forests

Review

Operational Research Techniques Used for Addressing Biodiversity Objectives into Forest Management: An Overview

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Abstract: The integration of biodiversity into forest management has traditionally been a challenge for many researchers and practitioners. In this paper, we have provided a survey of forest management papers that use different Operations Research (OR) methods in order to integrate biodiversity objectives into their planning models. One hundred and seventy-nine references appearing in the ISI Web of Science database in the last 30 years have been categorized and evaluated according to different attributes like model components, forest management elements, or biodiversity issues. The results show that many OR methods have been applied to deal with this challenging objective. Thus, up to 18 OR techniques, divided into four large groups, which have been employed in four or more articles, have been identified. However, it has been observed how the evolution of these papers in time apparently tended to increase only until 2008. Finally, two clear trends in this set of papers should be highlighted: the incorporation of spatial analysis tools into these operational research models and, second, the setting up of hybrid models, which combine different techniques to solve this type of problem.

Keywords: forest management; operational research; multi-criteria decision making; biodiversity; strategic planning

1. Introduction

Forest management objectives have undoubtedly evolved during the last decades and new criteria associated with goods and services with no market price (e.g., biodiversity conservation) have been incorporated. However, in some classic studies on forest management, biodiversity conservation was not included as a forest planning objective. Thus, it is not surprising to find that only one objective associated with biodiversity aspects, i.e., hunting (game preserve) [1], whereas this objective is not even explicitly mentioned in others [2]. However, as shown in some reference books, this new good is currently considered in the analysis [3–5].

The gradual incorporation of these new objectives (biodiversity, sustainability, watershed protection, etc.) has increased the complexity of forest management since, according to some authors, the spatial component should be included in the forest plans [6]. In synthesis, a situation in which the time component was the leading decision of forest management from a strategic point of view (when to cut) has changed to another in which it is not so important when or how much should be cut, but where and how the final cuts are done.

In this paper, we have used the classic concepts of strategic, tactical, and operational planning [7,8]. In short, leaving aside the links and conflicts between these levels [9,10], and the differences between countries, strategic planning involves long-term goals, is highly aggregated [11], and often includes other forecasts of different economic, ecological, and social outcomes [12]. Tactical planning focuses on medium-term or medium-scale goals [7] and on the areas or trees to be harvested [13]. Operational planning states when and how the operations are performed [14]. The use of Operations Research (OR) techniques in these planning levels has frequently been described for several decades [12,15,16].

Thus, although the inclusion of an objective related to biodiversity conservation may justify an increase in the length of the rotation [17], once biodiversity conservation aims are included, tactical decisions gain more relevance. However, this change involving the incorporation of spatial restrictions has triggered a search for more sophisticated analysis tools than those initially used in forest management (linear programming), as we will show in the next sections.

Furthermore, the importance of biodiversity conservation has led to certain critical decisions in forest management, which has been modified in some aspects. For instance, similar to the changes in the rotation length [18], some silvicultural models have been proposed that avoid clearcuttings. These models suggest leaving some trees in order to mitigate the impact of cuttings on biodiversity [19,20] or even the use of systems like Continuous Cover Forestry (CCF), which favors the creation of mixed stands and is widely accepted for biodiversity management [21].

In keeping with the above comments, it should be added that numerous techniques based on OR have been applied in an attempt to develop acceptable forest plans from a biodiversity perspective. These techniques have been used at different spatial scales, under diverse silvicultural treatments, and with multiple objectives. However, to our knowledge, no previous review has been made to date, although it is true that there has been a proliferation of different surveys related to the integration of biodiversity and some aspects of forest management in the past few years, especially in recognizing the interactions between the spatial relationships and scales. One of these approaches was focused on the application of Geographical Information Systems (GIS) in forest management when biodiversity is incorporated as an objective [22]. Furthermore, there is a review of studies using optimization tools to integrate spatial variables into forest management [23]. Unlike this current study, the bibliographic references are grouped into four categories according to the type of problem, but without taking into account the optimization technique used. Another study which should be mentioned is a review where the publications using OR techniques in North America on forest management issues up to 2001 are given [24]. On the other hand, some aspects related to forest planning at a spatial scale appear, with an emphasis on various objectives, among which biodiversity is found [13,25]. Also, different techniques (planning tools) to solve biodiversity conservation problems can be founded in the scientific literature [26]. A more recent work analyzes the application of different OR techniques to aspects related to the biodiversity in five particular cases, one of them being forest exploitation [27]. Finally, some reviews on the use of Multiple Criteria Decision Making (MCDM) techniques in forest management include references related to their application in problems in which biodiversity is an objective [28,29].

The main aim of this study is to critically compile and assess papers which tackle issues related to the integration of biodiversity into forest management when using techniques based on OR, as well as analyzing the technique employed in each case. We have differentiated these papers in two classes: case studies and methodological papers with illustrative examples. As secondary objectives, we examined aspects related to planning and the spatial scale used, or attributes associated with silviculture, like the stand structure or the biodiversity indices employed. Also, for some of these attributes, it was aimed to analyze their evolution over time throughout the set of articles selected.

