodules; and a graphical user interface for interaction with these submodules or, at a different level, for modification of the model.

In this figure the workflow of the system can also be seen. Firstly the decision-maker must define the optimization model by means of the selection or editing of objectives, land uses, production technologies available (through the modification of technological coefficients), or the constraints of land availability and demand for each use. Once the model is defined, the software provides several options for its resolution based on the degree of intervention of the decision-maker. The first submodule of the system allows generating techniques to be applied in order to approximate the set of efficient solutions. This allows the user to get an idea of the set of possible solutions and to gain an insight into the problem. Consequently, these techniques can be used during a first stage of the decision-making process, consisting of the learning of the problem structure. Next the decision-maker can use this information to build his/her preference scheme. To select the solutions closest to this scheme the decision-maker can assign his/her preferences *a priori* by means of the weights allocated to each objective in goal programming or can follow a more interactive procedure through the application of techniques with progressive preference assignment. This type of technique provides information throughout the process on the possible consequences of the decisions taken by means of graphs showing the achievement rates of objectives, so that the decision-maker progressively learns the trade-offs between objectives.

3.1. Generating techniques

The first analytical submodule allows sampling of the Pareto-optimal set by two solution-generating techniques: the weighting method (Cohon, 1978) and the constraint method (Goicoechea et al., 1982). To execute the weighting method, LUSE requires the user to specify the set of weights to be applied to each objective. In applying the constraint method, LUSE is based on the algorithm described in Azapagic and Clift (1999). All objectives but one are converted into constraints and the values of the constrained objectives are varied systematically by using the Eq. (8)

$$O_{j,\min} + (t/(r-1))(O_{j,\max} - O_{j,\min}) \quad (t = 0, \ldots, r-1) \tag{8}$$

where $O_{j,\max}$ and $O_{j,\min}$ are respectively the maximum and minimum values of the objective j in the payoff matrix, and the objective optimized and the number of different values of right-hand sides of the constrained objectives r are selected by the user. The user can choose between the two techniques: the constraint method, which is systematically applicable in that the user only needs to introduce the value of parameter r, or the weighting method, in which the selection of the set of weights is more complicated but the user can have more of an influence on the generated solutions by means of these weights.

3.2. Goal programming with a priori objective priorities

The second of LUSE's analytical submodules implements goal programming. The targets for the different objectives were obtained by individually optimizing each objective without considering the others. The user can specify the relative weights to be given to the objectives. If desired, options can be selected that force the specified weights to conform to one of three built-in objective-type priority rankings: one in which the economic objectives must be given greater weight than the social objectives, which in turn must be given greater weight than the environmental objectives (this option is labelled "Eco > Soc > Env" in the screenshot of Fig. 3); one in which the obligatory weighting order is social objectives > economic objectives > environmental objectives; and one in which the order is environmental objectives > social objectives > economic objectives. The metric used to measure overall deviation from the ideal point is the normalized one-sided city-block metric, i.e. there is no contribution from positive deviations from the ideal values of maximized objectives or negative deviations from those of

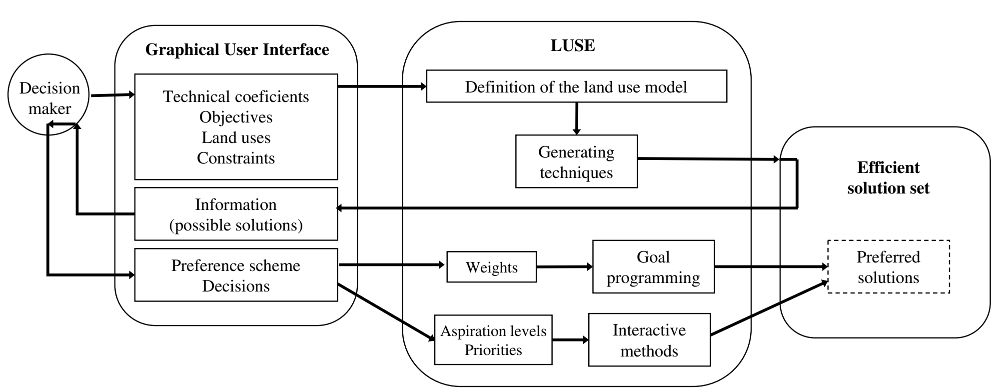

Fig. 2. The overall structure of LUSE.

minimized objectives, and the O_j component is normalized with respect to the ideal value of O_j. In order to assist the user to evaluate the result, a graph is provided that shows the achievement rate *Ach* of each objective, defined for maximized and minimized objectives respectively by Eqs. (9) and (10)

$$Ach = 100(O_j - O_{j,\min})/(O_{j,\max} - O_{j,\min}) \quad (9)$$

$$Ach = 100(O_{j,\max} - O_j)/(O_{j,\max} - O_{j,\min}) \quad (10)$$

where $O_{j,\max}$ is the maximum value of the objective O_j in the pay-off table, and $O_{j,\min}$ is the minimum value of the objective O_j in the pay-off table (note that the ideal value of O_j is $O_{j,\max}$ if O_j is maximized, and $O_{j,\min}$ if it is minimized).

3.3. Interactive techniques

LUSE's third analytical submodule allows the user to explore the Pareto-optimal set interactively by means of two different approaches. The first is the STEP method, in which at each step other than the first, what is essentially a goal-programming solution obtained by the system in the previous step can be responded to by the user by relaxing the goal, or aspiration level, corresponding to one of the objectives so as to favour others (see Cohon, 1978). In the LUSE implementation, goal modifications are made in terms of the tolerated percentage change *T* in achievement rate *Ach*: for a maximized objective O_j, the goal of which is relaxed in step *k*

$$Ach^{[i\geqslant k]} \geqslant (1-0.01T)Ach^{[i<k]}$$

and so

$$O_j^{[i\geqslant k]} \geqslant O_j^{[k-1]} - 0.01\ T(O_j^{[k-1]} - O_{j,\min})$$

where bracketed superscripts indicate the step in which the corresponding value is obtained.

