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Use of the process-based models in forest research: a bibliometric review

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FOREST MANAGEMENT

ABSTRACT

Background: Process-based modeling is made to simulate the interactions of the soil-plant-atmosphere system providing information and estimates for forest management and services. Through bibliometric evaluation we identify the quantitative state of the art on the use of Process-Based Models (PBMs) applied in forestry studies, contextualizing research fronts, and analyzing the main topics and emerging themes. Data from the Web of Science and Scopus were used for the bibliometric survey of 533 scientific records.

Results: We verified that (*i*) the number of publications related to the PBMs was boosted in the year 2000, and is growing; (*ii*) Forest Ecology and Management (74 publications) is the journal that most publishes on the subject; (*iii*) Annikki Mäkelä is the most productive researcher (20 publications) and most cited (h-index: 12); (*iv*) The USA (131 records) is the country with the highest number of research; (*v*) there are eight collaborative networks between the authors, three workings together, and five producing in isolation; (*vi*) the keywords are grouped into five clusters: (a) the effect of climate change on forests; (b) carbon studies; (c) physiology of trees; (d) silvicultural practices and; (e) analysis of model uncertainties. The separation of themes showed that the new search hotspots are the PBMs using of remote detection tools.

Conclusion: The results presented can be a fundamental theoretical tool for understanding the trends and development perspectives of this research line in future studies.

Keywords: Analysis of process-based models, Bibliometric Review, Forest management, Process-based modelling

HIGHLIGHTS

Bibliometric Review: Web of Science (core collection) and Scopus.
The use of process-based models (PBMs) is expanding in the forest sciences.
Annikki Mäkelä is the most productive and cited researcher in the field of forestry PBMs.
The United States of America leads forestry research with the use of PBMs.

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INTRODUCTION

The significant increase in carbon dioxide concentrations in the atmosphere, the increase in the global average temperature, and the variations in precipitation directly affect the processes of energy, carbon, water, and nutrient exchange in the soil-plant-atmosphere system. As a result, changes in the growth pattern, survival, and structure of the forest formations are observed (Chmura et al., 2011; Elli et al., 2020; Schlickmann et al., 2020).

Forest ecosystems and all their complexity have become key points of different research and analysis that attempt to present the impact of climate change in its composition, growth, and productivity (Castillo et al., 2019; Härkönen et al., 2019; Zhao et al., 2019). Thus, researchers and managers have been incorporating climatic variables into different model parameters for the simulation of data in the forest area (Chmura et al., 2011).

The models that can be used for this type of research are the so-called process-based models (PBMs) that encompass trees, at different spatial scales of analysis, from the biochemical scale of the leaf to landscape analysis. These models make it possible to carry out simulations of forest growth and productivity based on ecophysiological mechanisms. For example, photosynthesis, biomass allocation, respiratory processes, transpiration, nutrition, and leaf and branch senescence (Baesso et al., 2010).

Despite this, little information is found in the literature, with studies that answer the following questions: (i) In which field of forest science is the PBMs most used? (ii) Which are the leading research centers (country, institution and researcher) in the generation of scientific knowledge using of PBMs? (iii) Is the scientific/methodological progress with the use of PBMs in forestry studies the same between countries? (iv) What are the applicabilities of PBMs in forest studies? (v) What are the themes in the ascendancy with the use of the PBMs? Answers to these questions are essential and require attention in the field of forest science. Thus, it can help researchers in defining where to allocate efforts for new scientific investigations (Huang et al., 2020).

We have found that recent reviews dealing with PBMs in forestry studies, available in the literature, provide timely and specific information on certain types of models (Gupta and Sharma, 2019; Jin et al., 2016; Xi et al., 2009). The fact is that forest research using PMBs is interdisciplinary and has a wide field of application. Therefore, to promote a comprehensive view of the use of PMBs in forest studies, the development of a bibliometric analysis with this theme is justified.

In recent years there has been strong interest by researchers in developing bibliometric research. With this type of work, it is possible to analyze the trend in the development of different research topics of the same nature (Chiarello et al., 2019). In forestry science some bibliometric studies have been developed in different areas such as bibliometric analysis of community forestry research in Canada (Bullock and Lawler, 2015), Non-Timber Forest Products in Brazil (Silva et al., 2020) and global forest ecology (Song and Zhao, 2013).

The main question raised for the development of this study was what trends are presented in forestry research using PBMs in terms of thematic focus, geographical distribution, and scientific production over time. For the search of answers, we established the following specific objectives: (i) identify basic literary data on the use of the PBMs in forestry studies, such as the number of articles and the most productive journals; (ii) identify the research fronts and elite, such as the most productive countries and researchers; and (iii) analyze the main topics and emerging research themes.

Bibliometric analysis

Bibliometric analysis is a science that studies ways of understanding the internal structure of research in each area (Shukla et al., 2020), identifying and detailing patterns in the scientific development of a given subject (Huang et al., 2020). It is a method of analysis of scientific activities or techniques that use quantitative information from publications. Quantitative information is obtained through statistical data from published articles or through elements that group a series of statistical techniques, quantifying the scientific production. The methodology used for this analysis is considered practical and flexible and performs evaluations of the type, quantity, and quality of the sources of information cited in the studies (Silva et al., 2011).

