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Research article

Ranking of industrial forest plantations in terms of sustainability: A multicriteria approach

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ABSTRACT

As forest managers and owners must have precise assessments of sustainability, in this study we have proposed a methodology based on multi-criteria techniques for assessing sustainability in industrial forest plantations and establishing a ranking of these plantations in terms of sustainability. First, we identified and have briefly described a set of sustainability indicators (economic, environmental and social). Next, we developed a statistical procedure to determine if a linear relationship existed between the indicators. With this analysis, the final set of indicators was defined and normalized. Then, we formulated four goal programming models, by which to aggregate the different indicators. In these models, we introduced the preferences of the decision makers for each indicator, using a survey with questions formulated in a pairwise comparison format.

The procedure was applied to 30 *Eucalyptus globulus* Labill. plantations in northwestern Spain and 11 indicators were selected in order to define the sustainability. The results showed several rankings under each goal programming model. Although the results may not be the same in the different models, some plantations are always the most sustainable, while others are always the worst in terms of sustainability. The combination of initial values of indicators, goal programming models and preferences of stakeholders (preferential weights and targets) influence the results, and it cannot be predicted a priori which plantation is the best/worst in terms of sustainability. In our case study, we show how changes in preferential weights and targets substantially modify the results obtained.

1. Introduction

From its beginnings, when it basically served as a production objective, forest management included a sustainability component, usually comprised of the fulfillment of conditions ensuring sustained yield (Recknagel and Bentley, 1919). Thus, the perfect expression of the idea of sustainability was the ideal of a normal forest. Thus, some authors affirm that sustainability has been the basic idea of forest management for over 250 years (Schraml and Detten, 2010), and it was in the forestry sphere that this concept was born (Carlowitz, 1713 in Pretzsch, 2014). However, in the last few years, forest management has begun to ensure sustainability with other components in addition to the production sustainability (Bettinger et al., 2009; chap. 9). This idea has gradually been articulated since the initial proposal made in the United Nations Conference on Environment and Development held in Rio de Janeiro in 1992. Nowadays, there are various definitions of sustainable forest management, but they all essentially establish that the latter involves a process of managing forests which is economically viable, environmentally benign and socially beneficial, and which balances present and future needs (Higman et al., 2005). In short, sustainability has been addressed from several viewpoints, and there is a general agreement on the need to identify a multidisciplinary list of criteria and indicators (Raison et al., 2001).

Many studies have analyzed sustainability from a specific set of indicators at different levels, from local to regional and national ones, some of them showing the differences between the criteria and indicators suggested in several national schemes used to monitor sustainability in forest management (Grainger, 2012). Several indicators were initially fixed according to a small number

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of criteria all over the world, resulting in periodic measurements of certain forest attributes. However, with a few exceptions (Wolfslehner and Vacik, 2008; Giménez et al., 2013), most of these efforts have failed to respond to the immediate question of whether, in those cases, forest management is sustainable or not, because the indicators have not been properly aggregated, and for that reason were not able to assess the evolution of the sustainability.

In the case of industrial forest plantations, a correct management should include other spheres apart from environmental, social and economic ones, like long-term biological productivity and the business side of forestry (Poulsen et al., 2001). Thus, forest managers and owners must have precise assessments of sustainability, as well as a capacity to predict the effects of management regimes (Giménez et al., 2013). For this kind of forest system, some studies have defined sustainability incompletely, only focusing on certain aspects without including economic or social indicators (Watt et al., 2005; Evans, 2009; Palmer et al., 2005; Jeffries et al., 2010). An exception to this trend could be the study of Giménez et al. (2013), who propose a sequential procedure under a multi-criteria framework to address sustainable management in industrial forest plantations, using six indicators to define the sustainability of different management alternatives. Finally, Derak and Cortina (2014) have determined 14 indicators for evaluating several ecosystem services in *Pinus halepensis* plantations in Spain.

Intrinsic features associated with forest plantations, such as single-species and exotic species composition, short rotations, intensive management prescriptions, etc., have caused a considerable amount of conflicts between companies and local populations. These problems have increased in the case of *Eucalyptus* plantations in several countries (Gerber, 2011). These plantations cause a great deal of controversy in some areas due to forest fire policy (Diaz-Balteiro, 2007) or the ecological impacts reported when managed under intensive forestry practices (Lomba et al., 2011; Calviño-Cancela et al., 2012). In short, some authors affirm that sustainable management in these plantations should try to maintain economical productivity while maximizing biodiversity conservation (Calviño-Cancela, 2013). One potential solution for alleviating these problems would be to define a set of sustainability indicators in order to know which plantations are more sustainable and orientate their management towards achieving plantations with a high degree of sustainability. Finally, the ideas expounded here on the sustainability of different forest plantations should not be confused with the concept of certification. The methodology employed has nothing to do with that adopted for certifying these forest systems. Some authors even advocate, for example, the inclusion of indicators associated with financial viability in plantations under certification schemes (van Eijck et al., 2014).

The use of multiple criteria decision making (MCDM) methods to assess sustainability through previously defined indicators has been extended in recent years to diverse fields. Although the literature is already very extensive, three noteworthy papers are those of Brunner and Starkl (2004), in which several applications have addressed the sustainability issue using several MCDM methods, or Herva and Roca (2013) and Ibáñez-Forés et al. (2014) who focus on diverse sectors such as industry.

Given the multidimensional nature of the sustainability concept, several forest case studies have attempted to portray sustainability by means MCDM techniques (Diaz-Balteiro and Romero, 2008), with goal programming being one of those most employed in forestry applications (Diaz-Balteiro and Romero, 2004; Voces et al., 2012; Giménez et al., 2013), and in other studies (Lozano-Oyola et al., 2012). Other references, which use other MCDM techniques in forest sustainability issues, would be those of Balana et al. (2010) Rantala et al. (2012) and Jalilova et al. (2012).