In the second interactive method (Lu et al., 2004), the various objectives are successively optimized by means of single-objective optimizations in which the objectives preceding them in the priority order so constructed are subject to constraints of the form $O_j \geqslant O_j^* - \varepsilon_j$ (for a maximized objective) or $O_j \leqslant O_j^* + \varepsilon_j$ (for a minimized objective), where O_j^* is the value obtained for O_j when it was optimized. Fig. 4 shows a screenshot recorded following the second optimization in a typical run. At the top, the window still shows the values selected for the identity of the second objective (Production costs) and the tolerance ε_j introduced for the preceding objective (in this case Gross

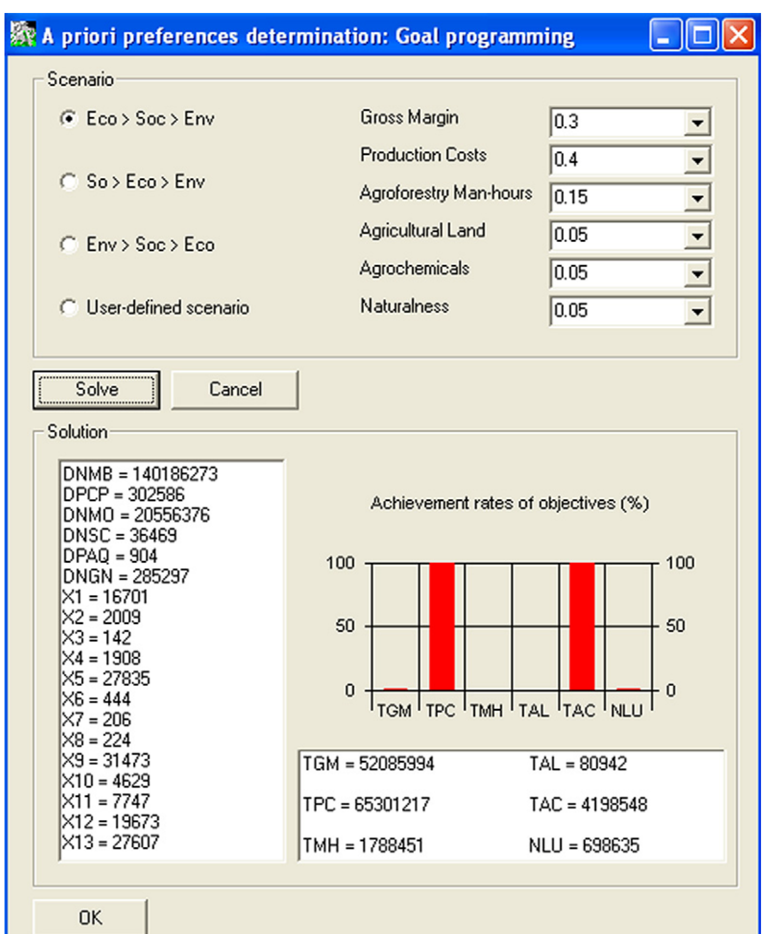

Fig. 3. LUSE goal programming window.

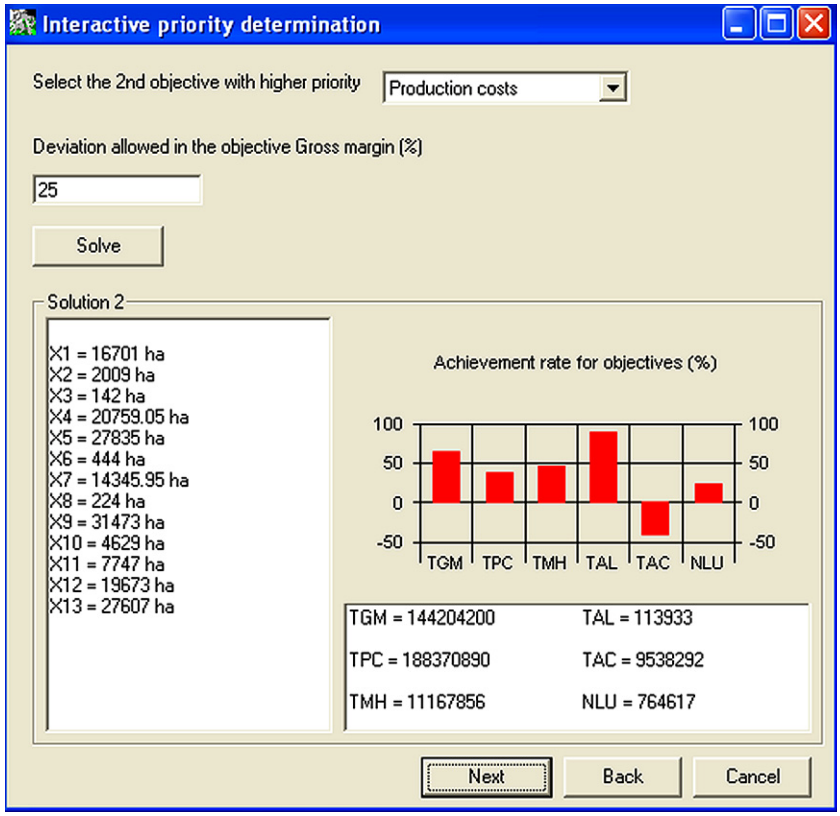

Fig. 4. LUSE window for application of the method of Lu et al. (2004).

Margin O_1), which is specified as a percentage of $O_{j,\max}$. At the bottom are the values of the decision variables at the solution point, the values of each objective function, and a graph of achievement rates. Note that the negative achievement rate for Agrochemicals is due to the current solution being the result of only the second of a series of single-objective optimizations; when all optimizations have been performed, all achievement rates are non-negative and the final solution is Pareto-optimal.

4. Illustrative analyses

To illustrate the performance of LUSE we compare the results afforded by the various methods it implements when they are applied to the Terra Chá data in accordance with the three objective-type priority rankings that in the case of the goal-programming method are available as built-in options: economic > social > environmental; social > economic > environmental; and environmental > social > economic.

4.1. Goal programming

To orient the application of goal programming, we first sampled the Pareto-optimal set using the weighting method, with weights that ranged between 0 and 100 and summed to 100. Several sets of weights were tried and an interval between weights of 5 units provided enough approximation of the non inferior set with medium computational costs. For each of the three objective-type priority rankings, all eight specific objective priority rankings that respected the given objective-type priorities were implemented using weights of 25, 20, 15, 10, 5 and 1 (see Table 2).

The solutions obtained by goal-programming using the above weighting schemes are compared in Fig. 5 with each other and with the *status quo*, i.e. the values of the decision variables X_i in 2001. With the Eco > Soc > Env philosophy, the only uses to which more land is devoted than in 2001 are forestry and, in some cases, meadowland (Fig. 5a). More specifically, when gross margin is given more weight than the other economic objective, production cost reduction, the areas of both eucalyptus and softwood forest always increase; and when production costs are given more weight than gross margin, the area of eucalyptus – which has lower production costs than softwood forest – rises to the maximum value allowed by the availability constraint. In both cases, weighting naturalness more than the other environmental objective, agrochemicals reduction, the area devoted to hardwood species also increases because this is the land use with the highest naturalness index. Also, when agricultural land maximization is given more weight than the other social objective, agroforestry man–hours, the area of meadowland generally increases because meadowland contributes to increasing agricultural land and forestry land uses do not.