Bibliometric studies have been developed as a collaborative method for the scientific understanding of different themes related to the environment and forests (Romanelli and Boschi, 2019), such as studies on agroecosystems (Liu et al., 2019), accounting of natural resources (Zhong et al., 2016), forest entrepreneurship (Mourão and Martinho, 2020), Artificial Neural Networks applied in biometrics and forest modeling (Chiarello et al., 2019), global research trends in forest carbon sequestration (Huang et al., 2020), global analysis of deforestation (Aleixandre-Benavent et al., 2018), among others.

Process-Based Models

Among the different forms of categorization of the models applied in forestry studies, the existence of biometric models, PBMs, and hybrid models are mentioned (Scolforo, 2006; Landsberg and Waring, 1997). Biometric models are applied to research aimed at forest growth and have been effective in summarizing large amounts of data, whether from silvicultural trials or operational forest inventories (Scolforo, 2006). They enable users to explore treatment results and alternative regimes through simulations. However, these models consider that the quality of the site is invariant, thus making it impossible to analyze the effect of climate change, such as water availability and local climate (Weiskittel et al., 2010).

PBMs are used to represent the forest behaviour and use a set of interlinked processes at different spatial and temporal scales, which interact with each other and with the environment as, for example, the processes involved in tree growth (Medlyn, 2004; Pretzsch et al., 2015).

Also, they are practical tools for simulating the behavior of a system in response to the availability of solar radiation, water, and nutrients. Their use enables forest managers to assess the consequences of these changes or stimuli on trees (Landsberg and Sands, 2011).

The hybrid models category consists of the joining of biometric models and PBMs into the same model. They are used to understand forest growth through dendrometric data together with ecophysiological data, for example of climate data (Scolforo et al., 2017; Landsberg and Sands, 2011; Pretzsch, et al., 2015). This combination can provide greater accuracy of information as it fills the gaps in biometric models, which are not sensitive to interannual climate variations, increasing the efficiency of productivity estimates of forests (Scolforo et al., 2017).

PBMs are important tools in operational decision-making in the forestry sector and are already used by forestry companies. Some PBMs are used in forest management, for example the 3-PG model (Landsberg and Waring, 1997); CABALA, (Battaglia et al., 2004), and the G'Day (Comins and McMurtrie, 1993; Marsden et al., 2013). These models present a simplified approach, quite attractive for the forest sector because they assume that the parameters and (or) the functions within the stand canopy are uniform (Christina et al., 2016). Another class of PBMs with greater complexity is the individual tree models, for example, the MAESTRA/MAESPA model (Medlyn, 2004; Duursma and Medlyn, 2012). MAESTRA represents three-dimensionally each crown of the forest canopy, thus allowing the study of radiation absorption and efficiency of the use of light absorbed by each tree. The MAESPA model is the combination of MAESTRA with another PBMs, the SPA. The SPA model has greater detail on the water balance in the soil, a limitation of the MAESTRA model (Williams et al., 2001). These models have been used in forestry studies in Brazil, producing important information on *Eucalyptus* forests (Christina et al., 2016; Christina et al., 2018).

PBMs can be used for different purposes within forest studies, with different levels of detail, spatial, and temporal scale. According to Xi et al. (2009) they can be classified into 'landscape models', 'ecosystem model', and 'regional model'. They are used, for example, to simulate the growth processes of a single tree, a forest landscape, or an overly complex ecosystem. The PBMs in ecosystem-scale can still be classified according to the level of detail of the physiological processes which can be defined in: simple physiological models, complex physiological models, and hybrid empirical-physiological models (Jin et al., 2016).

MATERIAL AND METHODS

The review of the central research theme describes the temporal evolution of theoretical and methodological trends that influence the use and development of PBMs in forestry studies. The data were collected, filtered, processed, and analyzed using scientometric analysis tools (Saikia et al., 2020). With the help of the R software (R core team, 2019), it was possible to access the Bibliometrix library and the Biblioshiny App web interface (Aria and Cuccurullo, 2017). This online extension is an aid tool for the development of research on the scientometric and bibliometric analysis (https://www.bibliometrix.org/). The methodological development was divided into two parts: (i) bibliometric analysis; and (ii) qualitative discussion of results (Jin et al., 2018).

The main indexers, Scopus, and Web of Science (core collection) were used to build the study database. These are considered the largest databases available in the metadata storage of scientific papers (Chadegani et al., 2013), providing high-quality documents with a wide range of themes (Wang and Liu, 2014).

We acquired the metadata referring to 557 publications in the WoS database (536 articles and 21 reviews) and 557 publications in the Scopus database (533 articles and 24 reviews), according to the research criteria presented in Tab. 1. The keywords used were included in a non-exclusive way, also considering the use of the particle "OR", to recover all the possible articles in the set of expressions with a direct link in the theme in question. Among the selected articles the English language was predominant (521 documents), with few exceptions (6 Chinese, 1 French, 1 German, 2 Japanese, 1 Portuguese, and 1 Russian). The metadata of the searched articles was retrieved in BibTeX (.bib) format and then converted to an Excel spreadsheet format (.xlsx). The search criteria considered the period between 1945 and 2019 in the WoS bank and between 1960 and 2019 in Scopus, where the lower dates are related to the limits of the indexers themselves. Thus, both indexers returned records from 1990 onwards.

