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Optimized Forest Harvest Planning with Adjacency Constraints: A Bibliometric Contribution

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ABSTRACT

BACKGROUND: One of the main stages in forest industry is harvest planning. The use of spatial adjacency constraints has increased in harvest planning models due to the growing interest in environmental aspects. **OBJECTIVE:** This study aims to present a bibliometric analysis of works that address the optimized forest harvest planning using ARM and URM adjacency constraints. We aim to identify the major countries responsible for publications, the main methods of resolution employed, the objective functions of the most significant interest in the formulation of the problem, citation analyses and the citation, co-citation, and word co-occurrence networks. Generating from these analyses a greater understanding of the subject and identifying the theoretical basis of the area. **RESULTS:** We conducted the research as a systematic review, supported by bibliometric techniques. The ISI Web of Science database was consulted, and the data was processed with VOSviewer and CitNetExplorer softwares. A total of 44 articles published between 2008 and 2018 were analyzed. Most papers used the ARM approach to model the harvest plan considering spatial adjacency constraints. Heuristic methods, such as simulated annealing, were the main resolution alternatives found to circumvent the time and computational processing demands caused by the complex nature of the problem. **CONCLUSION:** This research helped to identify the theoretical background of publications that deal with spatial adjacency constraints in the forest sector. A significant relationship between the publications in the sample was found, with only six articles not linked to the others. Finally, we conclude that the interest in research that incorporates environmental aspects in its scope has increased, thereby increasing the complexity of mathematical models that describe these new scenarios, providing a space for the development of new research in the area.

Keywords: Harvest planning, Adjacency restriction model, Bibliometric review, Operation Research, Forest management

INTRODUCTION

The forest industry uses wood almost exclusively. From the mechanical processing of logs, building construction, fiber production and pulp (Belgacem and Pizzi 2016). This industry has strategic importance in several countries with such a wide range of use. According to Broz et al. (2018), the forestry sector contributes about 2% to 3% of the world's gross product. The forestry industry contains several stages and actors with a divergent supply chain. Among them is forest management, which includes in its decisions the planning of harvest sequencing, which aims to satisfy industrial demand (Rönnqvist et al., 2015). According to Augustynczik et al. (2015), harvest planning problems have increased their complexity level since they also consider adjacency in their formulation relationships between stands. The first record of spatial adjacency restriction occurred in Thompson et al. (1973), where the authors limited the allowed area for harvesting in each pair of adjacent stands.

Among the formulations for adjacency problems, two approaches are worth mentioning, the Area Restriction Model (ARM) and the Unit Restriction Model (URM). URM-type restrictions prohibit adjacent management units from being harvested within the same period of the planning horizon. In addition, this approach considers that the maximum harvest area is defined by the management unit's size, regardless of its size (Kašpar et al.,2016).

According to Tóth et al. (2013), the harvest scheduling model using the URM approach can be represented by a graph, in which its nodes correspond to the management units and their arcs are the adjacent relationships between these units. Considering that the weight assigned to a node is the profit obtained from cutting the stand corresponding to it, one soon seeks to find the subset of unconnected nodes that return the greatest possible weight, that is, the highest revenue, at the end of the planning horizon, which makes the problem equivalent to the maximum weight stable problem (SSP). This equivalence implies that, as the SSP, the URM approach is NP-Hard; that is, its solution times increase exponentially according to the number of restrictions and variables of the problem (Tóth et al., 2013).

Models using the ARM approach are an extension of URM models. Instead of knowing in advance all the potential clusters for harvesting, as occurs in the URM formulation, the formation of clusters is incorporated into the problem without exceeding the maximum area allowed (Goycoolea et al., 2009). The ARM approach allows neighboring stands to be harvested in the same period if the total harvested area does not exceed the maximum limit imposed in the planning (Borges et al., 2014a). Contiguous stands can be merged as a harvest block, making the ARM models more flexible concerning the period and place of harvesting, theoretically producing larger revenues when compared to the URM models (Kašpar et al., 2016).

Initially, it was considered that problems using the ARM approach were impossible to be formulated as a linear problem and only heuristics or metaheuristics were used to solve them (Tóth et al., 2013). However, integer programming formulations were proposed for the problem (Goycoolea et al., 2009). As a result, three models described in the literature for ARM restriction problems are commonly used: path/cover, cluster, and bucket formulations.

The path formulation, proposed by McDill et al. (2002), lists recursively all the sets of stands that exceed the maximum area defined by the problem, creating restrictions for each identified infactibility. This formulation creates restrictions similar to the backpack problem (Tóth et al., 2013). This makes the number of restrictions increase exponentially (Martins et al., 2014). The cluster approach, also proposed by McDill et al. (2002), uses a variable for each block formed (cluster), whose total area added does not exceed the value established by the problem. This approach may use adjacent constraints used in the URM model, once potential clusters must be known before the model is built (Tóth et al., 2013). Unlike the path formulation, which has exponential restrictions, the cluster approach generates an exponential number of variables to the problem. Finally, the Bucket formulation, developed by Constantino et al. (2008). This formulation is based on the definition of a-priori buckets, in which each management unit i is allocated in only one bucket. The areas assigned to the same bucket must be neighboring. Otherwise, the cluster is divided, keeping only the neighboring areas. The sum of their areas must not exceed the limit determined in the model. The buckets scheduled for harvesting cannot be adjacent (Goycoolea et al.; 2009). In this formulation, the number of variables and restrictions is polynomial (Martins et al., 2014).