Table 2
Weights used in goal programming

Objective-type priority ranking	Objective ranking	Objectives					
		Gross margin	Production costs	Agroforestry man–hours	Agricultural land	Agrochemicals	Naturalness
Eco > Soc > Env	1	25	20	15	10	5	1
	2	25	20	15	10	1	5
	3	25	20	10	15	5	1
	4	25	20	10	15	1	5
	5	20	25	15	10	5	1
	6	20	25	15	10	1	5
	7	20	25	10	15	5	1
	8	20	25	10	15	1	5
Soc > Eco > Env	1	15	10	25	20	5	1
	2	15	10	25	20	1	5
	3	10	15	25	20	5	1
	4	10	15	25	20	1	5
	5	15	10	20	25	5	1
	6	15	10	20	25	1	5
	7	10	15	20	25	5	1
	8	10	15	20	25	1	5
Env > Soc > Eco	1	5	1	15	10	25	20
	2	1	5	15	10	25	20
	3	5	1	10	15	25	20
	4	1	5	10	15	25	20
	5	5	1	15	10	20	25
	6	1	5	15	10	20	25
	7	5	1	10	15	20	25
	8	1	5	10	15	20	25

With the Soc > Eco > Env philosophy, the only uses to which more land is devoted than in 2001 are fruit-growing, meadow, and other fodder crops (Fig. 5b). Only the social and economic objectives affect outcomes: when the major social objective is agricultural land maximization and the major economic objective gross margin, then only fruit-growing – the agricultural land use with the second highest gross margin – increases; when the major economic objective is production cost reduction, meadowland and other fodder crops increase instead of fruit-growing land because they have lower production costs.

With all the variants of the Env > Soc > Eco philosophy, the uses assigned larger areas than in 2001 are meadowland, pasture and hardwood forest, with meadowland and hardwood forest both reaching the availability limit (Fig. 5c). These land uses increase the achievement level of both environmental objectives because they have the three highest indices of naturalness and their coefficient of use of agrochemicals is low.

4.2. Interactive exploration using the STEP method

For each of the objective rankings used in goal programming (Table 2), the STEP method was applied so as to reproduce the same ranking, relaxing first the goal of the least important objective by the largest tolerated achievement relaxation T, then that of the next least important, and so on. Thus, for ranking 1 of Eco > Soc > Env type, the objective goals were relaxed in the order Naturalness, Agrochemicals, Agricultural land, Agroforestry man–hours, and Production costs (the goal of the most important objective is not relaxed). As Table 3 shows, the achievement relaxations T used were numerically the same as the weights used in goal programming.

The results of the STEP analyses are shown in Fig. 6. With the Eco > Soc > Env philosophy (Fig. 6a), the areas devoted to vegetables, softwoods and other fodder crops always rise above 2001 levels in an attempt to balance the gross margin and production cost objectives with land uses with different characteristics. The areas devoted to maize and eucalyptus also increase unless the prioritized social objective is agroforestry man–hours, in which case the area devoted to fruit growing, with its greater labour needs, increases instead of those of maize and eucalyptus.

With the Soc > Eco > Env philosophy, there is always an increase in fruit growing and other fodder crops (Fig. 6b). When the prioritized social objective is agroforestry man–hours, the areas devoted to vegetables or to perennial green fodder and potato can also increase. In any case, the main increments of area by order of magnitude take place in fruit-growing, other fodder crops and vegetables. These are the agricultural land uses with the highest labour needs.

With the Env > Soc > Eco philosophy, there is always an increase in meadowland (Fig. 6c), characterised by a high naturalness index and low use of agrochemical

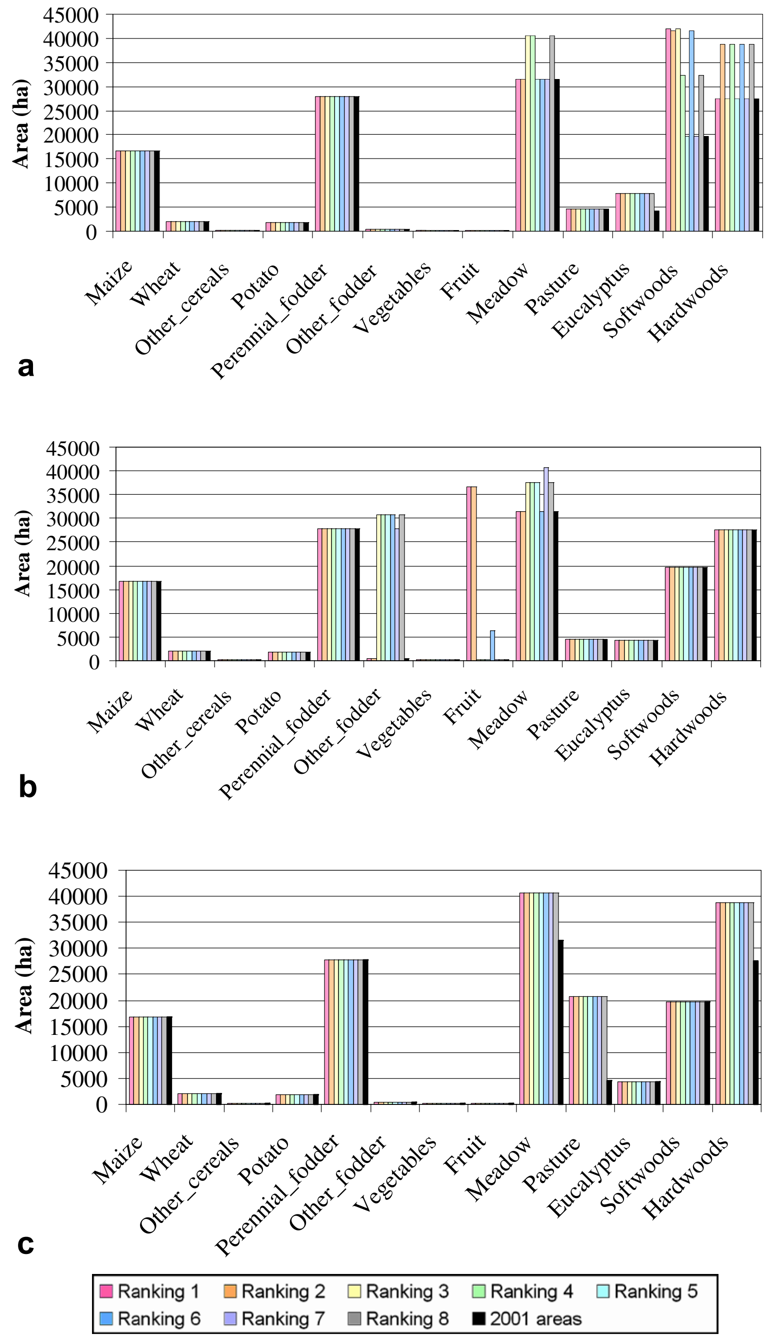

Fig. 5. Solutions obtained by goal programming within (a) the Eco > Soc > Env philosophy; (b) the Soc > Eco > Env philosophy; and (c) the Env > Soc > Eco philosophy.

products. When greatest priority is given to reducing agrochemical use, softwood forest and fruit growing also increase. The low use of agrochemical products in softwood forests allows an increase in the area of fruit-growing which improves social and economic objectives. When greatest priority is given to naturalness, there is always an increase in vegetable growing and hardwood forest. The high naturalness index of hardwood forests allows the vegetable growing area to be increased, improving social and economic objectives.