It is not an objective of this study to justify which OR method would be the best one for a particular forest management topic including objectives related to biodiversity conservation. Selecting the appropriate analysis tool for a particular issue is a difficult decision, as many authors have confirmed, both when talking about multi-criteria decision theories [30] and metaheuristic techniques [31]. To sum up, as it was stated: "There is no method that is universally best or even applicable for all situations." [5]

2. Material

To compile the papers included in this review, first, it should be noted that no articles present in non-Journal Citation Reports (JCR) journals and books or book chapters have been considered in this survey. These papers have been located mainly in a series of searches made in ISI Web of Science and SCOPUS databases including the following fields: biodiversity + forest management + optimization; biodiversity + conservation + optimization + forest; biodiversity + conservation + multi-criteria + forest; biodiversity + forest + multicriteria; AHP (Analytic Hierarchical Process) + conservation + biodiversity + forest heuristics + conservation + biodiversity + forest; simulated annealing + conservation + biodiversity + forest; multiobjective + conservation + biodiversity + forest; linear programming + conservation + biodiversity + forest; integer programming + conservation + biodiversity + forest.

In a second phase, a special search was made by only including the names of the principal OR techniques, which are described in a later section, together with the expression "forest management", and hence selecting possible studies not included previously. Discarding some surveys, an initial collection of 512 papers in all was taken, 179 of which were finally considered (up to 15 of which were from September 2015).

Once the papers were selected, the following step was to define a set of fields covered by all the articles analyzed. Firstly, the OR techniques employed, the objective functions, and the main constraints considered were analyzed. Similarly, for each case, the temporal (strategic or long-term, tactical or medium-term) and/or spatial (ecosystem, forest, or stand) planning level used was computed. The typology of the objective function (net present value, biodiversity, timber volume, and others) and some constraints (related to timber production or biodiversity) were studied. In addition, the number of different animal species present in the analysis, as well as the biodiversity indices included in these articles, has been recorded. According to the silviculture employed, diverse aspects related to the typology of the cuttings (final or intermediate ones), the use of systems like Green Tree Retention (GTR,) or the reserve selection destined for protection has been considered. The stand age structure (even or uneven) in each case study has also been analyzed. As a complement, in accordance with this growing concern about biodiversity conservation, the presence of protection figures in the various case studies has been recorded. Finally, we have analyzed whether the papers included in our database were mainly case studies, directed towards solving real forest planning problems, or papers with a methodological orientation, but which included a case study as an illustrative example.

Biodiversity as a concept can be very broad in scope and difficult to pin down [32]. Thus, it was necessary to define what attributes were presented in the articles considered in this study. In principle, the review was restricted to papers considering conservation objectives mainly related to wildlife and natural vegetation, excluding those articles related to hunting or fishing activities. However, we have not considered studies related to the following issues: biodiversity related to the water courses, wildfires, prescribed burning, pesticide or fertilizer treatments, and pest management.

3. OR Techniques

In order to provide a self-contained exposition of the methodologies, in the next paragraphs, we have included some concise comments explaining the basic ideas underlying the four large groups in which we have arranged the OR techniques mostly used in the papers reviewed. In Appendix A, featured at the end of this paper, brief explanations of the several approaches contain their key sources so that readers can go deeper into these methods, and some examples of applications of each method in forest management problems are given.

3.1. Classic Optimization Techniques

Beginning with the classic optimization techniques, Linear Programming (LP) is one of the most widely used techniques under which operations research has been developed. This technique is frequently used in forest management, especially for strategic forest planning problems, and notably for timber harvest scheduling. Given its importance, many forest management books have devoted chapters to explaining this technique [3,17]. Curiously, although the most widely extended algorithm (simplex method) for its resolution was proposed by Dantzig in 1947, a similar version had been presented in 1939 by the Nobel Prize winner Kantorovich in a work related to the forestry context: the reorganization of the timber industry in the former Soviet Union [33]. Other related problems are the presentation of non-linear objective functions and/or constraints, which led to the use of Non-linear Programming (NLP). Unlike LP and NLP, on other occasions, problems involving discrete (integer) decision variables are included in these models, with the integer variables mostly used being the binary ones. When the problem involves several interrelated decisions, linear programming may not be the most efficient solution method. Instead, Dynamic Programming (DP) provides an efficient procedure to solve this kind of problem. In contradiction with linear programming, no generalized dynamic programming formulation exists. A DP structure is usually formulated to represent a particular problem.

3.2. Metaheuristics Methods

Sometimes it has been difficult to solve different optimization problems, thus from the 1980s onwards some iterative procedures have been developed. These are sometimes named intelligent searches, the so-called Heuristics (H), although later they were denominated Metaheuristics (MH), following the definition provided by the author who coined this term [34]. Under these names different techniques have been encompassed and they are frequently applied in problems associated with forest management [5,6,35–37], but do not ensure the attainment of a global solution. In fact, some of them are those most commonly appearing in the detailed search in the previous section, as shown in Appendix A. Thus, one of the most popular ones is Simulated Annealing (SA), while other metaheuristics techniques often applied to forest management problems are Tabu Search (TS), Genetic Algorithms (GA), and a Heuristic optimization method developed for tactical forest planning (HERO).

