For. Sci. 63(1):49–61
http://dx.doi.org/10.5849/FS-2016-035

operations research

A Multiple Criteria Approach for Negotiating Ecosystem Services Supply Targets and Forest Owners' Programs

José G. Borges, Susete Marques, Jordi Garcia-Gonzalo, Arif Ur Rahman, Vladimir Bushenkov, Miguel Sottomayor, Pedro O. Carvalho, and Eva-Maria Nordström

Land tenure heterogeneity may be an obstacle to forested landscape-level management planning and the provision of ecosystem services. This research focused on the potential of combining participatory workshops and multiple criteria decision methods (MCDMs) to support the development and negotiation of targets for the supply of ecosystem services and help design the management plan needed to meet those targets. We describe an application to two forested landscapes with several ownership types in Portugal. The approach encompassed the design of two workshops involving more than 40 stakeholders (forests owners, the forest service, the forest industry, local municipalities and other nongovernmental organizations). The list of ecosystem services included carbon stocks, cork, pine cones, and forest inventory at the end of the planning horizon as well as volume flows from a range of forest species. Results demonstrated the potential of MCDM tools to help individual forest stakeholders set and adjust ecosystem services target levels. They further demonstrated the potential of MCDMs to facilitate the negotiation of these targets by the stakeholders and the reaching of meaningful solutions. Finally, they demonstrated that these tools provide valuable information to combine the negotiations of both targets and behaviors and programs needed to attain them.

Keywords: multiple criteria decision methods, group decisionmaking, land tenure, ecosystem services, collaborative planning, forest owners, forest management programs

The competition for fores t resources can be expected to increase in the future due to global change, e.g., climate change, market changes, population, and socioeconomic developments (Kraxner et al. 2013). An effective multiple-purpose approach to sustainable forest management requires the analysis of trade-offs among conflicting goals such as timber production and biodiversity conservation. Moreover, because multifunctional forest management considers multiple values and perspectives, stakeholders may need and want to be involved in the planning process. Trade-off analysis becomes even more important when one is addressing multiple-owner integrated planning problems, i.e., problems that emerge when several holdings controlled by different decisionmakers are bound together by economic, ecological, and social goals and constraints (Davis and Johnson 2001).

The supply of ecosystem services often relies on the spatial distribution of management options across several properties. Therefore, the provision of a wide range of ecosystem services from landscapes that encompass several property regimes depends on the success of collaborative planning processes. Nevertheless, the effectiveness of these processes and of the development and negotiation

Manuscript received August 1, 2016; accepted September 20, 2016; published online December 29, 2016.

Affiliations: *Jose G. Borges (joseborges@isa.ulisboa.pt), School of Agriculture, University of Lisbon, Lisbon, Portugal. Susete Marques (smarques@isa.ulisboa.pt), Forest Research Centre, School of Agriculture, University of Lisbon. Jordi Garcia-Gonzalo (j.garcia@ctfc.es), Forest Research Centre, Portugal and Forest Sciences Centre of Catalonia, Spain. Arif U. Rahman (badwanpk@bui.edu.pk), Forest Research Centre, Portugal and Bahria University, Pakistan. Vladimir Bushenkov (bushen@uevora.pt), Research Centre for Mathematics and Applications, University of Évora, Portugal. Miguel Sottomayor (msottomayor@porto.ucp.pt), Católica Porto Business School, Universidade Católica Portuguesa, Portugal. Pedro O. Carvalho (pedroochoa@isa.ulisboa.pt), Forest Research Centre, School of Agriculture, University of Lisbon. Eva-Maria Nordström (eva-maria.nordstrom@slu.se), Swedish Life Sciences University.*

Acknowledgments: *This research has received funding from the European Union's Seventh Program for research, technological development, and demonstration under grant agreement 282887 (INTEGRAL) as well as from project PTDC/AGR-FOR/4526/2012 Models and Decision Support Systems for Addressing Risk and Uncertainty in Forest Planning (SADRI) and the European Union's H2020 research and innovation programme under the Marie Sklodowska-Curie grant agreement No. 691149. We thank the Portuguese Science Foundation for funding the postdoctoral grant of Susete Marques (SFRH/BPD/96806/2013), the MINECO "Ramón y Cajal" (Ref. RYC-2013-14262) for funding the research contract of Jordi Garcia-Gonzalo, and the COST Action FP1207 ORCHESTRA for funding the Short Term Scientific Mission (STSM) of Eva-Maria Nordström.*

This article uses metric units; the applicable conversion factors are: hectares (ha): 1 ha = 2.47 ac.

of targets for the supply of ecosystem services relies on the availability of sound trade-off information (Tóth et al. 2006). Therefore, there is a call for tools that may provide this information and thus help develop forested landscape-level management planning when land tenure is fragmented into several ownership types.

Multiple criteria decision methods (MCDMs) encompass a collection of different mathematical methods for finding solutions to decision problems with multiple conflicting goals or criteria (Belton and Stewart 2002). Their potential to address collaborative forest management planning has been discussed by several authors (e.g., Mendoza and Martins, 2006, Martins and Borges 2007, Diaz-Balteiro and Romero 2008). The advantages of MCDMs are that they make it possible to explicitly incorporate stakeholders' preferences into the decisionmaking process and that they can support the exploration of alternative solutions and preferences. They may be used as learning devices to provide information about trade-offs between goals and thus more insights about the planning problems (e.g., Borges et al. 2014b).

MCDM techniques can be categorized according to how the decisionmaker's preferences are stated (Hwang and Masud 1979, Miettinen 1999). No preference methods are used when no preference information is available. In the case of a priori methods, the decisionmaker may state his or her preferences without a priori knowledge about solutions. The analyst takes into account those preferences to generate one or more alternative solutions. In the case of a posteriori methods, the analyst presents information about the solutions to the decisionmaker to help him or her state his or her preferences and make a decision. Both approaches may be used interactively to help the decisionmaker and the analyst formulate preferences and generate solutions.

The analytical hierarchy process (AHP) (Saaty 1990) is a frequently used a posteriori method. Local and regional studies that have applied AHP to involve stakeholders in the development and choice of forest management plans or strategies have been reported from Australia (Ananda 2007), Finland (Kangas 1994), Indonesia (Mendoza and Prabhu 2000), Kyrgyzstan (Jalilova et al. 2012), Nepal (Khadka and Vacik 2012), Spain (Rico and González 2015), and Sweden (Nordström et al. 2010, 2011). The method is considered suitable for participatory planning. It is relatively easy to understand, and the pairwise comparison procedure allows stakeholders to focus on the trade-off between two objectives at a time. However, with increasing numbers of objectives and alternatives to evaluate, the additional cognitive burden may increase the risk for inconsistent judgments (Kangas and Kangas 2005, Nordström et al. 2010, Korosuo et al. 2011).

Other a posteriori methods used in participatory forest planning studies are multicriteria approval voting (Laukkanen et al. 2002, Pykäläinen et al. 2007, Hiltunen et al. 2008), multiattribute value or utility models (Ananda and Herath 2003, Briceño-Elizondo et al. 2008, Mustajoki et al. 2011), the analytic network process (Grošelj et al. 2015), and outranking methods (PROMETHEE II and ELECTRE III in Kangas et al. 2001). Nevertheless, as the review of the literature shows, these methods have been used to evaluate a discrete set of alternatives. This means that planning problems were simplified so that stakeholders might choose from a predefined and usually small set of alternatives. Yet, as forest planning is about making decisions regarding what treatments to apply and when in a large number of forest stands (Rauscher et al. 2000), the planning problems usually have a continuous character and the number of possible alternatives is consequently very large.

Goal programming (GP) and different varieties of GP are the most common a priori methods used for participatory forest planning. Diaz-Balteiro et al. (2013) discussed approaches to model decisionmakers' preferences in a GP framework (e.g., weighted or lexicographic). Studies from Spain discuss a regional planning case where the aim is to incorporate social preferences (Maroto et al. 2013) and two local planning cases (Diaz-Balteiro et al. 2009, Aldea et al. 2014). Nevertheless, the study by Diaz-Balteiro et al. (2009) uses forestry students rather than local stakeholders for testing purposes. In a case of forest planning for preservation of biodiversity and fire prevention in Portugal, de Sousa Xavier et al. (2015) applied extended GP and compromise programming. Eyvindson and Kangas (2015) used compromise programming to include spatially explicit preferences (from simulated data) in a forest planning problem in Finland. Nordström et al. (2009) used extended GP to aggregate stakeholder preferences elicited with AHP in a local forest planning case study in Sweden. In the context of participatory forest planning, a major problem with GP and other a priori methods is the difficulty for stakeholders to state their preferences in terms of target levels for objectives. This difficulty is a consequence of the lack of knowledge about the production possibilities and the trade-offs between objectives (Tóth et al. 2006). One approach to overcome this difficulty is to work iteratively so that the stakeholders have the opportunity to learn about the problem, adjust their preferences, and develop new alternative solutions (e.g., Eyvindson et al. 2013). Nevertheless, this would lead to a convergence to an a posteriori approach without taking full advantage of its benefits. Tóth et al. (2006) presented an approach to finding the Pareto frontier for problems considering two goals. The Pareto frontier describes the limits of what is possible in terms of competing decision criteria, and it illustrates the degree to which improving one particular criterion requires accepting sacrifices in the achievements of others (i.e., trade-offs). Tóth and McDill (2009) extended the approach to provide information about the trade-offs among up to three goals. More recently, Borges et al. (2014b) presented an alternative method for finding and displaying the Pareto frontier for problems with up to seven goals. Garcia-Gonzalo et al. (2015) described further the computational implementation of this method within a decision support system (DSS).