The main aim of this study was to present several models, based on multi-criteria techniques for establishing different rankings of sustainable *Eucalyptus* plantations, and comparing the results obtained with these models. In order to achieve this objective, we have defined a group of indicators and applied them to a set of homogeneous plantations, in terms of ownership, in the northwest of Spain. These methods, based on goal programming, allows owners to find out which plantations are the most sustainable ones. Besides, they can see the effects in the rankings by giving different weights to each indicator or groups of indicators.

The remaining part of the paper is organized as follows. In the next section, we present the case study along with the MCDM framework proposed. Then, Section 3 presents a summary of the results obtained, and, finally, Section 4 provides a discussion on the results and gives the main conclusions.

2. Material and methods

In this section, we present the case study, and describe the sustainability indicators considered. Lastly, we detail the goal programming models used.

2.1. Case study

Eucalyptus plantations in northwestern Spain are some of the most productive forest systems in Europe (Diaz-Balteiro et al., 2009a), as they provide the raw material for an internationally competitive forest industry. Although these plantations are mostly privately owned and belong to non-industrial private forest owners, for our analysis we preferred the selection of industrial plantations in order to preserve a certain homogeneity in their management. Specifically, the study started from a database of forests managed by the firm ENCE in Galicia. This database contains over 200 forests, 29 of which belong to ENCE, covering a little over 10,500 ha. From a management perspective, it should be noted that all these forests are managed in a single management plan, which is divided up provincially. That is to say, there is no individualized management plan for any of the forests.

This firm pays special attention to the management of these forests for the production of pulpwood. For this purpose, in all the plantations, there are stands of *Eucalyptus globulus* Labill. (7.910has) and *Eucalyptus nitens* H. Deane & Maiden (1.570has). In some plantations there are productive species which take up over 400 ha (*Pinus radiata* D. Don, *Pinus pinaster* Ait.), but the firm sells this wood to others. There are also over 1150 ha for protection purposes, i.e. where no final cuts are made.

We took a sample of 30 forests in order to apply the methodology determining which of them was the most sustainable one. We aimed to have a representative sample and, in fact, these forests make up 13.76% of the total forests and 27.28% of the whole forest area managed by ENCE in Galicia, for a total of 2868 ha. Also, we attempted to select forests representing all sizes, as shown in Table 1. 3 of the 30 forests selected presented *Eucalyptus nitens* as their principal species, and the rest *Eucalyptus globulus*. According to the size of these forests, whose classification is displayed in Table 1, we proposed to analyze at least 10% of them in each category. Finally, we opted for forests in which information on all the indicators chosen was available. Namely, in no case did we use a method for imputing values to a plantation when no information was available for obtaining the value of a certain indicator.

2.2. Indicators considered

To select the indicators, we tried to dispose of an extensive set of them: a group with sufficient indicators to apply the methodology

Table 1
Eucalyptus plantations in the case study.

Plantation area (has)	Number of plantations	
	Case study	ENCE
>400	2	3
200–400	1	4
100–200	6	18
50–100	4	35
20–50	7	54
<20	10	93
	30	207

Source: author's own elaboration from ENCE data.

proposed, but with a minimum number of indicators in each pillar (economic, environmental or social). Thus, we decided that these indicators should be of an economic, environmental, and social nature. Table 2 shows the 11 indicators initially suggested, and classifying them in two categories: indicators of the " less is better" (−) or "more is better" (+) types, since any reduction or increment in the indicators' values supports the sustainability of these *Eucalyptus* plantations. We also included in that table the nature of each indicator (economic, environmental, social).

Starting with the economic indicators, the first one (I_1) represents the commercial profitability associated in each plantation with the eucalyptus cuts, and which is the "more is better" type. Indicator I_2 represents the area of each plantation affected by pests. These percentages do not mean that, a priori, this is an irreversible damage, but it will, at least, cause a lower growth of these stands, and for, it is the "less is better" type. In another direction, an estimation of the soil losses undergone by these plantations is available. Indicator I_3 represents the road density in each plantation. It has been considered to be the "more is better" type, because it is associated with a greater access to facilities for the enjoyment of the forest, a better exit in fire situations, etc. Indicator I_4 represents an estimate of the number of dead trees in each plantation. In this case, this mortality should not be seen as being something positive for improving biodiversity aspects but as a negative element, so that it is assumed to be the "less is better" type.

With regard to environmental indicators, indicator I_5 represents the quotient between the area of Eucalyptus in the forest plantation divided between the total area, and as under the environmental pillar diversity in the composition of plantations is preferred, it was assumed that it was the "less is better" type. The following indicator (I_6) represents the size of the area devoted to protection in each plantation, this being the "more is better" type. In another direction, an estimation of the soil losses undergone by these plantations is available. This is included in indicator I_7, and it is the "less is better" type. With indicator I_8, it was desired to include some aspects relative to the plantations' biodiversity, i.e. the number of threatened flora species present in each plantation, as well as their natural singularities, or the habitats of interest found in the management plan of these forests. As these botanical singularities occur in very few plantations, they have been grouped together, in such a way that any plantation could present a value of 3 in this indicator if it displays the three aforementioned elements. A value of 2 would mean that, in that plantation, two of those elements have been observed, whereas a value of 1 indicates that there is only one of them. Obviously, the value of 0 implies that no botanical singularity has been found in the plantation analyzed. Logically, this indicator is the "more is better" type.