3.3. Multiple-Criteria Decision-Making Approaches

The main Multi-Criteria Decision Making methods (MCDM) are used when the Decision Maker (DM) is faced with problems in which several criteria show a degree of conflict between each other. These MCDM methods have initially been assembled into two broad groups according to whether the problem is of a continuous or discrete type, although this does not mean that some methods habitually employed for continuous problems cannot be applied when a selection between a finite set of solutions has to be made. Some reviews of the application of these techniques to solve diverse forest management problems are considered [28,29,38,39]. The techniques analyzed and briefly explained in Appendix A are: Multi-Objective Programming (MOP), Goal Programming (GP), Compromise Programming (CP), Multi-Attribute Utility Theory (MAUT), with Simple Additive Weighting Method (SAW), Analytic Hierarchical Process (AHP), ELECTRE (Elimination and Choice Expressing Reality), and PROMETHEE (Preference Ranking Organization Method for Enrichment Evaluations) to be used when the problems are of a discrete nature. Furthermore, it should be noted that, on many occasions, there are hybrid methods which combine not only various MCDM methodologies but also techniques like MH ones with MCDMs [40]. In a recent review on applications of MCDM techniques to forest management [39], it was coined the term “hybrid approaches” to integrate an MCDM technique and other decision making ones.

3.4. Other Techniques

It should be made clear that, up until now, a deterministic environment had been assumed when defining the different methods mentioned above, although some of the heuristics ones like SA or GAs may have non-deterministic steps. However, there are many applications in which the random or uncertain future is considered, including stochastic techniques. On the other hand, sometimes these OR techniques have been used to aggregate individual preferences (e.g., stakeholders’ preferences in a forest management context). These aggregations belong to the group decision-making (GDM) techniques (also known as social choice methods or participatory decision-making methods), which do not exclusively use OR methods, although there are many examples where, for instance, MCDM and GDM methods have been merged [41,42].

4. Results

Table 1 shows, quantitatively, the number of papers which have used the different techniques previously introduced. These techniques have been divided into four large groups: classic optimization, heuristics, MCDM, and other techniques. Given that in one paper various methodologies may have been used (this occurs in 36.9% of the cases), the sum of all the papers employing each methodology obviously exceeds the number of papers considered (179). The whole list of papers appears in Supplementary Materials.

Table 1. Frequency of applied Operations Research Techniques.

Operations Research Techniques	Number of Papers
Optimization	73
Linear programming	19
Integer linear programming	22
Mixed integer programming	16
Non-linear programming	7
Dynamic programming	9
Heuristics	92
Simulated annealing	32
Tabu search	11
Genetic algorithms	12
HERO	8
Other heuristics	23
no specified	6
MCDM Techniques	101
Multiobjective programming	11
Goal programming	14
Compromise programming	4
AHP/ANP	20
MAUT	20
Outranking Methods	6
Simple additive weighting method	5
Other MCDM Techniques	21
Other Techniques	39
Group Decision Making	24
Non-Deterministic	15
Number of papers considered	179

HERO, Heuristic optimization method; AHP, Analytic Hierarchical Process; ANP, Analytic Network Process; MAUT, Multi-Attribute Utility Theory; MCDM, Multi-Criteria Decision Making.

The temporal evolution of these publications is shown in Figure 1. It can be seen how the prolific years correspond to the decade 2000–2010 (123 papers), in which both heuristics and multi-criteria techniques have been very often applied. The applications using classic optimization techniques keep up a relatively stable trend throughout the time, with the most abundant ones occurring before and after the aforementioned decade.

Table 2 shows the characteristics of those papers when addressing the composition of their objective function and their constraints, indicating which are the most common constraints in forest management problems included in our database. The average number of objectives included in the case study is 2.3%, and 57.5% of the papers include constraints associated with timber production, whereas 84% include those related to biodiversity conservation. On average, the case studies included 2 to 3 (2.3) different objectives with 57.5% and 84% of the papers including constraints associated with timber production and biodiversity conservation, respectively. Among the constraints associated with biodiversity conservation, the most frequent ones are those related to the proportion percentage of mature patches that ensure a minimum viable population of focal species, and adjacency constraints. These constraints prevent harvest in adjacent areas for one or several periods, preventing large harvesting areas [25]. Finally, we have included in this table the main OR techniques used when considering conservation as the objective function in the papers analyzed. In analyzing the papers where this objective function appeared, MCDM methodologies were the most numerous OR group.

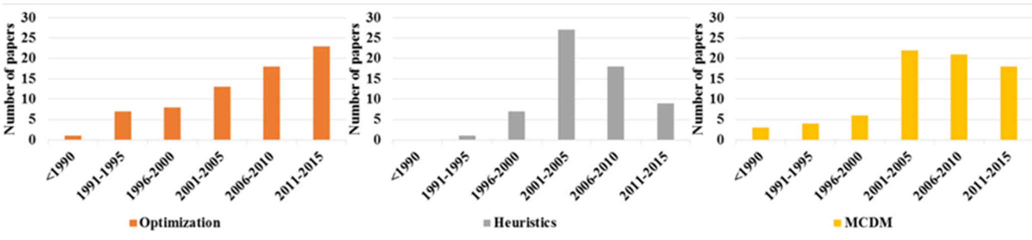

Figure 1. Temporal evolution of the Operations Research techniques included in the papers analyzed.