As each point of the Pareto frontier corresponds to an alternative plan, solutions by this method are not restricted to a small set of predefined alternatives as in the case of other a posteriori MCDMs. Other potentially more suitable solutions corresponding better to stakeholders' preferences may be identified. In addition, by visualizing the Pareto frontier, stakeholders may analyze trade-offs between criteria and state their preferences based on full knowledge of the production possibilities and ranges of the criteria. The reader is referred to Lotov et al. (2004) and Borges et al. (2014b) for a detailed description of this method as well as for its application to scenario analysis by a single decisionmaker. Nevertheless, its features suggested its potential to address multiple decisionmakers' problems.

In this article, we develop an approach to help overcome land tenure heterogeneity constraints to forested landscape-level management planning and to the provision of ecosystem services. The emphasis is on the combination of participatory workshops and Pareto frontier a posteriori MCDM to provide the trade-off information needed to address typical multiple objective and multiple decisionmakers' forest ecosystem management planning problems. This approach is described and applied to two problems involving forested landscapes where land tenure is heterogeneous—the Zonas de Intervenção Florestal (ZIF), joint management forest areas, in Northern and in Southern Portugal. The ZIFs' tenure heterogeneity derives from the number of ownership types involved, e.g., nonindustrial private forestland (NIPF), industry, and community/municipalities. ZIFs have a management board consisting of a forest owners association. This management board is responsible for developing the ZIFs' forest management plans. Typically, the management board holds meetings with representatives from each ownership type as well as with representatives from other stakeholders, e.g., other nongovernmental organizations (NGOs) or forest service, to engage them in the development of the plan. The list of ecosystem services encompassed both provisioning (e.g., timber and other forest products) and regulating services (e.g., carbon). Specifically, it included carbon stocks, cork, and pine cones as well as volume flows from a range of forest species. One of the ZIFs' forest ecosystem management planning problems encompassed further the standing volume at the end of the planning horizon as a criterion. We present results from two workshops, where more than 45 stakeholders negotiated targets, i.e., the desired supply levels, for each ecosystem service. We also discuss the forest management programs needed to achieve them, with the support of trade-off information provided by a Pareto frontier a posteriori MCDM.

Materials and Methods

Study Areas

After the 2003 wildfire season, when more than 400,000 ha burned (Marques et al. 2011), policymakers designed the tool ZIF—joint management areas that must encompass at least 1,000 ha and 50 forest owners—to promote the integration of multiple owners' forest management plans to address wildfire prevention goals (Martins and Borges 2007). Local forest owners associations, Associação de Agricultores da Charneca (ACHAR) and Associação Florestal de Vale do Sousa (AFVS), decided to use the tool to integrate forest management planning by their associates in Central and Northwest Portugal, respectively. ACHAR and AFVS represent about 800 forest owners, and their success in bringing together forest owners to develop the Zona de Intervenção Florestal Chouto Parreira (ZIF_Ch) and the Zona de Intervenção Florestal Paiva and Entre-Douro e Sousa (ZIF_VS), respectively, derives from the support they have provided to their associates over more than 20 years.

ZIF_Ch is located in a rural part of Chamusca County in Central Portugal, which has a Mediterranean climate. The ZIF_Ch area extends over 19,526 ha and was classified into 5,681 stands. It is dominated by cork oak (*Quercus suber*) and eucalypt (*Eucalyptus globulus* Labill) stands (63 and 30% of the ZIF_Ch area, respectively). Maritime pine (*Pinus pinaster* Ait.) and umbrella pine (*Pinus pinea*) stands occupy about 7% of the ZIF_Ch area. It is a privately owned area with 307 landowners. Small (<50 ha), medium (between 50 and 400 ha), and large (>400 ha) NIPF holdings extend over 6, 30, and 52% of the area, respectively. About 77% of the area of large holdings belongs to traditional forest owners for whom farming and forestry are the primary sources of income, whereas 12% is owned by the pulp and paper industry (Borges et al. 2014a). Cork and eucalypt pulpwood rank very high in the list of ecosystem services provided by ZIF_Ch. The list of ecosystem services also includes carbon storage, maritime pine saw logs, and umbrella pine cones (pine nuts) (Borges et al. 2014a).

ZIF_VS is located in a rural part of Northwest Portugal, which has a Mediterranean climate with an Atlantic influence. The ZIF_VS area extends over 14,388 ha and was classified into 1,976 stands. It is dominated by pure stands of eucalypt (*E. globulus* Labill) and mixed stands of eucalypt and maritime pine (*P. pinaster* Ait.) (about 66 and 33% of the ZIF_VS area, respectively). The remaining area is occupied by hardwoods. ZIF_VS encompasses 387 landowners. Community (local parish) property accounts for 35% of the ZIF_VS area. Medium and large private properties (area greater than 5 ha) extend over 60% of the ZIF_VS area. The remaining 5% is owned by small or very small forest owners (Borges et al. 2014a). Eucalypt pulpwood and maritime pine saw logs rank very high in the list of ecosystem services provided by ZIF_VS. This list also includes hardwood (chestnut) saw logs and carbon storage (Borges et al. 2014a).

Sottomayor et al. (2014a, 2014b) described the scenarios that drive change in both case study areas. These scenarios identified the elements that may have an impact on the forest owner's behavior and the distribution of corresponding management programs over the case study area over the next decades. In the case of ZIF_VS, stakeholders highlighted the importance of establishing a program for valuation of ecosystem nonmarket services (either by public subsidies or through market payments) and of increasing ZIFs eligibility for support by forest policies (e.g., by public subsidies). Stakeholders in ZIF_Ch emphasized the importance of the forest ownership structure and the occurrence of forest pests and diseases. Biber et al. (2015) used this information to assess the impact of scenarios on the provision of ecosystem services from both study areas. These scenarios were developed by the forest owners' associations and a set of stakeholders selected based on their representativeness (Sottomayor et al. 2014a, 2014b). They provided the context for the development of the ZIFs' management plans by ACHAR and AFVS and for the provision of ecosystem services from each ZIF. The number of forest ownership types involved, the multiplicity of stakeholders, and the diversity of ecosystem services provided an excellent framework to develop and test the combination of participatory workshops and Pareto frontier a posteriori MCDM to address multiple objectives and multiple decisionmakers' forest ecosystem management planning problems.

Model Building

The SADfLOR decision support toolbox (e.g., Borges et al. 2003, Ribeiro et al. 2004, Falcão and Borges 2005, Garcia-Gonzalo et al. 2013, 2015) was used to automate the process of model building for trade-off analysis. First, its management information module stored both alphanumeric and topological data from both case studies. Second, its prescription writer and simulation modules were developed to encapsulate the scenario information, namely silviculture and growth and yield models and thus generate the input to develop resource capability models (RCMs) (Davis and Johnson 2001) for both forest ecosystem management planning problems. The RCMs are defined by the decision variables, or prescriptions, as well as by their outcomes, i.e., their contribution to the provision of ecosystem services (Davis and Johnson 2001). A total of 84,227 and 69,783 stand-level prescriptions were simulated over a planning horizon extending over 90 years for the ZIF_Ch and ZIF_VS, respectively. The stand-level prescriptions were classified into forest management programs. The latter were associated with forest owners' behavior types identified by Sottomayor et al. (2014a, 2014b) (e.g., eucalypt short-rotation coppice systems by pulp and paper industry forest owners, cork oak agro-forestry system by small, medium, and large NIPFs).

The SADfLOR matrix generator automated the process of developing the resource capability linear programs from the output of its prescription writer and simulation modules. The latter include the forest models available to estimate the provision of ecosystem services from the study areas (Biber et al. 2015). In the RCM, stand-level prescriptions correspond to linear programming model I type decision variables (Johnson and Scheurman 1977). The RCM was further developed to include accounting variables to estimate the provision of each ecosystem service from each case study as well as to estimate the area assigned to each forest management program in each ZIF.

Finally, the RCMs were edited further to identify the ecosystem services for which trade-off information is needed. In the case of ZIF_Ch, the list of ecosystem services included cork, pine saw logs, pine cones, eucalypt pulpwood, and carbon. In the case of ZIF_VS, that list included pine saw logs, carbon, eucalypt pulpwood, and chestnut saw logs; an additional criterion was the standing volume in the ending inventory. These lists were developed by the stakeholders to reflect the relative importance of the ecosystem services in each ZIF (Borges et al. 2014a). The Pareto frontier MCDM module was then used to generate the set of criterion values for both forest ecosystem management problems as well as to produce and display the information about the trade-offs between criteria, i.e., ecosystem services (and standing volume in the ending inventory in the case of ZIF_VS).