According to Zhu et al. (2007), the difference between URM and ARM approaches lies in that unit models control the scheduling of neighboring stands during the green-up time. The ARM allows adjacent harvesting regions within the same period as long as the area limit is not exceeded.

Therefore, this study aims to present a bibliometric analysis of works addressing optimized forest harvest planning using ARM and URM adjacency constraints. We aim to identify the major countries responsible for publications, the main resolution methods, the objective functions of the most significant interest in the formulation of the problem, citation analyses and the citation, co-citation, and word co-occurrence networks. It is generating from these analyses a greater understanding of the subject and identifying the theoretical basis of the area.

MATERIALS AND METHODS

There are two categories of bibliometric indicators: activity and relationship indicators. According to Santos (2015), the first group provides information on the impact of research activities and their volume. In contrast, relationship indicators seek collaborations and bonds between authors and fields of research. Social relationship networks usually represent these criteria. We can cite as relationship indicators: co-citation, co-authorship, and co-occurrence of words.

The review period was fixed between 2008 and 2018. This interval was chosen in a long enough way to include a relevant number of articles, thus representing the current state of the art of the literature, but without making it impractical to analyze all selected articles.

We limited the search for articles published in scientific journals, available digitally and written in English. Regarding the database, we used the ISI Web of Science platform. We made this selection because the database offers a set of relevant data for the bibliometric analysis, such as the list of authors, impact factor (IF) of journals, etc. (Carvalho et al., 2013)

We have searched the selected key expressions in the articles' titles, abstracts and/or keywords. Figure 1 presents the search sequence and the key expressions defined by the authors.

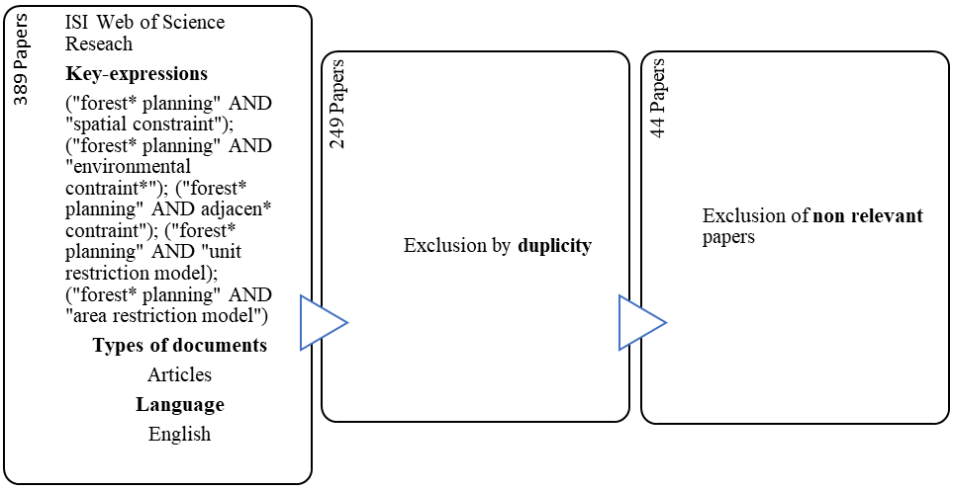


Fig 1: Flowchart of the sample defining process for the bibliometric analysis.

The initial search resulted in a total of 389 papers. After eliminating the duplicate items, we reduced the sample to 249 articles. For the final sample, we read the articles' abstracts to identify the papers that belonged to the defined scope, thus, resulting in a final sample of 44 articles.

After obtaining the data, the exploratory investigation of the bibliometric analysis was performed in Excel software. After the exploratory investigation, the citation relationship between the papers was performed with CitNetExplorer 1.0.0. (van Eck and Waltmanm 2014) and the articles' co-citation network and word co-occurrence network were analyzed with VOSviewer 1.6.13 (van Eck and Waltmanm 2019).

RESULTS AND DISCUSSION

Identification of growth or reduction trends in developing studies related to forest harvest planning using adjacency constraints was the first performed analysis. We compiled the articles according to the year of publication (Figure 2). The first years in the sample had a smaller number of publications, including the absence of publications in 2009, omitted from the figure. Then the volume of published papers increased. The peak of publications occurred in 2015, with 12 articles. The years following the peak maintained the average number of publications above the initial years, indicating constant interest in the subject.

