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ABSTRACT

We present an approach based on several quantitative techniques to derive a ranking of sustainable *Eucalyptus* plantations. A list of indicators was defined and applied to a set of heterogeneous *Eucalyptus globulus* plantations located in northwest Spain. These indicators were aggregated into a synthetic index with the help of a binary goal programming model. This model has been fed with the responses of 45 stakeholders to find out the preferential weights and targets attached to each indicator. In addition, we have analyzed the causes behind the level of sustainability achieved by each plantation. This task was carried out by taking the composite sustainability indexes as endogenous variables, and a tentative set of economic, environmental, and social variables as explanatory ones. The link between endogenous and exogenous variables was made with the help of a statistical analysis. The results show how some variables such as altitude or distance to pulp mills are statistically significant, while others like certification are not.

KEYWORDS: forest plantations; sustainability; stakeholders; goal programming

1. INTRODUCTION

Sustainability has been a basic ingredient of forest management for over 250 years (Schraml & Detten, 2010). In fact, this concept was conceived in forestry (Carlowitz, 1713 in Pretzsch, 2014). Thus, nowadays forest management takes into account in one way or another the sustainability issue (Bettinger et al., 2009, chap. 9). Currently, there are various definitions of sustainable forest management, but all of them essentially underline that it involves a process of managing forests which is economically viable, environmentally benign and socially beneficial, balancing present and future human 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).

Determining sustainability through an approach including a set of criteria and/or indicators has been the focus of research in many disciplines. Specifically, in forest management, many studies have analyzed sustainability from a set of indicators at different levels, from local to regional and national ones (Higman et al., 2005; Wolfslehner and Vacik, 2008; Grainger, 2012). However, with a few exceptions (Giménez et al., 2013; Diaz-Balteiro et al., 2016a), most of these works have failed to respond as to whether the management practice analyzed was sustainable or not. For example, Palmer et al. (2005), Watt et al. (2005) or Jeffries et al. (2010) have defined different indicators, but none of them include any economic or social ones. So, their sustainability measures would be somewhat incomplete, as they have only focused on partial aspects of the whole problem.

Regarding multidimensional characters underlying the sustainability concept, many works try to characterize this term by using Multiple Criteria Decision Making (MCDM) techniques. This theoretical orientation has been profusely applied in a large number of sectors (see Diaz-Balteiro et al., 2016b, for a recent review). In forestry, several forest management case studies have measured sustainability by applying MCDM techniques (Diaz-Balteiro and Romero, 2008). Within this orientation, goal programming has been one of the MCDM techniques most widely used for forest management applications (Diaz-Balteiro and Romero, 2004; Gimenez et al., 2013; Aldea et al., 2014; Diaz-Balteiro et al., 2013). Other references, which use other MCDM techniques in forest sustainability issues, would be those of Balana et al.

(2010) and Jalilova et al. (2012). However, regarding other sectors, the two most widely used MCDM techniques dealing with sustainability issues are Analytic Hierarchic Process (AHP) and Weighted Mean Arithmetic (WMA) (Diaz-Balteiro et al, 2016b).

For industrial forest plantations, managers and owners need a precise assessment of sustainability, as well as to predict the effects of management alternatives (Giménez et al., 2013). Sometimes, sustainability issues are introduced into MCDM models applied in forest plantations as constraints (Hernandez et al., 2014). For these forest systems, some studies have defined sustainability incompletely, only focusing on certain environmental aspects without including the economic or social aspects of the problem (Evans, 2009; Jeffries et al., 2010). Exceptions to this approach are the works of Ríos et al. (2008), Gimenez et al. (2013) and Diaz-Balteiro et al. (2015a), who propose a MCDM procedure to address sustainable management in *Eucalyptus* plantations.

Sometimes, intrinsic features associated with forest plantations have caused a significant number of conflicts between companies and local populations. One example of this issue is the case of *Eucalyptus* plantations in several countries (Gerber, 2011). These plantations cause much controversy in some areas due to forest fire policy (Diaz-Balteiro, 2007; Fernandes, 2008; Álvarez-Díaz et al., 2015), their impacts on poverty and the declining size of rural populations (Andersson et al., 2016), or the ecological impacts reported when they are managed under intensive forestry practices (Calviño-Cancela et al., 2012). On the other hand, some authors affirm that sustainable management in these plantations should try to balance economic performance with biodiversity conservation (Calviño-Cancela, 2013). One potential solution for relieving this type of conflict consists of defining a set of sustainability indicators in order to find out which plantations are more sustainable and guide their management towards these sustainable alternatives.

This paper has a twofold purpose. First, to present the sustainability of a set of heterogeneous *Eucalyptus* plantations in Spain. To undertake this task, the sustainability of each plantation has been defined by using nine indicators of an economic, environmental and social nature. These indicators were aggregated into a composite or synthetic index with the help of a binary goal programming model, and a ranking of the plantations in terms of sustainability was obtained. Some basic inputs for feeding the model were empirically obtained with the help of a survey, which was responded by 45 stakeholders. The second step in the research was to account for the causes determining the level of sustainability of each plantation. This task was undertaken by considering the synthetic indexes of sustainability as endogenous variables and a set of several variables as explanatory ones. The link between endogenous and exogenous variables was made with the help of a statistical analysis.

The rest of the paper has been organized in the following way: section 2 presents the goal programming method, the survey and the statistical analysis; section 3 presents the case study, and section 4 summarizes the results obtained. Finally, section 5 discusses the results and main conclusions derived from this research.

