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Review

Taxonomy for the optimization in forest management: a review and assessment

Orman amenajmanında optimizasyon için taksonomi: derleme ve değerlendirme

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ABSTRACT

In this review, we have developed a new taxonomic framework for the classification of forest management optimization studies. In the proposed taxonomy, we consider: the study type; model structure; methodology; modeling type; problem objectives, level and type; plan type; and forest structure. We have used the proposed taxonomy to classify 111 articles from the literature, providing a comprehensive overview of optimization approaches in forest management. Based on this classification, we suggest that some developments may be underrepresented in the forest management optimization literature. Accordingly, the most studied is deterministic modelling regarding harvest scheduling and the least studied are fuzzy and stochastic modeling regarding risk and uncertainty.

Keywords: Forest management, optimization, taxonomy, review

ÖZ

Bu derlemede, orman amenajmanında optimizasyon çalışmalarının sınıflandırılması için yeni bir taksonomi geliştirilmiştir. Önerilen sınıflandırmada: çalışma şekli; model yapısı; yöntem; modelleme tipi; problem amaçları, seviyesi ve tipi; plan tipi ve orman kuruluşu dikkate alınmıştır. Orman amenajmanında optimizasyon yaklaşımlarına kapsamlı bir genel bakış sunarak, literatürdeki 111 makaleyi sınıflandırmak için önerilen taksonomiyi kullanılmıştır. Bu sınıflandırmaya göre, orman amenajmanında optimizasyon literatüründeki bazı gelişmeler yeterince temsil edilemeyebilir. Buna göre, kesim düzeni oluşturmaya ilişkin en çok çalışılan deterministik modelleme ve en az çalışılan, risk ve belirsizlik ile ilgili bulanık ve stokastik modelleme çalışmalarıdır.

Anahtar Kelimeler: Orman amenajmanı, optimizasyon, taksonomi, derleme, kesim düzeni

INTRODUCTION

As the population grows, the demand for both timber and non-timber use of forest resources is increasing (Farrell et al., 2000). The harvesting of timber and non-timber forest products involves the assessment of many criteria such as the intangible and tangible values of ecosystem services (Uhde et al., 2015). Forest management plans have been developed to handle the contradictions between the goods and services demanded by society, and in particular to regulate the time and place of forestry activities (Bettinger et al., 2015). Forest policy allows for trade offs between ecological, socio-economic and political processes and values (Gregory and Keeney, 1994). Therefore, forest planning decisions are often characterized by complexity, irrevocability, and uncertainty. A large part of this complexity is due to the multi-use nature of forest products and services, to the difficulty in the monetary appreciation of ecological services, and to the participation of a large number of beneficiaries (Ananda and Herath, 2003).

In the 1960s, the complexity of social demands increased, and foresters faced many difficulties as they sought to integrate the conflicting demands into planning (Vacik and Lexer, 2014). As the complexity of decisions increases, it becomes more difficult for decision makers to determine a

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management plan that optimizes all decision criteria. Planning should be considered in a framework that minimizes disputes by taking into account the many political, economic, environmental and social dimensions. Therefore, analytical methods are required that examine a multi-perspective approach and provisions (Ananda and Herath, 2009). As a result of this, interest in decision support systems in forestry has been increasing since the 1980s (Vacik and Lexer, 2014).

The planning of forest resources includes various problems which need to be considered simultaneously during the decision-making process. These problems can be gathered under three main headings (Diaz-Balteiro and Romero, 2008):

1- Economic problems (timber, feed, animal, hunting, etc.)
2- Ecological problems (soil erosion, carbon accumulation, protection of biodiversity, etc.)
3- Social problems (recreation, level of employment, population arrangement, etc.)

Decision-making plays an important role at almost every stage of these planning problems. Quantitative and qualitative methods are used during the decision-making process. These methods are necessary to help land managers and landowners make the right choices when faced with many alternatives. The results of planning processes help to direct the activities of land managers and to ensure that land managers and landowners understand how to implement the strategies which optimize predetermined performance measures (Bettinger et al., 2010).

1. Study type
1.1. Application with hypothetical data
1.2. Application with real data
1.3. Review
2. Model structure
2.1. Deterministic
2.2. Stochastic
2.3. Fuzzy
2.4. Based on information technology
3. Methodology
3.1. Exact method
3.2. Heuristics
3.3. Metaheuristics
3.4. Approximation algorithm
3.5. Simulation
4. Modelling type
4.1. Linear programming
4.2. Mixed integer linear programming
4.3. Mixed integer non-linear programming
4.4. Goal programming
4.5. Stochastic programming
4.6. Integer linear programming
4.7. Non-linear programming
4.8. Dynamic programming
4.9. Fuzzy programming
4.10. Other
5. Problem objectives
5.1. Number of objectives
5.1.1. Single objective
5.1.2 Multi-objective
5.2. Financial objectives
5.1.1. Maximization of net present value
5.1.2. Minimization of costs
5.1.3. Maximization of land expectation value
5.1.4. Maximization of total utility or benefit
5.1.5. Maximization of net revenue
5.1.6. Maximization of income
5.1.7. Maximization of profit
5.1.8. Maximization of discounted revenue
5.1.9. Maximization of value-at-risk
5.1.10. Other
5.3. Non-financial objectives
5.3.1. Maximization or minimization of ecosystem services
5.3.2. Maximization of production (cork, harvest value…)
5.3.3. Maximization of carbon stocks/ sequestration
5.3.4. Maximization of the number of species or population
5.3.5. Minimization of the deviations from predefined goals
5.3.6. Other
6. Problem level
6.1. Tree level
6.2. Stand level
6.3. Forest level
6.4. Landscape level
7. Problem type
7.1. Harvest scheduling
7.2. Extended harvest scheduling
7.3. Risk
7.4. Uncertainty
7.5. Optimal rotation
7.6. Land use optimization (optimal site selection)
7.7. Non-wood forest product harvest
7.8. Optimal thinning
7.9. Adaptive forest management
7.10. Supply chain management
7.11. Forest residue harvesting
7.12. Regeneration model
7.13. Selecting of harvest tree or tree species mix
7.14. Restoration
8. Plan type
8.1. Strategic plan
8.2. Tactic plan
8.3. Operational plan
9. Forest structure
9.1. Even aged
9.2. Uneven aged
9.3. Plantation
9.4. Coppice
9.5. Forest + other land use
9.6. Any aged

Figure 1. Taxonomy of forest management optimization literature

In the forest industry, optimization models have been utilized for many years to solve planning problems (Rönnqvist, 2003, Weintraub and Romero, 2006). Optimization approaches in forest planning are often used to develop the optimal harvest scheduling that will best accomplish the objectives of landowners or land managers (Kaya et al., 2016). But with the increase of types of forest planning problems, optimization has become important not only for harvest scheduling problems, which are the most typical problems in forest planning, but also for other ecological and social problems. Economic, ecological and social objectives in forestry are considered as multiple objectives by using optimization methods (Chen et al., 2016). However, the usage of simulation and optimization in forest management practices is still not widespread in the world (Jin et al., 2016).