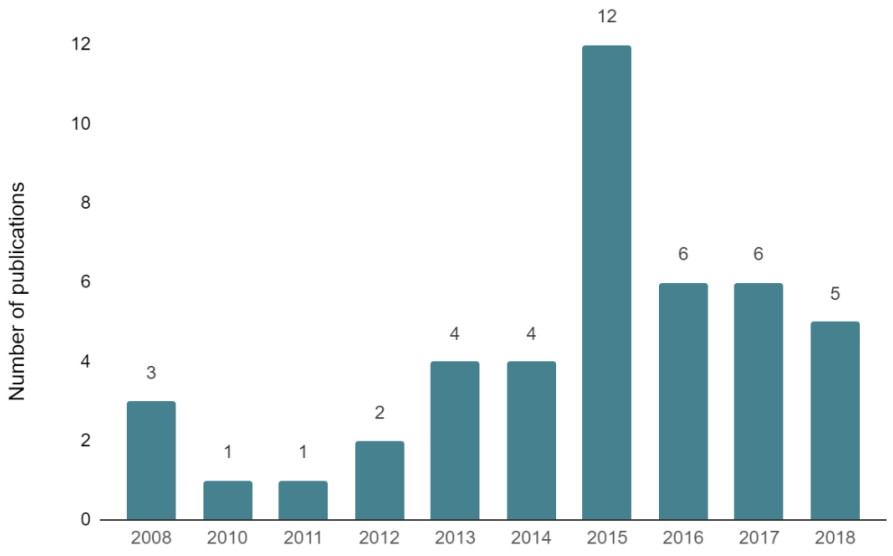


Fig 2: Temporal evolution of the number of papers.

Regarding the distribution of publications by country of origin, we identified articles from the American, European, and Asian continents. The predominance of the United States was observed, with 12 publications, double compared to the second place, China, with six publications. Figure 3 also shows where the articles' researches were applied. Thus, one can identify areas of

interest for research development and a shift between origin and application. It is important to note that the sum of applied sites exceeded the number of articles because, in some cases, more than one study site was used.

When we evaluate the areas of interest from the articles, the geographic distribution has a slight change compared to its origin. Canada, e.g., was not one of the primary sources of publications with only one article in the sample. However, six works used data from Canadian forests (Strimbu et al., 2010; Könnyu and Tóth, 2013, McDill et al., 2016; Neto et al., 2017; Cyr et al., 2017; Yoshimoto and Asante, 2018). The US also had an increase in the number of related papers, corroborating the importance of the subject for the country. Brazil remained with three works. All articles originating in the country were researches dedicated to local forests. China, Turkey, and Portugal had reduced one unit in their publications, indicating that authors affiliated with these countries carried out research directed to other regions. An example is a paper by Akbulut et al. (2017), whose first author is affiliated with the Institute of Forest Research of Southwest Anatolia, Turkey. The publication aimed to assess whether a heuristic with initial solutions generated by a relaxed linear programming model would lead to better management plans for forests located in Oregon, in the United States.

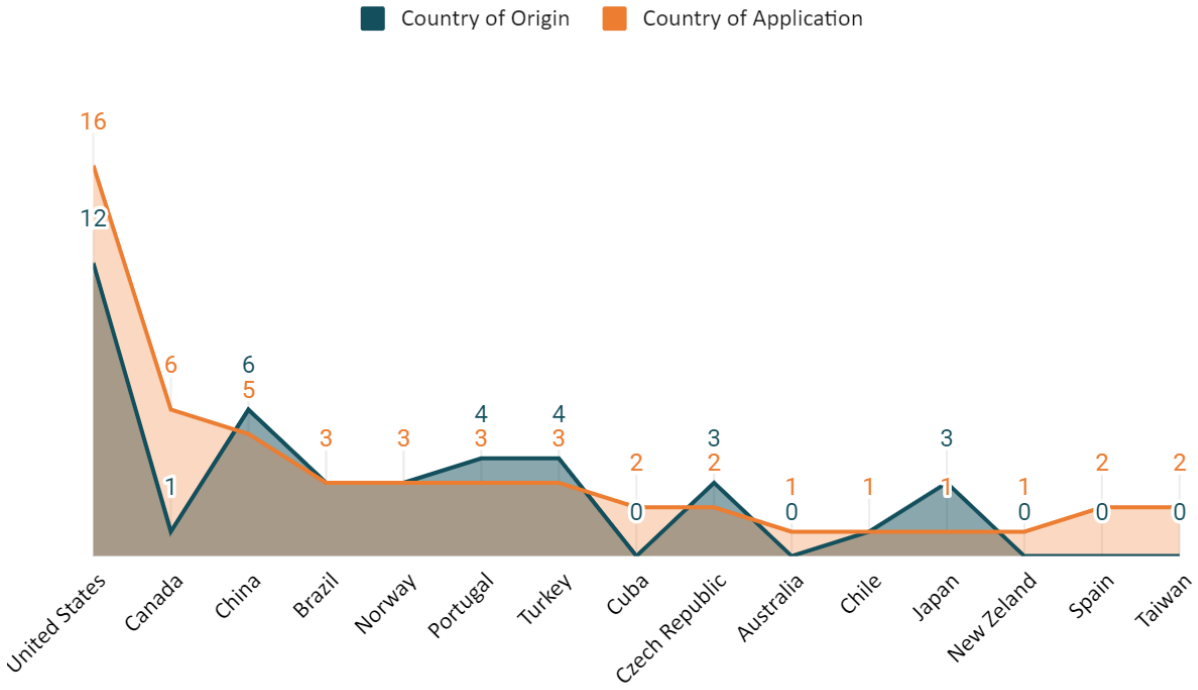


Fig 3: Absolute frequency of scientific production by country of origin and country of application.