Tab. 1 Data recovery configuration details.

Data source	WoS	Scopus
Search by topics	("Process-based model" OR "process based model" AND Forest) AND (Forest OR "light use efficiency" OR Tree OR Forestry OR Pinus OR Silviculture OR *Eucalyptus*)	
Document types	Article or Review	
Languages	All languages	
Time span	1945 to 2019	1960 to 2019
Retrieval time	1992 to 2019	1989 to 2019

We obtained the return of 1,114 articles in the search in both databases. Duplicate records were verified (Wang et al., 2020) and removed in the filtering process and data organization, resulting in 764 articles. Then we applied the "abstract screening" technique, which enhances the reliability and validity of research results (Shonhe, 2020), and the reading of the abstracts of each article returned in the research is performed. In the end, we selected 533 articles considered relevant for the development of the study, according to the scheme presented in Fig. 1. The other 231 articles made analogies to themes that were not the object of evaluation of this study; therefore, they were discarded.

With the final database, the following analyses were performed using the metadata of each article: (i) quantitative analysis of the annual scientific production; (ii) the journals that publish the most on the subject; (iii) the most productive authors and with the highest h-index; (iv)

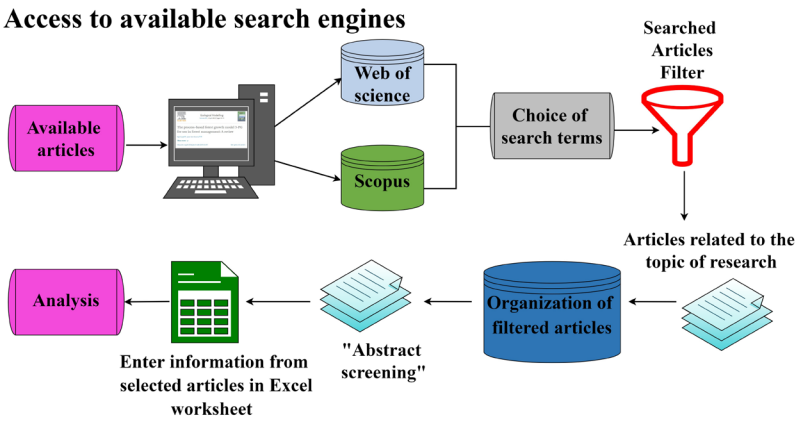

Fig. 1 Steps to perform the selection of the articles used in this research.

geographic distribution of the studies; (v) co-authorship analysis among the authors; and (vi) analysis of co-occurrence and clustering of keywords.

RESULT AND DISCUSSION

Database characterization

The 533 articles used were published in 161 different journal sources and involve a total of 1,726 authors (Tab. 2). Among these articles, there are 15 individual authors and 1,711 authors have collaborated among themselves on other works. The review articles are a minority (4.5%) compared to the other published articles (95.5%).

Annual scientific production

Despite the inter-annual variations, quantitatively the publications on PBMs showed a trend of linear increase, with an average of 4.4, 18.2, and 30.7 articles published per decade analyzed. The decisive impulse in the increase of publications on PBMs occurred in the mid-2000s. The first record of the use of PBMs in forestry studies occurred in the 1990s (Fig. 2). This study was published by Mcmurtrie et al. (1990) with an approach to the Pinus Radiata species.

Mcmurtrie et al. (1990) described the PBMs called BIOMAS and tested the impact of silvicultural treatments, thinning and fertilization, combined with solar radiation absorption and water availability for tree growth. The interaction between these factors presented answers on how the carbon was allocated in the trees and, consequently, in their growth.

From Fig. 2, it was noticed that there were fluctuations between the number of publications. After 1990, it was observed production peaks in the years 2000, 2002, 2006, 2008, 2010, 2014, 2017, and 2019. Besides that, there was steep drops in production in 1991 (no publications), 1999, 2003, 2007, 2012, and 2018.

In relation to scientific production and the year in which the studies with the use of PBMs in the forestry sector began, particularly in the 1990s, when analyzed in the environmental context of the time, they presented a possible relationship with the occurrence of important global environmental agreements and conferences, particularly with regard to the use of PBMs in ecological and environmental studies. In addition, other advances in computational capacity at the end of the last century also facilitated the handling and storage of large databases.

Global research in the forest sector using PBMs aimed at quantifying, for example, carbon flux in different forest ecosystems, was developed after the 1990s, as in the case of the models BIOME-BGC (Running and Hunt, 1993), CENTURY (Parton et al., 1993), INTCARB (Song and Woodcock, 2003) and FORCCHN (Yan and Zhao, 2007).

Distribution of journals

Research on the use of PBMs in forestry studies has been published in 161 international journals, with an average

Tab. 2 Main characteristics of the database.