2. METHODS

2.1 Goal Programming approach

Let us consider the following scenario in which there are n plantations, each of them evaluated according to m sustainability indicators in order to obtain a ranking of the plantations in terms of sustainability. In most cases, the sustainability indicators are measured in different units, achieving very different absolute values. For these reasons, a first step in our work consisted of a proper normalization of the indicators. We undertook this task by applying the procedure proposed by Diaz-Balteiro and Romero (2004) that, adapted to our scenario, can be formulated as:

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

Where $\overline{R}_{ij}$ is the normalized value attached to the *i*th plantation when it is evaluated according to the *j*th indicator; R_{ij} is the value reached by the *i*th plantation when it is evaluated according to the *j*th indicator; R_j^* is the ideal value for the *j*th sustainability indicator; i.e., the maximum value if the indicator is of type “more is better” or the minimum value if the indicator is of type “less is better”. On the other hand, R_{*j} is the worst value or anti-ideal value for the *j*th sustainability indicator. With this normalization, the indicator values have no dimension and all of them are bounded between 0 and 1. The same procedure was applied to normalize the aspiration values attached to the different indicators. These targets are exogenous and they were determined by the values obtained through a survey among different stakeholders (see next section). Once we obtained this basic information, the following binary extended goal programming model was formulated (Romero 2001, 2004):

Achievement function:

$$Min(1-\lambda)D + \lambda \sum_{j=1}^{m} \left(\alpha_j n_j + \beta_j p_j \right)$$

Goal and constraints:

$$\sum_{i=1}^{n} \overline{R}_{ij} X_i + n_j - p_j = \bar{t}_j \quad j \in \{1 \ldots m\} \tag{2}$$

$$\left(\alpha_j n_j + \beta_j p_j\right) - D \leq 0 \quad j \in \{1 \ldots m\}$$

$$\sum_{i=1}^{n} X_i = 1$$

$$X_i \in \{0,1\} \quad i \in \{1 \ldots n\}$$

$$\mathbf{n} \geq \mathbf{0} \quad \mathbf{p} \geq \mathbf{0}$$

where n_j is the negative deviation variable that quantifies the under-achievement of the jth indicator with respect to its target value $\left(\bar{t}_j\right)$, while p_j is the positive deviation variable that quantifies the over-achievement of this indicator. On the other hand, α_j are the preferential weights associated with both deviation variables, $\alpha_j = 0$ being when the goal derives from an attribute of the type "less is better" and $\beta_j = 0$ in the opposite case. It should be remarked that, as the targets were normalized values, the respective deviation variables included in the achievement function did not need to be normalized. Variable D measures the maximum deviation between the value achieved by an indicator and its respective target value. λ represents a control parameter, thus for $\lambda = 1$, the solution optimizing the "average" achievement is obtained, while for $\lambda = 0$ the most "balanced" solution was determined. For λ values belonging to the open interval (0,1) compromises solutions between the above two solutions, if they exist, will be obtained. Finally, the decision variables X_i are binary (i.e., they are equal to 1 if the ith plantation is chosen; otherwise they are equal to 0). By solving model (2) the most sustainable plantation was determined. Applying this procedure in an iterative way, the ranking of the plantation analyzed in sustainable terms was obtained. All the computations were implemented by resorting to the software LINGO15 (Lindo Systems, 2015).

2.2. Stakeholders survey

In order to quantify the inputs to feed the goal programming model, a survey among several stakeholders involved in plantations management in Galicia was undertaken. To be more precise, we contacted 64 stakeholders (Table 1). The suitability of the inclusion of each respondent to each stakeholder's category was established in this survey. The first group in Table 1 is "Foresters", and includes forest managers (from public administration and industrial companies), and private forestry consultants. Another group of stakeholders considered in the survey included the environmental organisations. Also, we included people from the primary non-industrial private forest owner associations, from associations involved in communal forestry land, and other forest associations ("Associations" in Table 1). Besides this, we included non-industrial private forest owners, either individuals or commoners ("N.I.P.F.O." in Table 1). Another stakeholder group listed in the survey was of researchers, including some university lecturers on Forestry ("Researchers" in Table 1). The stakeholder group "Certification" involved members of forest certification organizations (FSC and PEFC). Moreover, we included mayors and councillors from the municipalities for which plantations are crucial in their economy ("Local Authorities" in Table 1). Finally, we have included people from different companies and industrial associations ("Industry" in Table 1).

The questionnaires with 27 questions were sent by e-mail. The first group of questions concerned the preferential weights to be attached to the three pillars considered for sustainability criteria (economic, environmental and social). The second group of questions referred to the importance of categories of indicators in each criterion. The procedure was evolved through a "pairwise" comparison format by using Saaty's verbal scale (Saaty, 1977). The next question was about the target values attached by the stakeholders to each of the goals in terms of the percentage of achievement with respect to the ideal value of each goal. In order to provide the stakeholders with a wide range of choice, a scale from 10% to 100%

achievement for each target was used. The final question was addressed in the direction of how to aggregate the different goals. In short, the stakeholders were asked which achievement function best reflected her/his preferences. According to eq. 2, there were three orientations: the optimal average, the most balanced solution, or some intermediate solution between them. These three questions are shown in Supplementary Material Section.

The information related to weights and target values was aggregated by using the geometric mean of all the responses given by the stakeholders. Finally, the results correspond to the 45 (out of 64) stakeholders who answered the questionnaire. However, 26 out of the 45 participants did not reply as to which stakeholder group they belonged, so we classified them as “Non Identified” (see Table 1).

Table 1 approximately here

2.3 Statistical analysis

In order to explain the ranking obtained with a set of exogenous variables, which are different from the indicators used in the GP model, a multivariate data analysis appeared to be an attractive tool. In fact, the rankings obtained define the dependent variables, while a set of tentative exogenous variables define the independent ones. Thus, in our case, we distinguished two different scenarios, depending on the nature of the exogenous variables: the first scenario was constituted by variables with interval scales (continuous variables) and the second scenario by variables with nominal or ordinal scales (discrete or categorical variables). In the first case, we applied a correlation analysis to find statistically significant relationships between variables. Meanwhile, in the second scenario an Analysis of Variance (ANOVA) was proposed.

