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Article

Participatory Goal Programming in Forest Management: An Application Integrating Several Ecosystem Services

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Abstract: In this study, we propose a procedure for integrating several ecosystem services into forest management by using the well-known multi-criteria approach called goal programming. It shows how interactions with various stakeholders are essential in order to choose the goal programming model applied, as well as some of its basic components (variant, targets, preferential weights, *etc.*). This methodology has been applied to a real forest management case where five criteria have been selected: timber production, wild edible mushroom production, carbon sequestration, net present value of the underlying investment, and a criterion associated with the sustainability of forest management defined by the idea of a normal forest. Given the characteristics of some of these criteria, such as mushroom production, the model has been developed in two scenarios: one deterministic and another with a Monte Carlo analysis. The results show a considerable degree of conflict between the proposed criteria. By applying several goal programming models, different

Paretian efficient solutions were obtained. In addition, some results in Monte Carlo analysis for several criteria show notable variations. This fact is especially notable for the mushroom production criterion. Finally, the proposed approach seems attractive and can be directly applied to other forest management situations.

Keywords: multi-criteria decision-making; goal programming; stakeholders; forest management; edible wild mushrooms

1. Introduction

Forestry problems addressed with traditional mathematical programming models have currently formalised the idea of "economic scarcity" by using rigid constraints (*i.e.*, algebraic equalities and inequalities). This type of strategy is unrealistic in many situations, since it implies that a small violation of the right hand side figures provides an infeasible solution. However, optimisation approaches like goal programming (GP) can transform rigid constraints into flexible ones in a simple way by resorting to the goal concept, allowing but also penalising violations of the right hand side figures [1]. The use of GP models in forestry was started in 1973 [2], and many goal programming models have been developed in this field. Since this pioneer work was carried out, GP has been extensively used for addressing several forest resource management problems, with timber harvesting scheduling being the area of application where GP has been most widely used [3].

The complexity of forest management continues to increase, making it necessary to resort to new analytical tools like the Decision Support System (DSS) [4]. This increase in difficulty often justifies the employment of multi-criteria techniques like GP even as an integral part of diverse DSS. Thus, according to a recent, exhaustive study, GP is currently used in at least seven different countries as a computer-based tool for backing up forest management [5]. This combination of GP and DSS has been successfully explored in several studies [6,7].

On the other hand, in some studies, different criteria can be considered relevant for strategic forest management purposes. It is usual to consider the following ones: the maximisation of the net present value of the forest over the planning horizon, the equality of harvest volume in each cutting period, the area control criterion that seeks an ending regulated or even-aged forest, or the ending inventory criterion that ensures a solution for which the ending forest inventory is larger than or equal to the initial inventory [8]. The criteria regarding even flow policy and even-aged forests imply a "fully regulated forest" [9], which is an ideal forest structure proposed by the Forest Management German School ("normal forest") and widely pursued in many European countries [10,11].

In recent years, other non-timber forest products like mushroom production have been included in forest planning through the use of optimisation tools, confirming the economic significance of this resource, mainly in some mountainous areas [12]. There is an economic importance of fungal resources in different stands in Spain [13]. This work clearly shows that the value of the fungal resources greatly exceeds that of timber. Additionally, mushroom production can be integrated into strategic forest planning models, including figures for harvested mushrooms using models based on multi-criteria techniques like compromise programming [14]. Finally, carbon sequestration can also be included in strategic forest management models, as has been shown in several studies [8].

In another sense, the focus of forest management has also changed due to the manner in which different social groups or stakeholders perceive the relative importance of the different criteria involved in the decision-making process. In short, the forest management discipline needs to incorporate multiple criteria as well as multiple stakeholders into their models in order to make the analysis more realistic [9,15].

The principal aim of this work is to present a forest management model which permits the inclusion of timber and non-timber objectives through goal programming in two scenarios (one deterministic and another with a Monte Carlo analysis). It incorporates the preferences of the stakeholders both in the fixing of the weights given to each criterion and in the different aspects associated with the design of the final GP model. In short, this methodology allows both the integration of other non-timber forest goods and services in the management of the forest, and the quantification of the opportunity cost of achieving the ideal normal forest structure.