In this study, a literature review is carried out with the aim of revealing current trends and gaps in forest management optimization literature. For this purpose, a taxonomic framework, which is used to classify the forest management optimization literature, is proposed and the reviewed studies are examined in detail. With this classification, the aim is to make several inferences about the recent forest management optimization literature and to determine the potential research areas for further studies.

The rest of this paper is organized as follows. The next section gives a detailed explanation of a proposed taxonomy for forest management optimization. The subsequent section presents findings derived from a taxonomic review of recently published articles. Finally, the last section summaries our conclusions.

MATERIALS AND METHODS

A Taxonomy for Optimization in Forest Management

In this study, a taxonomic framework is proposed to classify and analyze optimization studies in forest management. The proposed framework is presented in Figure 1. We consider the main categories to be the study type; model structure; methodology; modeling type; problem objectives, level and type; plan type; and forest structure. In the first category, the study types are classified as application with hypothetical data, application with real data, or review. Since no theoretical papers were found within the scope of this study, "theory" is not added as a particular sub-category.

In the second category, articles are investigated with respect to their model structure, namely deterministic, stochastic, fuzzy, and based on information technology. The last sub-category, based on information technology, includes studies carried out with information technology to realize a reliable forest plan without giving any numerical results of the models. The technology includes software packages such as HYDRUS (Garcia-Prats et al., 2016), BIOME-BGC (Gonzalez-Sanchis et al., 2015), GUROBİ (Vopenka et al., 2015), AFM ToolBox (Rammer et al., 2014), logilab (Mansuy et al., 2015), ETÇAP (Baskent et al., 2014).

The third category, the methodologies used for optimization, is divided into five sub-categories, namely exact methods, heuristics, metaheuristics, approximation algorithms, and simulation. The techniques which guarantee an optimal solution for an optimization problem are classified as exact algorithms, such as branch and bound algorithm, Dijkstra algorithm, etc. Although heuristics and metaheuristics do not guarantee optimal solutions, several efficient techniques have been proposed to find sufficiently good results in a reasonable computational time. However, they do not give any information about the quality of the obtained solutions. Contrary to heuristics and metaheuristics, approximation algorithms investigate an approximate solution which is guaranteed to be within some factor of the optimum. Sample average approximation is one of the most widely used approximation algorithms applied to stochastic programming problems.

The fourth category is reserved for modelling type, and includes eleven sub-categories: linear programming, mixed integer linear programming, mixed integer non-linear programming, goal programming, stochastic programming, integer linear programming, non-linear programming, dynamic programming, fuzzy programming, and other types. (The sub-category "other" is added to classify the models which are not used as widely as the aforementioned models in the literature) .

The aim of forest planning is to obtain an optimal decision which has the best value performance measure under various constraints (Robinson et al., 2016). Although in many countries of the world forest management plans have typically focused on production and economic concerns for a long time, there is also an increasing awareness of the ecological functions of forests, such as wildlife, biological diversity, recreation, and water regulation (Dong et al., 2015). As a result of this awareness, new developments are needed in forest planning and it can be seen that the non-economic objectives of forests have begun to be studied in recent times as well as their economic functions. Therefore, in this study, objectives of forest optimization studies constitute the fifth category of the proposed taxonomy and have been divided into three sub-categories: the number of objectives, financial objectives, and non-financial objectives. In general, the number of objectives can be classified as either single objective or multi-objective. The most widely used financial and non-financial objectives in forest management optimization studies are seen in Figure 1. "Other" is added under both the financial and non-financial objectives sub-categories in order to satisfy the comprehensiveness of the proposed taxonomic framework.

The sixth category, problem level, is included using the classification scheme proposed by Kaya et al. (2016). It is divided into four sub-categories: tree level, stand level, forest level, and landscape level. Problems including decisions like "cut or not cut", "how to separate tree trunk according to product types", and "determination of the minimum time required to reach predetermined dimensions (diameter+height) that increase the ability to withstand the effects of fire" are classified as tree level (Kaya et al., 2016). Tree level optimization requires the determination of trees to be removed while the value of the remaining trees is expected to increase (Vauhkonen and Pukkala, 2016). It is not always economically possible to abide by the general rules, which stipulate the cutting down of mainly low-value trees. Moreover, it is claimed that cutting only high-quality trees will reduce the stagnation of the genetic pool (Nolet et al., 2014). Stand level optimization includes problems such as the determination of rotation periods according to the desire of each stand (for even-aged forests), spacing problems (even-aged, uneven-aged), and the planning of stand density (frequency) (Kaya et al., 2016). Forest level optimization problems include area control, volume control and/or minimum cutting. Area control includes area restriction model (ARM) or unit restriction model (URM) (Kaya et al., 2016). The landscape level optimization problems also include other land uses such as forest, pasture, farmland, cropland and plantation.

The seventh category, problem type, is the extension of the classification scheme proposed by Diaz-Balteiro and Romero (2008). The most typical problem in forest management is the harvest schedule problem. These are typical problems which include the ARM, URM and Green-up restriction constraints, which are commonly used in planning. The second sub-category, extended harvest scheduling problems, includes road maintenance, habitat patch, silvicultural operation, biodiversity, tree marketing, charcoal production, water supply, reindeer corridor, fire, and sedimentation. The most typical uncertainties in forest planning are market uncertainties, natural variations in future growth and yields, and the effects of fires and pests (Martell et al., 1998). The growth model, inventory data, future prices of timber products, climate, fire, and spatial uncertainty are also common uncertainties. Adaptive forest management (AFM) performs forest planning taking into account environmental factors, such as water supply, climate change, etc. by means of artificial regulation of forest structure and density.

The eighth category includes the plan type. Since the planning horizon is generally long-term in forest management, planning is typically done in a structure divided into three planning stages (Kong and Ronnqvist, 2014, Kuhlmann et al., 2015). Firstly, the long-term (strategic) forest management model is drawn up, in which the time and place of the cutting activity is decided. Secondly, the volumes of different types of wood to be produced (logs, firewood, etc.) for a medium-term period are decided. Finally, the planner works on logistical and harvest planning at the tactical level (Kong and Ronnqvist, 2014, Kuhlmann et al., 2015). The planning horizon is considered to be 10 years for strategic (long-term) planning, from 2 to 10 years for tactical planning, and up to 1 year for operational planning (Pasalodos-Tato et al., 2013, Nobre et al., 2016). Therefore, in this review, planning horizon is considered in three sub-categories, at the strategic, tactical, and operational levels.