3. CASE STUDY

The case study covered 48 plantations (Figure 1) all of them located in the Galicia (Spain) region, and whose principal species belong to the genus *Eucalyptus* (fundamentally, *Eucalyptus globulus* Labill). The total surface of the plantations analyzed reached 8,237 ha, with a mean of 171.6 ha. It is considered to be a relevant area since the entire *Eucalyptus globulus* area in Galicia is estimated at 310,000 ha (Vega-Nieva et al., 2015), but 63.7% of this area is occupied by small private plantations (Diaz-Balteiro et al., 2009b). In our case study, the plantation´s ownership is heterogeneous, since over half are managed by a large industry (ENCE) while others belong to private owners (mainly community forests). 8 of them are managed by public administrations.

Figure 1 approximately here

Nine indicators have been defined for these plantations (3 indicators in each pillar or criterion: economic, environmental or social). It should be noted that in this study all the indicators were obtained from the current management plans in this set of plantations, i.e. no value for any indicator was an assigned one. This partly explains the non-inclusion of indicators which would have been of interest (e.g., water resources) but whose values were not available for all the plantations. The nine indicators have been classified into 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. A previous correlation analysis was made in order to discard any redundant indicator. A description of the nine indicators used is shown in Table 2.

Table 2 approximately here

First of all, we decided to consider the three sustainability pillars (economic, environmental and social) because this is the approach most widely used in sustainability exercises (Diaz-Balteiro et al., 2015). These criteria have been employed in other studies that analyse the sustainability of Eucalyptus plantations (Giménez et al., 2013). Besides this, we initially decided to include a similar number of indicators under each criterion, mainly for operational reasons. One of these reasons was to facilitate the task to the stakeholders when they had to make the pairwise comparisons between indicators and criteria in order to obtain the preferential weights.

Starting with the economic indicators, and given the importance of these plantations in the production of biomass for pulp industries, we have chosen three indicators connected to the commercial profitability of these plantations in Galicia. They represent a measure of the earnings (I_1) and two of the main risks to this profitability: pests (I_2), which are considered to be a global constraint on the productivity of these plantations (Payn et al., 2015), and wildfires (I_3). Another possible indicator, like total harvest volume (Giménez et al., 2013), was discarded because in this kind of forest system it is usually positively correlated with the net present value. Finally, we did not incorporate any indicators associated with some socio-economic impacts of tree plantations, such as the loss of jobs caused by their expansion (e.g., Andersson et al., 2016), because these problems were beyond the scope of this study.

Going on to the environmental indicators, I_4 is related to a possible adverse effect of some forestry practices in the plantations: the soil losses. It is well known that in these forest systems, clearcutting, intensive site preparation and wildfires may have negative effects on the soil processes and compromise the sustainability of these plantations (Merino et al., 2004). The other two indicators refer to the existence of protected areas in these plantations. Since many protected area designation-types in Spain are specific to a regional level, we have decided to include an indicator (I_5) recording the number of protection figures recognized in each plantation. The main reason for supporting this idea is that in Europe different values can be partially or totally covered by some different designation types applied at a local, national, regional or international level (European Environment Agent, 2012). Since in many studies (Brockerhoff et al., 2013) the conservation benefits in plantations are associated with protected areas, in the analysis we have included an indicator (I_6) measuring the protected area in each plantation.

Among the indicators of a social type, Indicator I_7 covers important activities which exist in every forest system: recreational and cultural ones. Both categories are often included in the cultural services provided by forest plantations (de Groot and van der Meer, 2010, p. 19). We have assigned a value of 1 to each plantation if it presented infrastructures allowing recreational use (e.g., recreation areas), and 0 if it did not. Similarly, if any forest displayed any cultural element (e.g., cultural heritage elements), 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. Indicator I_8 represents the number of tree species present in each plantation. Although the number of tree species could be considered as an ecological indicator (Masiero et al., 2015), we included it as a social indicator. This is because on some occasions it is considered to be an indicator that measures an aspect of the corporate social strategies regarding the efforts of a company to preserve ecosystem services (D'Amato et al., 2015). Besides this, in some contexts, if a forest plantation is not a monoculture forest system, its perception by society is more positive (Andersson et al., 2016), and this kind of public perception could be considered as being a social indicator (Slee, 2007). Finally, Indicator I_9 represents the road density in each plantation. This has been considered to be a social indicator because accessibility is sometimes linked to the rights of public access or recreational aspects (Sténs et al., 2016). Table 3 shows the normalized values of each indicator for the 48 forest systems. In order to avoid confusion, it should be noted that by construction the ideal values of all the indicators (i.e., "more is better" and "less is better") take the value 1.

Table 3 approximately here

In the statistical analysis model the dependent variable is the result from the goal programming model previously described (eq. 2). In addition, 7 variables have been taken as being exogenous ones (Table 4). It should be noted that when the first GP model is solved, then the most sustainable plantation with this numerical valuation is obtained. Now, if we run the GP model again, we obtain the second most sustainable plantation. If we repeat the procedure iteratively for the remaining plantations, we obtain the complete ranking of sustainability with their respective numerical valuations.