Figure 4 contains the frequency distribution of the objective functions of the problems. An objective function is the mathematical translation of the objective that is intended to be achieved by solving the proposed model (Marins, 2011). Half of the articles evaluated, i.e., 22 publications, aimed to maximize the harvest's net present value (NPV) at the end of the planning horizon. The formulation of complex models, which consider not only a goal, but multi-objectives in their formulation, has gained prominence, with 22.7% of the articles incorporating more than one objective in their model. As examples of a multi-objective function, we can cite the work developed by Dong et al. (2018a), aiming to maximize the NPV of wood production and carbon sequestration. Furthermore, Wei and Murray (2015) published two multi-objective models, both with URM restrictions, aiming to understand the effects of spatial uncertainty on forest harvesting. The harvested volume maximization was another common objective found in forest harvesting problems, with 18.2% of the articles.

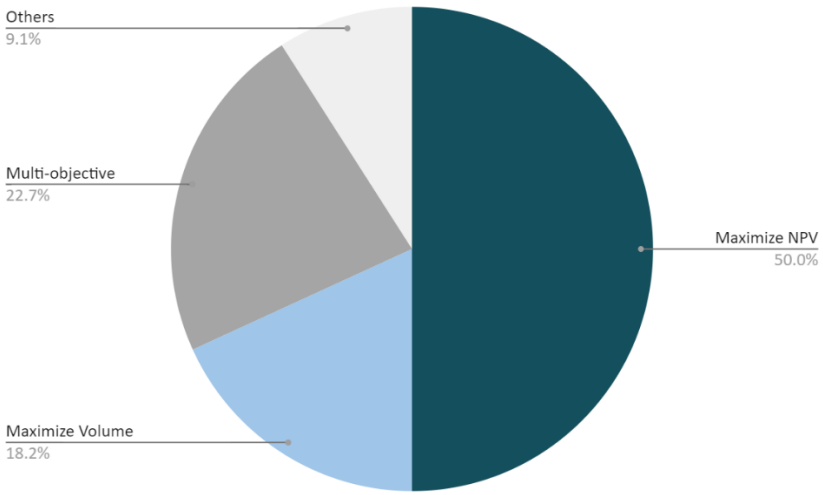


Fig 4: Frequency distribution of the objective function of the problems addressed.

Observing the frequency of ARM and URM constraints (Figure 5), problems formulated with the ARM approach were predominant, since, despite having a higher demand for computational capacity compared to URM models, this formulation makes the models more flexible. Publications using ARM restrictions accounted for 54.5% of the total, while those using the URM approach accounted for approximately 38% of the published articles. Although most papers chose to work with only one approach, 6.8% of the articles compared the effects of both restrictions in their studies. Dong et al. (2016) evaluated search techniques of the simulated annealing algorithm (SA) to solve spatial harvest scheduling problems, using the ARM and URM approaches in the formulation of their models, both with a green-up time of 3 years.

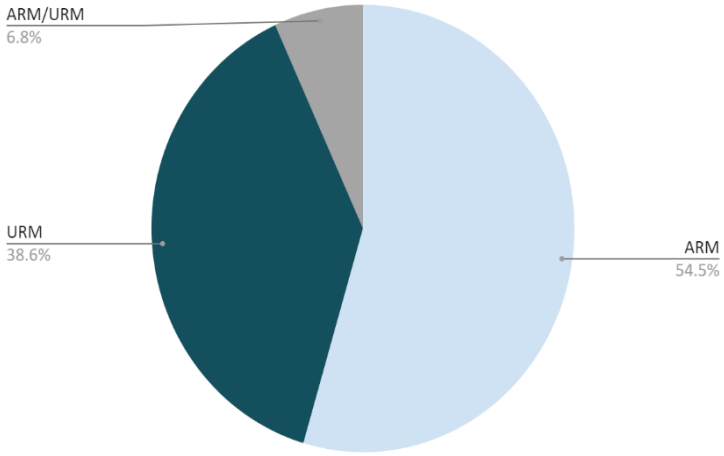


Fig 5: Frequency of use of ARM and URM constraints.

The method of resolution is strongly linked to the complexity of the problem. Since exact methods may require a higher processing capacity and time to solve, heuristic and metaheuristic methods become an alternative for authors. Figure 6 shows the absolute frequency distribution of the resolution methods used by authors. We proposed four major groups: (1) classical optimization, which includes exact optimization methods; (2) heuristics, which includes both heuristics and metaheuristics, such as the tabu search; (3) the hybrid method, in which the authors used a combination of techniques, such as exact and heuristic methods; and finally, (4) others, which includes different methods, such as simulation.