2. Experimental Section

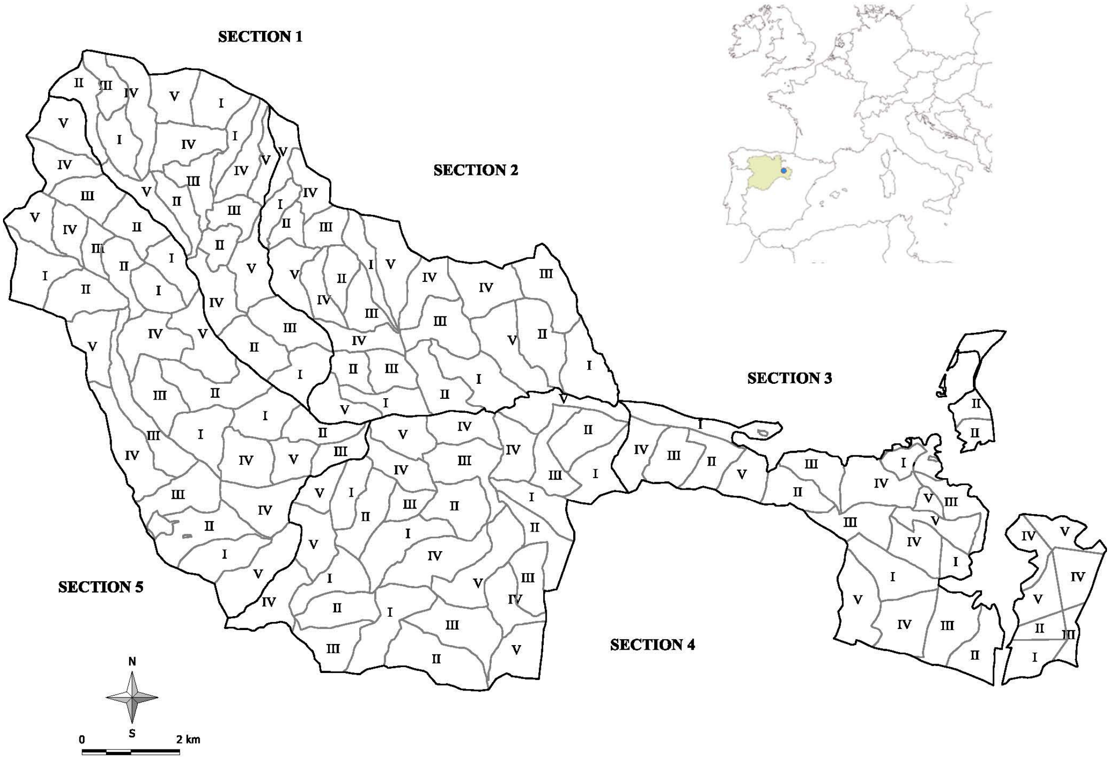
2.1. Material

This section describes the study area as well as the criteria selected for the real case which will be analysed.

2.1.1. Study Area

The study area is located in a public forest called "Pinar Grande", located in the northeast zone of the Iberian Peninsula (Sistema Ibérico mountain range, see Figure 1). This forest covers an area of 12,533 ha which comprises mainly pure and even-aged Scots pine (*Pinus sylvestris*) stands. Small mixed stands of *Pinus sylvestris* with *Pinus pinaster* Ait. or *Quercus pyrenaica* Willd. are also present in the forest. Elevation varies from 1097–1543 meters above sea level (a.s.l.), dominating east and west aspects. Mean annual rainfall is 865 mm/year, with an average temperature of 8.8 °C. Soils are acidic brown earths or alluvial with acid (pH 4–5) and a sandy loam or sandy texture. Management in Pinar Grande Forest began one century ago (in 1907), applying classical European management methods, but a fully regulated forest has not yet been achieved. The forest is divided into five sections and 135 compartments (Figure 1).

Figure 1. Location and description of forest management compartments in Pinar Grande Forest (Soria, Spain).



2.1.2. Criteria Considered

Until a few years ago, the main objective in this forest was timber production. To achieve this, an even-aged management was applied that consisted of strip clear-cutting with soil movement and sowing when necessary, followed by natural regeneration. However, in recent years, other ecosystem services have gained great importance in the forest. One of these is mushroom picking, which, under a conservation hypothesis, generates potential returns representing 20% of the income associated with timber [16]. In addition, as from 2011, it has been fitted into MYAS-RC, the system regulating mycological use and commercialisation, by which the forest receives an annual average income of 0.96 €/ha for mushroom picking licenses. These goods with a market price will define three of the criteria presented in this study: timber production, production of mushrooms of commercial interest (*Lactarius* gr. *deliciosus* and *Boletus edulis* Bull.:Fr.), and the commercial profitability associated with both productions. In another direction, an environmental criterion such as carbon sequestration has also been considered, as well as a last aspect associated with sustainability in this forest's management practices. The criterion selected would be the obtainment of a stand structure which is closest to the idea of a normal forest. The following is a brief explanation of how these five criteria have been defined.

Regarding timber production, although other tree species co-exist, this research has only investigated timber production associated with Scots pine, which accounts for 70% of timber stocks. The modelling of this production has been explained in other studies [16]. With these timber production data, its profitability was calculated taking into account that the income from thinnings is not considered due to these operations commonly being self-financed, thereby reducing the complexity of calculations. To estimate the price, the average adjudication price of the final cuttings during the period from 2002 and 2013 was considered. Using constant prices, that average was 50.9 €/m^3. With regard to the costs, an annual cost of 39.7 €/ha, taken from the data of the current forest management plan, was assumed.

Mushroom production has been estimated by performing a random sampling per stand-age class according to the forest's management [17] from 1995–2013 in trough areas of Pinar Grande Forest (Figure 3). Sampling was performed in the most productive season (autumn) on a weekly basis from weeks 35–50 every year. In addition, two mushroom site indices in the forest according to statistical analysis (ANOVA) of the fifth age class [18] have been defined, so we assumed this difference for all age classes. The mushroom production for each site quality was estimated following a tested methodology [19]. Moreover, the percentage of gross production picked each year was also estimated [18], and this information was used to predict the harvested mushroom production. Once the production of these two species was calculated, the following step was to estimate their profitability. As for the price, for the case of *Lactarius* gr. *deliciosus*, weekly information on Mercabarna prices updated until 2013 according to the CPI (Consumer price index) [20] was collected, with an average price assigned to this species of 12.5 €/kg. No information whatsoever was found for the *Boletus edulis* either in national markets or in the small businesses in the forest's vicinity. Therefore, an average price paid to the picker coming from field surveys in Pinar Grande was adopted [21]. That price when updated to 2013 was 6.4 €/kg. This was considered to be a conservative figure, as there was evidence of higher prices depending on the date. To calculate profitability (NPV), no cost derived from the mushroom collection was assumed, and a discount rate of 2% was considered for both the profitability of the timber and the mushrooms.