Regarding the independent variables, the first one (E_1) was the area of each plantation considered. Another two characteristics of those plantations were also included: their average altitude (E_2) and average slope (E_3). These three variables are defined by interval scales (continuous variables). Another two variables were directly concerned in the management of these plantations. On one hand, a variable associated with the ownership and the forest management carried out in each forest system (E_4). There are three options, i.e. private, forest industry or public (management by government agencies in forests privately owned). On the other, variable E_5 is associated with the presence or not of a certification system in each plantation. Thus, this variable takes values of 0 depending on whether or not the plantation has a certification system, 1 if it has one, and 2 if it has the two systems most used in Spain (FSC and PEFC). Thus, variables E_4 and E_5 are defined by nominal scales (categorical variables). Variable E_6 was intended for measuring the % of *Eucalyptus* spp. surface in the whole area of the plantation. That is, the purpose of this variable was to relate the larger or smaller surface of *Eucalyptus* to the greater or lesser sustainability of a plantation. Finally, given that the main destination of the products from these plantations was the cellulose industry, the distance nearest to each of the main cellulose industries in the north of Spain was taken and included in variable E_7. Again, these two variables are defined by interval scales (continuous variables)

Table 4 approximately here

4. RESULTS

The results of this survey (Table 5) allowed the selection of the GP model (eq.2), which, as can be seen, is the most balanced solution (i.e., $\lambda = 0$ in eq. 2). On the other hand, the results also allow the assignation of preferential weights to criteria and indicators, as well as the obtainment of the targets for each goal. It was noted how the economic indicators are those obtaining higher weights, and among those, the profitability indicator (NPV/ha) was the one most appreciated by the stakeholders. Finally, the aspiration level gave very similar values except for the NPV.

Table 5 approximately here

Next, Table 6 shows the results of the sustainability ranking of the 48 plantations, according to the solutions offered by the goal programming models explained above. There is a "ranking" column and a "plantations" column, which contains the plantations occupying each ranking position. It should be pointed out that, on several occasions, the same value is reached in the achievement function for more than one plantation. For example, the most sustainable plantations are (ex-aequo) 9 and 26. The least sustainable one would be, following the information in that Table 5, plantation 47.

Table 6 approximately here

In the case of continuous variables (first scenario), the correlation analysis leads us to the results included in Table 7.

Table 7 approximately here

For nominal (categorical) variables, an ANOVA analysis showed that there were no statistically significant relationships between those and the dependent variable. The results of the ANOVA analysis, for variables different from the indicators used in the GP models, showed that for nominal (categorical) variables (second scenario), no statistically significant relationships were found. (See Tables A1 and A2 in the Appendix).

The parenthesis number represents *p-values*. It can be observed that *eucalyptus area* and the *dependent variable* are statistically significant related to an inverse relationship, at 0.15 significance level. If we used a significance level of 0.35, the relationships with the dependent variable would be extended to the variables *average altitude, average slope* and *distance*; inverse, inverse, and direct relationship, respectively.

5. DISCUSSION

The results reported above have shown how the proposed methodology has provided a sustainability ranking in the plantations considered by taking into account the preferences of different stakeholders. Due to the aggregation of these preferences, only the most balanced solution has been shown. Notwithstanding, the versatility of this methodology allows supplying, in an easy way, solutions for other values of parameter λ□ included in equation (2). Thus, in Nordström et al. (2009), Voces et al. (2012), and Diaz-Balteiro et al. (2015a), among others cases, are shown in which the rankings obtained depend on the values attached to the control parameter λ.

Also, the ranking shown in Figure 1 is based, as remarked previously, on the preferences of the stakeholders who have answered the survey. At this point, it should be noted that, with the aim of facilitating the reading of this paper, a basic model of preference aggregation was selected, but which did not prevent employing other forms of aggregation, either using the same technique (Diaz-Balteiro et al., 2009a; González-Pachón and Romero, 2001; 2011), or others, such as for example the Borda count (Pérez et al., 2016). A possible additional analysis could consist of observing how the ranking varies if only the preferences of a single group of stakeholders (owners, technicians, ecologists, etc.) were to be taken into account.

With regard to the results shown in the statistical analysis, it was observed that those plantations with the largest area were, assuming the rest of the variables to be equal, less sustainable than those with a smaller area. On the other hand, it was also logical that the least sustainable ones were those at a higher altitude since it is well known that cold is a limiting factor for the development of plantations of *Eucalyptus globulus* in Galicia (Ruiz et al., 2008). However, the most surprising results *a priori* refer to the variables which were not significant in the analysis. Specifically, it should be noted that neither of the two variables directly related to the management of the plantations (type of management and certification) were statistically significant. In short, the way private owners, industrial companies or public administrators may manage the plantations did not affect the results of these rankings and, besides, their sustainability was not related to the plantations having one or two forest certification systems. This last conclusion opens up a new future research line (to go deeper into the links between certification and sustainability), but which should be viewed with precaution. It should be noted that the criteria and indicators used in the certification systems are different to those described here and are not totally equivalent concepts. For example, in other studies, sustainability indicators related to the possible certification of the plantations are considered (Diaz-Balteiro et al., 2016a). Besides, some authors even advocate the inclusion of indicators associated with financial viability in plantations under certification schemes (van Eijck et al., 2014). On those lines, other authors recommend combining the certification systems with life cycle analysis (LCA) tools in order to assure consumers that the product that they buy does not vulnerate any forest sustainability measure (Straka and Layton, 2010).

The above affirmation on the difference between the indicators used in certification systems in comparison to the indicators employed in this work implies pointing out that our methodology is totally compatible with the inclusion or exclusion of some of the indicators included in this work. Indicators which could have been incorporated are those associated with: the type of land use prior to the plantation (Brockerhoff et al., 2013), the soil preparation carried out before the plantation (Carneiro et al., 2014), the soil fertility level (Vega-Nieva et al., 2013), the silvicultural method employed, characterized by its low intensity (González-Ferreiro et al., 2013), water conservation in industrial forest plantations (Vanclay, 2009; Ferraz et al., 2013), the carbon capture (Machado el al., 2015), the stands being even or uneven-aged (Crecente-Campo et al., 2013), or the optimal rotation, since it has been proved in practice that in Galicia the rotation used is longer than the optimal one (Bertomeu et al., 2009; Diaz-Balteiro et al., 2009b; González-García et al., 2015).

Also, on many occasions, the assignation of indicators to one of the three pillars is not univocal. For instance, Eggers et al. (2015) consider the clearcutting area to be a social indicator, when it could perfectly be an indicator of an economic type. In addition, the importance of the indicators employed taking into account the specificities of forest plantations should be highlighted, since in many sustainable forest management standards or guidelines this fact is not borne in mind (Masiero et al., 2015).