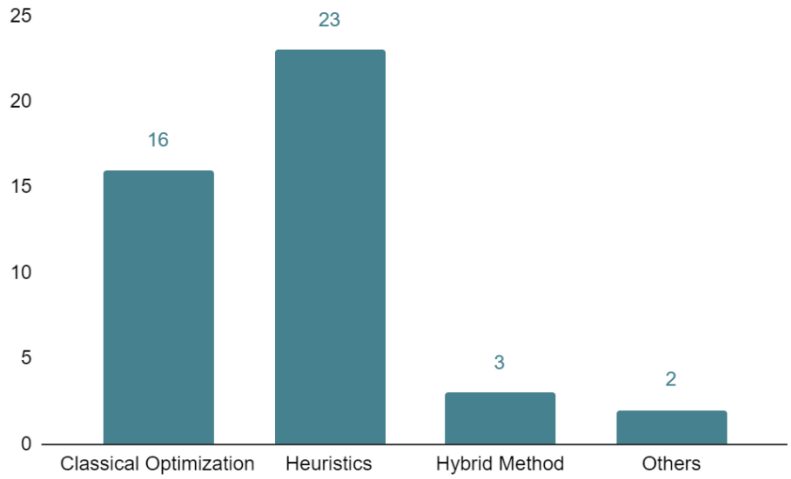


Fig 6: Absolute frequency by resolution method.

The problem of scheduling forest harvesting with adjacency restrictions is NP-Hard (Tóth et al., 2013). Problems of this nature have their solution times growing exponentially due to the number of constraints and variables, making the resolution time by exact methods long. Therefore, we observed that heuristic methods stand out compared to others, followed by classical optimization methods. Among the heuristic methods, metaheuristic SA was the most relevant, being used by seven articles (Borges et al., 2014b; Bachmatiuk et al., 2015; Dong et al., 2015a; Dong et al., 2016; Qin et al., 2017; Dong et al., 2018a; Dong et al., 2018b) and in one article with hybrid resolution method. The article by Cyr et al. (2017) used the SA algorithm to find the best harvesting schedule of the areas, and then the exact method was applied to maximize the harvested volume of wood.

Twenty-five unique journals published the sample's works. Four represented 40% of all publications (Table 1). For example, *Silva Fennica*, Forests, Forest Science and Forest Policy and Economics summed 18 articles. In contrast, 18 journals have only one publication in the sample. Table 1 also includes the journals IF, provided by Journal Citation Reports (JCR) for 2018. The IF allows comparing and assessing the importance of journals in a specific area (Endler et al., 2015). The IF of a period is calculated by dividing the total citations received by the journal in the two previous years, by the number of articles published in the journal and able to receive citations in those years. Therefore, for the year 2019, the IF's calculation is the ratio of the number of citations received in 2017 and 2018 to the total number of articles published in these years.

The graters IF journals in the sample are Environmental Modeling & Software, Landscape Ecology, and European Journal of Operational Research (EJOR). Liu and Lin's (2015) article, published in Environmental Modeling & Software, proposed a cultural algorithm to solve the forest harvesting planning problem with adjacency restrictions.

Könnyu and Tóth (2013), whose article was published in EJOR, compared the three main approaches to solve problems with ARM restriction (path, maximal click-based packing, and bucket) with a cutting plane algorithm applied to the Path approach. Borges et al. (2014b), who evaluated different neighborhood search methods in a forest planning problem, was also published in the same journal. The model used by the authors included pairwise constraints of URM adjacency and variation of the harvested volume between periods.

Table 1: Absolute and relative frequency of publications of the ten leading journals in the sample and their respective impact factors.

Journal	Total publications	%	Impact Factor
Silva Fennica	5	11,40	1,605
Forests	5	11,40	2,116
Forest Science	4	9,10	1,058
Forest Policy and Economics	4	9,10	3,099
Annals of Operations Research	4	9,10	2,284
European Journal of Operational Research (EJOR)	2	4,50	3,806
Operations Research	2	4,50	2,604
Environmental Modeling & Software	1	2,30	4,552
Landscape Ecology	1	2,30	4,349
Forest Ecology and Management	1	2,30	3,126

Citation analysis assumes that researchers base their works on already published papers, generating a list of references (Moraes et al., 2015). This analysis evaluates the number of citations received by an article, author, or institution, and makes it possible to examine the relevance of work in an area of knowledge (Grácio et al., 2009).

Figure 7 shows the temporal evolution of the number of citations received by the sample's articles. The growth in the first five years was discrete, and from 2014 the number of citations intensified, reaching its peak in 2018, with 104 citations. The sample's publications received 403 citations, equivalent to an average of 9.16 citations per article.

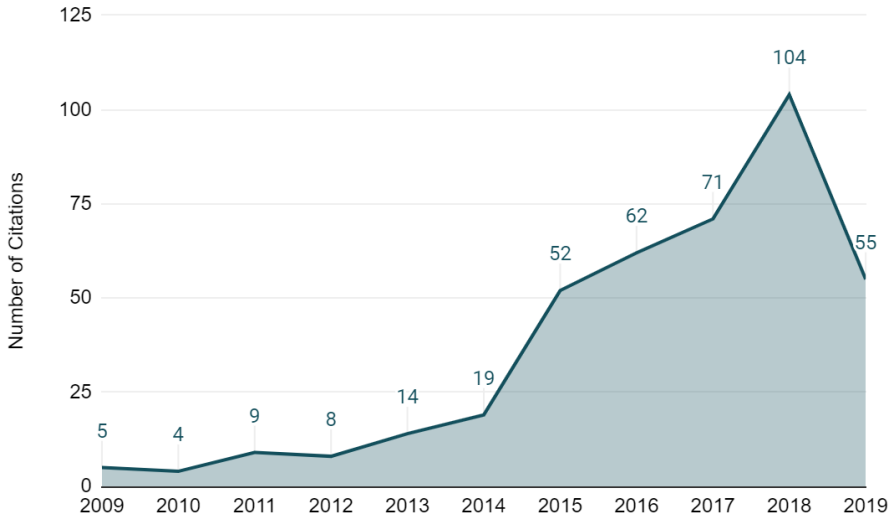


Fig 7: Evolution of the number of citations over time.