Table 2. Components of Operations Research models.

OR Model Components	% of Papers Where OR Models Are Included
Number of objectives (mean)	2.3
Objective function	
Net Present Value	39.1%
Biodiversity	69.8%
Optimization	20.3%
Heuristics	27.0%
MCDM	41.9%
GDM	10.8%
Timber volume	17.9%
Other	20.1%
Exogenous constraints	
Timber production	57.5%
Normal forest	24.6%
Volume	31.3%
Rotation age	30.7%
Area harvested	22.9%
Biodiversity conservation	83.8%
Mature forest (%)	48.0%
Dead wood, CWD	7.3%
Minimum viable population	33.5%
Minimum edge effect	11.2%
Adjacency	27.9%
Connectivity	11.7%
Other constraints	
Cost	53.6%
Social issues	3.9%

CWD, Coarse Woody Debris.

Table 3 displays some aspects related to the forest management applied in these papers. It can be seen how a strategic type of planning has been more commonly carried out than a tactical one, although in a reduced number of studies both scales have been approached—in most cases due to the addition of spatial considerations.

Table 3. Forest management issues.

Forest Management Issues	% of Papers Where Are Included
Temporal scale	
Strategic	61.5%
Tactical [1]	38.5%
Spatial scale	
Ecosystem	77.6%
Forest	19.1%
Stand	3.3%
Silvicultural practices	
Green Tree Retention [2]	41.9%
No Silvicultural treatment [3]	17.9%
Clearcutting	32.4%
Shelterwood	3.4%
Thinnings	19%
Other	24%
Forest structure	
Even-aged	33.0%
Uneven-aged	4.5%

[1] Considers tactical planning and those papers that employ both scales; [2] Or mature patch retention; [3] Referring to reserve superficies with no cutting treatment.

As shown in Figure 2, concerning the temporal evolution in approaching this type of forest management problem, a strategic temporal scale rather than a tactical one has been most frequently employed.

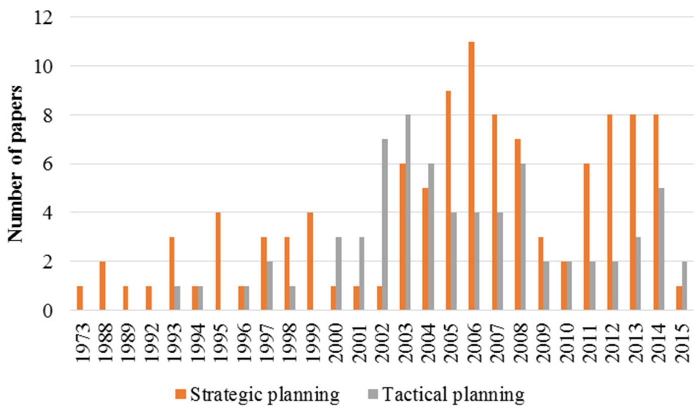

Figure 2. Temporal evolution of the temporal scale of forest management.

On the one hand, at a spatial level, ecosystem analyses are in a majority compared to other more disaggregated forms. With regard to the silviculture practiced in these cases, a notable number of papers apply silvicultural practices associated with the presence of areas with no final cuttings, although clearcutting is performed in almost one third of the studies. On the other hand, a limited number of papers indicate the structure of the forest stand in each case study, and only a few correspond to uneven-aged structures.

Table 4 shows the use of different groups of OR techniques in specific case studies, encompassing a total of 54.7% of the papers reviewed, and 45.3% of the papers describing methodological approaches. Furthermore, the percentage of papers using hybrid methods has been included. This percentage is defined as the use of two or more OR techniques included in the different groups shown in Table 1.

Table 4. Forest management issues.

	Case Study	Methodological Sample
Optimization	33.7%	43.2%
Heuristics	33.7%	35.8%
MCDM Techniques	46.9%	11.1%
Group Decision Making	14.3%	12.3%
Non-Deterministic	11.2%	2.5%
Hybrid Methods [1]	34.7%	34.6%
Total	54.7%	45.3%

[1] Combination of more than one method belonging to the different OR techniques defined above.

Going on to analyze how biodiversity has been introduced into these types of papers, Table 5 shows how more than half of them have tackled problems related to wildlife. In some cases, several indices have been used to define it, although this has not been a generalized trend in all the studies.

Table 5. Biodiversity issues.

Biodiversity Issues	% of Papers Where Biodiversity Issues Are Included
Biodiversity species analysed	
Wildlife	50.8%
Flora	10.6%
Both (wildlife and flora)	6.1%
Generic diversity	32.4%
Biodiversity indexes used	
Habitat (suitability and/or effectiveness index)	12.3%
Species richness	8.4%
Vulnerability and human impact	2.2%
Configuration (Shape and proximity)	5.6%
Connectivity and fragmentation	2.2%
Other	6.7%
Case study in Protected Areas	
National Park	4.4%
Other protected Areas	14.8%

5. Discussion

In this study, we have shown that the integration of biodiversity conservation objectives into forest management with the help of tools proceeding from OR has constituted a fruitful work area during the past few years. However, although we have previously said that the justification of choosing an OR method to address biodiversity was not an objective of this work, before discussing the results, it is necessary to emphasize the fact that none of the studies analyzed explain the benefits and drawbacks of all OR techniques shown here. The reasons provided for using a given OR method are always inadequate and partial, depending in some cases on the quality of the information available [5], not allowing one to extract reliable conclusions regarding the utilization of these methodologies.