In forestry terminology, the age of a tree refers to the age-class distribution of a forest. According to this age-class distribution, the forest structure is divided into two main sub-categories, even-aged and uneven-aged forest. Although plantation and coppice forests are even-aged forests, since different established forms are obtained by planting and coppicing, these forests were added as sub-categories in this review. "Forest + other land use" is the plan formed by considering other land uses such as pasture, farmland, cropland, and plantation, along with forest planning. The any-aged management system does not bring with it any requirements on the sequences of post-cutting diameter distributions (Pukkala et. al., 2014). Therefore, this system differs from the even-aged or uneven-aged management systems.

Classification of the Literature

The "Web of Science" (https://webofknowledge.com) database was used to search for articles classified in this study. The words "optimization" and "forest management" were entered into the "Title/Keywords/Abstract" field options. Three hundred and forty ninearticles were identified without considering unlimited time. Then, the publication year of the studies was limited to between 2013 and 2016. A total of 127 articles published within this period were accessed on 27.01.2017. Furthermore, an additional search was performed with the keywords "optimization" and "forest planning", and 47 articles were found on 03.15.2017. Twenty-two of these articles overlapped with the articles located by the previous review. A total of 152 articles were accessed on 03.15.2017. However, 35 of these were related to issues such as forest genetics, stand density, growth and yield model, wildlife habitats, forest roads, afforestation, soil and biomass, which do not deal directly with forest planning. Therefore, these 35 papers were not taken into account in this paper. Moreover, 6 papers were not included in the classification because their full texts were not available, they were written in a language other than English, or they were conference papers. As a result, 111 papers about forest management optimization were classified using the proposed taxonomic framework given in Figure 1. The investigated articles for the taxonomic review are listed in Figures 2a-d. The abstracts of the articles were primarily evaluated during this classification. However, articles were examined in detail when the required information was not achieved from the abstracts.

Table 1. Number and percentage of papers published between 2013 and 2016 for each journal

Source Titles	# articles	Percentage
CANADIAN JOURNAL OF FOREST RESEARCH	14	12.6
FOREST SCIENCE	9	8.1
SCANDINAVIAN JOURNAL OF FOREST RESEARCH	8	7.2
FOREST POLICY AND ECONOMICS	8	7.2
ANNALS OF OPERATIONS RESEARCH	7	6.3
SILVA FENNICA	5	4.5
FORESTS	5	4.5
EUROPEAN JOURNAL OF FOREST RESEARCH	5	4.5
FOREST ECOLOGY AND MANAGEMENT	4	3.6
FOREST SYSTEMS	3	2.7
EUROPEAN JOURNAL OF OPERATIONAL RESEARCH	3	2.7
ECOLOGICAL MODELLING	3	2.7
COMPUTERS AND ELECTRONICS IN AGRICULTURE	3	2.7
JOURNAL OF FORESTRY RESEARCH	2	1.8
JOURNAL OF FOREST ECONOMICS	2	1.8
JOURNAL OF ENVIRONMENTAL MANAGEMENT	2	1.8
FORESTRY	2	1.8
ENVIRONMENTAL MANAGEMENT	2	1.8
CERNE	2	1.8

RESULTS AND DISCUSSION

Hundred and two of these 111 papers are research articles while 9 of them are reviews (Figure 3). These literature review studies describe the development of forestry and its basic concepts. Pasalodos-Tato et al. (2013) investigated the risks and uncertainties in different forestry matters including forest management. Hujala et al. (2013) evaluated 32 research articles published between the years 2002 and 2011, according to computerized techniques for problem structuring in forest planning. Chen et al. (2016) reviewed 101 articles published between the years 1994 and 2016 which consist of articles on economic and ecological trade-offs for sustainable forest systems. Memmah et al. (2015) presented a review of 50 articles applying metaheuristics for land use optimization. Uhde et al. (2015) focused on hybrid multi-criteria decision-making approaches in forest management problems that demand analytic assessments as well as the consideration of multiple ecosystem services. Myllyviita et al. (2014) evaluated the benefits of hybrid approaches in actual case studies of natural resource management. Segura (Segura et al., 2014) focused on the models and methods that have been used in developing decision support systems (DSS) for forest management problems, and problems were assessed based on temporal scale, spatial context, spatial scale, number of objectives, and stakeholders. Kaya et al. (2016) reviewed forest management optimization articles published by 30 international journals between 2001 and 2015. They classified 85 articles according to the journal title, publication date, optimization method, problem level (tree, stand, forest, landscape), objectives and constraints. In the present study, a taxonomic framework, which is more comprehensive than the ones in previous review studies, is proposed. This taxonomic review is the first systematic study which allows the literature to be analyzed from a variety of aspects.

Although the numbers of papers published in 2014 and 2015 were the same, there was an increasing trend between 2013 and 2016 (Figure 4). It can also be said that approximately 32% of the forest management optimization studies have been carried out during the last 4 years (between 2013 and 2016).

Figure 5 shows the distribution of the publications by countries. Countries have been identified by looking at the_institutional affiliation of the authors. The authors from the same country are counted once. It is observed that Finland (27) and the USA (26) published the highest number of papers between 2013 and 2016 in 34 countries (Figure 5). Table 1 shows the number of papers for each journal where at least two articles have been published. It can be inferred that more than 30.6% of the articles have been published by the top three journals in the list.