Analyzing the sample's main publications in terms of citations (Table 2), Constantino et al. (2008) was the most cited publication. In this article, the authors presented one of the main resolution approaches for the ARM formulation, the Bucket formulation. This formulation is based on the definition of *a-priori* buckets, in which each stand *i* is allocated in only one bucket. Management units assigned to the same bucket must be adjacent. Otherwise, the cluster is divided by keeping only the contiguous stands, and the sum of their areas must not exceed the limit determined in the model. Buckets scheduled for harvest in the same period cannot be adjacent. Sándor Tóth, the second most relevant author in the sample, has three articles among the most relevant works. The author's most cited article was published in Environmental Modeling & Assessment, the journal with the highest IF of the sample. Also noteworthy is the publication of Carvajal et al. (2013), which appears as the second most relevant article of the sample, had the highest citation average per year. The authors used the ARM restriction to minimize large deforested areas in this article, creating contiguous regions of mature forests.

Table 2: Authors with the highest number of citations in the sample.

Authors	Periodic	Year of publication	Impact factor	Total citations	Average per year
Constantino M et al.	Operations Research	2008	2,604	51	4,25
Carvajal R et al.	Operations Research	2013	2,604	39	5,57
Tóth SF and McDill, ME.	Environmental Modeling & Assessment	2008	4,552	36	3,00
Borges P et al.	EJOR	2014	3,806	25	4,17
Tóth SF et al.	Forest Science	2013	1,058	21	3,00
Dong L et al.	Forests	2015	2,116	18	3,60
Könnyu N and Tóth SF	EJOR	2013	3,806	15	2,14
Zhu J and Bettinger P	Forest Policy and Economics	2008	3,099	13	1,08
Martins I et al.	Top	2014	0,965	11	1,83
Hernandez M et al.	Journal of Forest Economics	2014	1,761	11	1,83
Total				240	3.05

The representativeness over the years of the most cited articles can be examined in more detail in Figure 8. In the first year after the publication of the first articles in the sample, Tóth and McDill (2008) study was the most cited publication. It presents a multi-objective model that aimed to generate management alternatives that resulted in creating large stretches of mature forest with the minimum number of borders. From 2016 there has been an increased interest in researches related to environmental issues that go beyond the limitation of the maximum area allowed to be harvested, with the expansion in the number of citations in the works of Carvajal et al. (2013), Tóth and McDill (2008) and Dong et al. (2015b). The study presented by Dong et al. (2015b) proposes a multi-objective forest planning model that maximizes forest carbon stock among its goals.

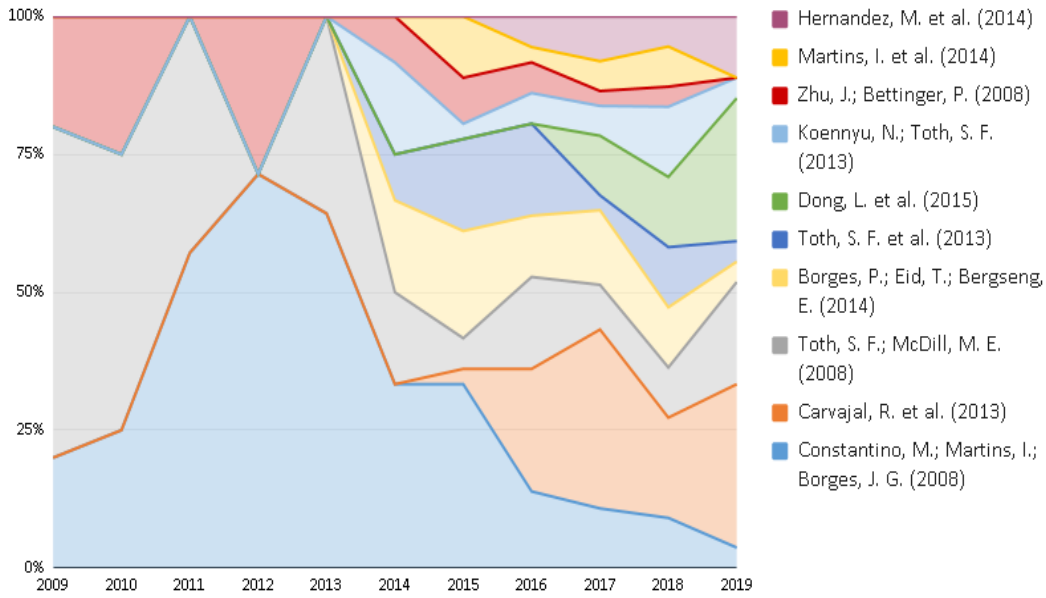
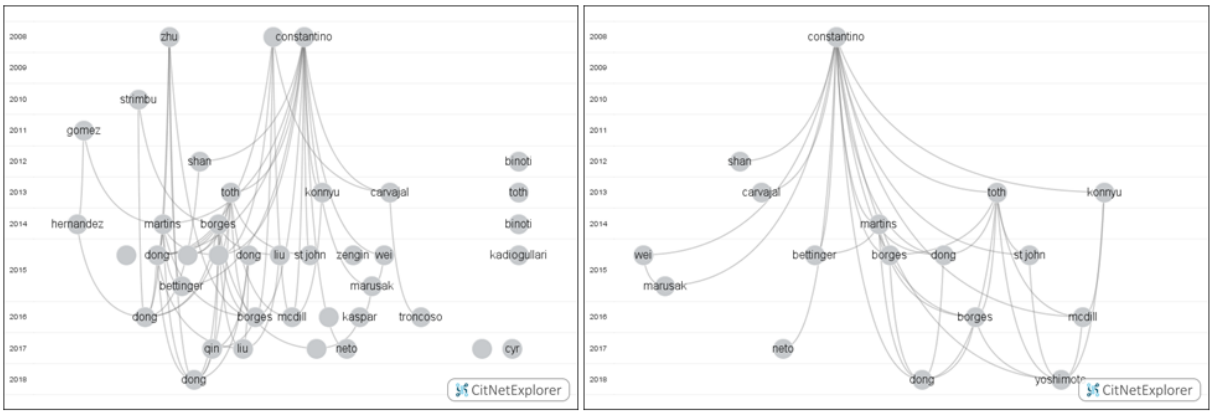