Main Information	Explanation	Results
Sources	The frequency distribution of sources as journals	161
Keywords Plus	Total number of phrases that frequently appear in the title of an article's references	2958
Author's Keywords	Total number of keywords	1543
Return period of articles	Years of publication	1990 – 2019
Average citations per article	Average number of citations in each article	39.44
Authors	Total number of authors	1726
Documents per Author	Average number of documents per author	0.309
Authors per article	Average number of authors in each document	3.24
Co-Authors per article	Average number of co-authors in each document	5.11
Collaboration Index	The ratio between as the total number of authors of multi-authored articles and total number of multi-authored articles (Elango and Rajendran, 2012)	3.31
Article	Total number of articles	509
Review	Total number of reviews	24

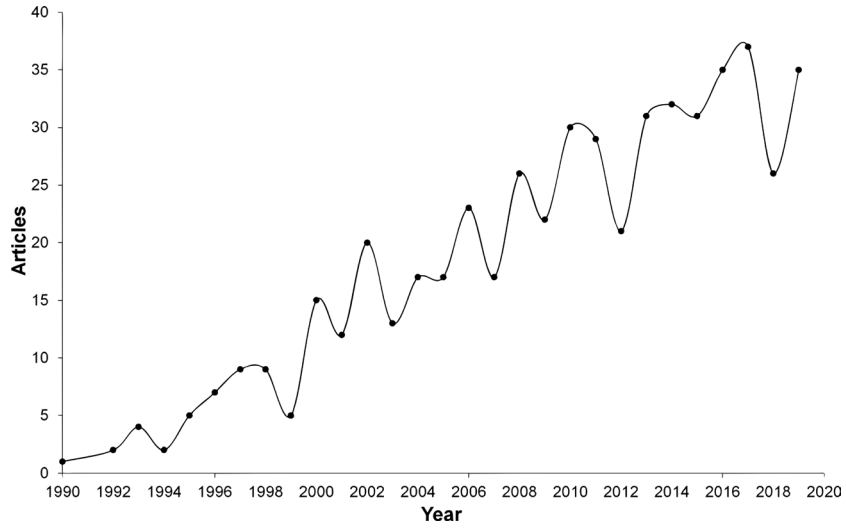

Fig. 2 Absolute number of annual scientific publications related to the PBMs.

of 3.31 articles per journal. Forest Ecology and Management (74 publications, h-index: 29), Ecological Modelling (50 publications, h-index: 22) and Global Change Biology (24 publications, h-index: 21) were the most published on the subject under study, representing approximately 28% of total publications (Fig. 3).

Research distribution among journals is decentralized according to the focus of the study in question. This occurred due to the wide employability of PBMs in forest studies, which can be used in ecological and environmental research (Sanchez-Salguero et al., 2018; Xu et al., 2019), with emphasis on forest production (Oliveira et al., 2018; Thomas et al., 2018) or on the optimization and management of forest resources (Ferreira et al., 2016; Venturas et al., 2018).

Authors' analysis

The distribution of publications over the years of the main authors using PBMs in forestry studies is presented in Figure 4. The size of the circle is linked to the number of articles published by each author and the color refers to the total citations each author had, both on an annual scale. Author Annikki Mäkelä (20 publications, Finland) was the most published, followed by Guerric Le Maire (16 publications, France), Michael Battaglia (14 publications, Australia), and Richard H. Waring (14 publications, USA).

Analyzing the author A. Mäkelä, we have observed publications since 1997, in which she is the corresponding author in five articles, the others are co-authored productions. Among her works, it is worth mentioning the studies focused on the *Pinus genre*. The author G. L. Marie started productions in 2005, is the corresponding author in three articles, and presents constancy in his publications since 2012. Among his surveys, the studies for the *Eucalyptus* genus stand out. As well as G. L. Marie, the author M. Battaglia presented studies for the *Eucalyptus genus*. He is the corresponding author in six articles and his publications started in 1998. The researcher R. H. Waring published for the first time in 1997, and is the corresponding author in six articles. His studies stand out for using the PBMs coupled with information from remote sensing; and part of his studies are focused on conifers.

It was observed that scientific production among the most productive authors in the PBMs approach gains

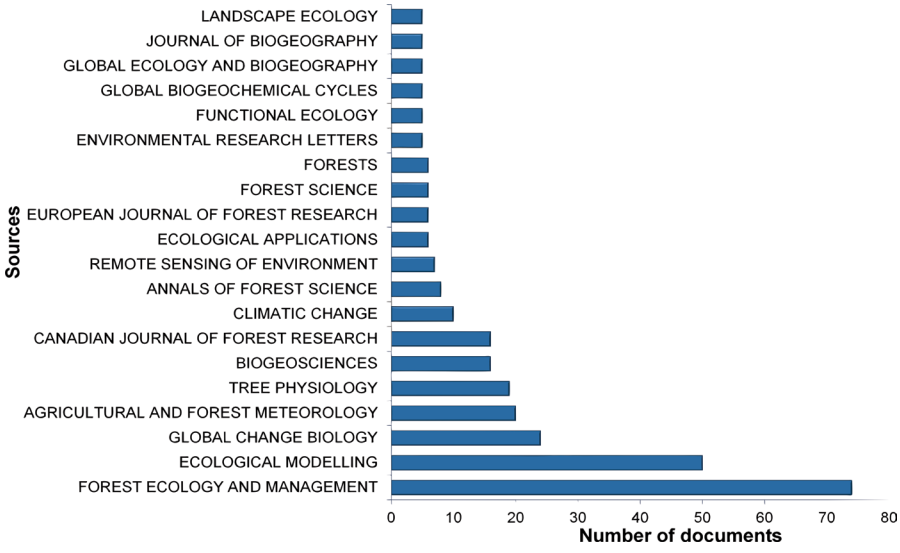

Fig. 3 Absolute number of publications (x-axis) related to PBMs per journal (y-axis).