4.3. Interactive exploration using Lu et al.'s method

For each of the objective rankings implied in Table 2, the method of Lu et al. (2004) was applied by performing single-objective optimizations in the corresponding order. Thus, for ranking 1 of Eco > Soc > Env type, the objectives were optimized in the order Gross margin, Production costs, Agroforestry man–hours, Agricultural land, Agrochemicals, and Naturalness. The allowed tolerances ε_j were always 25% for the first objective (the most important),

Table 3
Achievement relaxations T (%) employed in applying the STEP method

Objective-type priority ranking	Objective ranking	Objectives					
		Gross margin	Production costs	Agroforestry man–hours	Agricultural land	Agrochemicals	Naturalness
Eco > Soc > Env	1	–	5	10	15	20	25
	2	–	5	10	15	25	20
	3	–	5	15	10	20	25
	4	–	5	15	10	25	20
	5	5	–	10	15	20	25
	6	5	–	10	15	25	20
	7	5	–	15	10	20	25
	8	5	–	15	10	25	20
Soc > Eco > Env	1	10	15	–	5	20	25
	2	10	15	–	5	25	20
	3	15	10	–	5	20	25
	4	15	10	–	5	25	20
	5	10	15	5	–	20	25
	6	10	15	5	–	25	20
	7	15	10	5	–	20	25
	8	15	10	5	–	25	20
Env > Soc > Eco	1	20	25	10	15	–	5
	2	25	20	10	15	–	5
	3	20	25	15	10	–	5
	4	25	20	15	10	–	5
	5	20	25	10	15	5	–
	6	25	20	10	15	5	–
	7	20	25	15	10	5	–
	8	25	20	15	10	5	–

20% for the second, 15% for the third, 10% for the fourth, and 5% for the fifth.

Within the Eco > Soc > Env philosophy, the prescriptions of Lu et al.'s method vary considerably, depending on whether greatest priority is given to gross margin or production cost reduction (Fig. 7a). In the former case, the areas devoted to vegetables and hardwood forest are always greater than in 2001, and in the latter the areas devoted to meadow, pasture, other fodder crops and hardwood forest. The area of vegetables increases when gross margin is prioritized because this activity has the highest coefficient of gross margin. When production costs are prioritized, the area of vegetables is substituted by a larger area of land uses with lower production costs.

With the Soc > Eco > Env philosophy, the area devoted to vegetables always rises almost to the limit imposed by the availability of suitable land, the area of hardwood forest to above 32,000 ha (Fig. 7b), and the area of softwood forest also increases slightly. Vegetables satisfy the economic objective of gross margin and the two social objectives, as this is the agricultural use with the highest labour needs, while hardwood and softwood forests contribute to increase the environmental objectives.

With the Env > Soc > Eco philosophy, more land uses are assigned greater areas by Lu et al.'s method than with either of the other objective-type rankings. However only the areas devoted to vegetables, softwood forest and hardwood forest always increase (Fig. 7c). The reason is the same as in the previous case, although environmental objectives are now given more preference than social objectives, so that the increase in hardwood and softwood forest is higher than that of vegetables.

4.4. Comparisons between methods: achievement rates

With the Eco > Soc > Env philosophy, the only analytical method affording an achievement rate *Ach* greater than 45% for both economic objectives was the STEP method (Fig. 8). With Lu et al.'s method one of these objectives always had an achievement rate lower than 25%, and goal programming always led to a rate of almost 100% for production cost reduction and less than 10% for gross margin maximization, even when gross margin maximization was the most heavily weighted objective.

With the Soc > Eco > Env philosophy, the STEP method always led to a rate of 100% for agricultural land maximization and higher than 65% for maximization of agroforestry man–hours. In this case Lu et al.'s method also afforded achievement rates higher than 67% for both social objectives. As in the case of the Eco > Soc > Env objective-type ranking, goal programming afforded an achievement rate of 100% for one of the two highest-weighted objectives, agricultural land maximization, but a much lower value for maximization of agroforestry man–hours (except for ranking 1 and 2).

By contrast, with the Env > Soc > Eco philosophy, goal programming always afforded high achievement rates for the most prioritized objective type, with rates of almost