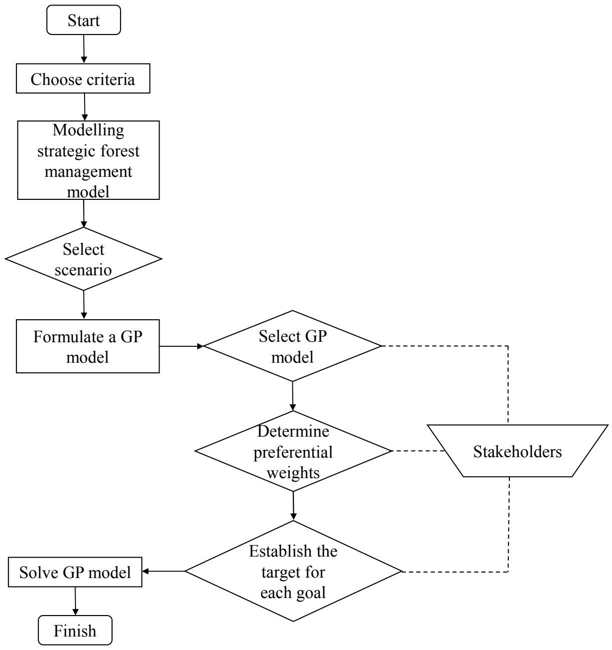
Also, the carbon fixed by the stands of Scots pine (trunk, branches, twigs, leaves, and roots) was measured by means of several methodologies [22,23]. The carbon fixed in the soil was not considered due to the lack of data on its annual variation. In addition to the fixed carbon, the carbon emitted by the final cuttings was taken into account, so that with this the corresponding annual assessment was made. The carbon emitted by forest fires has not been included, as there was no reliable estimation of the annual probability of their occurrence in this forest.

The last criterion considered was the achievement of a normal structure in the forest [10,11]. This aimed to obtain a structure which would be considered ideal for ensuring the sustainability of the forest's management, and it is thus included in the current planning of the forest. It was equal to jointly fulfilling three objectives: regulation, or achieving a balanced distribution of the different age classes; a final inventory, or, on finalising the planning horizon, making the inventoried volume end up being similar to those in existence at present; and, finally, to also ensure that the final cuttings in each period are similar.

2.2. Methods

This section describes the different methodologies employed, which go from strategic forest planning, the bases of the multi-criteria technique chosen (goal programming), the survey made of the stakeholders, and the description of the two scenarios selected. These are summarised in Figure 2.

Figure 2. Diagram of the methodologies shown in this section.



2.2.1. Strategic Forest Management

In this work, a strategic planning has been constructed by which it was aimed to establish the programming of final cuttings throughout the planning horizon (100 years) as of 2013. For this purpose, what is known as Model I [24] was followed, and the forest was divided into 258 management units, combining the site indices for timber and those established for mushroom production. The rotation planned ranges between 80 and 140 years, with a total of 1682 prescriptions being established. As for the constraints of the model, in addition to the endogenous ones, one obliging the final cuttings to occupy a minimum of 1 ha has been introduced. Another constraint is that the income obtained from mycological production should exceed the amount received annually for the issuing of licenses for the picking of this commodity. A more detailed description of this model can be consulted in a previous study [14].

2.2.2. Multi-Criteria Methodology

Since five different criteria have been defined to address the strategic forest planning model described above, the use of monocriterion tools like linear programming (LP) has been discarded *a priori*. However, we have resorted to this classic technique to quantify the degree of conflict among the criteria considered. This task has been undertaken by setting up the so-called pay-off matrix. This construct is a square matrix whose dimension coincides with the number of criteria considered. Each column of the matrix is obtained by optimising separately each one of the criteria considered, subjecting the optimisation process to the meeting of the endogenous constraints (for technical details, basic multi-criteria books can be accessed [25]). In short, in our application it was necessary to solve five LP problems. It is obvious that if the figures of two rows of the matrix are similar, it implies that the respective criteria are complementary, and, consequently, one of them is redundant and should be eliminated. Besides this, the pay-off matrix provides significant information in terms of ideal and anti-ideal values, which play a crucial role in the formulation of our models.

In view of the continuous nature of the problem confronting us, the technique chosen was goal programming. This technique is the one most used in forest management when we find ourselves faced with problems of this nature [1,3] due to its flexibility and versatility characteristics. The mathematical structure of the generic *i*th goal is represented by the following Equation (1):

$$f_i(X)+n_i-p_i=t_i \tag{1}$$

Where $f_i(X)$ is a function of the vector of decision variables or prescriptions *X*, representing the mathematical expression of the generic *i*th criterion. Parameter t_i is the target value attached to the *i*th criterion; that is, by using Simonian language, a satisficing achievement level for the decision-maker (DM). On the other hand, n_i and p_i are the deviation variables. The negative one n_i quantifies the under-achievement of the *i*th goal, while the positive one p_i quantifies the opposite effect—*i.e.*, the over-achievement of the *i*th goal. Now we have to detect the so-called unwanted deviation variables whose values have to be minimised. If the goal derives from a criterion of the type “more is better” (e.g., the net present value), then the unwanted deviation variable would be the negative one n_i and would have to be minimised. On the other hand, if the goal derives from an attribute of the type “less is better” (e.g., the risk of fire), then the unwanted deviation variable would be the positive one p_i and would have to be minimised. Finally, if the goal derives from a criterion that must be achieved exactly (e.g., to meet an even flow policy), both deviation variables are unwanted and must be minimised.

Once the basic variables and parameters of the GP model have been introduced, the next step is to formulate the achievement function of the GP model, which is a generic function of the unwanted deviation variables previously defined. This function has a typical “less is better behaviour” (*i.e.*, it implies a minimisation process). The arguments of the achievement function (*i.e.*, the unwanted deviation variables) must be subjected to a normalisation process in order to deal with goals measured in different units. Finally, in order to consider the preferences of DM, we introduce weights W_i measuring the relative importance attached to the generic *i*th goal, with respect to the achievement of the other goals.

Therefore, in order to implement the GP model that reflects the reality that we are analysing in a better way, we needed three different types of information:

(a) The satisficing target values for the five goals considered;
(b) the preferential weights to be attached to each goal, and
(c) general preferential information provided by the DM, in order to elicit the most suitable form of the achievement function of the GP model. This step is crucial, since, if the structure of the achievement function does not reflect the preferences of DM, it is very likely that the final solution will not be accepted by the DM [1].