Papers	1.	1.1.	1.2.	1.3.	2.	2.1.	2.2.	2.3.	2.4.	3.	3.1.	3.2.	3.3.	3.4.	3.5.	4.	4.1.	4.2.	4.3.	4.4.	4.5.	4.6.	4.7.	4.8.	4.9.	4.10.	5.	5.1.	5.1.1.	5.1.2.	5.2.	5.2.1.	5.2.2.	5.2.3.	5.2.4.	5.2.5.	5.2.6.	5.2.7.	5.2.8.	5.2.9.	5.2.10.
(Ager et al., 2016)			X			X						X			X							X							X												
(Bagdon et al., 2016)			X			X									X					X									X												
(Belavenutti et al., 2016)			X			X																X							X				X								
(Bilbao-Terol et al., 2016)			X					X												X										X											
(Borges et al., 2016)			X			X									X			X											X			X									
(Bugalho et al., 2016)			X			X																				X				X											
(Chen et al., 2016)				X																																					
(Corrigan and Nieuwenhuis, 2016)			X			X											X												X												
(Eyvindson and Kangas, 2016a)			X				X							X							X								X												
(Eyvindson and Cheng, 2016)			X				X								X						X								X												X
(Eyvindson and Kangas, 2016b)			X				X								X						X								X								X				X
(Ezquerro et al., 2016)				X																																					
(Ferreira et al., 2016)			X				X				X													X					X					X							
(Feuerbacher et al., 2016)			X			X									X			X											X				X								
(Garcia-Prats et al., 2016)			X						X																				X			X									
(Hartl et al., 2016)			X				X								X								X						X												X
(Jin et al., 2016b)			X			X						X			X														X						X						
(Matthies and Valsta, 2016)			X			X					X													X					X												X
(Nakajima et al., 2016)			X			X							X		X														X			X									
(Ochoa et al., 2016)			X			X									X														X												X
(Palma and Vergara, 2016)			X			X											X													X			X								X
(Pasalodos-Tato et al., 2016)			X				X					X			X								X						X					X							
(Peura et al., 2016)			X			X									X															X		X									
(Robinson et al., 2016)			X			X									X		X									X			X												
(Rode et al., 2016)			X			X											X												X			X									
(Roessiger et al., 2016)			X			X																	X						X			X									
(Ruppert et al., 2016)			X			X						X														X			X												
(St John et al., 2016)			X			X												X											X			X									
(Tahvonen and Ramo, 2016)			X			X													X										X			X									
(Tang et al., 2016)			X			X									X														X												
(Augustynczik et al., 2016)			X			X							X													X			X			X									
(Pascual et al., 2016)			X			X							X		X														X												
(Garcia-Gonzalo et al., 2016)			X				X																						X			X									
(Jin et al., 2016a)		X				X						X	X																X												
(Kaspar et al., 2016)		X				X					X											X							X												
(Dragicevic et al., 2016)			X				X								X											X				X				X							
(Yoshimoto and Konoshima, 2016)		X				X												X											X												
(Dong et al., 2016)			X			X							X																X												
(Vauhkonen and Pukkala, 2016)			X				X								X											X			X												X
(Bettinger et al., 2015)			X			X							X							X										X											
(Bettinger and Tang, 2015)			X			X						X							X										X												
(Borges et al., 2015)			X			X												X											X			X									
(Dems et al., 2015)			X			X												X											X									X			
(Dong et al., 2015)			X			X							X																X			X									
(Ferreira et al., 2015)			X			X												X											X							X					
(Gautam et al., 2015)			X			X												X											X									X			
(Gonzalez-Sanchis et al., 2015)			X						X						X														X												
(Kuhlmann et al., 2015)			X				X								X											X			X												X
(Mansuy et al., 2015)			X						X		X																		X												X
(Marusak et al., 2015)			X			X					X											X								X											
(Memmah et al., 2015)				X																																					
(Nghiem, 2015)			X			X																				X			X										X		
(Palma et al., 2015)			X			X									X					X									X												
(Pereira et al., 2015)			X			X									X														X			X									
(Repo et al., 2015)		X				X																	X						X												X
(Ronnqvist et al., 2015)				X																																					

Figure 2a. Classifications of the forest management optimization studies

Review studies constitute 8.1% of articles reviewed in this study, while the rest are classified as research papers. 80.2% of the research papers used real data, 4.5% used hypothetical data, and 7.2% used both real and hypothetical data. Figure 6 shows the model structure of research papers. 68.6% of the surveyed research studies include deterministic models. They are followed in descending order by stochastic models (24.5%), models based on information technologies (5.9%), and fuzzy models (1.0%). Fuzzy logic helps the decision makers to model the vagueness and ambiguousness in a problem. Forest planning is a decision issue that utilizes the qualitative judgements and opinions of decision makers as well as quantitative metrics. The ratio of fuzzy models used in the forest management optimization literature shows us that there is a significant lack of fuzzy models to represent decision makers' and/or stakeholders' qualitative opinions.

Papers	5.3.	5.3.1.	5.3.2.	5.3.3.	5.3.4.	5.3.5.	5.3.6.	6.	6.1.	6.2.	6.3.	6.4.
(Ager et al., 2016)							X					X
(Bagdon et al., 2016)						X				X	X	
(Belavenutti et al., 2016)											X	
(Bilbao-Terol et al., 2016)							X					X
(Borges et al., 2016)											X	
(Bugalho et al., 2016)		X										X
(Chen et al., 2016)												
(Corrigan and Nieuwenhuis, 2016)		X										X
(Eyvindson and Kangas, 2016a)			X								X	
(Eyvindson and Cheng, 2016)											X	
(Eyvindson and Kangas, 2016b)											X	
(Ezquerro et al., 2016)												
(Ferreira et al., 2016)										X		
(Feuerbacher et al., 2016)											X	
(Garcia-Prats et al., 2016)												
(Hartl et al., 2016)										X		
(Jin et al., 2016b)												X
(Matthies and Valsta, 2016)										X		
(Nakajima et al., 2016)										X	X	
(Ochoa et al., 2016)												X
(Palma and Vergara, 2016)									X			
(Pasalodos-Tato et al., 2016)										X		
(Peura et al., 2016)			X									X
(Robinson et al., 2016)			X							X	X	
(Rode et al., 2016)											X	
(Roessiger et al., 2016)										X		
(Ruppert et al., 2016)							X			X		
(St John et al., 2016)											X	
(Tahvonen and Ramo, 2016)										X		
(Tang et al., 2016)							X			X		
(Augustynczik et al., 2016)											X	
(Pascual et al., 2016)							X			X		
(Garcia-Gonzalo et al., 2016)											X	
(Jin et al., 2016a)							X				X	
(Kaspar et al., 2016)			X								X	
(Dragicevic et al., 2016)			X	X						X		
(Yoshimoto and Konoshima, 2016)			X								X	
(Dong et al., 2016)						X					X	
(Vauhkonen and Pukkala, 2016)									X	X		
(Bettinger et al., 2015)						X					X	
(Bettinger and Tang, 2015)							X		X			
(Borges et al., 2015)											X	
(Dems et al., 2015)											X	
(Dong et al., 2015)											X	
(Ferreira et al., 2015)										X		X
(Gautam et al., 2015)											X	
(Gonzalez-Sanchis et al., 2015)							X				X	
(Kuhlmann et al., 2015)											X	
(Mansuy et al., 2015)											X	
(Marusak et al., 2015)			X			X					X	
(Memmah et al., 2015)												
(Nghiem, 2015)										X		
(Palma et al., 2015)			X							X		
(Pereira et al., 2015)										X		
(Repo et al., 2015)										X		
(Ronnqvist et al., 2015)												