The final model may be described as follows:

$$\sum_{j=1}^{M_i} x_{ij} = a_i,\ i = 1, \ldots, N \tag{1}$$

$$\sum_{i=1}^{N}\sum_{j=1}^{M_i} pinew_{ijt} x_{ij} = PineW_t,\ t = 1, \ldots, T \tag{2}$$

$$\sum_{i=1}^{N}\sum_{j=1}^{M_i} eucalyptw_{ijt} x_{ij} = EucalyptW_t,\ t = 1, \ldots, T \tag{3}$$

$$\sum_{i=1}^{N}\sum_{j=1}^{M_i} chestnutw_{ijt} x_{ij} = ChestnutW_t,\ t = 1, \ldots, T \tag{4}$$

$$\sum_{i=1}^{N}\sum_{j=1}^{M_i} corkA_{ijt} x_{ij} = CORKA_t,\ t = 1, \ldots, T \tag{5}$$

$$\sum_{i=1}^{N}\sum_{j=1}^{M_i} cones_{ijt} x_{ij} = Cones_t,\ t = 1, \ldots, T \tag{6}$$

$$\sum_{i=1}^{N}\sum_{j=1}^{M_i} carb_{ijt} x_{ij} = CARB_t,\ t = 1, \ldots, T \tag{7}$$

$$NPV = \sum_{i=1}^{N}\sum_{j=1}^{M_i} c_{ij} x_{ij} \tag{8}$$

$$Cork = \sum_{t=1}^{T} CORKA_t \tag{9}$$

$$Cones = \sum_{t=1}^{T} Cones_t \tag{10}$$

$$PineSawlogs = \sum_{t=1}^{T} PineW_t \tag{11}$$

$$EucalyptPulpwood = \sum_{t=1}^{T} EucalyptW_t \tag{12}$$

$$ChestnutSawlogs = \sum_{t=1}^{T} ChestnutW_t \tag{13}$$

$$Carb = \sum_{t=1}^{T} CARB_t / T \tag{14}$$

$$VEI = \sum_{i=1}^{N}\sum_{j=1}^{M_i} vei_{ij} x_{ij} \tag{15}$$

$$A\_FMP_f = \sum_{i=1}^{N}\sum_{j=1}^{M_i} x_{ij} \tag{16}$$

where $f \in FMP_f$, $f = 1, \ldots, 3, F$.

$$x_{ij} \geq 0,\ \forall\ i,j \tag{17}$$

where

N = the number of stands (5,681 for ZIF_Ch and 1,976 for ZIF_VS)
M_i = the number of prescriptions for each stand i
F = the number of forest management programs (4) (see Tables 2 and 4)
FMP_f = the set of prescriptions that were classified as belonging to forest management program
T = the number of planning periods (9)
x_{ij} = the number of ha of stand i assigned to prescription j
a_i = the total area of the stand i
$pinew_{ijt}$ = the pine timber flow in period t that results from assigning prescription j to stand i
$eucalyptw_{ijt}$ = eucalypt timber flow in period t that results from assigning prescription j to stand i
$chestnutw_{ijt}$ = chestnut timber flow in period t that results from assigning prescription j to stand i
$corkA_{ijt}$ = adult cork flow in period t that results from assigning prescription j to stand i
$cones_{ijt}$ = pine cone flow in period t that results from assigning prescription j to stand i
$carb_{ijt}$ = average yearly carbon stock in period t that results from assigning prescription j to stand i
c_{ij} = net present value associated with prescription j in stand i (it includes the soil expectation value)
vei_{ij} = standing volume in the ending inventory in stand i when assigned to prescription j
A_FMP_f = the area assigned to forest management program f.

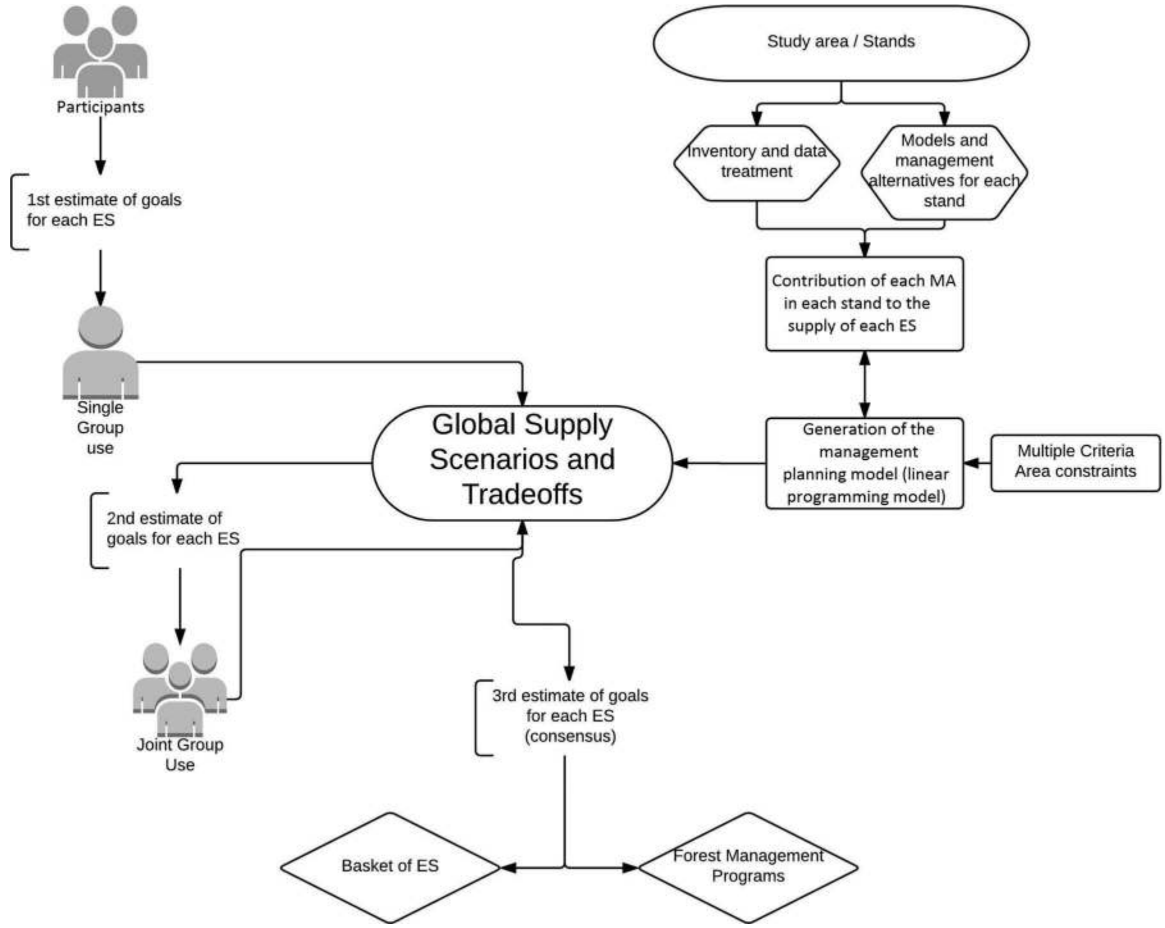

Figure 1. The workshop structure and information flow. ES, ecosystem service; MA, management alternative or prescription.

Equations 1 state that the sum of areas in a stand assigned to each prescription cannot exceed the corresponding stand area a_i. Equations 2, 3, and 4 define, respectively, the pine, eucalypt, and chestnut timber yield. Equation 4 was included only in the case of ZIF_VS. Equations 5, 6, and 7 define, respectively, the adult cork yield, the pine cone yield, and the average carbon stock in each planning period. Equations 5 and 6 were considered only in the case of ZIF_Ch. Equations 8 to 14 define, respectively, the net present value, the total adult cork yield, the total cone yield, the total pine saw logs yield, the total eucalypt pulpwood yield, the total chestnut saw logs yield, and the average carbon stock across planning periods. Equation 15 was included only in the case of ZIF_VS to define the standing volume in the case study area at the end of the planning horizon. These equations thus define the values of the criteria considered for testing purposes in each case study area. Equations 16 define the area assigned to each forest management program. They thus report the forest owner's behavior and corresponding management programs that would be needed to meet the ecosystem services target levels. The inequalities 17 state the nonnegativity constraints.

Group Decisionmaking

The workshops were designed to take place over a full day. The stakeholders in each set were selected with the support of ACHAR and AFVS to represent all relevant private and public interests. These participants were ACHAR and AFVS board members and other representatives of forest owners and representatives from industry, forestry firms, central and local public administration, environmental groups, and local development NGOs. Stakeholders had been formerly involved in meetings with the research team to develop the driver scenarios described by Sottomayor et al. (2014a, 2014b). In the case of ZIF_VS, the workshop involved 20 stakeholders, representing the NIPFs (3), the pulpwood industry forest owners (3), the maritime pine industry (2), the furniture industry (1), the forest services providers (1), the forest service (3), local municipalities (3) and NGOs (4). In the case of ZIF_Ch, the workshop involved 26 stakeholders, representing the NIPFs (8), the pulpwood industry forest owners (3), the pine industry (3), the cork industry (4), the forest service (3), local municipalities (2), and NGOs (3). The NGOs included environmental groups as well as local development organizations. The team that conducted the workshops included five researchers.

The workshops were structured so that stakeholders would provide first an estimate of the target supply level for each ecosystem service from the case study area. The first estimate resulted from a discussion by all stakeholders. No assistance from the DSS and from its Pareto frontier MCDM module was provided regarding the feasibility set or the trade-offs between criteria (Figure 1).

Next, the research team described the process by which it generated the RCM for each ZIF and the ecosystem services trade-off information for the global supply scenarios. It further demonstrated the use of the DSS and its Pareto frontier MCDM module so that stakeholders might take advantage of the information provided by it to redefine their ecosystem services target supply levels.