With regard to some of the problems associated with these plantations in Spain, a possible extension of this work would be to conduct this sustainability analysis at a spatial level, measuring the same sustainability indexes in other nearby or surrounding forest stands. In this case, the aim would be to compare the results of the aggregation of sustainability indicators in these plantations to other forest systems as it is known that some biodiversity indicators may notably vary (Calviño-Cancela, 2013) between different types of forest stands. This new way to incorporate sustainability aspects spatially could fit into the framework of the idea proposed by Lindemayer et al. (2015), according to which this type of forest systems ("novel plantation ecosystems") should enjoy *forms of management that could differ substantially from those typical of more natural ecosystems*. Besides, these new forms of management should include the interactions between native and non-native species (Calviño-Cancela and Neumann, 2015).

6. CONCLUSIONS

This study has presented a combined methodology that, first, permits the obtaining of a sustainability ranking of different forest plantations integrating the preferences of the stakeholders on basic aspects of the models and sustainability pillars and indicators. In order to procure this ranking, a binary goal programming model was used. The second part of the methodology aims to explain the reasons for each plantation achieving its position in the ranking previously defined, taking the statistical analysis and the sustainability index underlying the previous ranking obtained as endogenous variables.

The application of this methodology in a set of 48 Eucalyptus plantations in northwest Spain showed a ranking of these forest plantations by integrating the preferences of 45 stakeholders. Although the multi-criteria model used embraces a great flexibility, making it possible to choose different solutions, the stakeholders opted for the most balanced one. Using seven exogenous variables in the statistical analysis the results show the Eucalyptus area in each plantation, its altitude and distance to pulp mills as being statistically significant, while others directly related to management like certification were not statistically significant with the previous ranking obtained.

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Figure 1. Map with the plantations of the case study

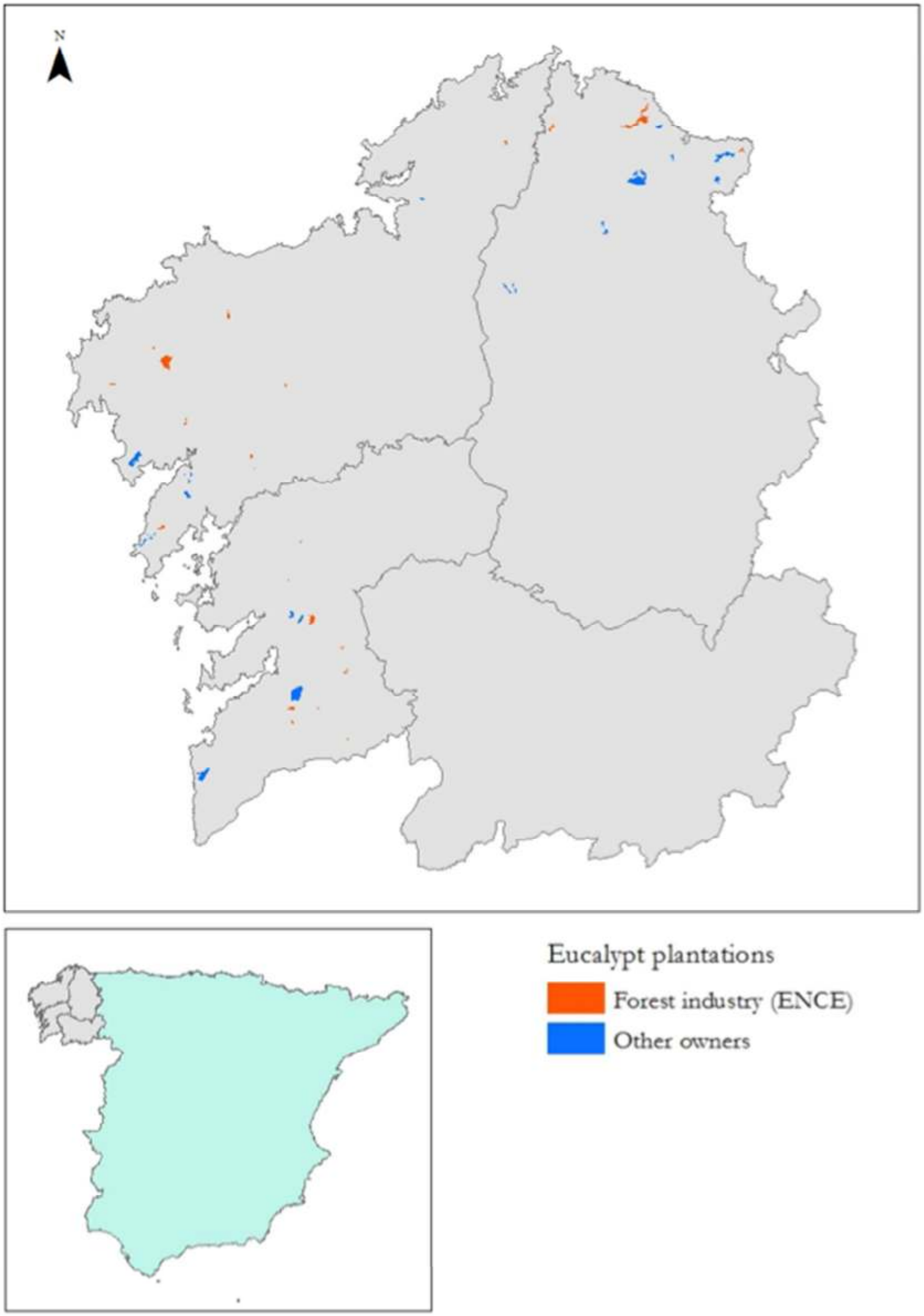

Table 1. Stakeholder groups considered in the study.