Finally, we have defined three indicators under the social pillar. Indicator I_9 represents the number of tree species present in each plantation, occupying at least 1% of the area of each of them. It is also the "more is better" type. Indicator I_{10} represents an increasingly important aspect in these productive plantations: their certification. We opted to introduce this indicator with 3 values: value 0 implies that the forest is not certified by either of the two systems usually present: PEFC (Programme for the Endorsement of Forest Certification) and FSC (Forest Stewardship Council). Value 1 means that the forest is certified by PEFC and not by FSC, and value 2 present in a forest plantation demonstrates that it is certified by both systems. It is also the "more is better" type. With indicator I_{11} we wished to cover two types of activities which are important in every forest system: recreational and cultural ones. Given that very few plantations present those elements, we considered it to be appropriate to group them together, imputing a value of 1 to each plantation if it presented infrastructures facilitating recreational enjoyment, and 0 if it did not. Similarly, if any forest displayed any cultural element, we granted it a value of 1, and 0 if it did not. Adding both together, we found that the plantations can have values of 2, 1 and 0. Obviously, this would be an indicator of the "more is better" type.

2.3. Methods

In this section, we introduce the methodologies that we employed in this work. As a preliminary step, we undertook a correlation analysis with the battery of indicators. This type of exercise is necessary in order to determine possible linear relationships between two different indicators. Thus, if the correlation coefficient achieves a significant value, then one of the indicators conveyed redundant information and, consequently, should have to be eliminated from the analysis. This fact permitted us to reduce the dimension of the original problem. The result of this analysis was a smaller set of indicators. The following step is to

Table 2
Indicators used in this study.

Sustainability pillar	Indicator	Name	Type
Economic	Net present value (€/ha)	I_1	(+)
Economic	% Plantation area affected by diseases	I_2	(−)
Economic	Road network (m/ha)	I_3	(+)
Economic	% Dead trees	I_4	(−)
Environmental	Eucalyptus area/Plantation area	I_5	(−)
Environmental	Protection area/Plantation area	I_6	(+)
Environmental	Soil erosion losses (t/ha)	I_7	(−)
Environmental	Aggregated biodiversity	I_8	(+)
Social	nº of species embracing an area bigger than 1% of Plantation area	I_9	(+)
Social	Certification	I_{10}	(+)
Social	Recreational and cultural elements inside plantations	I_{11}	(+)

(−): the indicator belongs to the type "less is better".
(+): the indicator belongs to the type "more is better".
Source: author's own elaboration from diverse public and private (ENCE) data.

propose a procedure based on goal programming in order to aggregate these indicators.

2.3.1. Goal programming models

Let us introduce the following scenario. We have $i = 1,2, \ldots n$ plantations, each one is evaluated according to $j = 1,2, \ldots m$ sustainability indicators. The key question is to obtain a cardinal "ranking" of the n plantations in terms of aggregate sustainability. We shall undertake this task by adapting a procedure proposed by Diaz-Balteiro et al. (2011). The first step will consist of defining nxm outcomes that measure the value reached by the ith plantation when it is evaluated according to the jth sustainability indicator, R_{ij}. Given that, normally, sustainability indicators are measured in different units and their absolute values might differ considerably, the application of any aggregation rule (e.g., a weighted sum of indicators) has no meaning. In order to avoid this type of problem, the following normalization system is proposed:

$$\overline{R}_{ij} = 1 - \frac{R_j^* - R_{ij}}{R_j^* - R_{*j}} = \frac{R_{ij} - R_{*j}}{R_j^* - R_{*j}} \quad \forall i,j \tag{1}$$

where $\overline{R}_{ij}$ is the normalised value reached by the ith plantation when it is evaluated according to the jth indicator. It should be noted that R_j^* is the optimal or ideal value for the jth sustainability indicator. This ideal value represents the maximum value if the indicator is the "more is better" type or the minimum value if the indicator is the "less is better" type. In the same way, R_{*j} is the worst value or anti-ideal value for the jth sustainability indicator; that is, the minimum value if the indicator is the "more is better" type and the maximum value if the indicator is the "less is better" type. With this normalization system, the indicators do not have any dimension and they are all them bounded between 0 and 1; that is, from the worst to the best of the criteria values according to a local scale. Moreover, for this normalization system, the ideal vector for the normalized values is = (1,1, …, 1) and the anti-ideal vector (0,0, …,0).

Let us now introduce the Simonian "satisficing" targets t_j to be attached to each indicator. These figures represent "good enough" achievements for the indicators considered; that is, figures that, if they are achieved, the decision maker (DM) feels satisfied. Taking into account that, due to the normalization system used, the target values must hold the following inequation:

$$\overline{R}_{ij} \geq t_j \;\; \forall i \tag{2}$$

According to the above normalization process, these targets $t_j$could be defined as a percentage α_j of achievement with respect to the respective ideal values (i.e., $t_j = \alpha_j t_j^*$, being $\alpha_j < 1$). These target values might be specified according to legal restrictions or bearing in mind stakeholders' aspirations. Once the outcomes R_{ij} and the targets t_j have been defined, we introduce parameters W_j that represent preferential weights measuring the relative importance attached by an expert or by a panel of experts to the jth indicator of sustainability with respect to the other indicators. Finally, we introduced binary variables X_i into the analysis. In this way, if for optimal solution $X_i = 1$, then the ith plantation is the most sustainable one. After that, we removed this variable from the model by making $X_i = 0$, and then computed the new model again in order to obtain the second most sustainable plantation. By operating in this way, we obtained the "ranking" of the n plantations in terms of sustainability. With this strategy in mind, we formulated four goal programming (GP) models which have been selected according to different preferential interpretations of the stakeholders. (Diaz-Balteiro et al., 2013). All the models are GP ones, but the last one unify the other three. In what follows the four GP models are introduced.