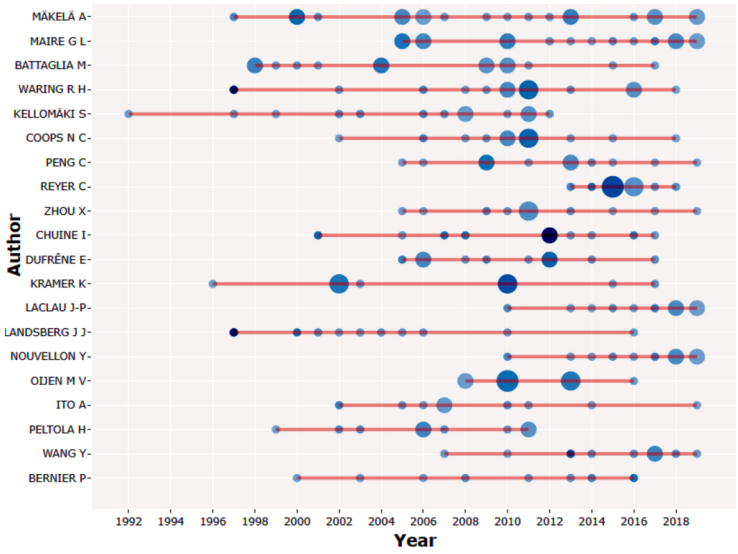

Fig. 4 Main authors with publications related to PBMs over the last 27 years, from 1992 to 2019.

emphasis from the beginning of the 21st century, with a greater grouping of individual production between the years 2008 to 2017, with dispersions upwards and downwards (Fig. 4), in accordance with the total annual production chart (Fig. 2).

In addition to performing analyses on which authors are the most productive, it is important to evaluate the quality of scientific productions on the subject under study. For this, the h-index proposed by Hirsch (2005) is used, as it is an index that combines the number of publications and the number of citations of a publication (Fig. 5).

It is possible to observe that A. Mäkelä (h-index: 13), R. H. Waring (h-index: 12), and S. Kellomäki (h-index:12) are, in this order, the three most cited authors, and as already observed in Fig. 4, they are among the five most productive authors. This analysis is important to evaluate the relevance of the research of scientists that are highlighted.

Geographical distribution of studies

The USA (131 records), France (72 records), Australia (67 records), China (62 records) and Germany (56 records) are among the countries that have most published on the subject (Fig. 6). Together, they contributed approximately 73% of the total number of publications. In addition to the U.S. leading research on forest data modeling using PBMs, they have led other research focused on studies involving forests and the environment, such as studies on forest entrepreneurship (Mourão and Martinho, 2020), forest carbon sequestration (Huang et al., 2020) and ecosystem services (Zhang et al., 2019).

Another important aspect is the dissemination of knowledge and research around the world (Fig. 6). For developing countries, such as Brazil, this knowledge exchange is relevant. Because, in the global context, the research centers of developed countries present characteristics of rapid change and transformation in the search for solutions to social or productive problems. And to this end, they seek to increase scientific and academic production (Rezende et al., 2017). This exchange of knowledge can be justified by the fact that in recent decades several countries have sought to build international partnerships between universities and renowned institutions from different countries (Pfotenhauer et al., 2016).

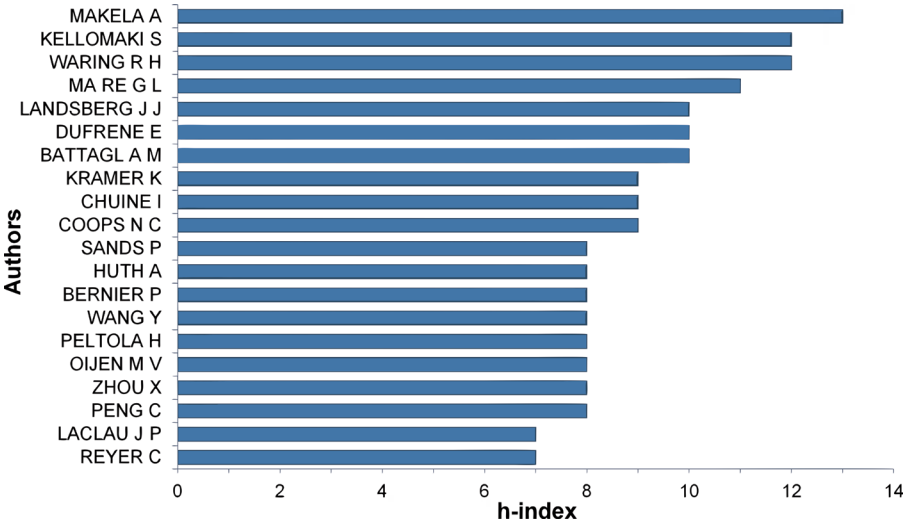

Fig. 5 Distribution of authors (y-axis) associated with the number of the h-index (x-axis) of each author.