Stakeholder group	Description	People Asked	Respondents
Foresters	forest managers (from public administration and industrial companies), and private forestry consultants	24	9
Environmental Organizations	members of different environmental organizations	4	2
Associations	people from the main non-industrial private forest owner associations, from associations involved in communal forestry land, and other forest associations	9	2
N.I.P.F.O.*	non-industrial private forest owners, either individuals or commoners	8	3
Researchers	researchers, including some University lecturers on forestry	5	2
Certification	members from forest certification organizations (FSC and PEFC)	4	
Local Authorities	Mayors, councillors and trade unioners	5	
Industry	people from different companies and industry associations	5	1
Non-Identified	--		26
		64	45

* : Non-Industrial Private Forest Owners

Table 2. Description of sustainability criteria and indicators

Criteria		Indicator	Units	Comments	Type
Economic	I_1	Net Present Value	€/ha	only eucalyptus incomes and costs included in each forest management plan	+
	I_2	Area affected by pests (%)	ha	area of each plantation affected by pests (mainly insect attack, like gum-tree weevil)	-
	I_3	Fire occurrence (%)		fire occurrence percentage (percentage of the total area affected by fires) in ten years	-
Environment	I_4	Erosion	(t/ha)	soil losses undergone by these plantations	-
	I_5	Protected Areas Categories		different protected areas designation-types (by European, national or regional legislation)	+
	I_6	Protected area/Total area		protected area (hectares) in each plantation	+
Social	I_7	Recreational and cultural elements		Presence of recreational and cultural elements in each plantation	+
	I_8	Number of tree species with an area larger than 1% total area		the number of tree species present in each plantation, occupying at least 1% of the area in each of them	+
	I_9	Road density	(m/ha)	quotient between the total length of roads and plantation area	+

Type +: indicator is the “more is better” type
Type - : indicator is the "less is better” type

Table 3. Case study: normalized matrix of the indicators for each plantation (bold characters denote ideal values and underlined figures anti-ideals).

Plantation	Economic			Environment			Social		
	Net Present Value (€/ha)	Area affected by pests (%)	Fire occurrence (%)	Erosion (t/ha)	Protected Areas Categories	Protected area/Total area	Recreational and cultural elements	Number of sp with an area larger than 1% total area	Road density (m/ha)
	+	-	-	-	+	+	+	+	+
1	0.136	0.700	**1.000**	0.990	**1.000**	0.178	0.000	0.500	0.000
2	0.087	**1.000**	0.999	0.709	**1.000**	0.000	0.000	0.500	0.386
3	0.454	0.850	**1.000**	0.852	0.250	0.010	0.000	0.167	0.370
4	0.190	0.750	0.974	0.833	0.750	0.737	0.500	0.667	0.785
5	0.086	**1.000**	0.964	0.650	0.000	0.000	**1.000**	0.167	0.575
6	0.078	0.700	0.940	0.804	0.750	0.074	0.000	0.500	0.102
7	0.423	0.900	0.846	0.039	0.000	0.000	0.500	0.167	0.514
8	0.236	0.909	0.829	0.951	0.500	0.047	0.500	0.333	0.583
9	0.252	0.900	0.000	0.960	0.000	0.615	0.000	0.333	0.240
10	0.235	0.711	0.993	0.743	0.000	0.000	0.000	0.333	0.397
11	0.158	0.816	0.997	0.943	0.750	0.000	0.000	0.333	0.613
12	0.463	**1.000**	0.966	0.764	0.250	0.000	0.000	0.000	0.435
13	0.147	0.950	0.966	0.764	0.250	0.000	0.000	0.333	0.435
14	0.087	**1.000**	**1.000**	0.000	**1.000**	0.000	0.000	0.167	0.152
15	**1.000**	0.950	0.999	0.967	0.000	0.078	0.500	**1.000**	0.430
16	0.240	**1.000**	**1.000**	0.654	0.250	0.000	0.000	0.333	0.565
17	0.112	**1.000**	0.720	0.581	0.000	0.354	0.500	0.333	0.404
18	0.189	0.100	0.951	0.978	0.000	0.000	0.500	0.167	0.606
19	0.280	0.181	0.999	0.618	0.250	0.011	0.500	0.000	0.253
20	0.374	**1.000**	**1.000**	0.949	0.250	0.421	0.000	0.167	0.331
21	0.263	0.006	0.961	**1.000**	0.000	0.000	0.000	0.000	0.104
22	0.161	0.313	0.999	0.706	0.750	0.208	0.000	0.500	0.496
23	0.133	**1.000**	0.987	0.948	0.000	0.310	0.000	0.333	0.624
24	0.242	0.296	0.978	0.544	0.000	0.086	0.000	0.333	0.407
25	0.223	0.339	0.734	**1.000**	0.000	0.362	**1.000**	0.500	0.226
26	0.290	0.201	0.735	**1.000**	0.000	0.306	0.000	0.167	0.226
27	0.149	0.065	0.999	**1.000**	0.250	0.021	0.500	0.333	0.208
28	0.205	0.031	0.996	**1.000**	0.250	0.955	0.000	0.000	0.213
29	0.182	0.384	0.974	**1.000**	0.000	0.375	0.500	0.167	0.573
30	0.173	**1.000**	0.992	**1.000**	0.000	0.214	0.000	0.000	0.602
31	0.224	**1.000**	0.785	**1.000**	0.000	0.179	0.000	0.000	0.207
32	0.144	0.419	0.999	0.818	0.000	0.502	0.000	0.500	0.459
33	0.344	**1.000**	0.985	0.905	0.000	0.027	0.000	0.167	0.686
34	0.146	0.255	0.911	0.366	0.000	**1.000**	0.000	0.333	0.369
35	0.152	0.734	0.989	0.904	0.000	0.000	0.500	0.167	0.480
36	0.132	0.357	0.922	0.865	0.000	0.070	0.000	0.167	0.016
37	0.101	0.502	0.981	0.963	0.000	0.103	0.500	0.333	0.138
38	0.259	0.172	0.956	0.864	0.000	0.076	0.000	0.333	0.080
39	0.140	0.702	0.342	0.400	0.000	0.376	0.000	0.167	0.251
40	0.276	**1.000**	0.979	0.895	0.000	0.079	0.000	0.167	**1.000**
41	0.205	**1.000**	0.856	0.950	0.000	0.000	0.000	0.000	0.235
42	0.165	0.533	0.322	0.635	0.000	0.557	0.000	0.333	0.630
43	0.285	0.083	0.999	**1.000**	0.000	0.000	0.000	0.000	0.771
44	0.314	0.135	0.999	**1.000**	0.000	0.000	0.500	0.000	0.335
45	0.068	0.085	0.679	0.994	0.000	0.000	0.000	0.000	0.080
46	0.217	**1.000**	0.712	**1.000**	0.000	0.034	0.000	0.333	0.139
47	0.000	0.000	0.997	**1.000**	0.000	0.210	0.000	0.333	0.281
48	0.127	**1.000**	0.951	**1.000**	0.000	0.096	0.000	0.000	0.345