In order to obtain reliable information on the three directions pointed out above, we established an interaction with a group of stakeholders. This type of participatory approach allowed us to build models compatible with the preferential information provided by the stakeholders. This crucial issue for our work was undertaken by resorting to “pairwise” comparison techniques and will be explained in Section 2.2.3, but in order to facilitate the whole understanding of this methodology, the results of this interaction with the stakeholders are shown in this section.

The following is the set of criteria considered in our case study. Let us start with the timber production criterion. Along the exercise we considered I management units (258) and J prescriptions. Hence, the mathematical expression of this criterion is the following:

$$\sum_{i=1}^{I}\sum_{j=1}^{J} V_{ij}X_{ij} + n_V - p_V = t_v V^* \tag{2}$$

Where V_{ij} is the cutting volume for the prescription *j* of the management unit *i*, X_{ij} the surface of the cutting of the prescription *j* of the management unit *i*, n_V the negative deviation variable, p_V the positive deviation variable, and t_v is the desired percentage of achievement with respect to the maximum value (ideal value) V^* for this criterion, according to the preferences of the stakeholders. Concretely, for this criterion, the unwanted deviation variable which should be minimised would be n_V.

The criterion linked to mushroom picking estimates the amount of mushrooms harvested (kg), in agreement with the forest stand production in terms of the age classes of the trees, of the accessibility and site index for mushroom production, and of the picking rates in the forest. Their mathematical expression is as follows:

$$\sum_{i=1}^{I}\sum_{j=1}^{J} S_{ij}X_{ij} + n_S - p_S = t_s S^* \tag{3}$$

Where S_{ij} is the amount of mushrooms picked (*Boletus edulis* and *Lactarius gr.deliciosus*) in the prescription *j* of the management unit *i*, n_S is the negative deviation variable, p_S is the positive deviation variable, and t_s is the desired percentage of achievement with respect to the maximum value (ideal value) S^* for this criterion, according to the preferences of the stakeholders. We would therefore be talking about a "more is better" type goal, and the unwanted deviation variable to be minimised would be n_S.

As remarked on previously, another criterion introduced would be that of maximising the fixed carbon per wooded area (tons of C) throughout the planning horizon, as shown in the following equation:

$$\sum_{i=1}^{I}\sum_{j=1}^{J}\left(\gamma\left(BV_{ij}^{f} + BH_{ij}\right) - CE_{ij}\right)X_{ij} + n_{CB} - p_{CB} = t_{CB}CB^* \tag{4}$$

Where γ is the average content of carbon per ton of timber biomass (0.509 t of C/t of timber biomass, following seminal studies [23]), BV_{ij}^{f} corresponds to the biomass generated for the prescription *j* of the management unit *i* at the end of the planning horizon, and BH_{ij} is the biomass generated by the cuttings extracted throughout the planning horizon for the prescription *j* of the management unit *i*. On the contrary, CE_{ij} is the amount of carbon emitted in tons for the prescription *j* of the management unit *i* in agreement with the different residues and type of final products proceeding from the cuttings [26]. Continuing with the elements typical of a goal structure, n_{CB} is the negative deviation variable, p_{CB} the positive deviation variable, and t_{CB} is the desired percentage of achievement with respect to the maximum value (ideal value) CB^* for this criterion, according to the preferences of the stakeholder. In short, the unwanted deviation variable to be minimised would be n_{CB}.

The private economic profitability criterion in the forest assimilates the net present value (*NPV*) derived from the timber cuttings and from the previously mentioned mushroom picking. This seeks to estimate the income associated with the production of these two products at the end of the planning horizon. Its units are monetary (€), and its mathematical expression is shown in the following equation:

$$\sum_{i=1}^{I}\sum_{j=1}^{J}\left(NPVm_{ij}+NPVs_{ij}\right)X_{ij}+n_{NPV}-p_{NPV}=t_{NPV}NPV^{*} \quad (5)$$

Where $NPVm_{ij}$ is the net present value generated by the timber cuttings and $NPVs_{ij}$ that correspond to mushroom picking in the prescription j of the management unit i. The variable n_{NPV} would be the negative deviation variable, while p_{NPV} symbolises the positive deviation variable, and t_{NPV} is the desired percentage of achievement with respect to the maximum value (ideal value) NPV^{*} for this criterion, according to the preferences of the stakeholders. Thus, the same as in the previous criteria, the unwanted deviation variable to be minimised would be n_{NPV}.

The last criterion incorporated into the analysis is aimed at simulating a structure considered to be ideal for ensuring the basic principles of forest management. This criterion is equal to jointly fulfilling three objectives. The first of these is the forest's regulation by which it is sought to obtain a balanced distribution of ages (*i.e.*, that each age class of the trees occupies the same surface) on finalising the planning horizon:

$$\sum_{i=1}^{I}\sum_{j=1}^{J=A}X_{ijA}+n_{A}-p_{A}=t_{n}X_{A} \quad (6)$$

Where X_{ijA} is the area occupied at the end of the planning horizon by the prescription j belonging to age class A in the management unit i, n_A is the negative deviation variable, p_A is the positive deviation variable, and t_n is the desired percentage of achievement with respect to the area X_A for this criterion, according to the preferences of the stakeholders. It should be noted that X_A is the area which every age class should have so that all of them occupy the same one. Therefore, the unwanted deviation variable to be minimised would be the sum of the deviation variables $(n_A + p_A)$ for all the age classes existing in the forest.