2.3.1.1. First model. A weighted goal programming (WGP) formulation is proposed (see Romero, 1991):

$$\begin{aligned}
&\textit{Achievement function}\\
&\textit{Min} \sum_{j=1}^{m} W_j n_j\\
&\textit{Goals}:\\
&\sum_{i=1}^{n} \overline{R}_{ij} X_i + n_j - p_j = \alpha_j t_j^* \quad \forall j\\
&\textit{Constraints}:\\
&\sum_{i=1}^{n} X_i = 1\\
&X_i \in \{0,1\}\\
&\alpha_j \leq 1 \quad \forall j\\
&\mathbf{n \geq 0 \quad p \geq 0}
\end{aligned} \tag{3}$$

The meaning of all the variables and parameters of equation (3) were previously defined with the exception of the deviation variables n_j and p_j. The negative deviation variables n_j quantifies the possible under-achievement of the solution with respect to the target values, while the positive deviation variables p_j quantify the opposite effect, that is, the possible over-achievements of the solution with respect to the corresponding target values. It should be noted that, due to the normalization process undertaken, we defined all the goals in the sense of "more is better", so that the unwanted deviation variables to be included in the achievement function were only the negative ones. Besides this, as we were working with normalized values, the negative deviations variables appearing in the achievement function did not need to be affected by a normalization process. By solving equation (3) we obtained the "most sustainable" plantation. As indicated above, the model can also provide the ranking of the n plantations in terms of aggregate sustainability. To fulfill that purpose, we only needed to solve equation (3) in an iterative way. Thus, we solved equation (3) n times by incorporating into each iteration an additional constraint such as $X_k = 0$, when the kth plantation is the most sustainable one. Moreover, with this procedure the optimal values of the respective n achievement functions obtained in each iteration provide the aggregate index of sustainability associated with each one of the n plantations.

In other words, for this solution, the average discrepancy between the achievement of all the goals and their corresponding targets is minimized (see Romero, 2001, 2004 for a preferential interpretation of this type of solution). However, the optimization of the average is not exempt from difficulties. Thus, for this solution, one or some of the indicators considered may perform very poorly. For that reason, it might be interesting to seek the plantation that provides "the most balanced solution" in the achievement of the different goals. This type of solution can be obtained by minimizing the maximum discrepancy (i.e., by minimizing the negative deviation corresponding to the indicator most displaced with respect to the average obtained). The determination of this "most balanced" solution leads to the formulation of the following MINMAX Chebyshev model:

2.3.1.2. Second model. A MINMAX Chebyshev formulation is proposed (see Romero, 1991):

$$\begin{aligned}
&\textit{Achievement function}\\
&\textit{Min } D\\
&\textit{subject to}:\\
&W_j n_j - D \leq 0 \quad \forall j\\
&\textit{Goal and constraints of eq.}(3)
\end{aligned} \tag{4}$$

where the new variable D represents the maximum deviation; i.e., the discrepancy with respect to its target value of the goal most displaced with respect to the solution obtained. Hence model (4) provides a solution for which a maximum balance in the achievement of the *m* indicators is obtained (again see Romero, 2001, 2004 for the preferential interpretation of this type of solution). Again this solution is appealing but is not exempt from difficulties, since now the “optimum balance” can provide a “poor average”. This possible conflict between “balance” and “average” will be tackled below.

2.3.1.3. Third model. Another possible orientation consists of assuming that the DM wishes to be as far away as possible from its respective anti-ideal values. With this new orientation, the target values t_j represent a percentage of over-achievement with respect to the respective anti-ideal values. On the other hand, as, according to our normalization system, the anti-ideal values are zero, the target value t_j will be equal to β_j, β_j being the percentage of over-achievement tolerated with respect to the anti-ideal value for the *i*th indicator. This orientation leads to the following new goal programming (GP) model:

2.3.1.3.1. Achievement function.

$$\begin{aligned} & Max \sum_{j=1}^{m} \left(W_j \rho_j \right) \\ & subject\ to: \\ & \sum_{i=1}^{n} \overline{R}_{ij} X_i + \eta_j - \rho_j = \beta_j (1 + t_{*j}) \quad \forall j \\ & Constraints\ of\ eq.(3) \end{aligned} \tag{5}$$

It is obvious that in this case the unwanted deviation variables to be included in the achievement function are only the positive ones ρ_j.

2.3.1.4. Fourth model. The three models proposed so far enjoy good preferential properties but they also represent solutions with potential conflicts between them. Thus we have: “optimum average” versus “optimum balance”, “maximum proximity to the ideal” versus “maximum distance to the anti-ideal” and so on. Because of that, it is tempting to merge the three proposed models in to a single one. In this way, with the new model, we could quantify possible conflicts between the three preferential orientations underlying the above proposals as well as to seek compromises between them. This task can be undertaken by implementing a linear convex combination of equations (3)–(5), which leads to an upload of the extended goal programming (EGP) formulation (see Romero, 2001, 2004):

$$\begin{aligned} & Min \lambda_1 D + \lambda_2 \sum_{j=1}^{m} W_j n_j - (1 - \lambda_1 - \lambda_2) \sum_{j=1}^{m} W_j \rho_j \\ & subjectto: \\ & \sum_{i=1}^{n} \overline{R}_{ij} X_i + n_j - p_j = \alpha_j t_j^* \quad \forall j \\ & W_j n_j - D \le 0 \quad \forall j \\ & \sum_{i=1}^{n} \overline{R}_{ij} X_i + \eta_j - \rho_j = \beta_j (1 + t_{*j}) \quad \forall j \\ & constraintsofeq.(3) \\ & being \quad \lambda_1 + \lambda_2 \in [0,1] \\ & \alpha_j \le 1 \quad \beta_j \ge 0 \quad \forall j \end{aligned} \tag{6}$$