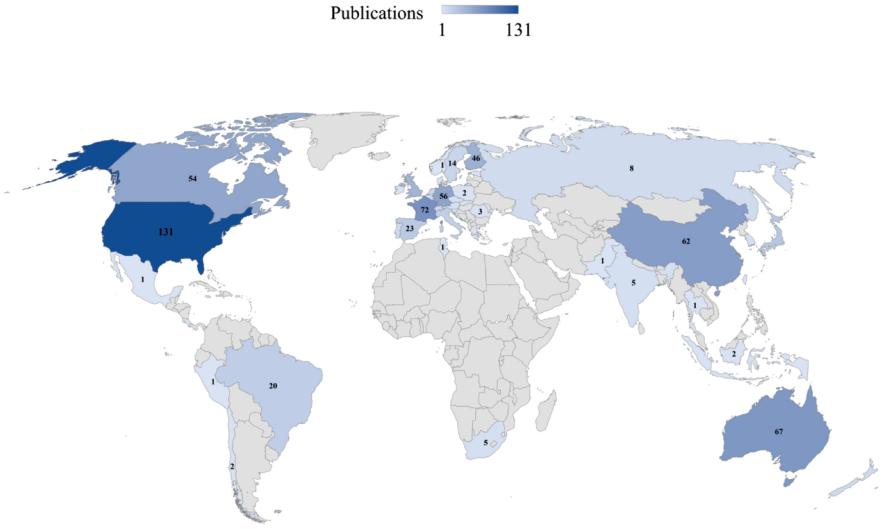

Fig. 6 The geographical distribution of the origin of the publications considered in the study. The numbers and the color scale represent the number of publications per country, counting one work for each country of the authors affiliated to the article.

In Fig. 7, we can confirm the importance of universities in the development of forestry research with the use of PMBs. Because by analyzing the flow patterns between the institution responsible for conducting the research, the most productive authors and/or those with the highest h-index, and the keywords of the publications, it is possible to observe the expressive presence of universities in the development of forestry research using the PBMs. Among the 18 research institutes presented, 13 are university centers.

The keywords most cited by the 20 most productive authors and/or with the highest h-index are process-based model (cited by 19 authors), climate change (cited by 13 authors), and carbon balance and forest management (both cited by 9 authors) (Fig. 7). This result lists the focus of PBMs use in the research that has been carried out by them, and reinforces the concern of researchers on the effect of climate change on forested areas.

The plurality of the authors' research pattern was verified in relation to the research themes (Fig. 7). The authors (central column), are associated with multiple keywords (right column). For example, the author A. Mäkelä shows great participation in the production of scientific knowledge in the field of PBMs, and this author is associated with the University of Helsinki, although, in a smaller flow of occurrence, she also presents connection with other lines of research, as observed in the diagram. In the graph, the size of the rectangles is proportional to the number of authors' publications, with emphasis on keyword research and the amount of production in a given institution, depending on the column under analysis. The width of the lines is proportional to the inclusion index among the connected themes.

Collaboration Network authors

We analyzed the relationship between published research and the number of co-authored productions (Fig. 8). It is possible to notice the grouping of the main researchers into eight groups. Each node in the network represents an author and the link between the nodes represents the collaboration between the authors, that

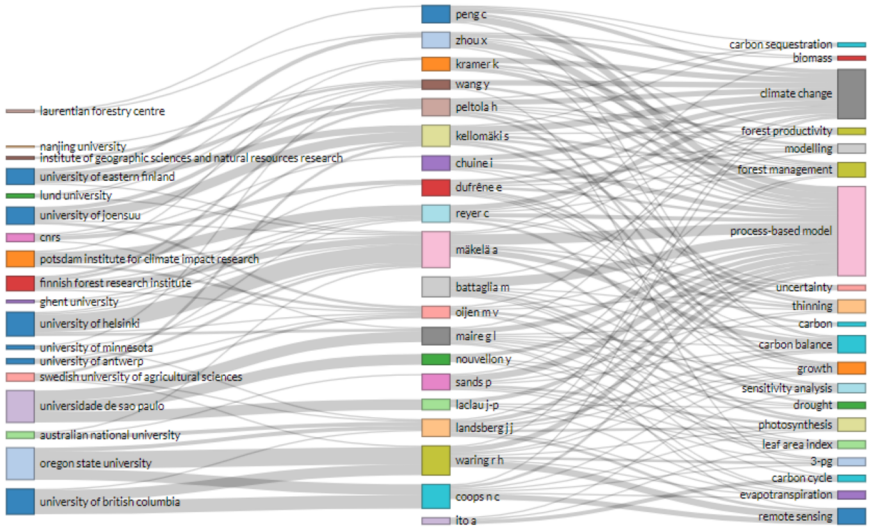

Fig. 7 Network visualization map based on bibliographic data between authors, research institutions and keywords.