Following the division into large blocks made in this study, which does not coincide with that reported in other studies [25], it was observed how papers employing multi-criteria decision and MH techniques predominated over classic optimization ones. However, following Table 1, the most common methodology is a metaheuristic (SA) one. These results are quite different from another one, which analyzed optimization in forestry using 85 papers published since 2010 [12]. Their results show how heuristics are the techniques most used at the stand level, with some optimization techniques (MIP and LP) also used at the forest and landscape level. As for the temporal evolution of these papers, it was seen that there has been an apparently increasing trend in the whole period considered up to 2008, followed by an abrupt drop from which it has recovered in recent years. That trend up to 2008 coincides with what has been noted in other similar reviews [29].

When analyzing our results, it is seen that no OR technique was used more than others for solving these type of problems. As observed in Table 1, none of the techniques were applied in more than 20% of the studies analyzed. This dispersion in the use of different methodologies may indicate that this is an open problem in which various approaches are entirely compatible. This conclusion was observed in a recent study [9], in which a set of open forest management problems where OR techniques had been applied were included, and some of them were precisely directly related to biodiversity conservation.

Regarding the temporal scale of forest planning, and following the results shown in Table 3 and Figure 2, strategic planning clearly predominated, although the tactical and strategic levels were merged in some papers. It is hard to obtain conclusions from these results for several reasons: how biodiversity is considered in each case study, how strategic and tactical planning has been defined, the different spatial component of each problem, and the integration of strategic and tactical planning, that is not necessarily univocal [7,43]. It should be pointed out that operational planning has not been included as it was only approached directly or indirectly in 5 of the 179 studies. Similarly, at a spatial level, the ecosystem component apparently prevails, and the most frequent silvicultural practice is the one that includes aspects close to GTR. Finally, the forest structure predominating in the papers analyzed was even-aged systems. This circumstance is surprising because, traditionally, it has been considered that more complex structures (multiaged stands) presented higher biodiversity levels [44]. However, it is worth noting that less than 40% of the studies analyzed have detailed the structure type of the stand ages in their respective case studies. Actually, these more complex structures are more difficult to model, and they have therefore been investigated to a lesser extent [17].

The consideration of objectives not presenting a market price, and which need a greater knowledge applied of disciplines like ecology, offers, from an economic perspective, a more significative challenge. However, nowadays, forest management has assumed the idea that it is necessary to integrate timber production and biodiversity conservation into the areas where cuttings are produced [45]. All this has led to a duality within forest management between production and conservation objectives, with different tools being applied to integrate both objectives, and with different relationships (positive or negative) between each other [46]. Thus, although some authors suggest that the cost of applying certain measures in order to favor biodiversity can be estimated [3], other papers introduce economic concepts like the Production Possibility Frontier (PPF) to tackle problems in forest management which include, among others, those associated with timber production and biodiversity conservation [47,48]. It is widely known that the combination of a production objective and a conservation purpose that are located in this curve are, at least, efficient (i.e., that conservation objectives are fulfilled at a lower cost) [49]. However, and independently from the objectives of each study analyzed, what does come out of the previous results (Table 2) is that the production-conservation duality has been taken into account in numerous studies mentioned here. Indeed, there were a notable number of papers in which objectives measured private profitability from the production of different forest outputs, or that included elements of an economic nature in the constraints of the models used.

One aspect to be considered is the gradual incorporation of spatial results which accompanied the solutions provided by the different operations research methods collected in this study. Approximately half of the studies analyzed already explicitly incorporated GIS data and/or used software fully integrated into GIS. Obviously, GIS produces displays of geographic information for analysis, but does not ensure a spatial approach to biodiversity. However, in our study, all the papers dealing with connectivity and fragmentation, and forest mature patches have used a GIS. The integration of spatial aspects with several OR methods using GIS could be feasible [25], and it has been already mentioned as being a beneficial research line for years [11]. Finally, some authors suggest an interest in integration in the future, mainly referring to the merging of MCDM techniques with GIS [39].

Since the biodiversity concept is very broad, and throughout this paper it has been included under different objective functions and constraints, it might be useful to see how these aspects have been considered in various geographical regions and countries. Thus, we have selected some results corresponding to the seven most represented countries in our database: United States, Finland, Sweden, Canada, Portugal, Australia, and Germany (see Appendix B). These countries constitute more than 78% of the papers. This Table shows some differences between the countries relative to the use of strategic and tactical planning, the use of mono-criteria or MCDM techniques, the objectives and constraints, and also the silvicultural practices specified in the models.