In eq. (6) λ_1 and λ_2 play the role of control parameters that allow us to establish the linear convex combination of the above three models. Thus, when $\lambda_1 = 0$ and $\lambda_2 = 0$, the solution farthest away with respect to the anti-ideal (eq. (5)) is obtained, when $\lambda_1 = 1$ and $\lambda_2 = 0$, the most balanced solution is elicited (eq. (4)), and when $\lambda_1 = 0$ and $\lambda_2 = 1$, the optimization of the average is achieved (eq. (3)). For values of the control parameters λ_1 and λ_2 such as $\lambda_1 + \lambda_2 \in$ [0,1] compromises between the above three solutions, if they exist, will be obtained. The interest of this proposal will be clarified in the Results section. For the resolution of these models, the software LINGO 13 (Lindo Systems, 2011) was applied.

2.3.2. Preferential weights and target values

In the previous models it can be verified that there are two parameters which it is necessary for us to determine exogenously. One is the weights given to each indicator (W_j), whereas the other is the target associated with each goal (that is, the percentages of under-achievement with respect to the ideal α_j, and of over-achievement with respect to the anti-ideal β_j). For their calculation, we took a survey among technicians from the firm managing the plantations, sending a questionnaire to 31 of them and receiving answers from 12.

To calculate the weights we opted to ask them, first, about the importance of the indicators of an economic, social or environmental nature, and then questioning them about the importance of the indicators included in each of the three groups mentioned above. We carried out the interviews by resorting to a “pairwise” comparison format. That is, to each of the ENCE’s technicians we posed the following type of question: “between the *i*th indicator and the*j*th indicator” which one is the most important and by which ratio? We formulated the questions with the help of Saaty’s verbal scale (Saaty, 1977, 1980), which has been widely used and tested in practice (see e.g., Diaz-Balteiro et al., 2009b). By using a WGP formulation (for technical details see González-Pachón and Romero, 2007) from the above “pairwise” information the *s* group preferential weights (W_1, …, W_i, …, W_s) to be attached to each sustainability indicator were obtained.

We calculated the targets by obtaining, for each indicator, the median of the values obtained as responses from the different technicians to the question on which values associated with each of the indicators (not optimal values) they would accept. That is to say, starting from the basis that not all the indicators can reach an optimal value in all the forests, we asked them which values would be acceptable to them. In relation to GP model (5), the targets were fixed in the respective anti-ideal values (i.e., $\beta_j = 0\ \forall j$).

3. Results

In this section, first, we show the indicator values for each forest, and, next, the matrix including those values, now normalized, and excluding indicators presenting a strong correlation. Finally, before presenting the results of the models, the values of the preferential weights and of the targets are given.

3.1. Outcome matrices and correlation analysis

With the 30 forests and the 11 indicators selected, the outcome matrix shown in Appendix A (supplementary material) was obtained. We developed the correlation analysis with the figures shown in Appendix A, and included it in Appendix B (supplementary material). Only the correlation between indicators I_5 (Eucalyptus area/plantation area) and I_6 (Protection area/plantation area) is relatively high (−0.633), and the p-value is low (0.0002), suggesting an inverse linear association between these variables so that we dropped this indicator (I_5). Nevertheless, nothing can be inferred about the direction of the causation between the variables. Regarding the rest of the coefficients in the correlation matrix, their values are smaller, signifying the existence of weak linear links between the variables (see Appendix B).

Once we had removed this indicator, the results were normalized in accordance with the procedure explained above, and they appear in Table 3. Note that in that matrix we show the ideal values for an indicator in bold print, while the anti-ideal ones appear in italics.

3.2. Weights and targets

After receiving 12 surveys filled in out of 31 sent to the technicians, the first question we have addressed is the consistency in the responses, especially in the pairwise comparisons. In this case the responses have been very consistent. Of 156 results (12*(3 + 4+3 + 3)), only 5 have been inconsistent. By solving each matrix, we have obtained the value of each comparison (pillars or indicators of each pillar). Only with these consistent responses did we calculate the respective mean values, and those were the figures that we incorporated into the GP models. Table 4 displays the weight obtained for each indicator, along with its respective target value. Note that the sum of the weights for the ten indicators equals 1. Finally, it should be observed that economic pillar was the one most valued by the technicians (46.5%), followed by the environmental (32.5%) and social (21%) pillars.

3.3. Goal programming models

We begin this sub-section by showing the results of the three models previously developed, using model 4 (eq. (6)) for this purpose. Thus, Table 5 contains the three rankings corresponding to the three solutions defined above: "optimum average" (I), "optimum balance" (II) and that which maximizes the distance to the anti-ideal point (III). Thus, the solution optimizing the average (I) implies that plantation 5 was the most sustainable one, followed by plantation 15, and so on. Conversely, plantation 18 was the least sustainable of all. A similar interpretation can be made for solutions derived from the other two models (II and III) shown in that Table 5, in which it is seen how the ranking was modified by using one model or another. Finally, it might be of interest to offer other results for different combinations of control parameters λ_1 and λ_2. Some of the results obtained are given in Table 6. These results are self-explanatory, although some comments might be useful for a better appreciation of the potentiality of the proposed approach. Thus, the ranking corresponding to $\lambda_1 = \lambda_2 = 0.333$, represents the solution obtained when the same importance is attached to the three models considered. The next solution, that is the one corresponding to $\lambda_1 = \lambda_2 = 0.5$ implies a result for which the third model is not considered and the same importance is attached to the first two models. The other solutions can be read in a similar way. It is interesting to note that for our exercise there is a certain degree of robustness for the rankings obtained. Thus, for all the combinations of models tested, plantations 15, 5 and 30 form something like a

Table 4
Values of preferential weights and targets used in this study.