The second objective integrated into this criterion refers to the final inventory condition by which it is attempted to ensure the persistence of the stand, obliging all the timber stock in the forest at the end of the planning horizon in each of the five sections (denoted on the following equations with superscript *K*) to be similar to those present at the beginning. This condition is expressed mathematically as:

$$\begin{gathered}\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K}V_{ijk}^{f}X_{ijk}=V_{k}^{f}\\ V_{k}^{f}+n_{f}-p_{f}=t_{n}V_{k}^{I}\end{gathered} \quad (7)$$

Where V_{ijk}^{f} is the volume of timber at the end of the planning horizon for the prescription j in the management unit i, and section k; X_{ijk} is the area harvested in the management unit i defined by prescription j belonging to the section k, while V_{k}^{f} is the final volume for each of the five sections k into which the forest is divided. Also, n_f is the negative deviation variable and p_f the positive deviation variable, while t_n is the desired percentage of achievement with respect to the volume of timber at the beginning of the planning horizon for the section k, V_{k}^{I}, according to the preferences of the stakeholders. Consequently, the unwanted deviation variable to be minimised is the sum of the deviation variables $n_f + p_f$ for each of the forest sections, since it is considered that the present inventory achieves sufficient values.

The third condition associated with the idea of a normal forest refers to the equality of the cuttings in each period. That is to say, with the aim of obtaining a prevision of homogeneous incomes, the objective established was that the volume associated with the final cuttings should be similar in each period into which the planning horizon has been divided. In short, this type of even flow policy is expressed mathematically as:

$$\begin{aligned}&\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{l=1}^{K}V_{ijl}X_{ijl}=H_l\\&H_{l+1}-t_nH_l+n_{lH}-p_{lH}=0\end{aligned}\tag{8}$$

Where V_{ijl} is the volume of timber for the prescription *j* in the management unit *i*, and period *l*; X_{ijl} is the area harvested in the management unit *i* defined by prescription *j* in period *l*, whereas t_n is the desired percentage of achievement with respect a perfect even flow policy, according to the preferences of the stakeholders. The variable H_l is the volume of the cutting in the period *l*, while n_{lH} is the negative deviation variable for the period *l* and p_{lH} the positive deviation variable for the period *l*. So, the unwanted deviation variable to be minimised is the sum of the deviation variables $n_{lH}+p_{lH}$ for all the planning periods.

Therefore, the normal forest criterion was defined by the sum of the negative and positive deviation variables associated to the three goals—one for each component. In short:

$$\begin{aligned}(n_N)&=\left\{\frac{1}{r_l}\sum_{l=1}^{L}n_{lH}+\frac{1}{r_A}\sum_{A=1}^{A}n_A+\frac{1}{r_f}\sum_{k=1}^{K}n_f\right\}\\(p_N)&=\left\{\frac{1}{r_l}\sum_{l=1}^{L}p_{lH}+\frac{1}{r_A}\sum_{A=1}^{A}p_A+\frac{1}{r_f}\sum_{k=1}^{K}p_f\right\}\end{aligned}\tag{9}$$

Besides, according to the above characterisation of our set of relevant criteria, the unwanted deviation variables which must be minimised for our exercise are the following $\left[n_V, n_S, n_{CB}, n_{NPV}, n_N+p_N\right]$, which leads to the following generic general achievement function:

$$Min\left(n_V, n_S, n_{CB}, n_{NPV}, n_N+p_N\right)\tag{10}$$

In order to characterise the functional form that best reflects the preferences of the DM, a survey was undertaken. The details of the survey are presented below. According to the survey, the goals that must be achieved in a pre-emptive way are timber production and the three goals concerning the search for a normal forest. The next priority in order of absolute importance is made up of the rest of the goals, but accepting relative compensations in their respective achievements. Therefore, the achievement function for our exercise, according to the results of the survey, implies the following lexicographic structure:

$$\begin{aligned}&Lex\min a=\left[\mathrm{U}_1,\mathrm{U}_2,-\mathrm{U}_3\right]\\&\text{being:}\\&\mathrm{U}_1=\left\{\frac{W_1}{r_1}n_V+\frac{W_2}{r_2}(n_N+p_N)\right\}\\&\mathrm{U}_2=\left\{\frac{W_3}{r_3}n_s+\frac{W_4}{r_4}n_{NPV}+\frac{W_5}{r_5}n_{CB}\right\}\\&\mathrm{U}_3=\left\{p_V+p_S+p_{NPV}+p_{CB}\right\}\end{aligned}\tag{11}$$

subject to the respective constraints and goals Equations (2)–(8).

It should be noted that the criteria are measured in different units, so we need to resort to a normalisation system. In this way, the parameters *r* are introduced into Equations (9) and (11). The value of these parameters was calculated as the differences between the ideal and the anti-ideal values for each criterion (*i.e.*, their range of variation). In this way, the different criteria are measured as percentages. This type of normalization system, widely used in the literature, like other normalization systems is not exempt from difficulties. A review of the pros and cons of different systems like the use of Euclidian norms, zero-one normalization, *etc.* can be seen in [27]. Finally, it should be noted that the third component of the lexicographic vector U_3 only plays an auxiliary role in order to guarantee the Pareto efficiency of the GP solution obtained. Thus, if the solution obtained by maximizing U_3 coincides with the solution obtained by minimizing U_2, then this solution is efficient. However, if the solution changes, then the latter one dominates the former one in a Paretian sense. This type of procedure will be implemented in all the calculations made in the next section, in order to guarantee the efficiency of the solutions obtained. A mathematical justification of this procedure can be seen in several studies [27–29].