It is interesting to note that some techniques (SA, AHP, MAUT) are clearly associated with a few of the countries, while in others their application is much lower. Also, comparing these figures with others obtained at the forest and stand level, their results are quite different in the geographical distribution and the OR technique used in each of the 85 papers analyzed [12]. However, it should be noted (Tables 2 and 5, and Appendix B) that some key elements in the management of biodiversity issues using spatial requirements like connectivity or adjacency are not any of the topics most addressed with OR techniques in this context. This can also be said about the use of biodiversity indicators in these optimization models, even when they provide interesting results [50,51]. These issues could be lines of further research.

If we raise the issue as to what direction biodiversity modeling could go within forest management using these OR tools, one clear trend is that of employing more sophisticated models which hybridize diverse techniques. For some authors, this increase in model complexity is due to the introduction of biology principles in biodiversity conservation problems [26]. This circumstance has been verified in the papers analyzed here since around 35% of the articles already include more than one different OR technique (Table 4). Thus, the hybridization of methods could improve decision-making in comparison with the use of a single technique [39].

In this sense, some aspects are gradually being introduced into forest management incorporating this set of techniques. One of them is the inclusion of stakeholders' preferences in relation to problems associated with biodiversity conservation through group decision methods [52]. In fact, most of the few studies that have used these techniques when incorporating biodiversity conservation into forest management have been published in the last few years. An example of another field in vogue is in the solving of these problems under non-deterministic environments, as mentioned in some papers [53] and having shown an increased tendency to appear in the last decades [54]. Other methodologies that, a priori, could be addressed to integrate biodiversity would be the Decision Support Systems (DSS). However, in the papers analyzed this methodology is still of a minor importance (it only appears in 7 of the 179 papers). This fact had already been pointed out in reviews dealing with the implementation of DSS in forest management [55].

Although, as discussed above, there is not a clearly predominant OR technique for addressing biodiversity conservation problems in forest management, when partitioning our database some clear trends appear (besides the importance of the hybrid methods). These methods have been developed in spatial forest planning issues [25]. On the other hand, what should be highlighted is the wider use of MCDM techniques when the problem includes an objective function related to biodiversity conservation (41.9% of the papers, see Table 2), especially in countries like Finland (Appendix B). This latter trend appears again in Table 4, in which the use of MCDM techniques in studies with the aim of solving a given real-life planning problem reaches 46.9%. This finding suggests that, as some authors indicate, many biodiversity management problems have more than one dimension [56], so MCDM techniques fit very well. Furthermore, Table 4 clearly shows how the use of non-deterministic techniques is practically concentrated in those papers associated with case studies.

6. Conclusions

The analysis of the integration of biodiversity into forest management using OR tools has demonstrated which techniques are preferred for solving a specific problem. This has been characterized by the techniques and groups of techniques employed, the components (objective functions and constraints) of those OR models, of the different scales (temporal, spatial), and of the silvicultural and management aspects. Likewise, the biodiversity issues most frequently dealt with in these types of problems have been detailed.

Regarding the methodologies used to integrate biodiversity objectives into forest management plans using OR techniques, our results show how MCDM techniques and MH predominated over classic optimization ones. Additionally, the most frequent MCDM methodologies are the techniques applied to discrete problems (AHP, MAUT, etc.), while SA is the metaheuristic one most often used. However, it has been verified that the use of certain techniques has been concentrated in some countries in which scientific production on this topic has been more prolific, probably due to the fact that the selection of a certain technique is directly related to the abilities and experiences of the authors. Finally, from the point of view of forest management, these optimization models have been designed for different silvicultural scenarios, although GTR and clearcutting predominate, especially in even-aged stands.

As for the cases analyzed, the aspects related to biodiversity using OR techniques have been approached mainly at more aggregated spatial scales (ecosystem level) in different problems associated with wildlife, and in forest systems which do not have to be subjected to protection figures. However, it should be realized that this problem type is one of the cases analyzed, and that, unlike other objectives, biodiversity consideration as a criterion in forest management can be defined or introduced into the model in different ways.

The same as for other ecosystem services which do not correspond to productive aspects, there is a great diversity in the optimization techniques employed for the integration of aspects related to biodiversity in forest management, and no universal and valid combination for all the cases analyzed has been found. However, forest managers, when confronting these problems, and once the temporal and spatial scales of the model to be developed have been fixed, should first ask themselves which OR technique fits their approach best. For this purpose, they should define its nature (i.e., mono- or multicriteria), as well as whether they need to integrate the opinions of the different stakeholders and use a DSS to carry this out. By answering these questions the next step is obtained towards designing a model which permits them to solve the problem being tackled with only one item lacking: the consideration of a deterministic or stochastic environment. With the latter, there will be occasions when conceptually simpler models can be justified, and on others in which it will be necessary to hybridize different methodologies in order to solve certain types of problems in an adequate manner. Throughout this work numerous examples have been cited which can serve as an aid in this respect.

Supplementary Materials: The following are available online at www.mdpi.com/1999-4907/7/10/229/s1.

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Appendix A

A.1. Classic Optimization Techniques

Despite its multiple applications in a forest context, the use of LP has been decreasing in the past few years as the awareness of problem complexity has increased, and, thus, more complex models are needed. Moreover, LP does not allow for the input of spatial variables. Furthermore, other new techniques and algorithms have allowed a relaxation of the starting-off hypotheses associated with this method. On the other hand, it should be pointed out that there are notable differences between

LP and NLP problems. Basically, the computational algorithms of non-linear programming involve an iterative scheme to solve the problem, often characterized as search algorithms.