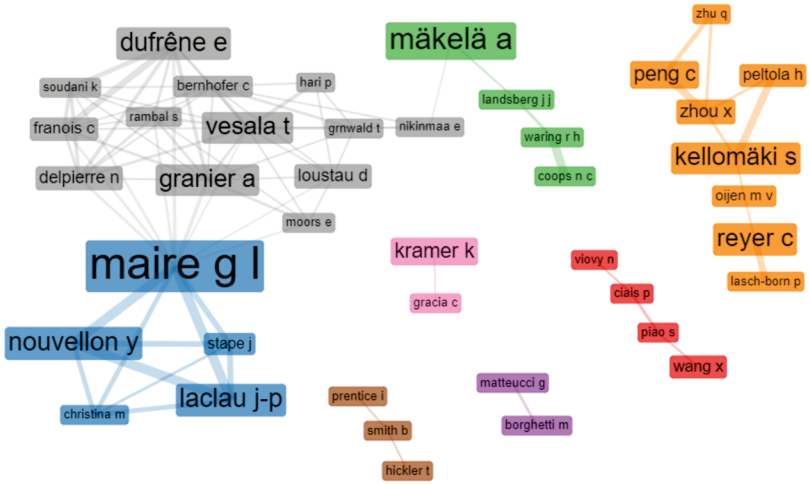

Fig. 8 Network visualization map based on bibliographic data co-authorship among authors.

is, if one of the authors has a co-author relationship, it means that there is a connection between the two nodes in order n, and the size of the nodes reflects the frequency of collaborations. In addition, authors close to each other in the collaboration network (Fig. 8), are considered those who are influenced by each other or who present some degree of thematic interaction. The connection lines indicate the range of values of the collaborations, that is, the thinner-thickness radial represents a smaller number of collaborations. The thicker radial represents a greater number of collaborations.

Among the eight groups formed, the subnet (*i*) green demonstrates the author A. Mäkelä with the largest number of co-authored publications with three other authors from the same scientific approach group. In cluster (*ii*) blue, author G. L. Marie appears in the collaboration stream as the most productive author. It is interesting to note that the two main authors have links with two different research groups. This leads to the belief that the relevance of their group's publications attracts partnerships with other researchers interested in the same topic and who until then belonged to the other contribution network. The other clusters (*iii* - brown, *iv* - pink, *v* - red, *vi* - lilac and *vii* - orange), present themselves as groups producing separately among their authors, without necessarily being in connection and collaboration with the other groups.

Keywords, Themes and PBMs applications

The co-occurrence analysis of the authors' keywords in the articles used in this research is fundamental and serves to highlight the main research themes in a given field of analysis and filter the main messages of an article (Martinez et al., 2019). Thus, Fig. 9 represents the main topics within the field of study.

The main fields of studies were grouped into five clusters, visually differentiated by means of colors (Fig. 9). Keywords portraying climate change and its effect on forests are highlighted in the orange cluster. This cluster contains the word 'process-based model' and 'climate change', as the most significant of the cluster, connected with the words 'forest management', 'leaf area index', 'forest productivity', 'eucalypt', 'uncertainty', 'carbon sequestration', and 'drought'. The blue cluster represents carbon-related research related to 'model', 'modelling', 'growth', 'competition', 'phenology', and 'evapotranspiration' forming this cluster. The lilac color cluster consists of keywords related to the physiological processes of trees (biomass, respiration, photosynthesis and carbon balance). The red cluster is associated with activities related to silvicultural treatments, formed by 'thinning', 'scots pine', 'Pinus sylvestris', and 'boreal forest'. Finally, the green cluster reports on the analysis of the uncertainties related to the estimates of forest data using PBMs, namely 'sensitivity analysis', 'uncertainty analysis', 'carbon cycle', 'remote sensing', and '3-PG'.

Also, according to the co-occurrence analysis of the authors' keywords (Fig. 9), we can observe that among the vast availability of PBMs that the 3-PG (Physiological Principles Predicting Growth) model developed by Landsberg and Waring (1997) is one of the most widely used PBMs in forestry research. In such a way that advances were made regarding this PBMs, with the development of its successor, the model 3-PGS (Physiological Principles in Predicting Growth with Satellite) that integrates spatial information in the process of estimating biophysical variables in forest research (Gupta and Sharma, 2019).

As for the separation of themes, the strategic diagram presented in Fig. 10 shows a distribution of those that are more usual in forest studies using the PBMs, and are divided into four quadrants. The interpretation of this diagram follows the works of Cobo et al., (2011) and Lam-Gordillo et al., (2020). Thus, the first quadrant, the upper left, contains the themes that are highly developed and specialized (as in the case of the studies on thinning and photosynthesis). In the lower left quadrant, it is equivalent to the emerging themes, such as biomass, and it is observed that 'carbon sequestration' is on the rise, so it presents itself in transition between the quadrants of the left region.