Indicator	Weight	Target (%)[a]
I_2 (+)	0.249	80
I_3 (+)	0.110	50
I_4 (+)	0.058	50
I_5 (−)	0.048	35
I_6 (−)	0.102	40
I_7 (+)	0.126	55
I_8 (+)	0.097	60
I_9 (−)	0.038	50
I_{10} (+)	0.146	75
I_{11} (+)	0.026	20

[a] It refers to the percentage with respect to the optimal value.
Source: author's own elaboration.

Table 3
Normalized matrix of outcomes.

Plantation	Indicators									
	Economic pillar				Environmental pillar			Social pillar		
	I_1 (+)	I_2 (−)	I_3 (+)	I_4 (−)	I_6 (+)	I_7 (−)	I_8 (+)	I_9 (+)	I_{10} (+)	I_{11} (+)
1	0.385	0.419	0.185	**1.000**	0.502	0.618	*0.000*	**1.000**	0.500	*0.000*
2	0.374	0.702	0.148	0.900	0.376	0.091	**1.000**	0.333	**1.000**	*0.000*
3	0.692	0.172	0.161	0.866	0.076	0.609	*0.000*	0.667	0.500	*0.000*
4	0.270	0.502	0.100	0.752	0.103	0.769	*0.000*	0.667	0.500	0.500
5	0.486	0.384	0.082	0.734	0.375	0.824	**1.000**	0.333	**1.000**	0.500
6	0.339	**1.000**	0.233	**1.000**	0.096	0.824	0.667	0.000	*0.000*	*0.000*
7	0.597	0.339	0.176	0.397	0.362	0.824	*0.000*	**1.000**	**1.000**	**1.000**
8	0.776	0.201	0.035	0.681	0.306	0.824	*0.000*	0.333	0.500	*0.000*
9	0.748	0.181	0.156	0.821	0.011	0.747	*0.000*	*0.000*	**1.000**	0.500
10	0.429	0.313	0.078	0.443	0.208	0.533	**1.000**	**1.000**	**1.000**	*0.000*
11	0.647	0.296	0.098	**1.000**	0.086	**1.000**	*0.000*	0.667	0.500	*0.000*
12	0.355	**1.000**	0.056	0.865	0.310	0.760	*0.000*	0.667	0.500	*0.000*
13	**1.000**	**1.000**	0.179	**1.000**	0.421	0.777	*0.000*	0.333	*0.000*	*0.000*
14	0.702	0.006	0.113	**1.000**	*0.000*	0.824	*0.000*	*0.000*	0.500	*0.000*
15	0.600	**1.000**	0.328	**1.000**	0.179	0.824	0.333	*0.000*	**1.000**	*0.000*
16	0.840	0.135	**1.000**	*0.000*	0.000	0.824	*0.000*	*0.000*	0.500	0.500
17	0.463	**1.000**	0.030	**1.000**	0.214	0.824	*0.000*	*0.000*	*0.000*	*0.000*
18	*0.000*	*0.000*	0.279	0.730	0.210	0.824	*0.000*	0.667	0.500	*0.000*
19	0.391	0.255	0.152	0.844	**1.000**	*0.000*	0.333	0.667	**1.000**	*0.000*
20	0.442	0.533	0.186	0.829	0.557	0.371	*0.000*	0.667	0.500	*0.000*
21	0.405	0.734	0.289	**1.000**	*0.000*	0.765	0.333	0.333	**1.000**	0.500
22	0.739	**1.000**	0.141	**1.000**	0.079	0.699	*0.000*	0.333	0.500	*0.000*
23	0.353	0.357	*0.000*	**1.000**	0.070	0.653	*0.000*	0.333	0.500	*0.000*
24	0.398	0.065	0.372	0.906	0.021	0.824	*0.000*	0.667	0.500	0.500
25	0.549	0.031	0.139	0.893	0.955	0.823	*0.000*	*0.000*	0.500	*0.000*
26	0.579	**1.000**	0.138	**1.000**	0.034	0.823	*0.000*	0.667	0.500	*0.000*
27	0.763	0.083	0.116	0.724	*0.000*	0.824	*0.000*	*0.000*	0.500	*0.000*
28	0.183	0.085	0.259	**1.000**	*0.000*	0.822	*0.000*	*0.000*	0.500	*0.000*
29	0.547	**1.000**	0.254	**1.000**	*0.000*	0.770	*0.000*	*0.000*	0.000	*0.000*
30	0.919	**1.000**	0.714	**1.000**	0.027	0.673	*0.000*	0.333	0.500	*0.000*

Source: author's own elaboration.

Table 5
Ranking of the plantations following Models 1, 2 and 3.