Papers	7.	7.1.	7.2.	7.3.	7.4.	7.5.	7.6.	7.7.	7.8.	7.9.	7.10.	7.11.	7.12.	7.13.	7.14.
(Ager et al., 2016)															X
(Bagdon et al., 2016)			X												
(Belavenutti et al., 2016)			X												
(Bilbao-Terol et al., 2016)			X												
(Borges et al., 2016)		X													
(Bugalho et al., 2016)							X								
(Chen et al., 2016)															
(Corrigan and Nieuwenhuis, 2016)							X								
(Eyvindson and Kangas, 2016a)		X		X	X										
(Eyvindson and Cheng, 2016)		X		X	X										
(Eyvindson and Kangas, 2016b)		X		X	X										
(Ezquerro et al., 2016)															
(Ferreira et al., 2016)		X		X	X										
(Feuerbacher et al., 2016)			X												
(Garcia-Prats et al., 2016)			X												
(Hartl et al., 2016)			X	X											
(Jin et al., 2016b)		X													
(Matthies and Valsta, 2016)						X			X						
(Nakajima et al., 2016)		X													
(Ochoa et al., 2016)							X								
(Palma and Vergara, 2016)		X													
(Pasalodos-Tato et al., 2016)		X						X							
(Peura et al., 2016)		X						X							
(Robinson et al., 2016)		X		X	X										
(Rode et al., 2016)		X													
(Roessiger et al., 2016)		X													
(Ruppert et al., 2016)			X												
(St John et al., 2016)			X												
(Tahvonen and Ramo, 2016)		X				X			X						
(Tang et al., 2016)			X						X						
(Augustynczik et al., 2016)		X													
(Pascual et al., 2016)		X													
(Garcia-Gonzalo et al., 2016)		X			X										
(Jin et al., 2016a)		X													
(Kaspar et al., 2016)		X													
(Dragicevic et al., 2016)				X										X	
(Yoshimoto and Konoshima, 2016)		X													
(Dong et al., 2016)		X													
(Vauhkonen and Pukkala, 2016)				X	X				X						
(Bettinger et al., 2015)		X													
(Bettinger and Tang, 2015)														X	
(Borges et al., 2015)		X													
(Dems et al., 2015)											X				
(Dong et al., 2015)		X													
(Ferreira et al., 2015)		X		X											
(Gautam et al., 2015)											X				
(Gonzalez-Sanchis et al., 2015)										X					
(Kuhlmann et al., 2015)			X		X										
(Mansuy et al., 2015)				X	X						X	X			
(Marusak et al., 2015)		X													
(Memmah et al., 2015)															
(Nghiem, 2015)			X			X									
(Palma et al., 2015)										X					
(Pereira et al., 2015)		X						X							
(Repo et al., 2015)												X			
(Ronnqvist et al., 2015)															

Papers	8.	8.1.	8.2.	8.3.	9.	9.1.	9.2.	9.3.	9.4.	9.5.	9.6.
(Ager et al., 2016)	5		X			X					
(Bagdon et al., 2016)	45	X				X					
(Belavenutti et al., 2016)	5		X					X			
(Bilbao-Terol et al., 2016)	35	X								X	
(Borges et al., 2016)	50	X				X					
(Bugalho et al., 2016)						X					
(Chen et al., 2016)											
(Corrigan and Nieuwenhuis, 2016)	70	X				X					
(Eyvindson and Kangas, 2016a)	30	X				X					
(Eyvindson and Cheng, 2016)	30	X				X					
(Eyvindson and Kangas, 2016b)	30	X				X					
(Ezquerro et al., 2016)											
(Ferreira et al., 2016)	65	X							X		
(Feuerbacher et al., 2016)	15	X				X	X				
(Garcia-Prats et al., 2016)											
(Hartl et al., 2016)	100	X				X	X				
(Jin et al., 2016b)	60	X				X	X				
(Matthies and Valsta, 2016)	60	X				X					
(Nakajima et al., 2016)	200	X						X			
(Ochoa et al., 2016)	20	X								X	
(Palma and Vergara, 2016)	1			X							
(Pasalodos-Tato et al., 2016)	17	X				X					
(Peura et al., 2016)	50	X				X					
(Robinson et al., 2016)	20	X				X	X				
(Rode et al., 2016)	18	X						X			
(Roessiger et al., 2016)	100	X					X				
(Ruppert et al., 2016)	100	X				X					
(St John et al., 2016)	50	X				X					
(Tahvonen and Ramo, 2016)	140	X				X	X				
(Tang et al., 2016)	1			X				X			
(Augustynczik et al., 2016)	16	X						X			
(Pascual et al., 2016)	30	X				X	X				
(Garcia-Gonzalo et al., 2016)		X						X			
(Jin et al., 2016a)	30	X				X					
(Kaspar et al., 2016)		X				X					
(Dragicevic et al., 2016)											
(Yoshimoto and Konoshima, 2016)	10pe.	X				X					
(Dong et al., 2016)			X			X					
(Vauhkonen and Pukkala, 2016)	5		X			X	X				
(Bettinger et al., 2015)	30	X				X					
(Bettinger and Tang, 2015)	100	X					X				
(Borges et al., 2015)	50	X				X					
(Dems et al., 2015)	1			X		X					
(Dong et al., 2015)	30	X				X					
(Ferreira et al., 2015)	40	X				X					
(Gautam et al., 2015)	1			X			X				
(Gonzalez-Sanchis et al., 2015)								X			
(Kuhlmann et al., 2015)		X									
(Mansuy et al., 2015)	10		X								
(Marusak et al., 2015)	100	X				X					
(Memmah et al., 2015)											
(Nghiem, 2015)	50	X						X			
(Palma et al., 2015)	90	X				X		X			
(Pereira et al., 2015)	100	X				X					
(Repo et al., 2015)	50	X				X					
(Ronnqvist et al., 2015)											

Figure 2b. Classifications of the forest management optimization studies

Since simulation is used to generate data for optimization models, simulation is the most used approach in the reviewed literature. 39 papers used simulation and the others can be listed as metaheuristics (16), heuristics (10), exact methods (8), and approximation algorithms (1) respectively. The simulators utilized in these studies are GAYA (Borges et al., 2016), SİMO (Eyvindson and Cheng, 2016), YAFO (Hartl et al., 2016), MELA (Lappi and Lempinen, 2014), and MOTTİ (Peura et al., 2016). Simulated annealing, genetic algorithms and the tabu search algorithm are the most widely applied metaheuristics in forest management optimization studies. Only a few papers encountered in the review use hybridizing algorithms to improve the computational performance and solution quality. Hybrid algorithms can be developed in further research.