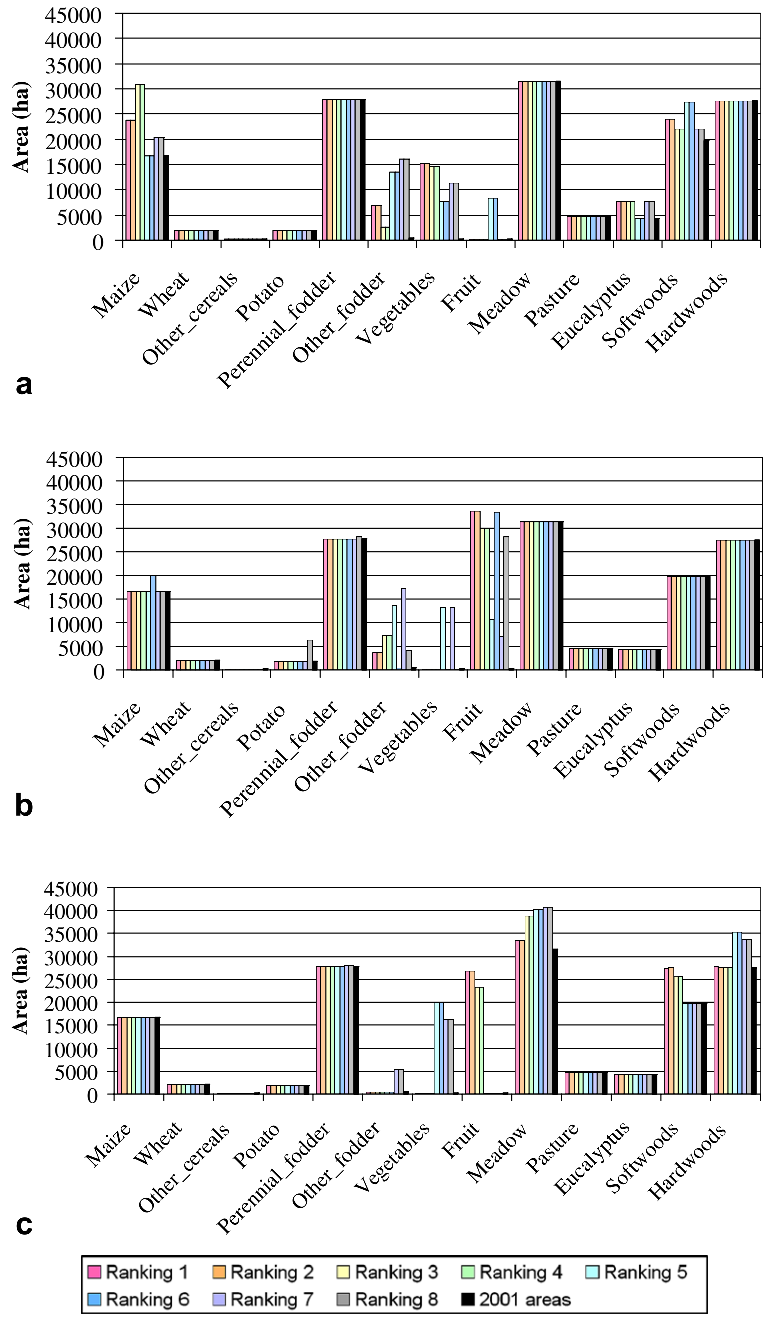

Fig. 6. Solutions obtained by the STEP method within (a) the Eco > Soc > Env philosophy; (b) the Soc > Eco > Env philosophy; and (c) the Env > Soc > Eco philosophy.

90% for reduction of agrochemicals use and 100% for naturalness. The STEP method afforded lower achievements for the two highest-weighted objectives, especially leading to naturalness having very low achievement rates (25%) when greatest priority was given to reduction of agrochemicals use. Lu et al.'s method always led to achievement rates of 70–80% for reduction of agrochemicals use, and of only 20–35% for naturalness.

When applied in accordance with the Eco > Soc > Env philosophy, both the interactive methods tended to respect the relative priorities established for gross margin and production cost reduction; indeed, Lu et al.'s method practically excluded achievement of the second-priority objective. With this method, maximization of agroforestry man–hours and agricultural land, and minimization of agrochemicals use, were also strongly linked to maximization of gross margin (Fig. 8c). In fact, although this link is most evident in Fig. 8c, which shows results with both high and low gross margin achievement, the pattern high-*Ach*(TGM), low-*Ach*(TPC), high-*Ach*(TMH), high-*Ach*(TAL), low-*Ach*(TAC) (or the inverse pattern low-*Ach*(TGM), high-*Ach*(TPC), etc.) was also the outcome of a number of other methods and objective-type ranking philosophies (see Figs. 8a; 9b and c; and 10a and c). This pattern is partly explained by the high

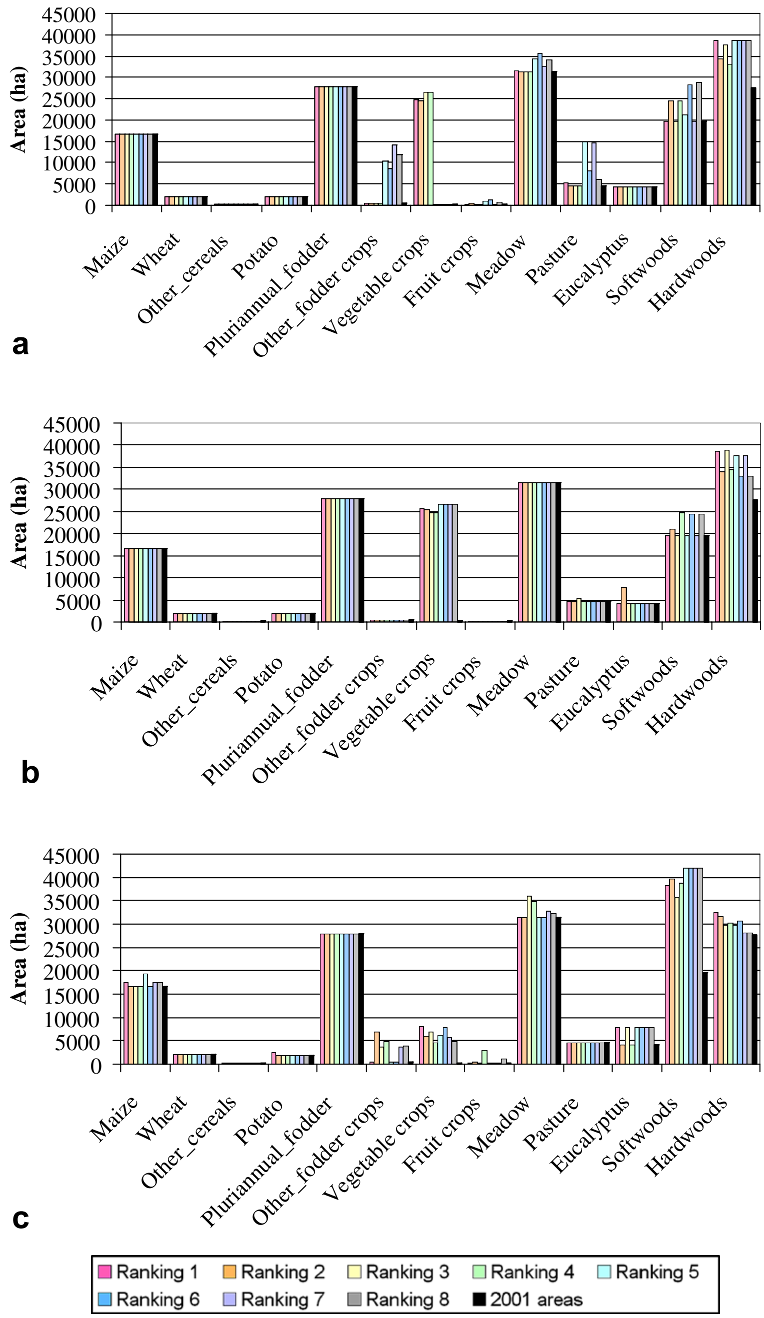

Fig. 7. Solutions obtained by the method of Lu et al. (2004) within (a) the Eco > Soc > Env philosophy; (b) the Soc > Eco > Env philosophy; and (c) the Env > Soc > Eco philosophy.

requirement for expensive agrochemicals and labour in intensive farming schemes that afford high gross margin (e.g. vegetable and fruit growing). However, generalization requires caution: potato farming, for example, has by far the greatest agrochemical needs but not the highest production costs, so neither of these objectives can be omitted from the analyses without loss of information; and although TAL is high whenever TMH is (Figs. 9b and c; and 10b) the outcome of goal-programming when a Soc > Eco > Env philosophy is adopted shows that the reverse is not the case (Fig. 9a).