Fig 8: Evolution of the number of citations over time of the most cited publications.

Several criteria establish the relationships between different authors, based on the degree of direct citation between their works, co-citations analysis, and co-words analysis, among others (Franco and Faria, 2019). Figure 9 (a) presents the citation's network of the article's sample, in which one can visualize the citation relationships among the publications. Each node in the figure represents an article, and the connecting edges symbolize a citation. The links start from the most recent articles to the older ones. A significant relationship between the publications in the sample is observed, with only six articles not linked to the others.



a) b)

Fig 9: (a) Citation relationship between publications in the sample. (b) Citations network from Constantino et al. (2008).

Figure 9 (b) contains a fragment of the complete network, presenting the citation network whose origin node is represented by Constantino et al. (2008). Sixteen works present in the sample cited the article. Published in 2008, since 2012, was cited at least once in each year of the research horizon. As previously mentioned, the relevance of this research is explained by the Bucket resolution approach. Publications that have, in their scope, the proposal of new resolution approaches, new algorithms, etc., tend to have a higher number of citations once they become the theoretical basis of new researches.

According to Santos (2015), co-citation is an important way to associate documents and authors because if two documents, or two authors, are cited simultaneously in several subsequent works, there is a strong indication that these authors, or these cited documents, deal with the same theme. Co-citation networks are used to assist in identifying the theoretical background of publications (Endler, 2016).

Figure 10 illustrates the co-citation network, consisting of references cited by at least ten articles in the sample. The network generated two distinct clusters. The green cluster has Murray's (1999) publication as a primary reference, with 34 citations from the sample works. The author reviews the URM and ARM approaches to modeling forest harvesting with adjacent restrictions in that work. The red cluster has the publication of McDill et al. (2002) as the central article, with 24 citations. That work proposed the Path and Cluster approaches.

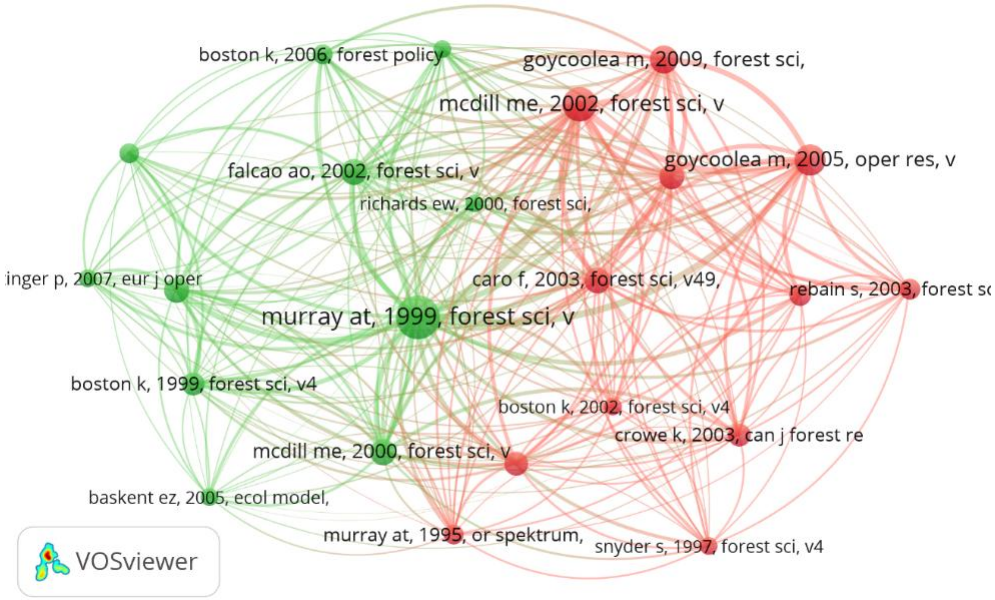


Fig 10: Co-citation network.