Papers	1.	1.1.	1.2.	1.3.	2.	2.1.	2.2.	2.3.	2.4.	3.	3.1.	3.2.	3.3.	3.4.	3.5.	4.	4.1.	4.2.	4.3.	4.4.	4.5.	4.6.	4.7.	4.8.	4.9.	4.10.	5.	5.1.	5.1.1.	5.1.2.	5.2.	5.2.1.	5.2.2.	5.2.3.	5.2.4.	5.2.5.	5.2.6.	5.2.7.	5.2.8.	5.2.9.	5.2.10.
(Shahi and Pulkki, 2015)			X				X						X		X														X				X								
(Trivino et al., 2015)			X			X																				X				X		X									
(Uhde et al., 2015)				X																																					
(Vopenka et al., 2015)			X						X									X											X												
(Wei and Murray, 2015)			X			X												X												X					X						
(Xavier et al., 2015)			X				X																			X				X											X
(Zhou, 2015)		X					X																						X										X		
(Fotakis, 2015)			X				X						X																	X											
(Veliz et al., 2015)			X				X														X								X							X					
(Liu and Lin, 2015)		X					X						X		X														X												
(Alam et al., 2014)			X			X					X													X					X									X			
(Alvarez and Vera, 2014)			X				X				X						X							X					X						X						
(Baskent et al., 2014)			X						X								X												X												
(Bont et al., 2014)			X			X												X											X				X								
(Borges et al., 2014a)			X			X											X									X				X		X									X
(de-Miguel et al., 2014a)			X			X							X		X														X												
(de-Miguel et al., 2014b)			X			X						X											X						X					X							
(Eyvindson and Kangas, 2014)			X				X								X					X										X											X
(Hahn et al., 2014)		X	X				X																X						X			X								X	X
(Hartl and Knoke, 2014)		X					X								X								X						X			X								X	X
(Hernandez et al., 2014)			X			X							X										X							X		X									
(Kangas et al., 2014)			X			X							X				X													X							X				X
(Kong and Ronnqvist, 2014)			X			X						X						X											X			X									
(Manso et al., 2014)			X				X					X			X														X												
(Marshalek et al., 2014)			X			X									X			X											X												
(Monkkonen et al., 2014)			X			X																				X				X		X									X
(Mur et al., 2014)		X	X			X									X											X			X								X				
(Myllyviita et al., 2014)				X																																					
(Nolet et al., 2014)			X			X							X		X														X												
(Palma and Nelson, 2014)			X			X									X			X											X				X								
(Pukkala et al., 2014)			X			X									X														X			X									
(Rammer et al., 2014)			X						X									X											X												
(Segura et al., 2014)				X																																					
(Lappi and Lempinen, 2014)			X			X									X		X												X			X									
(Garcia-Gonzalo et al., 2014)			X				X					X			X														X			X									
(Borges et al., 2014b)		X					X						X		X														X			X									
(Konnyu et al., 2014)			X			X												X											X			X									
(Ager et al., 2013)			X			X									X														X												
(Baskent and Celik, 2013)			X			X									X		X												X												
(Burns et al., 2013)		X	X			X																X								X			X								
(Carvajal et al., 2013)			X			X																X							X			X									
(Cerda and Martin-Barroso, 2013)			X			X																				X			X										X		
(Gimenez et al., 2013)			X			X																								X		X									
(Hartl et al., 2013)			X			X									X								X						X			X								X	
(Konnyu and Toth, 2013)		X	X			X					X											X							X										X		
(Moreira et al., 2013)			X			X														X									X									X			
(Najafi and Richards, 2013)			X			X												X											X				X								
(Neuner et al., 2013)			X				X								X											X			X			X								X	X
(Niinimaki et al., 2013)			X			X																				X			X					X							
(Pasalodos-Tato et al., 2013)				X																																					
(Rabotyagov et al., 2013)			X			X																				X				X						X					
(Tahvonen et al., 2013)			X			X																							X			X									
(Hujala et al., 2013)				X																																					
(Toth et al., 2013)		X	X			X																X							X										X		
(Strimbu and Paun, 2013)			X				X						X																X												

Figure 2c. Classifications of the forest management optimization studies

The distribution of publications according to modeling type is given in Figure 7. As stated by Dong et al. (2015), it can be also inferred from our classification that integer variables are mostly preferred to model operations. Mixed integer linear programming (17) has mostly been used to formulate forest planning in the past four years. The models considering uncertainty have not been studied widely. Only 4 of the studies used stochastic programming, while none of them used fuzzy programming. Modeling the uncertainties in forest management could be a potential research area for further studies.

Problems with a single objective represent 81.4% of the total, the remaining problems include multi-objectives. Forestry planning concentrates on a single objective through timber harvest-

Papers	5.3.	5.3.1.	5.3.2.	5.3.3.	5.3.4.	5.3.5.	5.3.6.	6.	6.1.	6.2.	6.3.	6.4.	7.	7.1.	7.2.	7.3.	7.4.	7.5.	7.6.	7.7.	7.8.	7.9.	7.10.	7.11.	7.12.	7.13.	7.14.	8.	8.1.	8.2.	8.3.	9.	9.1.	9.2.	9.3.	9.4.	9.5.	9.6.
(Shahi and Pulkki, 2015)										X							X						X					1			X							
(Trivino et al., 2015)				X								X			X													50	X				X					
(Uhde et al., 2015)																																						
(Vopenka et al., 2015)			X								X			X														30	X				X					
(Wei and Murray, 2015)							X				X			X			X											1 pe.			X							
(Xavier et al., 2015)							X					X			X	X																					X	
(Zhou, 2015)										X				X		X	X																X					
(Fotakis, 2015)			X				X			X					X													50	X				X					
(Veliz et al., 2015)											X*				X		X											3		X			X					
(Liu and Lin, 2015)			X											X																								
(Alam et al., 2014)																							X					50w.			X							
(Alvarez and Vera, 2014)																	X						X					1			X							
(Baskent et al., 2014)			X							X				X														160	X				X					
(Bont et al., 2014)															X																X							
(Borges et al., 2014a)											X				X													50	X				X	X				
(de-Miguel et al., 2014a)			X									X								X									X				X	X				
(de-Miguel et al., 2014b)										X										X								150	X									
(Eyvindson and Kangas, 2014)											X			X			X											30	X				X					
(Hahn et al., 2014)														X		X	X											30	X				X					
(Hartl and Knoke, 2014)										X				X		X												30	X		X		X	X				
(Hernandez et al., 2014)				X			X				X				X													30	X						X			
(Kangas et al., 2014)										X				X														10	X	X			X					
(Kong and Ronnqvist, 2014)										X													X												X			
(Manso et al., 2014)							X		X	X					X										X													
(Marshalek et al., 2014)					X							X			X													8 pe.	X					X				
(Monkkonen et al., 2014)												X							X									50	X				X					
(Mur et al., 2014)									X																	X		200	X				X					
(Myllyviita et al., 2014)																																						
(Nolet et al., 2014)							X		X	X																X		40	X					X				
(Palma and Nelson, 2014)											X				X													9		X								
(Pukkala et al., 2014)										X				X														20	X					X				X
(Rammer et al., 2014)												X										X						100	X									
(Segura et al., 2014)																																						
(Lappi and Lempinen, 2014)										X	X			X														50	X				X					
(Garcia-Gonzalo et al., 2014)										X					X															X					X			
(Borges et al., 2014b)														X														100	X				X					
(Konnyu et al., 2014)											X				X													40	X				X					
(Ager et al., 2013)					X							X															X	10	X					X				
(Baskent and Celik, 2013)			X							X	X				X													120	X				X					
(Burns et al., 2013)					X		X			X									X																			
(Carvajal et al., 2013)											X				X													3 pe.	X									
(Cerda and Martin-Barroso, 2013)											X								X									100	X				X	X				
(Gimenez et al., 2013)			X	X						X					X													40	X						X			
(Hartl et al., 2013)											X			X		X	X											60	X				X					
(Konnyu and Toth, 2013)											X			X														60	X				X					
(Moreira et al., 2013)															X																				X			
(Najafi and Richards, 2013)															X															X								
(Neuner et al., 2013)											X						X									X			X				X					
(Niinimaki et al., 2013)										X								X			X								X				X					
(Pasalodos-Tato et al., 2013)																																						
(Rabotyagov et al., 2013)		X		X											X													45	X				X					
(Tahvonen et al., 2013)										X	X			X				X			X								X				X					
(Hujala et al., 2013)																																						
(Toth et al., 2013)											X			X														60	X				X					
(Strimbu and Paun, 2013)			X							X				X														100	X				X					

Figure 2d. Classifications of the forest management optimization studies

ing. However, society has various expectations from the forests. In other words, the variety of objectives expected from forest planning increases while the number of stakeholders increases. These ratios show us that there is a potential need for more research into multi-objective optimization, in which several objectives are optimized at the same time.