After this stage, stakeholders were organized into heterogeneous

Table 1. ZIF_Ch ecosystem services target levels by stakeholders.

Ecosystem services	Unit	90-yr period			
		First estimate	Second estimates		Third estimate solution
			Group 1	Group 2	
Cork	@ (15 kg)	13.6×10^6	14.65×10^6	14.65×10^6	14.65×10^6
Pulpwood	m^3	8.14×10^6	8.14×10^6	8.14×10^6	8.14×10^6
Pine saw logs	m^3	0.24×10^6	0.26×10^6	0.27×10^6	0.05×10^6
Pine cones	Mg	0.06×10^6	0.03×10^6	0.06×10^6	0.16×10^6
Average carbon stock	Mg/yr		0.98×10^6	0.94×10^6	0.98×10^6

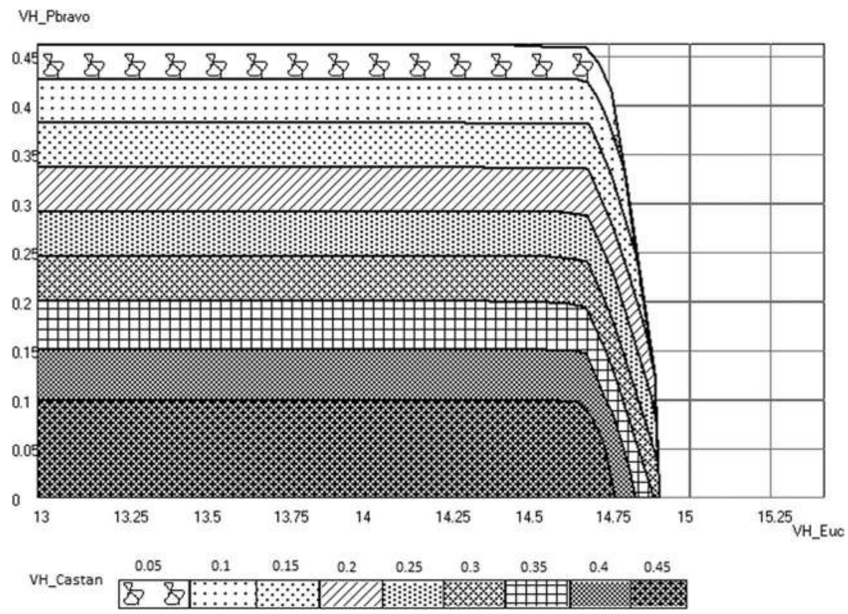

Figure 2. Tradeoffs between three ecosystem services: VH_Pbravo, pine saw logs; VH_Euc, eucalypt pulpwood; VH_Castan, chestnut saw logs. Each of the nine decision maps corresponds to a level of supply of VH_Castan; the latter ranges from 0.05 to 0.45 × 10^6 m^3. Each decision map displays the trade-offs between the provisions of VH_Pbravo and VH_Euc for each level of supply of VH_Castan.

working groups with representatives from all stakeholders' categories (forest owners, industry, public administration, and NGOs). This setting was designed so that the negotiation process might be initiated at this stage with the support of the DSS and its Pareto frontier MCDM module. Each working group was provided with a laptop computer on which the DSS had been installed. The group used the DSS to generate information about the feasibility frontier and the trade-offs between criteria. Using this information, the group developed a second estimate of the target supply level for each ecosystem service from the case study area. The research team compiled these estimates and made them available to all participants at the end of the working session. During the last stage of the workshop, all stakeholders worked together using the DSS and its Pareto frontier MCDM module in an effort to reach a solution that might be accepted by all groups and participants.

At the end of each workshop, each participant was asked to complete a questionnaire (see Figure 6). The questionnaire was developed for evaluating the workshop and the support provided by the a posteriori MCDM approach for defining the ecosystem services target levels and corresponding landscape-level forest ecosystem management programs. It contained 11 statements. Participants were asked their degree of agreement or disagreement with each statement. Answers were provided on a 5-point Likert scale, and it was possible for participants to write comments.

Table 2. Areas allocated to each forest management program to meet the ecosystem services target levels solution in ZIF_Ch.

Forest management programs	Current		To meet targets (third estimate)	
	ha	%	ha	%
1. Cork oak (*Quercus suber*) forest system for cork production	12,323	63.1	12,323	63.1
2. Eucalypt (*Eucalyptus globulus*) forest system for pulpwood production	5,878	30.1	5,878	30.1
3. Umbrella pine (*Pinus pinea)* forest system for pine nuts production	205	1.1	436	4.6
4. Even-aged maritime pine (*Pinus pinaster*) forest system for saw logs production	1,121	5.7	890	2.2

Results

The first estimates by the stakeholders (Tables 1 and 3) resulted from a discussion with no support from the DSS and its Pareto frontier MCDM module. Stakeholders were allowed to define the targets they thought desirable for the case study area. For example, in the case of ZIF_VS representatives from NGOs put emphasis on the provision of chestnut saw logs, whereas the pulp industry was

Table 3. ZIF_VS ecosystem services target levels by stakeholders.

Ecosystem services	Units	2014–2104				
		First estimate	Second estimates			Third estimate solution
			Group 1	Group 2	Group 3	
Eucalypt pulpwood	m^3	15.4×10^6	14.6×10^6	14.6×10^6	14.9×10^6	14.5×10^6
Pine saw logs	m^3	0.69×10^6	0.01×10^6	0.24×10^6	0.27×10^6	0.2×10^6
Chestnut saw logs	m^3	0.01×10^6	0.45×10^6	0.31×10^6	0.27×10^6	0.34×10^6
Volume of ending inventory	m^3		1.5×10^6	1.5×10^6	1.1×10^6	1.4×10^6
Average carbon stock	Mg/yr		0.6×10^6	0.6×10^6	0.6×10^6	0.6×10^6

mostly concerned with the provision of eucalypt pulpwood. Thus, with no check on the overall feasibility of meeting those targets. Furthermore, they could not be translated into a quantifiable set of forest owner behaviors and corresponding forest management programs (e.g., to an allocation of area to each forest management program). Nevertheless, they were grounded by the stakeholders' experience and former knowledge about the study area and its potential for supplying the range of ecosystem services. Stakeholders thus felt confident about providing targets for most ecosystem services. Nevertheless, they decided to check the information provided by the tool before setting targets for the average carbon stock in both case study areas and for the volume of ending inventory in the case of ZIF_VS.

The DSS demonstration session did provide the expertise needed for the stakeholders to work independently with the Pareto frontier MCDM module. Stakeholders used the tool to check the feasibility of their first estimates. For that purpose, they started by selecting three ecosystem services out of the range provided by each case study area (Figure 2). For example, in the case of ZIF_VS, they started by analyzing the trade-offs between the provision of pine saw logs, chestnut saw logs, and eucalypt pulpwood. The Pareto frontier MCDM module displays this information in decision maps. Each decision map is associated with a specific level of chestnut saw logs and thus provided information about the trade-offs between eucalypt pulpwood and pine saw logs (Figure 2). Each decision map corresponds to a set of solutions in a two-criteria space, the two criteria being in this case the eucalypt pulpwood and the pine saw logs. It represents all feasible combinations of supply values for eucalypt pulpwood and pine saw logs for a given value of the third criterion, chestnut saw logs. The set of decision maps highlights further the trade-offs between the supply of chestnut saw logs and the supply of the two other ecosystem services. The supply of chestnut saw logs competes more with the supply of pine saw logs than with that of eucalypt pulpwood.

After this first check, participants considered all ecosystem services simultaneously. Use of the DSS and MCDM module facilitated this procedure and helped stakeholders interpret the information provided by the tool about the set of feasible values for the criteria as well as about the trade-offs between the ecosystem services. The tool enabled the generation of a solution that all stakeholders in the group were comfortable with (Tables 1 and 3). The development of the second estimate also made use of the information provided by the tool about the areas that would be needed for allocation to each forest management program to meet the targets. The resulting estimated area allocation was all the more acceptable because all groups included representatives of forest owners.

Results show that the Pareto frontier MCDM module helped stakeholders revise their initial estimates to take into account the

Table 4. Areas allocated to each forest management program to meet the ecosystem services target levels solution in ZIF_VS.

Management programs	Current		To meet targets (third estimate)	
	ha	%	ha	%
1. Mixed maritime pine (*Pinus pinaster*) and eucalypt (*Eucalyptus globulus*) forest system, dominance of maritime pine	2302	16.0	462	3.2
2. Mixed maritime pine (*Pinus pinaster*) and eucalypt (*Eucalyptus globulus*) forest system, dominance of eucalypt	2446	17.0	769	5.3
3. Chestnut (*Castanea sativa*) forest systems for production of chestnut saw logs	101	1	1282	8.9
4. Eucalypt (*Eucalyptus globulus*) forest system for pulpwood production	9499	66.0	11875	82.5

feasibility of the proposed ecosystem services baskets. In the case of ZIF_VS, the initial estimate of the target provision of eucalypt pulpwood over the 90-year period was decreased by about 0.8×10^6 m^3 (Table 3). This was a consequence of an overestimation of the potential for joint supply of eucalypt pulpwood and pine saw logs from areas where mixed stands predominated (areas allocated by NIPFs to programs for the management of eucalypt and pine forests). The stakeholders' development of the second estimate for targets in the ZIF_VS took further advantage of the exploration of the potential for change in current behavior: participants considered the potential for converting small NIPFs' lightly managed mixed stands to more actively managed chestnut stands or to pure eucalypt stands. The decrease in the target provision of eucalypt pulpwood and pine saw logs was matched by an increase in the target provision of chestnut saw logs by all groups. All three groups in ZIF_VS had representatives from all stakeholders' categories. Nevertheless, one group stood out for targeting higher harvest levels at the expense of the volume of ending inventory (Table 3).