Discrete optimization problems can be classified as integer programming (IP), Mixed Integer Linear Programming (MILP), and Mixed Integer Nonlinear Programming (MINLP) [57]. It is of interest to emphasize that there are many important forest management problems that can be formulated as integer programming problems, such as spatial considerations in harvest scheduling problems, including adjacency constraints [6,58] or the shortest road network for the harvesting of some stands [17]. A commonly used solution method for solving IP and MILP problems is the branch-and-bound method. Potentially, it involves solving a large number of (related) linear programming problems in its search for an optimal integer solution [59]. In MILP problems, the objective function and constraints are linear, and some of the decision variables are integers while others are continuous. Finally, one example of the application of this technique in wildlife habitat problems under different forest practices can be highlighted [60], while another one explains the advantages of Integer Linear Programming (ILP) methods in some conservation planning problems [61].

In contradiction with linear programming, no generalized dynamic programming formulation exists. A DP structure is usually formulated to represent a particular problem. Dynamic programming is a method used to solve sizeable, difficult problems by splitting them into smaller subproblems that are both easier to solve and yield the same optimal solution as the original problem [62]. This methodology has been applied to classic forest management issues, such as the optimal rotation period, timber harvest scheduling or the optimization of the intensity of several silvicultural practices like thinning [6,63].

A.2. Metaheuristics Methods

Given the large variety of methods available, only the essential characteristics of the four MH techniques mostly used in forest management [64] will be commented on. One of the most popular is Simulated Annealing (SA). This is an iterative algorithm capable of escaping from local optima that is mainly applied to discrete optimization problems. The algorithm compares the values of two solutions for each iteration. Improving solutions and a fraction of inferior solutions are accepted as a strategy for avoiding poor local optima [65], but, by definition, this iterative improvement terminates in a local optimum, which is a solution with a cost at least as good as all of its neighbors [66]. This technique has numerous applications for typical forest management problems, such as harvest scheduling [67,68].

Tabu Search (TS) is a metaheuristic technique that guides a local heuristic search procedure to explore the solution space beyond local optimality, starting from a random initial solution [69]. It incorporates an adaptive memory and responsive exploration. The adaptive memory feature of TS enables the implementation of procedures that are capable of searching the solution space economically and efficiently using tabu lists. These lists memorize recent moves and control the process, prohibiting the repetition of some of them. In the same way as other MH methodologies, TS methods can be used to generate hybrid methodologies with other MH and OR methods. Various applications of this technique to forest management problems can also be found in the literature [70,71].

GAs are based on obtaining a set of possible solutions to a given problem starting from some initial solutions, using operators inspired by natural genetic variation and natural selection [72]. Sometimes, a useful equivalence of GAs and forest management terminologies are shown [5], and other studies deal with the fundamental concepts of this technique and its application to a forest management problem in Portugal [73]. Finally, another MH method is the one known as HERO, basically developed for tactical planning problems [74] and usually associated with an objective maximizing an additive utility function.

A.3. Multiple-Criteria Decision-Making Approaches

Beginning with the techniques applied to continuous problems, the solutions to the latter should be Pareto-optimum, also known as efficient, non-inferior or non-dominated, solutions [75].

A Pareto-solution is a feasible solution for which an increase in the value of one objective only can be achieved if another objective decreases its value. The first technique to be highlighted is Multi-Objective Programming (MOP). MOP deals with optimization problems with two or more objective functions (see [76] for further developments). There are clear differences between LP and MOP. In addition to its number of objective functions, MOP involves two search spaces: decision variable space and criterion space. MOP finds Pareto-optimum (or non-dominated) solutions among an initial set of solutions. Finally, on some occasions, MOP models contain integer variables, so it is called multi-objective integer programming (MOIP) [77].

The next methodology, Goal Programming (GP), can be viewed as a generalization of LP, but it is often cited as a satisficing-based technique. The word "satisficing" describes the behavior of the DM whose purpose is to reach a set of targets [78]. Within a GP context, a target has been established that represents a desirable level of achievement for each of the criteria considered. After defining unwanted deviations between the target values and the actual figures achieved by the respective criteria, GP puts together these unwanted variables in an achievement function, which must be minimized. There are several variants of this technique [79,80] and primary texts for the correct application of this method [81]. This methodology is the one mostly used in forest management when we are facing problems of this nature, due to its flexibility and versatility characteristics [82]. A binary goal programming models have been used in forest management issues related to habitat diversity [83,84].

Compromise Programming (CP) defines the ideal point as a vector whose components are given by the optimum values of the criteria considered. The ideal point is obviously unfeasible, and it is only used as a reference point. Within CP, the "most suitable" or "best-compromise" solution is defined as the efficient solution closest to the ideal point [85]. By using different distance measures (metrics), a set of compromise solutions can be established as being the "most suitable solutions" [75,86].