In the upper right quadrant, the authors found the well developed and important themes, also called engines, because they are of extreme importance for the structuring of the research field (the PBMs and forest management). In the lower right region, important themes are found, however, little developed, called basic themes. We observed that the theme 'remote sensing' is growing and is located

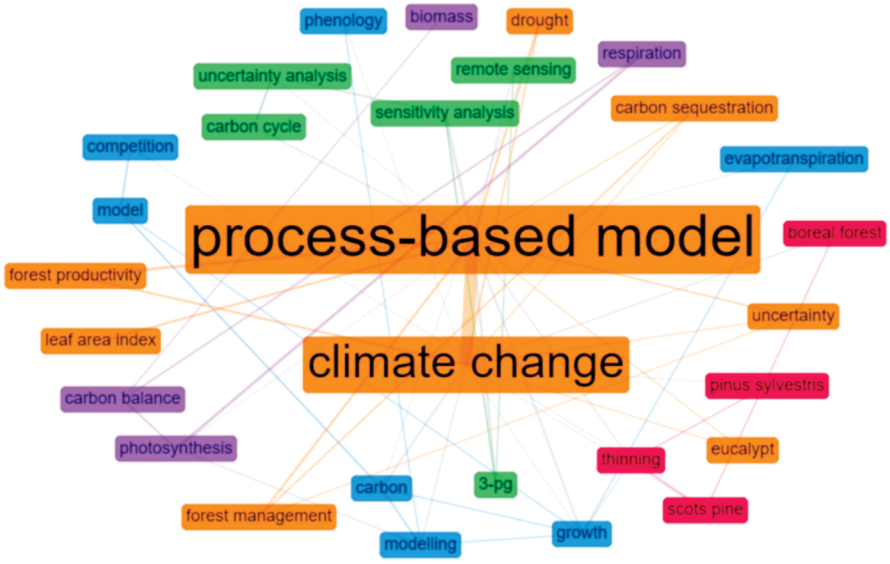

Fig. 9 Co-occurrence Network based on Authors's Keywords.

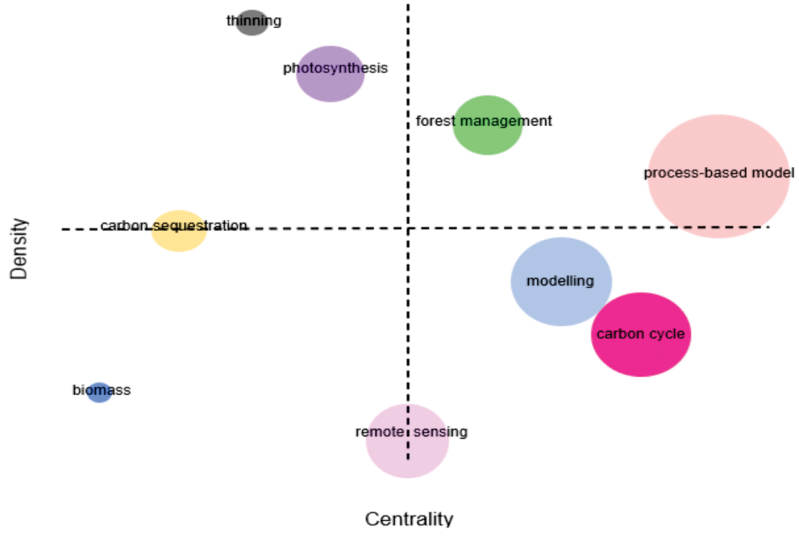

Fig. 10 Strategic diagram with the distribution of the most common themes in studies using the PBMs.

between the lower quadrants, because it is a field of basic research because it is methodological, but it is in a phase of development and advances in deep learning, associated with PBMs (Yuan et al., 2020).

Therefore, taking into account the information provided in these analyses, it was found that most of the literature returned in the research on the application of PBMs in forest studies has addressed with greater emphasis the ecological factors of forested areas, seeking to simulate the effect of climate change on different tree processes and the quantification of the carbon balance.

CONCLUSIONS

The use of PBMs in forestry research has shown a growing trend in their development over the years. At least three journals have stood out from the others regarding the total number of publications, and the developed countries in the world are the ones that most conduct research with the use of PBMs in forestry studies. The analysis of the themes demonstrated that thinning and photosynthesis are highly developed and specialized themes and that the new research hotspot focuses on the use of remote sensing techniques.

The keyword groupings revealed that studies on the effect of climate change on forests, in addition to research on carbon, tree physiology, silvicultural treatments, and the analysis of uncertainties using PBMs are the most widely used keywords. It is noted that research using PBMs applied to forest studies requires special attention from stakeholders: researchers, forest managers, and public policymakers. PBMs are a type of data modeling that has an extended application and has improved the incorporation of new technologies in its development methodology base. It is an important technique for quantifying sustainability and the effect of climate change on natural forests worldwide. It serves as a bridge of understanding of environmental interactions and in the development of simulations of complex forest processes.

Therefore, this proposed bibliometric analysis was exclusively at the quantitative level; thus, no analysis of the content of the works was performed, leaving this field of research open with the possibility of developing new complimentary revisions in a more in-depth way in the content of articles and state of the art of the central theme.

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