Conversely, in the case of ZIF_Ch, the Pareto frontier MCDM module indicated that the initial target estimates underestimated the productive potential of the case study area. The initial estimate of the target provision of cork over the 90-year period was increased by about 1.05×10^6 kg (Table 1). This increase did not lead to a decrease in the provision of any of the other ecosystem services. Although both groups targeted the same levels of cork and eucalypt pulpwood supply, they differed in the targets assigned to the supply of maritime pine saw logs and umbrella pine cones (Table 1). The trade-off information provided by the Pareto frontier MCDM module helped each group negotiate the target levels for both ecosystem services. Higher cone and pine harvest levels in the case of targets set by group 2 led to a decrease in the average carbon stock. The information about the allocation of areas to the corresponding forest

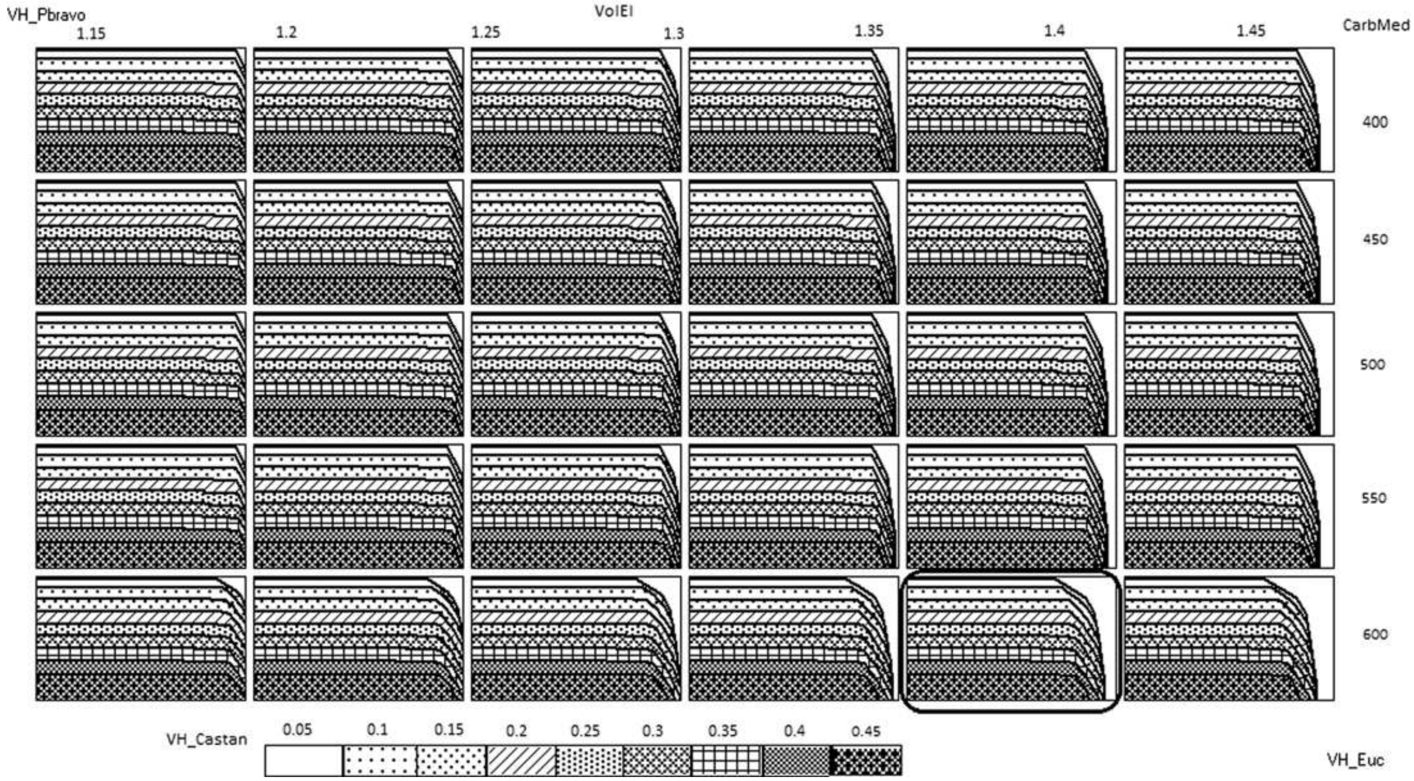

Figure 3. Tradeoffs between five ecosystem services: VolEI, volume of the ending inventory; CarbMedio, average carbon stock; VH_Pbravo, pine saw logs; VH_Euc, eucalypt pulpwood; VH_Castan, chestnut saw logs. Each line displays the sets of decision maps for a level of CarbMedio; the latter ranges from 400 to 600 × 10^3 Mg/year. Each column displays the sets of decision maps for a level of VolEI; the latter ranges from 1.15 to 1.45 × 10^6 m^3. Each set of nine decision maps displays the trade-offs between VH_Pbravo, VH_Euc, and VH_Castan for specific levels of CarbMedio and VolEI. Each of the nine decision maps in a set corresponds to a level of supply of VH_Castan; the latter ranges from 0.05 to 0.45 × 10^6 m^3. Each decision map displays the trade-offs between the provisions of VH_Pbravo and VH_Euc for each level of supply of VH_Castan. The set of decision maps selected by stakeholders in ZIF_VS for further exploration and selection of a solution is circled.

management programs provided by the tool helped further check the acceptability by forest landowners of the resulting landscape-level plans.

Results from the third stage confirmed the usefulness of the tool to sort out differences between stakeholders and working groups and to reach a solution: a basket of ecosystem services and the corresponding landscape-level management plan. The baskets reflected the vision negotiated by all stakeholders. The landscape-level management plan for each case study area was the means to help each ZIF meet the ecosystem services supply target values that the stakeholders collectively envisioned. Those plans were accepted by the forest owners' representatives and specify the area to be allocated to each forest management program.

In the case of ZIF_VS, stakeholders started by agreeing on levels of average carbon stock and volume of ending inventory: both the level of the inventory stock over the planning horizon as measured by carbon stored (0.6 × 10^6 Mg/year) and the level of the inventory to be left after the implementation of the 90-year landscapewide plan (1.4 × 10^6 m^3) (Figure 3). They used the corresponding set of decision maps to check the trade-offs between the three other ecosystem services and select the solution that best reflected their joint preferences (Figure 4). The final target provision of eucalypt pulpwood was slightly lower than the targets set earlier by all working groups (Table 3). The negotiation of targets for the remaining two ecosystem services led to a basket where the provision of chestnut and pine saw logs was set to 0.34 × 10^6 m^3 and 0.2 × 10^6 m^3, respectively (Table 3). This negotiation was supported by the information regarding the allocation of area to each management program provided by the Pareto frontier MCDM module. Several solutions were analyzed before the final one was selected. The increase in the area assigned to the chestnut and the eucalypt forest systems at the expense of mixed forest systems stood out as the major change to take place in the landscape (Table 4).

In the case of ZIF_Ch, the stakeholders followed a similar process to arrive at the solution. After agreeing on the average carbon stock level (0.98 × 10^6 Mg/year) and on the level of pine saw logs supply (0.05 × 10^6 m^3), they used the tool to analyze the trade-offs between the remaining three ecosystem services and select potential baskets (Figure 5). The corresponding allocation of areas to forest management programs by the Pareto frontier MCDM module helped the participants to select the solution. In this solution, the area allocated to the umbrella pine system was increased at the expense of the area allocated to the maritime pine system (Table 2). The shift from the second to the third estimate (Table 1) resulted from a more thorough discussion of the impacts of wildfires and outbreaks of insects and disease on the sustainability of the maritime pine system.