2.2.3. Stakeholder Survey

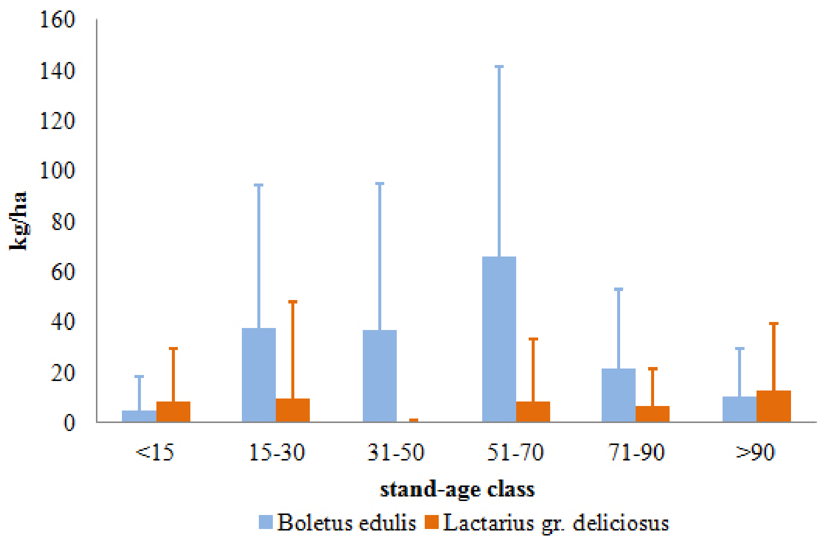
The survey was taken from the stakeholders implicated in the management of the Pinar Grande forest. To be specific, 48 surveys were carried out involving public authorities, technicians, private forest owners, mycologists and mushroom pickers, researchers and university lecturers, as well as excursionists and citizens who take part in recreation activities in this forest. The questionnaires were sent by e-mail and consisted of 23 questions ordered in sections. First, the recipients were asked about the importance of the goods and services associated with the case study. The following question was of an ordinal type and asked participants about the importance of diverse goods and services in forest management. The next question was about the weights, which should be awarded to the five criteria considered in this work through a "pairwise" comparison by using a habitual scale in the AHP method (Analytic Hierarchical Process, [30]). Another question was on the achievement function type of model and, in the case of opting for a lexicographical model, for the criteria which should be included in the first achievement level. The next question was about the level of aspiration granted by each stakeholder to each of the goals in terms of the percentage of attainment of the ideal value of each goal. The last two groups of questions referred to the stakeholders and specific aspects of mycological resources.

Initially, it was proposed to aggregate the preferences shown by the stakeholders by means of a group decision-making model [15], but in view of the small number of valid responses (only 12 answers were received corresponding to five groups of stakeholders from the 11 defined initially, and in some of them only one replied), it was decided to aggregate the answers by simply calculating the average of the values awarded by the stakeholders to each answer. As some authors state, there are several ways to aggregate the judgements of different stakeholders [31]. The aggregation rule used in our exercise implies the best-compromise consensus from the point of view of the majority. A discussion about the theoretical properties of the different aggregation rules can be seen in [32].

2.2.4. Scenarios Considered

Two scenarios were considered in this analysis. The first (Scenario 1) corresponds to the one explained above, and was characterised by having assumed that the variables follow a deterministic behaviour. The second (Scenario 2) it was supposed that some variables are simulated under situations of risk, so we have called it non-deterministic scenario. This was due to some criteria considered undergoing notable changes throughout the time caused, in the case of mushrooms, by their great dependence on variations in weather factors [33,34]. In particular, mushroom production, the price of one of them (*Lactarius* gr. *deliciosus*), and the price of timber were selected as variables which are modified in this second scenario. For this purpose, data corresponding to the period from 2002–2013—weekly ones in the case of the mushrooms—were gathered, and, next, the corresponding simulations using the Monte Carlo method were undertaken. The latter sets out to solve mathematical problems by simulating the values of particular random variables [35]. This method can be applied both in situations of risk (when the probability density functions for certain variables are known) and *in situ*ations of uncertainty (when those probabilities are unknown). In the latter case (Scenario 2), the Monte Carlo method is similar to a sensitivity analysis, and the software @RISK (Palisade Corporation, Ithaca, NY USA) was used. This Monte Carlo analysis has been applied only to the three variables cited above. In all the cases, the number of iterations used was 1000, and several distribution functions were tested to achieve the best goodness-of-fit test, which provides a quantitative measure of how closely the distribution of the data from the variables chosen being fit resembles the fitted distribution. In the case of mushroom production, the variability has been considered separately into different intervals (see Figure 3), and the same distribution function was not used for all the variables. For example, in the case of the price of timber, we selected the inverse gaussian distribution, and a Weibull function for the price of mushrooms. In all the cases, the test chosen was the Akaike Information Criterion (AIC).

Figure 3. Mushroom production per stand-age class in period 2002–2013. (Error bars represent the standard deviation).



3. Results and Discussion

In this section, first, the results of the pay-off matrix for the two scenarios considered are shown. Next, the GP model employed has been justified on the basis of the results of the survey taken from the different stakeholders. Then, the actual results of the strategic planning carried out in the study case are exhibited. Finally, a discussion section has been included.

3.1. Pay-off Matrix

Table 1 shows the pay-off matrix for the five criteria considered in Scenario 1 (deterministic scenario), with the values of the main diagonal being the ideal ones for each criterion, and those in italics the anti-ideal ones. From this matrix, it is obvious that there is a strong degree of conflict among the five criteria considered, which justifies their inclusion in the GP model.

Table 1. Pay-off matrix under Scenario 1 (ideal values in bold; anti-ideal values in italics).

	Timber production (m^3)	Mushroom production (kg)	Carbon captured (t)	NPV (€)	Normal forest structure (adimensional)
Timber production (m^3)	**3,615,695**	1,911,489	*1,742,425*	3,423,320	2,253,409
Mushroom production (kg)	7,155,902	**7,972,607**	7,933,012	7,731,015	*6,502,992*
Carbon captured (t)	*277,491*	522,197	**543,536**	306,393	399,609
NPV (€)	97,838,280	86,514,870	85,470,730	**102,919,100**	*61,193,220*
Normal forest structure	*7.9*	4.9	5.4	5.7	**0.1**

Following the same logic, Table 2 shows the pay-off matrix for the five criteria considered in Scenario 2. The degree of conflict among the five criteria is similar with respect to the deterministic case.