5. Discussion and conclusions

The analyses of the previous section illustrate not only that, as would be expected, the various ways of combining multiple objectives into a single objective afford different solutions to a given problem, but also that examination of the results of these different approaches enriches appreciation of the conflicts, coincidences and trade-offs among objectives, thus enabling final decisions to be made with fuller understanding of their implications. It is therefore eminently desirable for comprehensive decision-making

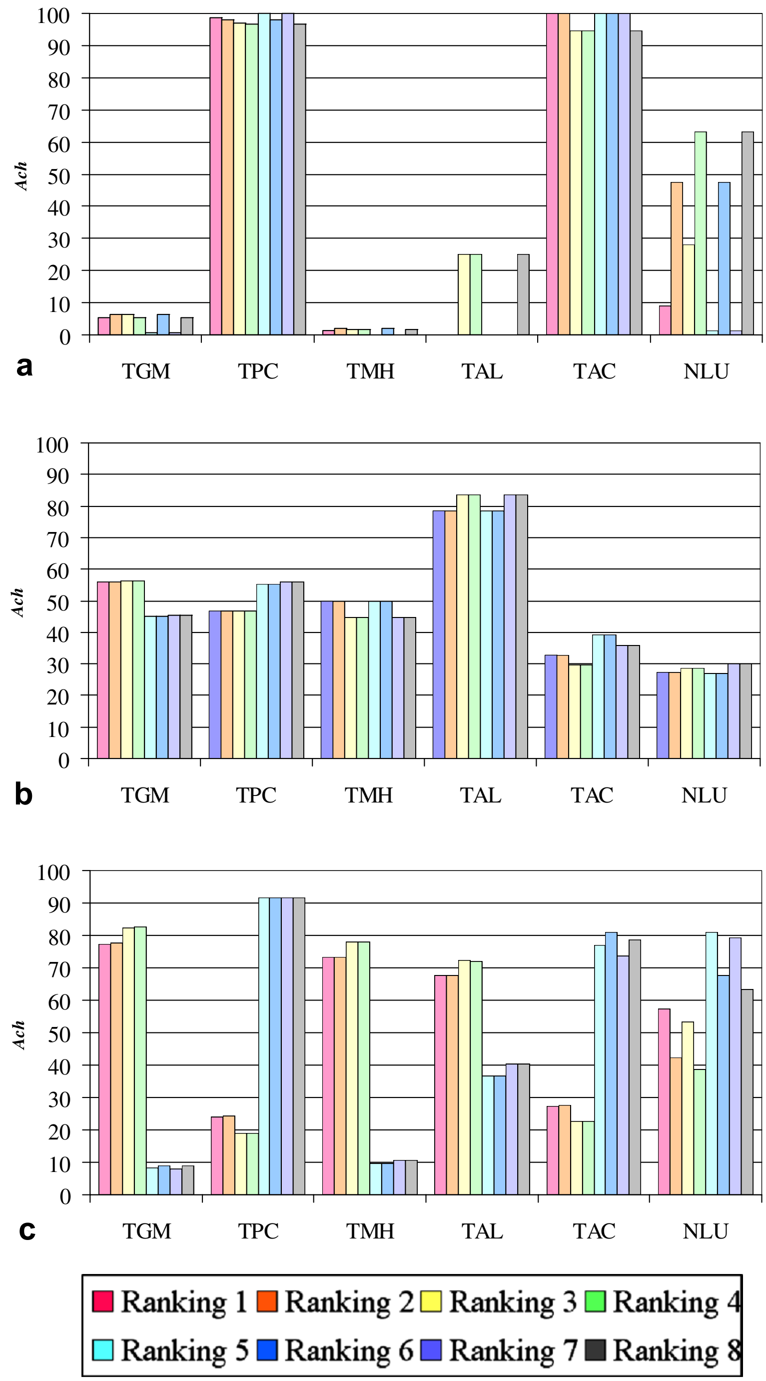

Fig. 8. Achievement rates *Ach* of the six objectives within Eco > Soc > Env philosophy for solutions obtained by (a) goal programming; (b) the STEP method; and (c) the method of Lu et al. (2004) (for objective abbreviations see Section 2.3).

tools such as LUSE, which integrate a variety of different multiobjective optimization approaches, to be made available to the rural planner. For the Terra Chá example considered in this work, the main conclusions that can be drawn regarding the relationships among different objectives in the region of the Pareto-optimal set that is sampled by the analyses may be summarized as follows.

(a) Gross margin and employment in agriculture appear to be positively correlated.
(b) High gross margin requires high production costs and high use of agrochemicals.
(c) The solutions displaying greatest balance among the above four objectives (maximization of gross margin and employment, and minimization of production costs and the use of agrochemicals) manage achievement rates of at least 40% for all objectives except naturalness by combining an increase in the area of high-yielding fruit and vegetable crops (with respect to 2001 levels) with an