The results of the questionnaires showed the potential of the approach proposed to overcome obstacles of landscape tenure heterogeneity to landscapewide management planning (Figure 6). Overall, the participants were positive, especially about the negotiated solution (Questions 8–11) but also about the use of the a posteriori approach in the framework of the workshop to get to that solution (Questions 1–7). In the case of ZIF_Ch, the participants

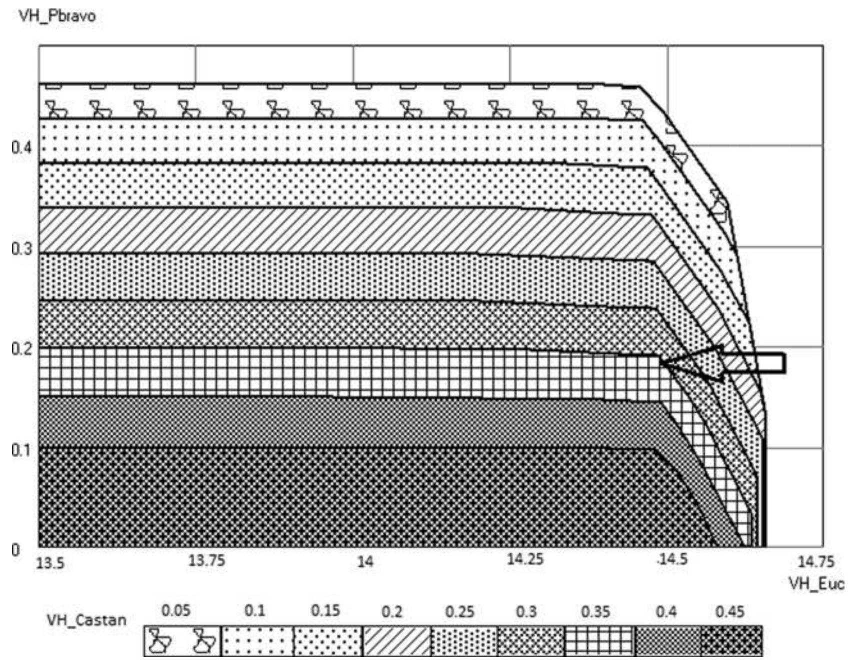

Figure 4. **Set of decision maps (for volume of the ending inventory equal to 1.4 × 10^6 m^3 and average carbon stock equal to 0.6 × 10^6 Mg/year) from which stakeholders selected the solution (third estimate). VH_Pbravo, pine saw logs; VH_Euc, eucalypt pulpwood; VH_Castan, chestnut saw logs. Each of the nine decision maps corresponds to a level of supply of VH_Castan; the latter ranges from 0.05 to 0.45 × 10^6 m^3. Each decision map displays the trade-offs between the provisions of VH_Pbravo and VH_Euc for each level of supply of VH_Castan. The white line represents the Pareto frontier selected by stakeholders; it is associated to VH_Castan = 0.34 × 10^6 m^3. The point selected by stakeholders in this frontier corresponds to VH_Euc = 14.5 × 10^6 m^3 and VH_Pbravo = 0.2 × 10^6 m^3.**

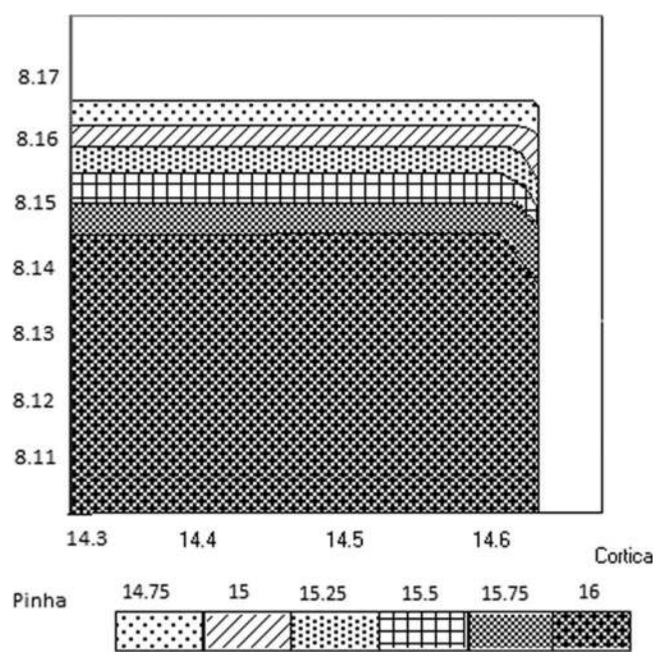

Figure 5. **Set of decision maps (for average carbon stock equal to 0.98 Mg/year and pine saw logs supply equal to 0.05 × 10^6 m^3) from which stakeholders in ZIF_Ch selected the solution (third estimate). VH_Euc, eucalypt pulpwood Chamusca; Cortica, cork; Pinha, umbrella pine cones. Each of the six decision maps corresponds to a level of supply of Pinha; the latter ranges from 14.75 to 16.0 × 10^4 Mg. Each decision map displays the trade-offs between the provisions of Cortica and VH_Euc for each level of supply of Pinha.**

were in general positive about the MCDM tool and especially about the vision produced. Time for using the tool, in both the intragroup and the intergroup settings (Questions 6 and 7), seems to have been the most critical point. In the case of ZIF_VS, the participants were more critical about the tool and the scarcity of time for using it, and yet they were as positive about the vision created as the participants in the case of ZIF_Ch. In ZIF_VS and ZIF_Ch, a certain share of participants either did not answer the questions or stated that they did not know how to answer; this uncertainty pertains especially to the questions on the vision (Questions 8–11).

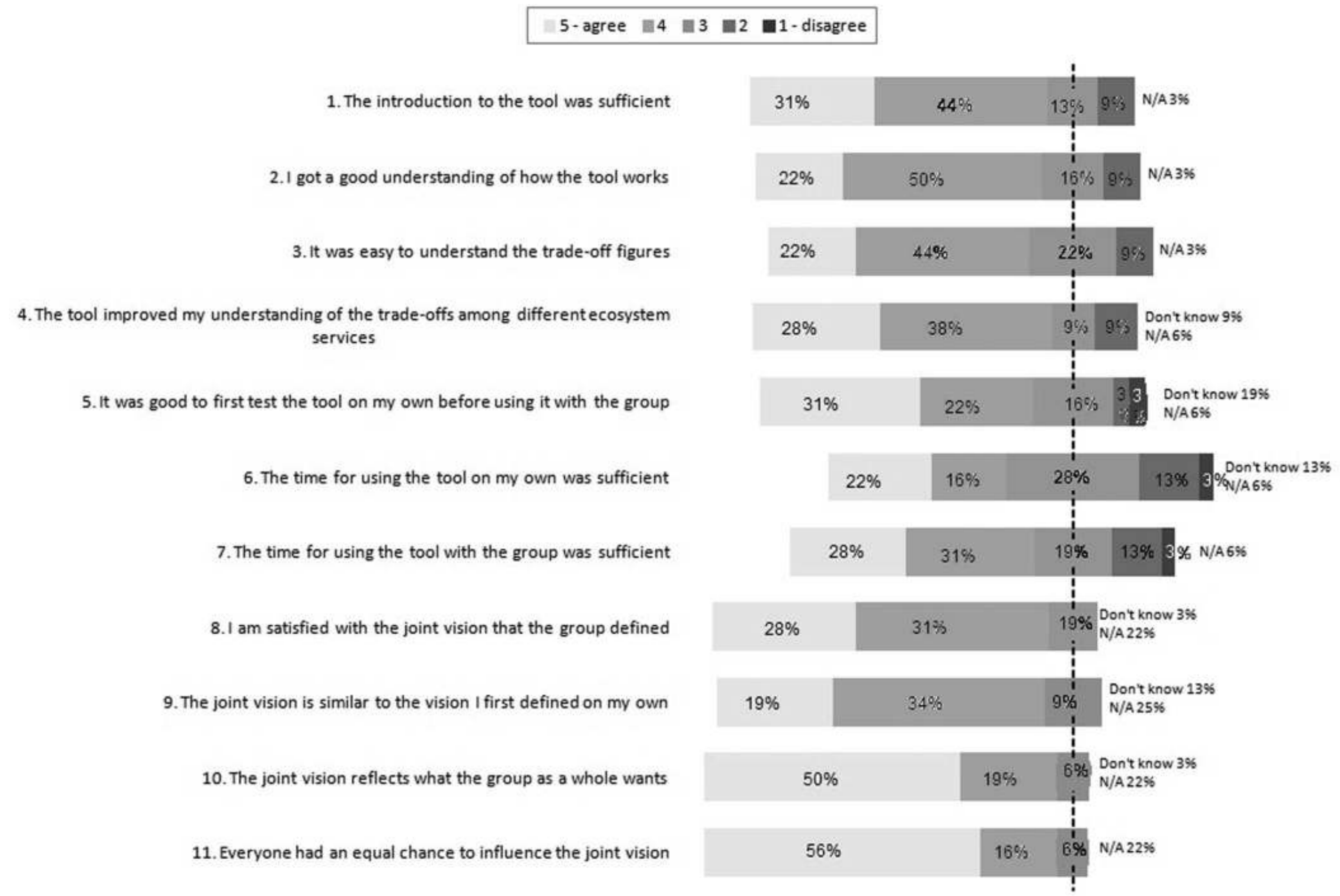

Figure 6. Results of the questionnaires from the two workshops ($n = 46$). The vertical, dashed line shows the midpoint of the five-point Likert scale; the share of respondents that agree with the statements is displayed to the left of the midpoint line (in lighter shades) and the share of respondents that disagree to the right (in darker shades). Neutral responses (value 3 on the Likert scale) are displayed in gray with equal shares on either side of the midpoint line.

Discussion and Conclusions

The combination of participatory workshops and Pareto frontier a posteriori MCDM developed by this research did meet the efficiency and effectiveness requirements for addressing typical multiple objective and multiple decisionmakers' forest ecosystem management planning problems. The data and information management processes to generate the trade-offs between the forest management decision criteria were fully automated, thus meeting the forest management process efficiency requirement. This was a key factor for the success of the participatory workshops as it provided real-time support to the negotiation between stakeholders. Computational improvements may be possible. These relate to the coding of DSS modules and of the linkages between them. Nevertheless, SADfLOR and the current implementation of the Pareto frontier a posteriori MCDM module ran efficiently and did provide the timely information required by the participants in the workshops. The approach was influential in helping the stakeholders frame the problem and set targets for the criteria. As a result, the approach contributed to enhance forest management effectiveness in both study areas.