Table 2. Pay-off matrix under Scenario 2 (ideal values in bold; anti-ideal values in italics).

	Timber production (m^3)	Mushroom production (kg)	Carbon captured (t)	NPV (€)	Normal forest structure (a-dimensional)
Timber production (m^3)	**3,615,695**	2,013,018	*1,742,425*	3,425,750	2,253,409
Mushroom production (kg)	*2,702,695*	**3,225,487**	2,899,517	2,770,103	3,020,446
Carbon captured (t)	*277,491*	458,826	**543,536**	305,390	399,609
NPV (€)	83,687,630	56,142,430	70,430,700	**88,083,240**	*50,350,040*
Normal forest structure	*7.9*	3.3	5.4	5.7	**0.1**

3.2. GP Model Selected

The results shown in Tables 1 and 2 reveal the need to approach this problem by using a multi-criteria tool like goal programming. When analysing the results of the stakeholders' survey, it is observed how, first, there were two criteria of extreme importance with respect to the rest and which should have been fulfilled: the timber production and the normal forest structure. This circumstance implies that the variant of the goal programming model should be a lexicographic one. In fact, the two criteria cited above would constitute the first priority of this model, whereas the rest of the criteria (mushroom harvesting, profitability, and carbon sequestered) would be included in a second priority. On the other hand, given that there is more than one criterion in each of the priorities, a compensatory character between them has been accepted by means of a weighted goal programming model at each priority level. In addition, starting from that survey, the weights and achievement levels for each of the criteria were obtained. Also, the targets related to the different criteria ranged between 60% and 75% of their respective ideal values (Table 3). Similarly, for the calculation of the preferential weights and of the targets, the median of the replies given by the whole group of stakeholders was used. Hence, the following preferential weights were incorporated into the lexicographic achievement function given by equation (10): $W_1 = 0.47$ and $W_2 = 0.53$ for the two goals placed in the first priority level, and $W_3 = 0.21$, $W_4 = 0.59$ and $W_5 = 0.20$ for the three goals placed in the second priority level (Table 3).

Table 3. Stakeholders survey results.

	Timber production (m^3)	Mushroom production (kg)	Carbon captured (t)	NPV (€)	Normal forest structure
Order of importance	1	2	2	2	1
Preferential weights (W_i)	0.47 (W_1)	0.21 (W_3)	0.20 (W_5)	0.59 (W_4)	0.53 (W_2)
Targets (t_i)	0.60	0.75	0.60	0.65	0.70

3.3. Results of Strategic Planning

Finally, the multi-criteria model detailed above has been resolved for both scenarios. The results are given in Table 4, where it can be seen how the values are equal for those criteria which are not subject to a non-deterministic component.

Table 4. Results of the Lexicographic Goal Programming (LGP) model for both scenarios and for the case where the preferential weights were the same.

criteria	Scenario 1	Scenario 2	Equal weights
Timber production (m^3)	2,634,970	2,634,970	2,375,940
Mushroom production (kg)	7,095,220	3,012,234	6,721,150
Carbon captured (t)	371,419	371,419	408,908
Net present value (€)	78,412,510	65,995,910	67,072,000
Normal structure (a-dimensional)	0.7	0.7	0.2

3.4. Discussion

The above results show the possibility of finding a harvest schedule which permits the stakeholders' preferences to be satisfied in accordance with the five criteria considered. However, taking into account Table 1, a high degree of conflict between the different criteria can be observed. In some cases, this conflict is especially relevant, like in that of timber production and the forest's profitability with the normal structure or sequestered carbon criteria. Furthermore, maximising mushroom picking signifies a high opportunity cost in some of the criteria, such as the cutting volume or the normal forest structure. All this implies that no solution obtained by maximising separately each of the criteria would turn out to be an attractive one for the DM, so that constructing a multi-criteria forest management model would be justified.

In addition, it should be pointed out that the methodology proposed here means considering a GP as a participatory technique, or, in other words, as being interactive with the decision-making centre. This approach is not frequently used in the literature, although some authors have recommended it [29]. Along these lines, due to the limited number of surveys answered by the stakeholders, it was not acceptable to differentiate between the surveys according to the type of stakeholder when adding the answers in a suitable form, such as following some group decision-making methodologies [15]. Also, the breakdown shown in Figure 2 could be valid for its integration into a DSS as a problem processing system [4].

On analysing both scenarios with respect to the non-deterministic one (Table 4), some differences in the criteria concerning the mushroom picking and the profitability of the forest can be observed. Thus, with regard to profitability, the decline is practically generated by the drop in the net present value associated with mushroom picking, which is 61%. In the deterministic scenario, the value triggered by mushroom harvesting represents 24% of the forest total, whereas in the other scenario it only represents 11%. This reveals the high variability of the mushroom picking function when risk is included in the analysis, as its production is highly dependent on weather factors. In short, those differences are caused to a great extent by variations in mushroom production, and not so much by the variability in the market prices of the saffron milk cap mushroom or the timber.

The results obtained in the deterministic scenario for the final solution of the LGP when the preferences of the stakeholders were considered reflects an achievement level of 73% with respect to the ideal for the cutting volume criterion, 70% for the ideal for the normal forest structure, 89% for mushroom picking, 76% for the ideal for the stand profitability, and 68% with respect to carbon sequestration.

Arriving at this point, one question that arises is whether the solutions are more or less sensitive at the preferential weights considered. Table 4 shows the solution with equal weights for Scenario 1. Along these lines, it was observed that the solutions obtained in the timber production, mushroom picking, and carbon sequestration criteria were below 10% with the changes in the preferential weights. Profitability varied 15%, while the criterion associated with a normal structure was considerably modified.