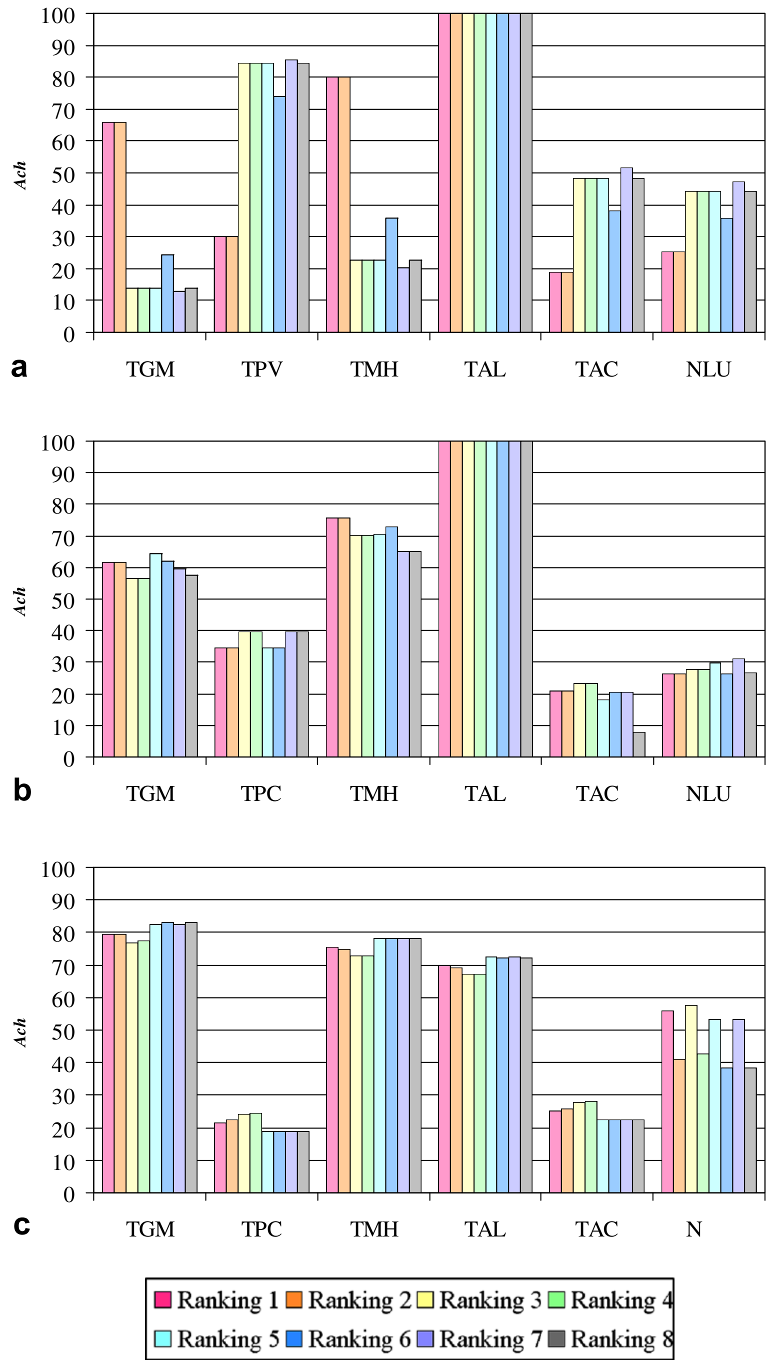

Fig. 9. Achievement rates *Ach* of the six objectives within Soc > Eco > Env philosophy for solutions obtained by (a) goal programming; (b) the STEP method; and (c) the method of Lu et al. (2004) (for objective abbreviations see Section 2.3).

increase in the area of eucalyptus and softwood forest. The achievement rate of naturalness can be increased by reducing the area of one or more of the above uses and increasing the area of hardwood forest or pasture.

(d) The greater the priority given to environmental objectives, the greater the area of hardwood forest and pasture. If only the minimization of the use of agrochemicals is considered to be relevant, it suffices to increase forestry in general, but if maximization of naturalness is pursued so as to conserve habitats, non-autochthonous eucalyptus and softwood forest must be replaced by uses with greater naturalness, such as pasture.

(e) The two social objectives, maximization of agroforestry employment and maximization of agricultural land, are broadly compatible with each other and with maximization of gross margin, and all three objectives can be achieved by increasing fruit and vegetable growing with respect to 2001 levels. If partial sacrifice of the achievement of the social objectives is accepted in order to increase the achieve-

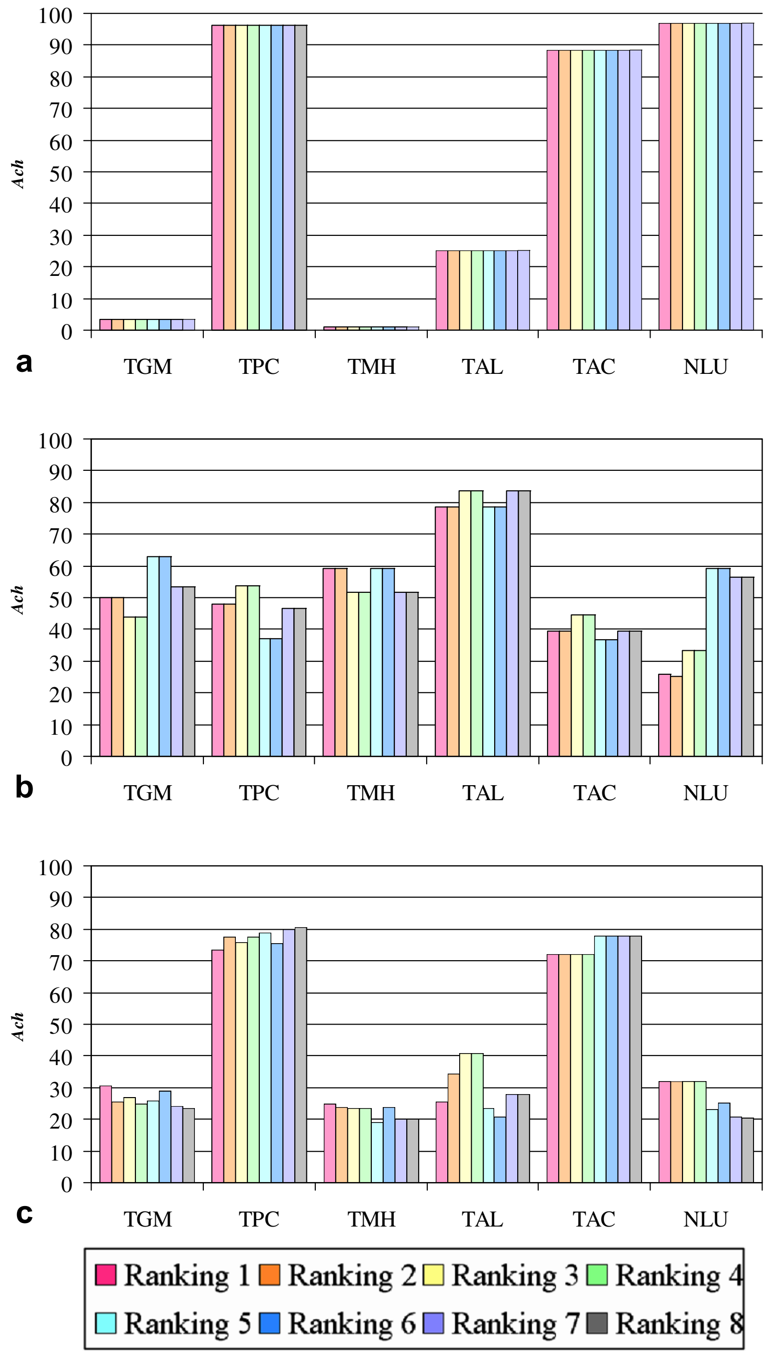

Fig. 10. Achievement rates *Ach* of the six objectives within Env > Soc > Eco philosophy for solutions obtained by (a) goal programming; (b) the STEP method; and (c) the method of Lu et al. (2004) (for objective abbreviations see Section 2.3).

ment of other objectives, then how this should best be done depends on the relative priorities among economic and environmental objectives.

A question that has been latent throughout the foregoing analyses and discussion is whether there exist objective criteria for preferring one or another of the various possible objective-type priority philosophies. One approach that might be employed when using LUSE to plan for a given rural district is to adopt a philosophy or combination of philosophies in accordance with the European Commission's classification of rural areas into five groups (European Commission, 1994): (i) areas close to urban areas; (ii) areas of pronounced attractiveness for tourism; (iii) areas with diversified activities; (iv) predominantly agricultural areas; and (v) areas that are difficult to reach. In areas of pronounced attractiveness for tourism or that are difficult to reach, it seems logical to apply an environmentally oriented philosophy (Env > Soc > Eco) leading to promotion of native forestry species and other non-intensive land uses. In predominantly agricultural areas, an economically oriented philosophy (Eco > Soc > Env) would favour their main social group, farmers. In areas with diversified activities, the presumable conflicts of interest as regards the use of land suggest that a socially oriented philosophy (Soc > Eco > Env) might be most appropriate.