I: $\lambda_1 = 0$; $\lambda_2 = 0$		II: $\lambda_1 = 1$; $\lambda_2 = 0$		III: $\lambda_1 = 0$; $\lambda_2 = 1$	
Plantation	Achievement function	Plantation	Achievement function	Plantation	Achievement function
5	0.1241	15	0.0498	15	−0.6268
15	0.1324	3	0.0582	5	−0.6140
30	0.1443	22	0.0582	30	−0.6014
7	0.1491	8	0.0582	13	−0.5709
10	0.1644	14	0.0582	7	−0.5660
22	0.1750	27	0.0582	21	−0.5467
8	0.1817	16	0.0582	10	−0.5364
21	0.1836	11	0.0582	22	−0.5320
9	0.1849	26	0.0582	2	−0.5276
13	0.1979	9	0.0582	26	−0.5157
2	0.1983	30	0.0582	9	−0.5089
16	0.2115	7	0.0582	11	−0.4805
26	0.2133	25	0.0625	19	−0.4804
3	0.2156	5	0.0782	16	−0.4718
11	0.2158	20	0.0891	8	−0.4707
20	0.2298	10	0.9238	12	−0.4689
1	0.2304	21	0.0984	25	−0.4651
27	0.2371	24	0.1001	1	−0.4408
12	0.2456	19	0.1018	6	−0.4342
19	0.2494	1	0.1033	3	−0.4250
25	0.2539	2	0.1061	20	−0.4212
14	0.2609	29	0.1095	27	−0.4174
4	0.2802	17	0.1095	14	−0.4068
24	0.2887	13	0.1095	29	−0.4060
6	0.2950	12	0.1108	17	−0.4007
23	0.2959	23	0.1113	24	−0.3886
29	0.3100	6	0.1148	4	−0.3831
17	0.3220	4	0.1320	23	−0.3502
28	0.3730	28	0.1536	28	−0.2945
18	0.3863	18	0.1992	18	−0.2748

In colour grey, appear the plantations which presents the same value for the optimum balanced ranking.
Source: author's own elaboration.

Table 6
Other solutions for different combinations of λ_1 and λ_2.

$\lambda_1 = 0.333$	$\lambda_1 = 0.5$	$\lambda_1 = 0$	$\lambda_1 = 0.5$	$\lambda_1 = 0.25$	$\lambda_1 = 0.5$	$\lambda_1 = 0.25$	$\lambda_1 = 0.2$	$\lambda_1 = 0.6$	$\lambda_1 = 0.2$
$\lambda_2 = 0.333$	$\lambda_2 = 0.5$	$\lambda_2 = 0.5$	$\lambda_2 = 0$	$\lambda_2 = 0.25$	$\lambda_2 = 0.25$	$\lambda_2 = 0.5$	$\lambda_2 = 0.2$	$\lambda_2 = 0.2$	$\lambda_2 = 0.6$
Plantation	Plantation	Plantation	Plantation	Plantation	Plantation	Plantation	Plantation	Plantation	Plantation
15	15	15	15	15	15	15	15	15	15
5	30	5	5	5	30	5	5	30	5
30	5	30	30	30	5	30	30	5	30
7	7	7	7	7	7	7	7	7	7
22	22	13	22	22	22	13	10	22	13
10	13	10	8	10	9	22	22	9	22
9	26	21	9	21	10	10	21	26	21
21	9	22	10	9	26	21	9	8	10
13	21	2	16	13	8	9	13	10	9
26	10	9	26	8	21	26	8	11	2
8	11	26	3	26	13	2	2	16	26
2	2	8	11	2	11	8	26	21	8
11	16	11	21	16	16	11	16	13	11
16	8	16	27	11	2	16	11	3	16
3	25	19	2	3	3	25	3	25	19
25	19	12	13	25	25	19	27	2	25
19	3	25	25	27	27	12	1	27	12
27	27	1	20	19	14	3	20	14	3
12	12	3	14	1	19	1	25	19	1
1	14	20	1	20	20	27	19	20	27
20	1	27	19	12	1	20	12	1	20
14	20	14	12	14	12	14	14	12	14
6	6	6	24	6	6	6	6	24	6
24	29	4	23	24	24	29	24	6	29
29	17	24	6	4	29	24	4	29	24
4	24	29	4	29	17	17	29	17	17
17	4	17	29	17	4	4	23	23	4
23	23	23	17	23	23	23	17	4	23
28	28	28	28	28	28	28	28	28	28
18	18	18	18	18	18	18	18	18	18

Source: author's own elaboration.

kernel of the “most sustainable plantations”. On the other hand, it is also significant that plantations 18, 28, and 23 are for all the cases studied the “less sustainable ones”.

4. Discussion and conclusions

When a sustainability analysis is made of a forest system using a set of indicators, the first issue which arises is related to the presence or absence of some of them. For this study we should explain that some indicators usually used in these studies (Giménez et al., 2013) were unable to be employed in this case for different reasons. Thus, in some cases, no reliable data were available, like any estimation of the carbon capture to be made in the next 10 years in these forests. We did not consider some other indicators due to the actual characteristics of the plantations. However, one indicator that could, a priori, be contemplated for incorporating into this analysis would be a ratio between growth and the annual allowable cut. Unfortunately, as we are dealing with production plantations, this ratio in the productive stands tends to be 1 in all the forests, so that we did not take it into account. Furthermore, as the management is very similar in all the plantations, we did not consider any indicator associated with the silviculture applied in each of them, in spite of its possible importance to reaching a sustainable forest management (Bravo and Diaz-Balteiro, 2004). Also worth noting is that we did not consider any indicator associated with forest fires (for example, fire occurrence probability) due to there being no results available at a plantation level.

In this work we took a set of indicators which incorporates the sustainability pillars habitually accepted (Rametsteiner et al., 2011), as those pillars fulfilled the minimum requirements for such acceptance (Ferris and Humphries, 1999). However, the objective of the work was not to define a set of indicators which were valid for all the plantations. In fact, in the literature, there are numerous examples of ad hoc indicators for evaluating sustainability in plantations (Smith et al., 2008). Thus, some authors prioritize certain indicators over the rest (West, 2006). However, it should be realized that in this work we only took the measurements of the indicators once, so that no indicators were available that could tackle what Evans (2009) called “narrow-sense’ sustainability”, i.e. if the plantations can remain indefinitely without any risks to their survival.