Table 4. Statistical analysis: values of the dependent and the independent variables for each plantation

Plantation	Dependent variable	Area (ha)	Management	Average altitude (m)	Average slope (%)	Certificatión (yes/not)	Eucalyptus area/Total area	Distance to a pulp mill (km)
1	0.564	168.92	1	502.6	4.0	0	90.2%	96,849.5
2	0.613	1057.54	1	561.8	15.2	1	5.4%	54,142.7
3	0.500	247.99	1	285.0	14.7	2	63.1%	29,829.3
4	0.510	80.27	1	84.7	26.7	0	17.9%	113,522.8
5	0.614	534.13	2	299.4	20.7	1	21.9%	53,397.5
6	0.622	161.85	1	75.8	7.0	0	19.1%	35,986.9
7	0.461	69.97	1	139.5	18.9	0	59.8%	41,299.8
8	0.464	492.35	1	350.0	20.9	0	19.4%	41,650.9
9	0.450	170.32	2	365.2	11.0	0	73.5%	9,707.8
10	0.493	135.38	2	139.4	15.5	0	41.2%	7,455.0
11	0.542	84.11	3	209.9	21.8	0	87.1%	46,142.1
12	0.466	197.88	3	275.3	16.6	0	96.5%	33,991.1
13	0.553	197.88	1	275.3	16.6	2	21.5%	33,991.1
14	0.613	164.00	3	503.6	8.4	0	37.0%	68,262.8
15	0.499	110.58	3	218.3	16.5	0	31.2%	48,935.0
16	0.500	204.24	3	266.2	20.4	1	89.9%	32,769.8
17	0.588	180.05	2	521.8	15.7	0	13.4%	37,604.8
18	0.511	890.31	1	489.7	21.6	0	60.9%	20,296.2
19	0.499	74.08	4	124.6	11.3	2	99.4%	27,052.8
20	0.500	103.97	5	444.5	13.6	0	76.8%	77,845.2
21	0.494	16.90	4	138.8	7.0	1	100.0%	54,348.1
22	0.539	424.27	4	382.5	18.4	2	86.9%	54,172.3
23	0.567	249.25	4	356.4	22.1	1	66.5%	52,677.2
24	0.478	115.00	4	187.7	15.8	1	87.6%	53,343.5
25	0.477	168.01	4	425.4	10.5	2	69.1%	11,833.8
26	0.450	168.01	4	425.4	10.5	1	83.1%	11,833.8
27	0.551	105.19	4	455.4	10.0	1	98.9%	13,410.5
28	0.496	36.59	4	550.8	10.2	1	47.3%	22,401.0
29	0.518	37.64	4	604.1	20.6	2	79.4%	26,203.4
30	0.527	163.46	4	345.9	21.4	0	88.2%	24,552.2
31	0.476	12.74	4	375.6	10.0	2	90.1%	39,085.9
32	0.556	17.43	4	329.9	17.3	1	68.8%	27,838.3
33	0.485	46.68	5	340.4	23.9	1	98.5%	90,223.3
34	0.554	10.26	6	280.4	14.7	2	44.8%	61,335.5
35	0.548	44.92	6	249.4	17.9	2	39.3%	62,423.1
36	0.568	46.18	5	302.1	4.4	1	88.5%	73,888.7
37	0.599	44.39	6	333.9	8.0	1	78.9%	77,597.1
38	0.456	675.62	5	361.3	6.3	1	90.6%	71,190.0
39	0.560	102.51	5	194.3	11.3	2	80.5%	81,073.2
40	0.479	94.39	5	313.2	33.0	1	53.3%	35,766.6
41	0.495	42.24	5	440.3	10.8	0	100.0%	55,806.5
42	0.535	8.77	4	99.8	22.3	1	69.2%	40,375.9
43	0.499	77.41	4	346.2	26.4	1	100.0%	43,230.7
44	0.499	13.38	4	299.0	13.7	1	100.0%	23,201.8
45	0.632	4.62	4	281.6	6.3	1	100.0%	23,201.3
46	0.483	12.34	4	487.2	8.0	1	68.8%	12,540.6
47	0.700	24.34	4	542.6	12.1	1	88.4%	19,574.0
48	0.573	8.36	4	296.7	14.0	0	94.7%	47,098.0

Table 5. Results from stakeholders' survey

Criterion	Weight	Indicator	weight	target	GP solution	nº responses
Economic	0.467	Net Present Value (€/ha)	0.445	61.3	most balanced	21
		Area affected by pests (%)	0.288	38.2	most efficient	5
		Fire occurrence (%)	0.267	38.2	intermediate solution	16
Environment	0.273	Erosion (t/ha)	0.373	37.7		
		Protected Areas Categories	0.277	31.3		
		Protected area/Total area	0.349	31.8		
Social	0.260	Recreational and cultural elements	0.378	33.1		
		Number of sp with an area larger than 1% total area	0.359	36.3		
		Road density (m/ha)	0.263	36.8		