LUSE was designed to assist in defining the objectives and quantifying land use allocation in a rural land use plan on a regional scale. Such a rural land use plan must define which land uses must be promoted, prohibited, permitted, or subject to conditional consent in each area of the region. In order to provide guidance in these land allocation decisions it is necessary that the land use areas which maximize the achievement of each objective be known. The stakeholders involved in the land use plan will be not only farmers, but also politicians, land owners, environmentalists, local residents, etc. LUSE provides an opportunity for the decision-makers to improve their understanding of the problem, as the system's results show the consequences of prioritising different objectives, the technical feasibility of meeting different sets of objectives, and the trade-offs among objectives. The analysis of the scenarios generated by the system will allow the future use of natural resources to be decided by the identification of compromise solutions among conflicting objectives. Planning should be carried out with the active participation of all stakeholders. The possibilities and impossibilities pointed to by a system such as LUSE should be used throughout the process to orient and support discussion among the groups that will be affected by the planning outcome, until successive contributions hopefully lead to agreement on an acceptable outcome. This will allow a more 'transparent' plan to be obtained, based on available information and appropriate methods, consistent with planning policies and which incorporates negotiations between conflicting interests.

LUSE is equipped with a reparameterization unit allowing its application to rural areas of similar characteristics and it is planned to introduce further improvements both to expand its scope and to refine its prescriptions.

References

Agrell, P.J., Stam, A., Fischer, G.W., 2004. Interactive multiobjective agro-ecological land use planning: The Bungoma region in Kenya. Eur. J. Oper. Res. 158, 194–217.

Azapagic, A., Clift, R., 1999. Life cycle assessment and multiobjective optimisation. J. Clean Prod. 7, 135–143.

Campbell, J.C., Radke, J., Gless, J.T., Wirtshafter, R.M., 1992. An application of linear programming and geographic information systems: cropland allocation in Antigua. Environ. Plann. A 24, 535–549.

Chuvieco, E., 1993. Integration of linear programming and GIS for land-use modelling. Int. J. Geogr. Inf. Sci. 7 (1), 71–83.

Cohon, J.L., 1978. Multiobjective Programming and Planning. Academic Press, New York.

De Wit, C.T., Van Keulen, H., Seligman, N.G., Spharim, I., 1988. Application of interactive multiple goal programming techniques for analysis and planning of regional agricultural development. Agr. Syst. 26, 211–230.

Dogliotti, S., van Ittersum, M.K., Rossing, W.A.H., 2004. A method for exploring sustainable development options at farm scale: a case study for vegetable farms in South Uruguay. Agr. Syst. 80 (3), 277–302.

European Commission, 1994. Europe 2000+ Cooperation for European territorial development. European Commission, Luxemburg.

Fischer, G., Makowski, M., 1996. Multiple Criteria Land Use Analysis. Working Paper-96-006. International Institute for Applied Systems Analysis, Laxenburg.

Fischer, G., Makowski, M., Granat, J., 1998. AEZWIN. An Interactive Multiple-Criteria Analysis Tool for Land Resources Appraisal. International Institute for Applied Systems Analysis, Laxenburg.

Géhu, J.M., Géhu-Franck, J., 1979. Essai d-évaluation pytocoenotique de l'artificialisation des paysages. In: Gehu, J.M. (Ed.), Phytosociologie et paysage. Science Publishers, Stuttgart, pp. 497–515.

Giupponi, C., Rosato, P., 1998. A farm multicriteria analysis model for the economic and environmental evaluation of agricultural land use. In: Beinat, E., Nijkamp, P. (Eds.), Multicriteria Analysis for Land-Use Management. Kluwer Academic Publishers, Dordrecht, pp. 115–136.

Goicoechea, A., Hansen, D.R., Duckstein, L., 1982. Multiobjective Decision Analysis with Engineering and Business Applications. John Wiley & Sons, United States.

Ive, J.R., Cocks, K.D., 1983. SIRO-PLAN and LUPLAN: an Australian approach to land-use planning. 2. The LUPLAN land-use planning package. Environ. Plann. B 10, 347–355.

López, R., 1997. Estudio Socioeconómico de Terra Chá. Servicio de Publicaciones de la Diputación Provincial, Lugo.

Lu, C.H., van Ittersum, M.K., Rabbinge, R., 2004. A scenario exploration of strategic land use options for the Loess Plateau in northern China. Agr. Syst. 79, 145–170.

Oliveira, F., Patias, N.M., Sanquetta, C.R., 2003. Goal programming in a planning problem. Appl. Math. Comput. 140, 165–178.

Rehman, T., Romero, C., 1993. The application of the MCDM paradigm to the management of agricultural systems: some basic considerations. Agr. Syst. 41, 239–255.

Santé, I., Crecente, R., 2005. Evaluación de métodos para la obtención de mapas continuos de aptitud para usos agroforestales. GeoFocus 5, 40–68.

Shakya, K.M., Leuschner, W.A., 1990. A multiple objective land use planning model for Nepalese Hills farms. Agr. Syst. 34, 133–149.

Shukla, S., Yadav, P.D., Goel. R.K., 2003. Land use planning using GIS and linear programming. In: Conference Proceedings of Map Asia 2003. GIS Development, Kuala Lumpur.

Siskos, Y., Despotis, D.K., Ghediri, M., 1994. Multiobjective modelling for regional agricultural planning: Case study in Tunisia. Eur. J. Oper. Res. 77, 375–391.

Suhaedi, E., Metternicht, G., Lodwick, G., 2002. Geographic information systems and multiple goal analysis for spatial land use modelling in Indonesia. In: 23rd Asian Conference on Remote Sensing. Assian Association on Remote Sensing (AARS), Katmandú.

van Ittersum, M.K., 1995. Description and User Guide of GOAL-QUASI: an IMGLP Model for the Exploration of Future Land Use. DLO-Research Institute for Agrobiology and Soil Fertilization, Wageningen.

van Ittersum, M.K., Rabbinge, R., van Latesteijn, H.C., 1998. Exploratory land use studies and their role in strategic policy making. Agr. Syst. 58 (3), 309–330.

van Ittersum, M.K., Roetter, R.P., van Keulen, H., de Ridder, N., Hoanh, C.T., Laborte, A.G., Aggarwal, P.K., Ismail, A.B., Tawang, A., 2004. A system network (SysNet) approach for interactively evaluating strategic land use options at sub-national scale in South and South-east Asia. Land Use Policy 21, 101–113.

van Leeuwen, C.J., Köbrich C., Maino, M., 2001. Programación lineal para la elaboración de escenarios óptimos de uso de la tierra. FAO, Santiago de Chile.

Wascher, D.W., 2000. Agri-Environmental Indicators for Sustainable Agriculture in Europe. European Centre for Nature Conservation, Tilburg.

Zander, P., Kächele, H., 1999. Modelling multiple objectives of land use for sustainable development. Agr. Syst. 59, 311–325.