Generally, forest planning is done by maximizing an objective such as the net present value of a product (Robinson et al., 2016). Although social values have changed recently, forest management plans have focused on production and economic concerns for a long time in many countries (Dong et al., 2015). This situation is also verified by the findings of this review. 69.9%

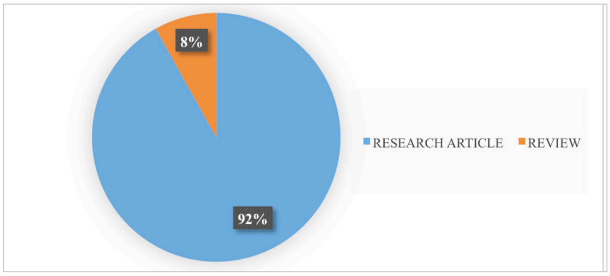

Figure 3. Study type

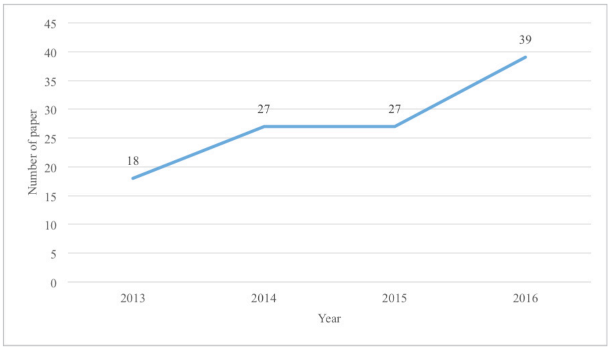

Figure 4. Number of paper by year (between 2013 and 2016)

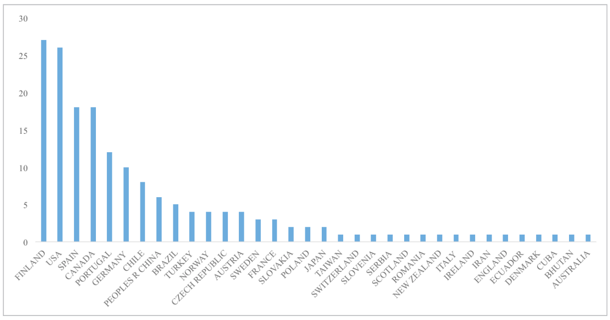

Figure 5. Number of articles with respect to countries

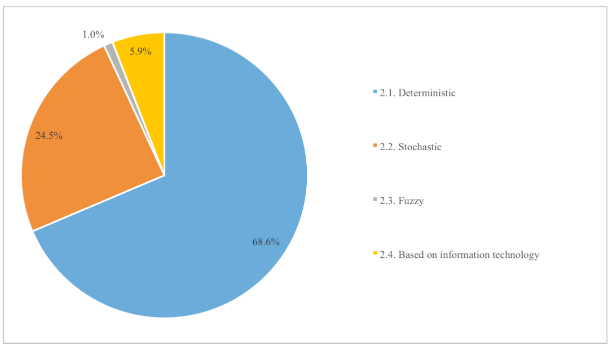

Figure 6. Distribution of models

of studies having single objective are financial and 30.1% are non-financial. 26.3% of multi-objective optimization studies have financial objectives, 26.3% have non-financial, and 47.4% have both financial and non-financial objectives. The most widely used financial objective is the maximization of the net present value (Figure 8). It is observed in this review that the non-financial objectives of forests have increasingly been studied recently as well as economic functions. As is shown in Figure 9, the most widely used non-financial performance measure is the production amount which cannot be seen as an ecological factor. Today, there is an increasing awareness of the ecological functions of forests (e.g. wildlife, biological diversity, recreation, and water regulation) (Dong et al., 2015). As a result of this awareness, new developments considering ecological concerns are needed in forest planning. Our findings show that, in addition to economic factors, objectives which are related to ecological factors should also be studied.

The problems dealt with in the investigated studies were mostly modeled at the forest level (42). This is followed by the stand level (38), the landscape level (15), and the tree level (6), respectively. In real life, new methods that would explore how forest sustainability – protecting water and wildlife, replanting trees, etc. – is ensured are studied at the landscape level. Therefore, further research should focus on the landscape level in terms of sustainability.

Figure 10 shows the number of papers according to the type of inspected problem. According to Borges et al. (2016) and Baskent et al. (2014), harvest scheduling is the most studied forest planning problem considering temporal and spatial constraints. We have seen that this result has not changed in the last four years. A majority of the papers (65.8%) studied either harvest scheduling or extended harvest scheduling problems. Dealing with uncertainties is also a very important topic in forest planning and these are usually ignored in real-life cases. In these problems, the growth models are assumed to be deterministic (Eyvindson and Cheng, 2016). Uncertainties on natural degradation processes, the future cost of collecting and processing forest resources, the prices of forest products to be sold, and social preferences make forest management much more complicated (Kuhlmann et al., 2015). Therefore, the number of studies on forest management planning under uncertainty have increased in recent years (Kuhlmann et al., 2015). This inference can easily be observed in Figure 10, which shows that risks and uncertainties are the most studied subjects after harvest scheduling problems. After cutting, small trees, branches, tops and unmerchantable wood are left in the forest and collected for bioenergy. This results in a decrease of carbon storage, and the capacity of the forest declines. Repo et al. (2015) aimed to create a financially suitable management plan to compensate for the loss of carbon resulting from the extraction of forest harvest residuals. According to the taxonomic review, forest residue harvesting is one of the least studied subjects in the literature. When habitat availability and potential to produce economic values of the forests, considered as adaptive forest management problems, are examined, it has been concluded that habitat availability can be improved significantly with a few economic losses (Monkkonen et al., 2014). In many countries, when planning is addressed with reference to the ecosystem with living beings in forests, planning tends towards a reduction of clearcutting and planting and an increase of continuous cover management (Pukkala et