According to Franco and Faria (2019), authors from a field may not have worked together, but they publish studies that use the same keywords and similar themes. Since a group of authors recognizes the same relationship pattern between specific terms, one can conclude that this relationship between words has a meaning within the studied area (Santos, 2015). Therefore, the analysis of word co-occurrence, whether keywords, title words or abstract, allows establishing the linking forces between terms and creating a knowledge map (Franco and Faria, 2019).

The word co-occurrence network illustrated by Figure 11, was constructed using the "all keywords" option of the VOSviewer co-occurrence map. The minimum number of occurrences of a term to be part of the network was defined in five, resulting in 24 nodes. Four clusters were generated from the selected terms. In general, we observed the presence of terms that refer to the type of problem addressed: 'forest scheduling'; specific characteristics of the problem: 'adjacency restrictions', 'maximum area restrictions'; and methods used to solve the problem: 'integer programming', 'mixed-integer programming', 'algorithms' etc.

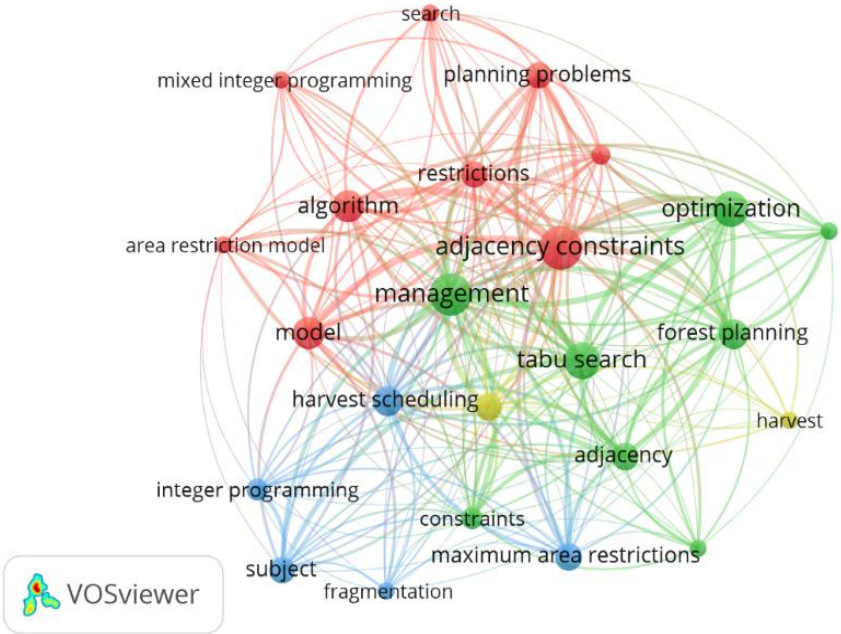


Fig 11: Word co-occurrence network.

CONCLUSION

The largest number of publications (65.9%) on forest harvesting considering adjacency restrictions was found from 2015 onwards. We found 25 journals in the sample, with Silva Fennica, Forests, Forest Science, Forest Policy and Economics, and Annals of

Operations Research accounting for half of the published articles. On the other hand, environmental Modeling & Software, Landscape Ecology, and EJOR were the journals with the highest IF.

The publications were distributed in three continents, America, Europe, and Asia, regarding the articles' origin. The American continent has the most considerable contribution, with 38.6% of the articles, highlighting the United States with 12 publications. However, a change in geographic distribution was observed, increasing the number of studies conducted using Canadian forests as a database and Oceania's inclusion among the evaluated continents.

The ARM-type constraint was the most used in the articles. The preference for ARM over URM lies in the flexibility achieved with this type of approach, making it possible to harvest neighboring stands once their combined area does not exceed the limit imposed by the model.

To deal with the complex nature of the forest harvesting problem considering adjacency restrictions, 52.3% of the articles used heuristic methods as a resolution method. NP-Hard problems have their solution times growing exponentially due to constraints and variables. The complexity of the problem tends to make resolution time by exact methods extremely long, justifying heuristics' choice to find good solutions with less processing time. Among the algorithms used, we emphasize the relevance of the metaheuristic SA used by eight articles.

The analysis of the temporal evolution of citations showed that from 2016 there was an increase of interest in researches related to environmental issues. We prove that with the expansion of the number of citations in works that incorporate multi-objective decisions into their problems, often considering the carbon market and the restriction of the maximum cutting area in forest harvesting.

From the citation and co-citations networks, we concluded that the articles by Murray (1999), who discussed the URM and ARM approaches in a review, McDill et al. (2002), who presented the Path and Cluster approaches and Constantino et al. (2008), who presented the Bucket formulation, serve as a theoretical basis for works developed in the area.

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