Table 6. Ranking of the plantations following the goal programming model

ranking	plantations			
1	9	26		
2	38			
3	7			
4	8			
5	12			
6	31			
7	25			
8	24			
9	40			
10	46			
11	33			
12	10			
13	21			
14	41			
15	28			
16	15	19	43	44
17	3	16	20	
18	4			
19	18			
20	29			
21	30			
22	42			
23	22			
24	11			
25	35			
26	27			
27	13			
28	34			
29	32			
30	39			
31	1			
32	23			
33	36			
34	48			
35	17			
36	37			
37	2	14		
38	5			
39	6			
40	45			
41	47			

Table 7. Results from the statistical analysis*

	Dependent variable	Area	Average altitude	Average slope	Eucalyptus area/Total area	Distance pulp mill
Dependent variable	10,000 (0,0000)					
Area	0,0407 (0,7836)	10,000 (0,0000)				
Average altitude	0,1525 (0,3008)	0,2753 (0,0583)	10,000 (0,0000)			
Average slope (m)	-0,1955 (0,1830)	0,1163 (0,4312)	-0,1732 (0,2392)	10,000 (0,0000)		
Eucalyptus area/Total area	-0,2198 (0,1333)	-0,3685 (0,0100)	0,0286 (0,8470)	-0,2242 (0,1255)	10,000 (0,0000)	
Distance pulp mill	0,1514 (0,3043)	0,0215 (0,8844)	-0,1623 (0,8844)	0,0273 (0,8538)	-0,0758 (0,6088)	10,000 (0,0000)

*The parenthesis number represents *p-values*

Table A1. One-way Analysis of Variance (ANOVA) with Management as the independent measure

Source of Variation	Sum Square	DF	Mean Square	F-ratio	P-value
Between Group	0.00849755	5	0.00169951	0.52	0.7585
Within Group	0.136853	42	0.00325842		
Total (Corr.)	0.145351	47			

Table A2. One-way Analysis of Variance (ANOVA) with Certification as the independent measure

Source of Variation	Sum Square	DF	Mean Square	F-ratio	P-value
Between Group	0.00218773	2	0, 00109387	0.34	0.7109
Within Group	0.143163	45	0, 00318141		
Total (Corr.)	0.145351	47			

Supplementary Material. Extract from the questionnaire distributed to stakeholders

S.2.2. First, we ask you to answer the following questions relating to the above-defined three categories of indicators (economic, environmental and social ones). In these questions, various comparisons between pairs of these categories are shown. Please indicate which you consider to be the most appropriate one (only one answer for each box). In case your choice is at an intermediate value of those presented, indicate this in the space reserved at the end of each question. Finally, it is important to remember that these responses do not address forest systems in general, but specifically eucalyptus plantations in Galicia.

S.2.2.1. If you were to compare the importance between two categories of indicators (e.g. economic indicators, environmental indicators), what sentence would you choose from the nine which are shown below? Put the letter (a, b, c, ..., i) that best reflects your choice in the grey box:

a) Economic indicators are of equal importance than Environment indicators
b) Economic indicators have a moderate importance than Environment indicators
c) Economic indicators have a strong importance than Environment indicators
d) Economic indicators have a very strong importance than Environment indicators
e) Economic indicators have a extreme importance than Environment indicators
f) Environment indicators have a moderate importance than Economic indicators
g) Environment indicators have a strong importance than Economic indicators
h) Environment indicators have a very strong importance than Economic indicators
i) Environment indicators have a extreme importance than Economic indicators
j) o ...

Note: this kind of question was repeated for all the combinations: Two for the remaining combinations regarding criteria and nine for the combinations covering the three indicators chosen for each criterion. Due to space constraints, we did not include these eleven questions.

3. On the other hand, when your are choosing which forest plantation is the most sustainable one, it is very likely that you should assume values of different indicators that are not the optimal ones, but, however, they could be acceptable. In short, it must be understood that all the indicators cannot reach their optimal value in all the plantations (either the maximum or minimum value, depending on the indicator category). Therefore, we are asking you which values of these indicators would be acceptable to you, without necessarily being forced to qualify as being unsustainable the plantations do not reach that value. [For example, if for the net present value indicator, you accept a value for any of the plantations analysed which reaches 70% of the optimal value of the indicator, you should mark the cell of the table below sheaded 70% on the "net present value" row].

3.1. Targets assumable for each indicator in relation to the optimal value

	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
Net present value										
Area affected by pests										
Fire occurrence										
Erosion										
Protected area categories										
Protected area/Total area										
Recreational and cultural elements										
Number of tree species with an area larger than 1% of total area										
Road density										

4. With the values of the indicators for each plantation, the weights and targets collected with this survey, we will apply a multiple criteria decision-making model to establish a ranking of sustainability among plantations considered. This model provides different solutions, and we would like you to help us to choose the solution that best suits your preferences. Specifically, the model proposes a set of solutions with two clear limits. One would be appropriate for pursuing an efficient as possible solution, which seeks to obtain the values for the indicators reaching the greatest achievement regarding their sustainability (Solution 1). For example, the most efficient solution would be a plantation which is more sustainable, because it reaches optimal values in several indicators. However, this plantation shows values very far away from the optimal ones for other indicators considered. The other limit is given by the most balanced solution, which would be the best alternative in terms of a balance between the results achieved by the various indicators (Solution 0). For example, this could be one where a plantation is sustainable without reaching the optimal values but almost no indicator, while it does not show values at some distance from the optimal values for the other indicators considered. In short, the question is: what solution do you prefer? Is it Solution 1, Solution 0 or intermediate values between them (Option 2)? Fill in the appropriate box in the table below indicating the solution that best suits your preferences:

4.1. Solutions provided by multiple criteria decision-making models

Solutions	**0**	**1**	**2**