In many decision issues, the alternatives chosen can influence multiple attributes. One of these alternatives can be selected depending on how well it scores on each attribute and its relative importance. Multi-Attribute Utility Theory (MAUT) quantifies the relative attractiveness of these multi-attribute alternatives [87], and this utility function involves the decision maker's preferences. If several conditions are satisfied, this multi-attribute utility function can be decomposed into smaller parts. Thus, the evaluations of the alternatives are performed, in terms of utility, for each criterion, and the results (utility scores) are then aggregated (for example, with a weighted sum or addition) [88]. Readers interested in going deeper into this technique may consult [89].

Going on to briefly describe the MCDM methods used when the problems are of a discrete nature, it should be noted that the most intuitive and simplest, and the one widely used in forest management problems [90], is the Simple Additive Weighting Method (SAW). This method consists of selecting the alternative which supplies the highest value of the objective function. This value is obtained by summing up the products of the performance of each criterion and alternative for the value of a constant reflecting the weights of each of the criterion. It is very often hybridized with MAUT [5].

However, the multi-criteria method mostly used, at least in a forest environment [29], has been the Analytic Hierarchical Process (AHP). This method was based on the breaking down of a problem hierarchically [91]. In a subsequent step its different elements (criterion, alternatives) are compared two by two, thus obtaining some individual weights using a certain scale which, by means of an aggregation through the hierarchy mentioned above, permits a ranking of the alternatives initially considered to be obtained. This method was later extended until the so-called Analytical Network Process (ANP) [92] was configured. Worth mentioning in a forestry context is a reference, in which there are various applications of this technique [93], either by itself or hybridized with other multi-criteria methodologies, or the study in which different discrete MCDM methods, including AHP, are reviewed [38].

Other MCDM methods applied in discrete problems are those based on the comparison of alternatives using outranking relationships. These MCDM methods are known as Outranking methods and the two most generally used are ELECTRE (Elimination and Choice Expressing Reality) and PROMETHEE (Preference Ranking Organization Method for Enrichment Evaluations) (see [88,94] for further developments). Besides, some authors have used both techniques in a forest management problem [95].

Furthermore, it should be noted that, on many occasions, there are hybrid methods which combine not only various MCDM methodologies but also techniques like MH ones and MCDMs [40]. Another example of these types of synergies consists of the merging of MCDM methods and fuzzy number properties to give rise to Fuzzy Multi-Criteria Programming (FMCP) methods. The latter are employed to introduce both imprecisions in the available information and uncertainty situations into the analysis. Finally, some authors have compiled several examples of hybridized fuzzy models with other MCDM techniques previously described [96].

A.4. Other Techniques

Also, and related to non-deterministic techniques, an extensive review of papers in which aspects regarding risk and uncertainty in forest management should be highlighted [53]. Some of the latter have incorporated objectives related to biodiversity. This current work, in a section called "non-deterministic", has assembled the studies presenting a stochastic component, Monte Carlo simulation models, and those using FMCP. Finally, it should be noted a review of GDM in forest management [97], and two examples in which GDM and MCDM are used in forest management problems when biodiversity is an objective [52,98].

Appendix B

Table B1. Geographical distribution of some biodiversity aspects.

	USA	FIN	SWE	CAN	PRT	AUS	DEU
Number of papers	61	28	14	12	10	9	6
OR Technique (%)							
Mono-criteria	68.3	31.0	73.3	91.7	80.0	80.0	50.0
LP	9.8	3.6	21.4	0.0	11.1	12.5	16.7
ILP	14.8	10.7	7.1	0.0	11.1	37.5	0.0
SA	14.8	17.9	42.9	41.7	22.2	12.5	0.0
Multi-criteria	31.8	69.0	26.7	8.3	20.0	20.0	50.0
AHP/ANP	4.9	25.0	7.1	0.0	0.0	0.0	0.0
MAUT	3.3	46.4	7.1	0.0	0.0	0.0	33.3
GDM	8.2	21.4	0.0	0.0	0.0	25.0	16.7
Objective Function (%)							
NPV	19.6	11.8	48.0	21.1	35.7	9.5	23.1
Biodiversity	54.3	67.1	44.0	52.6	42.9	71.4	61.5
Constraints (%)							
Dead wood	0.0	13.0	8.1	3.0	0.0	0.0	14.3
Adjacency	13.7	8.7	18.9	15.2	19.2	10.0	0.0
Connectivity	4.3	8.7	0.0	6.1	11.5	5.0	7.1
Temporal scale (%)							
Strategic	65.6	71.4	42.9	33.3	60.0	66.7	83.3
Tactical [1]	34.4	28.6	57.1	66.7	40.0	33.3	16.7
Silvicultural practices (%)							
GTR [2]	29.3	29.6	35.3	37.5	30.0	28.6	16.7
Reserves [3]	14.7	13.6	5.9	12.5	10.0	42.9	8.3
Clearcutting	22.7	25.0	29.4	6.3	40.0	14.3	16.7
Shelterwood	2.7	0.0	0.0	0.0	0.0	0,00	16.7

[1] Considers tactical planning and those papers that employ both scales; [2] Green-Tree Retention or forest mature patches; [3] No forest-cutting treatment; USA, United States of America; FIN, Finland; SWE, Sweden; CAN, Canada; PRT, Portugal; AUS, Australia; DEU, Deutschland.

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