Web-based DSS platforms have been proposed to address forest management planning problems (e.g., Reynolds et al. 2008, Rammer et al. 2014). Future research will target the integration of Pareto frontier a posteriori MCDM modules in such platforms. This may help widen the involvement of stakeholders in participatory workshops and thus contribute to enhance the effectiveness of the forest management process and the quality of the decisions. In some cases, a higher number of forest owners' representatives might be necessary for a negotiated solution to be accepted.

Results demonstrated the effectiveness of the approach. In contrast with other a posteriori methods used in participatory forest planning (e.g., Mendoza and Prabhu 2000, Kangas and Kangas 2005, Pykäläinen et al. 2007, Korosuo et al. 2011, Nordström et al. 2010, 2011, Grošelj et al. 2015, Rico and González 2015), our Pareto frontier approach was not constrained by the need to simplify the problem and select a smaller discrete set of alternatives. In fact, our forest management decisionmaking problems in ZIF_VS and ZIF_Ch involved a large number of alternatives. Further it did not require stakeholders to define the ecosystem services target supply values before considering the possible supply values that derive from the resource capability models. This may contribute to a comprehensive representation of forest management decisionmaking problems involving large number of alternatives. The framing of the problem took into account complexity at the landscape level. Models were developed from 84,227 stand-level alternatives for ZIF_Ch and 69,783 stand-level alternatives for ZIF_VS. Stakeholders were able to check information about all landscapewide combinations of these alternatives when making decisions.

The modular structure of the SADfLOR decision support toolbox facilitates the update of forest models to estimate the provision of ecosystem services from the study areas. As the trade-off curves depend on the projections made by these models, that modularity is important to increase the accuracy of the trade-off information as new models become available. The set of ecosystem services from each ZIF was designed in cooperation with the forest owners associations and the stakeholders to reflect a balance between flows (timber, cones, and cork) and stocks (carbon and inventory). It included thus only provisioning and regulating ecosystem services. Other forest ecosystem management planning objectives may be relevant in other contexts. Therefore, the research may be expected to focus on diversifying the range of objectives considered, such as protection against wildfires (Ferreira et al. 2015) and biodiversity (Bugalho et al. 2011), to increase the applicability of the approach. This will entail the development of forest models to assess the impact of stand-level management options on the provision of other ecosystem services. This research highlighted how to address obstacles to landscape-level management planning that derive from a heterogeneous land tenure structure. However, no spatial optimization methods were used, and stakeholders did not check the solution spatial patterns. Future research will thus also explore the incorporation of other planning techniques, e.g., such as mixed integer programs with spatial conditions' targets into the Pareto frontier MCDM tool to address objectives as well as the provision of ecosystem services that depend on the spatial distribution of stand-level management options. This work will help evaluate the effect of spatial context on both stand- and landscape-level outcomes.

Although the workshop participants had former knowledge about the study area and had actually been involved in the development of its driver scenarios (Sottomayor et al. 2014a, 2014b), they either overestimated or underestimated the forested landscapes' production potential. This outcome highlights the importance of trade-off information in developing effective natural resources management policies, such as those for forest plantations. The tool helped them realize what that potential was and contributed to a better informed negotiation to develop the second estimate of what the targets should be. Stakeholders were fully aware of the implications of their selection of ecosystem services supply values on the allocation of areas to forest management programs, when selecting the landscape-level solution (the workshop third estimate). This information was provided in real time by the tool. Current research is building on these findings to explore the policy options that may facilitate the implementation of the forest management programs.

The effectiveness of the approach was demonstrated further by stakeholders' responses to the questionnaires. Overall, the evaluations were quite positive. In both case studies, the participants were especially satisfied with the resulting vision. The tool did provide the information needed for an informed negotiation of the ecosystem services targets and of the forest management programs needed to realize the stakeholders' vision. Nevertheless, the responses suggest that the effectiveness of the participatory workshops may be increased further by the development of laboratory sessions for stakeholders to become more familiar with the use of the tool. Sufficient time for exploring and using the tool is clearly important. Limited time is often a problem in participatory forest planning (Duinker 1998, Buchy and Hoverman 2000), and it may be accentuated by the use of technical tools that provide complex information that the stakeholders need to understand for the process to be meaningful to them (Menzel et al. 2012). Responses from ZIF_VS stakeholders expressed this need; the research team provided less instruction about the use of the tool to these groups than to ZIF_Ch stakeholders. ZIF_VS participants perceived time to be a limiting factor during their negotiation. This constraint will be more severe if concerns with spatial impacts of solutions are to be analyzed. The SADfLOR decision support toolbox integrates a geographical information module. Nevertheless, the spatial analysis by multiple decisionmakers will require more workshop time. Using computational tools in participatory settings may be problematic if the tool is not comprehensible to stakeholders but seen as a black box (Menzel et al. 2012). Future research could aim to improve the participatory component of our approach by considering the development of an outreach session before the participatory workshop and by testing alternative workshop settings, e.g., the number and size of working groups.

In summary, this research demonstrated that the combination of participatory workshops and Pareto frontier a posteriori MCDM may help overcome land tenure heterogeneity constraints to landscape-level management planning and to the provision of forest ecosystem services. The use of the Pareto frontier a posteriori MCDM in participatory planning contexts is innovative and may contribute to facilitate negotiation and planning as it does not require stakeholders to specify ecosystem services supply values before they check their feasibility and trade-offs. It efficiently and effectively provides an informed negotiation setting, where stakeholders and decisionmakers may sort out their differences to set targets for the provision of ecosystem services and to develop an acceptable landscape-level plan. The assessment of the approach by stakeholders was overall positive as shown in the responses to the questionnaires. The approach may thus be used to support and enhance any ecosystem management planning process in which collaborative planning and participatory processes are key to the success of the effort.

Literature Cited

Aldea, J., F. Martínez-Peña, C. Romero, and L. Diaz-Balteiro. 2014. Participatory goal programming in forest management: An application integrating several ecosystem services. *Forests* 5:33–52.

Ananda, J. 2007. Implementing participatory decision making in forest planning. *Environ. Manage.* 39:534–544.

Ananda, J., G. Herath. 2003. Incorporating stakeholder values into regional forest planning: A value function approach. *Ecol. Econ.* 45:75–90.

Belton, V., and T.J. Stewart. 2002. *Multiple criteria decision analysis—An integrated approach*. Kluwer Academic Publishers, Dordrecht, The Netherlands. 372 p.

Biber, P., J.G. Borges, R. Moshammer, S. Barreiro, B. Botequim, Y. Brodrechtová, V. Brukas, et al. 2015. How sensitive are ecosystem services in European forest landscapes to silvicultural treatment? *Forests* 6:1666–1695.

Borges, J.G., A. Falcão, C. Miragaia, P. Marques, and M. Marques. 2003. A decision support system for forest resources management in Portugal. P. 155–164 in *System analysis in forest resources: Proc. of the Eighth Symposium, held 2000 Sept. 27–30, Snowmass Village, Colorado, USA*, Arthaud, G.J., and T. Barrett (eds.). Managing Forest Ecosystems, Vol. 7, Springer Netherlands, Dordrecht, The Netherlands.

Borges, J.G., J. Garcia-Gonzalo, B. Botequim, S. Barreiro, S. Marques, and M. Tomé. 2014a. *Scenario development at landscape level under different management strategies*. Deliverable 2.2 of the INTEGRAL project. Available online at www.integral-project.eu/images/Documents/Publications/Deliverables/D2.2%20Scenario%20development%20at%20landscape%20level%20under%20different%20management.pdf; last accessed Oct. 21, 2016.

Borges, J.G., J. Garcia-Gonzalo, V. Bushenkov, M.E. McDill, S.

Marques, and M.M. Oliveira. 2014b. Addressing multicriteria forest management with Pareto frontier methods: An application in Portugal. *For. Sci.* 60:63–72.

Briceño-Elizondo, E., D. Jäger, M.J. Lexer, J. Garcia-Gonzalo, H. Peltola, and S. Kellomäki. 2008. Multi-criteria evaluation of multi-purpose stand treatment programmes for Finnish boreal forests under changing climate. *Ecol. Indicators* 8:26–45.

Buchy, M., and S. Hoverman. 2000. Understanding public participation in forest planning: A review. *For. Policy Econ.* 1(1):15–25.

Bugalho, M.N., M.C. Caldeira, J.S. Pereira, J.A. Aronson, and J. Pausas. 2011. Mediterranean oak savannas require human use to sustain biodiversity and ecosystem services. *Front. Ecol. Environ.* 5:278–286.

de Sousa Xavier, A.M., M.B. Costa Freitas, and R.M. de Sousa Fragoso. 2015. Management of Mediterranean forests—A compromise programming approach considering different stakeholders and different objectives. *For. Policy Econ.* 57:38–46.

Davis, L.S., and K.N. Johnson. 2001. *Forest management*, 3rd ed. McGraw Hill Publishing Company, New York. 816 p.

Diaz-Balteiro, L., J. Gonzalez-Pachon, and C. Romero. 2009. Forest management with multiple criteria and multiple stakeholders: An application to two public forests in Spain. *Scand. J. For. Res.* 24:87–93.

Diaz-Balteiro, L., J. Gonzalez-Pachon, and C. Romero. 2013. Goal programming in forest management: Customizing models for the decision-maker's preferences. *Scand. J. For. Res.* 28:166–173.

Diaz-Balteiro, L., and C. Romero. 2008. Making forestry decisions with multiple criteria: A review and an assessment. *For. Ecol. Manage.* 255:3222–3241.