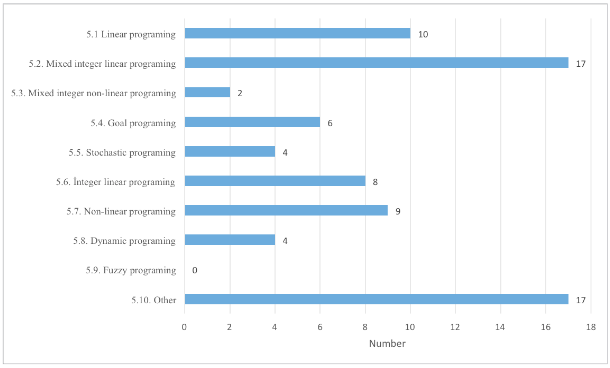

Figure 7. Distribution of publications according to the modeling type

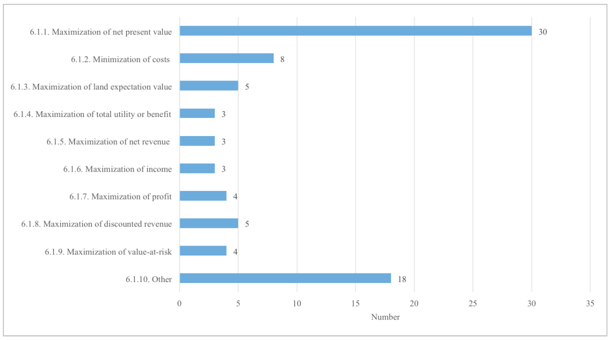

Figure 8. Distribution of publications according to financial objectives

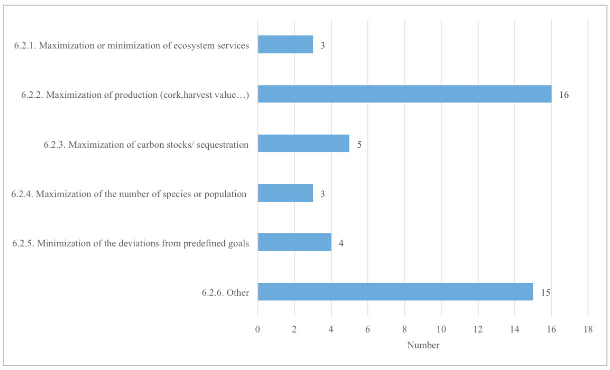

Figure 9. Distribution of publications according to the non-financial objectives

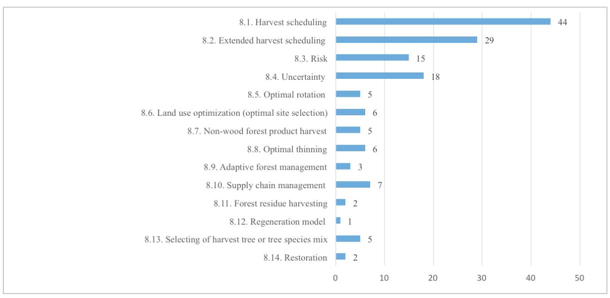

Figure 10. Problem type

al., 2014). Therefore, it can be said that adaptive forest management is a significant issue in terms of sustainable forestry. The review shows that research into adaptive forest management is greatly needed, a topic which was only studied in 3 papers in the last four years.

Since some papers have an unspecified time horizon or infinite time horizon, 91 papers are evaluated within the category of "Plan type". The majority of these articles are at strategic level (78.0%). The reason for this is that the planning horizon needs to be at least 10 years to ensure consistent implementation of sustainable forest management activities and to ensure the necessary stability (FAO, 2017). The strategic level is followed by tactical (9.9%) and operational levels (9.9%). 2.2% of the papers are hybrid, or multi-level. Mid-term tactical and short-term operational planning are also necessary for forest management practices. For instance, a successful "best practice" from the world is seen in Canada's northeast forest areas, in which the strategic planning horizons last for 100 years or more, while tactical plans for a few years, and daily, weekly and monthly operational plans are also developed and implemented (Kuhlmann et al., 2015).

Forest structure is examined in only 83 papers since this topic is not specified in the rest of them. Even-aged forests constitute 56.5% of the studies. The percentages for uneven-aged is 8.2%, plantation 16.5%, coppices 1.2%, forest+other land use 3.5%, and any-aged 1.2%. The reason why even-aged forests are the most studied structure is that this forest structure is not as complicated as the uneven-aged forests, so the decision-making process is much easier.

CONCLUSION

This paper employs a comprehensive taxonomic framework to classify recent studies on optimization of forest management and to make inferences about further research directions. In the proposed taxonomy, we consider the main categories to be: the study type; model structure; methodology; modeling type; problem objectives, level and type; plan type; and forest structure. 111 articles published between 2013 and 2016 in forest management optimization field are classified according to the proposed framework. Finland and USA are the leading countries working on the optimization of forest management. Approximately 21% of the papers were published in the Canadian Journal of Forest Research and Forest Science. The findings obtained from this review are given as follows:

√ The majority of the papers (92%) are classified as research studies. 95% of these research studies include real applications while the rest use only hypothetical data. In many countries, a big proportion of forests belong to private owners or companies who seek for optimal forest plans. This could be an important reason for the high ratio of real applications.

√ Most of the optimization problems in forest management are handled as deterministic (68.6%), in which the fluctuations, uncertainties and risks have not been taken into account. There is an obvious need to model forest planning problems taking uncertainties into account. Stochastic and fuzzy models could be utilized to meet this requirement. Fuzzy models in particular, which are studied in only 1% of the investigated papers, constitute a great potential for further research in forest management optimization.

√ The modeling types utilized in the papers were quite diverse and were led by mixed integer linear programming and linear programming.

√ Harvest scheduling, i.e. the process that specifies where, when and how much to harvest, is the most common planning problem. The applications of extended harvest scheduling problems, which need a broad point of view, and the problems dealing with uncertainties and risks, have also been increasingly studied in recent years. On the other hand, adaptive forest management, which has been examined in only a few studies, is still an important field for further research.

√ The percentage of harvest scheduling and extended harvest scheduling problems with single objectives is much greater than that of multi-objective cases. Single objectives are more frequently analyzed in the papers involving stand and forest level. However, multiple objectives are more frequently analyzed in the papers involving landscape level and forest level.

√ Simulation is the most widely applied approach in the literature. Several exact algorithms, heuristics, metaheuristics, and approximation algorithms were also used for optimization. Hybridizing various algorithms to improve the computational performance and solution quality of these algorithms is another research direction for further studies.

Although about 50% of the Earth is covered with forests, there is a limited number of optimization studies in forestry. This paper presents directions for further optimization studies in forest management. The proposed taxonomic framework can also be utilized and improved by adding new categories for further state-of-the-art reviews.

Peer-review: Externally peer-reviewed.

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