In this study, we have defined several forest management objectives that are not usually addressed in timber harvest scheduling problems. In fact, few works have dealt with wild mushroom picking, although none has added carbon capture to these models. As we have said above, some research into mushroom production has been included in forest planning through the use of optimisation tools, confirming the economic significance of this resource. Most of the studies have been only applied in different parts of Spain [13,14,36,37]. However, the economic importance of this non-wood product in Spain, just like in other countries, is moderate [38]. Perhaps, reasons like difficulties in data collection and complexities in mushroom markets [20] can justify the absence of many studies in this area. Finally, this investigation shows the positive implications of obtaining income from mushroom production in forest management. Other authors have also reached similar conclusions without using optimisation tools [39].

With regard to the criterion associated with the normal structure of the forest, this was proposed by means of the aggregation of the conditions habitually employed for its definition [8]. However, on observing the results, the doubt arises as to how the three conditions behave in the different scenarios established in this study. Table 5 shows the results of the three conditions for the pay-off matrix (Table 1) and for the results of both scenarios (Table 4).

Table 5. Numerical variations of the three components characterizing the normal forest formerly included in Tables 1 and 4: A_i is the area occupied by age class *i*; F_i is the timber inventory in the section *i* at the end of the planning horizon; H_i is timber harvested in period *i*.

	Pay-off Matrix (Table 1)					**(Table 4)**	
	Timber production (m^3)	**Mushroom production (kg)**	**Carbon captured (t)**	**NPV (€)**	**Normal forest structure**	**Scenario 1**	**Scenario 2**
Normal forest structure (a-dimensional)	7.9	4.9	5.4	5.7	0.1	0.7	0.7
			Regulation (has)				
A1	11,322	0	0	8,471	2,075	3,083	3,078
A2	1,128	564	0	1,811	2,255	1,827	1,827
A3	0	0	0	42	2,075	1,606	1,608
A4	0	2,168	2,176	2,126	2,075	2,821	2,824
A5	0	8,387	8,379	0	2,075	1,556	1,556
A6	0	1,331	1,895	0	1,895	1,556	1,556
			Final Inventory (m^3)				
F1	892	249,104	252,255	33,155	146,657	109,993	109,993
F2	4,069	323,263	383,945	32,115	183,576	137,682	137,682
F3	2,885	355,706	434,656	59,005	181,877	136,408	136,408
F4	4,765	541,238	567,747	64,728	361,356	271,017	271,017
F5	2,816	411,826	417,841	43,936	269,494	202,121	202,121
			Evenness of harvests in each period (m^3)				
H1	1,402,301	1,142,229	1,402,301	1,307,160	276,154	521,721	521,721
H2	120,891	403,027	120,452	220,897	276,154	391,291	391,291
H3	0	99,946	100,420	99,946	276,154	293,468	293,468
H4	0	119,288	119,288	118,278	242,412	220,101	220,101
H5	0	0	0	1,094	242,412	165,076	165,076
H6	0	0	0	0	242,412	123,807	123,807
H7	0	97,277	0	97,277	174,427	92,855	92,855
H8	136,680	54,234	0	229,113	174,427	209,040	209,040
H9	143,324	0	0	682,625	174,427	352,920	352,920
H10	1,812,499	0	0	666,930	174,427	264,690	264,690

This table shows the variation in this composite criterion in Tables 1 and 4, taking as a reference its three components. Along with the ease with which it can be handled, this aggregation offers advantages when interacting with the stakeholders due to the reduction in the number of questions, especially if they have been posed through comparisons in pairs. Also, in this work, it has been assumed that there was a perfect exchange between the deviations of the three components making up the criterion, given that the weight of each of them was identical. If that is not so—*i.e.*, in the case of lower deviations being preferred in one of the components—different weights could be given to each of them in order to reach a certain weighting.

On the other hand, if the results obtained with those of other studies using optimisation tools for the same forest are compared [14], they are similar, although with differences in the amount of mushrooms picked and in the forest's profitability, as a result of considering a different period of historical data in the calculations for the mushroom production and prices. Finally, the incomes from mushroom production could be more protected against price variations if some annual harvesting permits for pickers in this forest would be consolidated under the MYAS-RC system. This regulation may be beneficial for the forest, especially when the saffron milk cap mushroom price is low. Nevertheless, if this alternative would be consolidated, the figures of NPV in this harvest scheduling model should be re-calculated [14].

4. Conclusions

The methodology proposed in this work permits efficient solutions to be obtained to problems related to strategic forest planning by incorporating criteria of a different nature. To be specific, through the interaction with different stakeholders, the goal programming model to be used is justified, as well as certain aspects of this model (preferential weights and targets). This participatory approach permits the refinement of the methodology employed with the preferences of the different stakeholders.

However, the solutions obtained from the GP models by taking the criteria considered in the handling of the case study (timber production, mushroom harvest, carbon sequestration, profitability, and normal structure of the forest) evidence the existence of a high level of conflict between each of them. This makes necessary the use of multi-criteria techniques, and, in accordance with the stakeholders' preferences, a LGP model with two priority levels was selected.

In agreement with the LGP solutions when Monte Carlo analysis is considered, an important variation in the mushroom harvest and, to a lesser extent, in the profitability criterion (58% and 16%, respectively, compared to the deterministic scenario) was noted. Those differences reveal the great variability or analysis of risk in mushroom production, which is highly dependent on weather conditions.

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Author Contributions

Jorge Aldea carried out the forest's strategic planning, wrote the manuscript, and compiled the stakeholders' opinions. Fernando Martínez-Peña revised everything to do with the criterion associated with the mushroom production. Carlos Romero contributed to defining the multi-criteria model and also revised this work. Luis Diaz-Balteiro wrote the manuscript and designed the stakeholders' survey.

Conflicts of Interest

The authors declare no conflict of interest.

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