Duinker, P.N. 1998. Public participation's promising progress: Advances in forest decision-making in Canada. *Commonw. For. Rev.* 77(2): 107–112.

Eyvindson, K., T. Hujala, M. Kurttila, and A. Kangas. 2013. Interactive preference elicitation incorporating a priori and a posteriori methods. *Ann. Oper. Res.* 232(1):99–113.

Eyvindson, K., and A. Kangas. 2015. Using a compromise programming framework to integrating spatially specific preference information for forest management problems. *J. Multi-Criteria Decis. Anal.* 22:3–15.

Falcão, A., and J.G. Borges. 2005. Designing decision support tools for Mediterranean forest ecosystems management: A case study in Portugal. *Ann. For. Sci.* 62:751–760.

Ferreira, L., M. Constantino, J.G. Borges, and J. Garcia-Gonzalo. 2015. Addressing wildfire risk in a landscape-level scheduling model. An application in Portugal. *For. Sci.* 61:266–277.

Garcia-Gonzalo, J., V. Bushenkov, M.E. McDill, and J.G. Borges. 2015. A decision support system for assessing trade-offs between ecosystem management goals: An application in Portugal forests. *Forests* 6(1):65–87.

Garcia-Gonzalo, J., J. Palma, J. Freire, M. Tomé, R. Mateus, L.C.E. Rodriguez, V. Bushenkov, and J.G. Borges. 2013. A decision support system for a multi stakeholder's decision process in a Portuguese National Forest. *For. Syst.* 22:359–373.

Grošelj, P., D.G. Hodges, and L. Zadnik. 2015. Participatory and multi-criteria analysis for forest (ecosystem) management: A case study of Pohorje, Slovenia. *For. Policy Econ*. 71:80–86.

Hiltunen, V., J. Kangas, and J. Pykäläinen. 2008. Voting methods in strategic forest planning—Experiences from Metsähallitus. *For. Policy Econ.* 10:117–127.

Hwang, C.-L., and A.S.M. Masud. 1979. *Multi objective decision making—Methods and applications*. Springer, Berlin, Germany. 259 p.

Jalilova, G., C. Khadka, and H. Vacik. 2012. Developing criteria and indicators for evaluating sustainable forest management: A case study in Kyrgyzstan. *For. Policy Econ.* 21:32–43.

Johnson, K.N., and H.L. Scheurman. 1977. *Techniques for prescribing optimal timber harvest and investment under different objectives—Discussion and synthesis*. For. Sci. Monogr. 18, Society for American Foresters, Bethesda, MD. 31 p

Kangas, A., J. Kangas, and J. Pykäläinen. 2001. Outranking methods as tools in strategic natural resources planning. *Silva Fenn.* 35:215–227.

Kangas, J. 1994. An approach to public participation in strategic forest management planning. *For. Ecol. Manage.* 70:75–88.

Kangas, J., and A. Kangas. 2005. Multiple criteria decision support in forest management—The approach, methods applied, and experiences gained. *For. Ecol. Manage.* 207:133–143.

Khadka, C., and H. Vacik. 2012. Use of multi-criteria analysis (MCA) for supporting community forest management. *iForest* 5:60–71.

Korosuo, A., P. Wikström, K. Öhman, and L.-O. Eriksson. 2011. An integrated mcda software application for forest planning: A case study in southwestern Sweden. *Math. Comput. For. Nat. Resour. Sci.* 3:75–86.

Kraxner, F., E.M. Nordström, O. Havlík, M. Gusti, A. Mosnier, S. Frank, H. Valin, et al. 2013. Global bioenergy scenarios—Future forest development, land-use implications, and trade-offs. *Biomass Bioenergy* 57:86–96.

Laukkanen, S., A. Kangas, and J. Kangas. 2002. Applying voting theory in natural resource management: A case of multiple-criteria group decision support. *J. Environ. Manage.* 64:127–137.

Lotov, A., V.A. Bushenkov, and G.K. Kamenev. 2004. *Interactive decision maps. Approximation and visualization of Pareto frontier*. Kluwer Academic Publishers, Norwell, MA. 319 p.

Maroto, C., M. Segura, C. Ginestar, J. Uriol, and B. Segura. 2013. Sustainable forest management in a Mediterranean region: Social preferences. *For. Syst.* 22:546–558.

Marques, S., J.G. Borges, J. Garcia-Gonzalo, F. Moreira, J.M.B. Carreiras, M.M. Oliveira, A. Cantarinha, B. Botequim, and J.M.C. Pereira. 2011. Characterization of wildfires in Portugal. *Eur. J. For. Res.* 130:775–784.

Martins, H., and J.G. Borges. 2007. Addressing collaborative planning methods and tools in forest management. *For. Ecol. Manage.* 248:107–118.

Mendoza, G.A., and H. Martins. 2006. Multi-criteria decision analysis in natural resource management: A critical review of methods and new modelling paradigms. *For. Ecol. Manage.* 230:1–22.

Mendoza, G.A., and R. Prabhu. 2000. Development of a methodology for selecting criteria and indicators of sustainable forest management: A case study on participatory assessment. *Environ. Manage.* 26:659–673.

Menzel, S., E.-M. Nordström, M. Buchecker, A. Marques, H. Saarikoski, and A. Kangas. 2012. Decision support systems in forest management: Requirements from a participatory planning perspective. *Eur. J. For. Res.* 131(5):1367–1379.

Miettinen, K. 1999. *Nonlinear multiobjective optimization*. Kluwer, Dordrecht, The Netherlands. 297 p.

Mustajoki, J., H. Saarikoski, M. Marttunen, A. Ahtikoski, V. Hallikainen, T. Helle, M. Hyppönen, et al. 2011. Use of decision analysis interviews to support the sustainable use of the forests in Finnish Upper Lapland. *J. Environ. Manage.* 92:1550–1563.

Nordström, E.M., L.O. Eriksson, and K. Öhman. 2010. Integrating multiple criteria decision analysis in participatory forest planning: Experience from a case study in northern Sweden. *For. Policy Econ.* 12:562–574.

Nordström, E.M., L.O. Eriksson, and K. Öhman. 2011. Multiple criteria decision analysis with consideration to place-specific values in participatory forest planning. *Silva Fenn.* 45:253–265.

Nordström, E.M., V. Romero, L.O. Eriksson, and K. Öhman. 2009. Aggregation of preferences in participatory forest planning with multiple criteria: An application to the urban forest in Lycksele, Sweden. *Can. J. For. Res.* 39:1979–1992.

Pykäläinen, J., V. Hiltunen, and P. Leskinen. 2007. Complementary use of voting methods and interactive utility analysis in participatory strategic forest planning: Experiences gained from western Finland. *Can. J. For. Res.* 37:853–865.

Rammer, W., C. Schauflinger, V. Vacik, J.H.N. Palma, J. Garcia-Gonzalo, J.G. Borges, and M.J. Lexer. 2014. A web-based ToolBox approach to support adaptive forest management under climate change. *Scand. J. For. Res.* 29(Suppl. 1):96–107.

Rauscher, H.M., F.T. Lloyd, D.L. Loftis, and M.J. Twery. 2000. A practical decision-analysis process for forest ecosystem management. *Comput. Electron. Agri.* 27:195–226.

Reynolds, K.M., M. Twery, M.J. Lexer, H. Vacik, D. Ray, G. Shao, and J.G. Borges. 2008. Decision support systems in natural resource management. P. 499–534 in *Handbook on decision support systems 2*, Burstein, F. and C. Holsapple (eds.). International Handbooks on Information Systems Series, Springer, New York.

Ribeiro, R.P., J.G. Borges, and V. Oliveira. 2004. A framework for data quality for Mediterranean sustainable ecosystem management. *Ann. For. Sci.* 61:557–568.

Rico, M., and A. González. 2015. Social participation into regional forest planning attending to multifunctional objectives. *For. Policy Econ.* 59:27–34.

Saaty, T.L. 1990. *The analytic hierarchy process: Planning, priority setting, resource allocation*, 2nd ed. RWS Publications, Pittsburgh. PA. 287 p.

Sottomayor, M., A. Mendes, M. Ribeiro, P.O. Carvalho, J.G. Borges, and J. Garcia-Gonzalo. 2014a. *Integral project WP3.2 scenario process report, Chamusca case study, Southern Portugal*. 48 p. Available at http://www.integral-project.eu/images/Documents/Publications/Deliverables/CaseStudyReports/Case%20Study%20Reports_Portugal.pdf (p. 2–47); last accessed Oct. 21, 2016.

Sottomayor, M., A. Mendes, M. Ribeiro, P.O. Carvalho, J.G. Borges, and J. Garcia-Gonzalo. 2014b. *Integral project WP3.2 scenario process report, Vale do Sousa case study, Southern Portugal*. 44 p. Available at http://www.integral-project.eu/images/Documents/Publications/Deliverables/CaseStudyReports/Case%20Study%20Reports_Portugal.pdf (p. 90–134); last accessed Oct. 21, 2016.

Tóth, S.F., and M.E. McDill. 2009. Finding efficient harvest schedules under three conflicting objectives. *For. Sci.* 55:117–131.

Tóth, S.F., M.E. McDill, and S. Rebain, S. 2006. Finding the efficient frontier of a bi-criteria, spatially explicit, harvest scheduling problem. *For. Sci.* 52:93–107.