The GP models proposed have been a useful tool for establishing a ranking of *Eucalyptus* plantations considered in this study in terms of sustainability, taking into account the set of indicators defined, as well as the preferential weights and target values attached to these indicators. Thus, with the help of this methodological tool, we established several optimal rankings according to different values of λ_1 and λ_2. It is interesting to point out that the methodology presented permits an easy integration of the stakeholders’ opinions both to weigh up the different importance of the indicators considered and to establish some of the key elements of the models, such as the targets. The consideration of these elements exogenously determined is a striking difference from previous papers (Diaz-Balteiro and Romero, 2004).

Now going on to analyze the results, it should be emphasized that, of the 13 different rankings shown in Tables 6 and 7, plantation 15 is always the most sustainable one, except for the case in which we found the most efficient solution, where 5 is the most sustainable plantation. Plantations 28 and 18 are the least sustainable ones in all the rankings. In short, there would appear to be a certain consistency in these rankings.

On analyzing the components of the different models that we employed, and since it is fairly infrequent in many WGP applications, it should be mentioned that, in this work, we determined both the preferential weights and the target values exogenously. One initial question posed is whether the introduction of these weights and targets substantially modifies, or not, the results obtained for some equal weights and a target common to all the indicators and determined ad hoc. Table 7 shows the ranking obtained when assuming equal weights and targets for models I, II and III. As can be seen, the results differ from those given in Table 6, especially for models II and III. This variability indicates the importance of introducing the stakeholders preferences considered in the analysis. Finally, it should be noted that both in Table 5 and in Table 7 shaded areas appear in some rankings. These results, especially for the most sustainable solutions (Diaz-Balteiro and Romero, 2004), denote indifference zones or, what comes to the same thing, that the sustainability value is the same for those plantations.

By observing the results globally, the importance of four factors when selecting the most sustainable plantation is appreciated. The first factor would obviously be the values of the indicators, while another is related to the multi-criteria model chosen. In short, to address this problem the Decision Maker (DM) should choose the model on the basis that each type of achievement function is supported by a precise structure of the DM’s preferences. In short, the right model chosen depends chiefly on the desires and preferences of the decision-maker (Diaz-Balteiro et al., 2013). The other two factors are the weights and target values provided by the DMs. Possible changes in the values of these parameters could substantially modify the obtained solution. For example, in our case study we can see how, if the weights or targets in two models are modified, plantation 15 is no longer the most sustainable one, *ceteris paribus* (Table 7). This variability makes it difficult to determine a priori which plantations can be more or less sustainable, although the normalization matrix may give some clue. For example, it seems reasonable to think that those plantations that do not show anti-ideal values for all the indicators and, at the same time, some indicators reach their ideal value could be high up in the rankings, which happens for plantation 5. In the same way, a priori those plantations present a larger number of indicators with anti-ideals values, while fewer indicators with a greater number of ideal values, could occupy the lowest positions in the ranking. This happens, for example, for plantations 18 and 27, and while plantation 18 is the worst in all the rankings shown in Tables 5 and 6, 27 gives a slightly better performance. However, when the weights are the same, planting 27 is below 18 in the two rankings (Table 7). This indicates that there is not a priori explanation of the reason for the positions in any of the rankings. However, with the set of results included, the DM has collected information to take precise measures in each plantation to improve the performance of some of the selected indicators.

We should like to indicate that the methodology proposed in this work is of sufficient versatility to enable it to be applied to other kinds of forest systems. Also, the procedure followed to obtain an overall measurement of plantations sustainability permits an easy integration of different indicators of a highly diverse nature. Also, we must insist that these theoretical developments, based on the aggregation of a heterogeneous set of indicators incorporating different weights different from them, have advantages like facilitating the interpretation of the sustainability idea (Baycheva et al., 2013).

It is necessary to stress that the GP methods applied have shown themselves to be very flexible, allowing us to obtain the best solution from different points of view, or compromises between them. On these lines, this research could be continued in order to seek the causes behind the level of the sustainability of a plantation. This task is carried out by taking the composite sustainability indexes as endogenous variables and a tentative set of economic, environmental and social variables as explanatory variables. The

Table 7
Solutions with the same preferential weights and targets.

I: $\lambda_1 = 0; \lambda_2 = 0$		II: $\lambda_1 = 1; \lambda_2 = 0$		III: $\lambda_1 = 0; \lambda_2 = 1$	
Equal weights	Equal target = 100%	Equal weights	Equal target = 100%	Equal weights	Equal target = 100%
5	15	21	8	5	15
7	5	5	11	7	5
10	30	10	3	21	30
21	13	2	22	15	13
15	7	15	30	30	7
30	21	19	15	10	21
2	10	20	7	2	10
1	22	8	9	26	22
20	2	27	16	13	2
22	26	16	27	19	26
26	9	3	26	1	9
19	11	26	14	12	11
12	19	11	25	22	19
13	16	1	5	11	16
14	8	22	20	24	8
4	12	14	10	9	12
8	25	25	13	4	25
11	1	9	29	6	1
3	6	30	17	20	6
24	3	7	21	25	3
9	20	12	24	16	20
16	27	24	19	3	27
6	14	4	1	8	14
25	29	23	2	29	29
23	17	28	12	17	17
18	24	17	23	23	24
27	4	6	6	18	4
29	23	29	4	14	23
17	28	13	28	27	28
28	18	18	18	28	18

In colour grey, appear the plantations which presents the same value for the optimum balanced ranking.
Source: author's own elaboration

link between endogenous and exogenous variables is made with the help of a statistical analysis. In this line, a multivariate data analysis appeared to be an attractive tool (see e.g. Diaz-Balteiro et al., 2016).

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jenvman.2016.05.022.

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