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Review Article

Forest landscape planning and management: A state-of-the-art review

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ABSTRACT

Visual environmental aesthetics as a combinatorial output of a mathematical model can enhance public acceptance of forest activities and increase the perception of sustainability of forest enterprises. This article provides a comprehensive review of the state of the art in landscape management in forest areas worldwide. In forest planning, little research has examined how the visual impact management on wood production can be compatible with the economic viability of forest enterprises. With this review, we seek to contextualize the problem, listing the challenges, trends, and advances achieved recently. The first part of the review is devoted to considerations about the following: (i) landscape management in forested areas, with a history of the landscape planning in major global regions; and (ii) spatial forest planning, including operational research, forest optimization, and GIS to solve problems at the landscape scale. In the second part, we present a bibliometric survey to statistically examine the growth of the landscape planning between 1980 and 2021. The number of studies related to the topic has increased, especially in the last decade. North America and Europe are the regions with the highest scientific production in forest landscape planning and management. There is still little research dedicated to landscape management in commercially planted forests. The approach in the form of spatial structure, considering the inclusion of multi-objective restrictions and functions, is a desirable evolution in the planning and management of sustainable forest plantations.

1. Introduction

According to the Global Forest Resources Assessment (FAO, 2020) and the Global Forest Goals Report (United Nations, 2021), the world forest cover is about 4.06 billion hectares, and the natural forests cover 93%, or 3.7 billion hectares. The total area of planted forests globally is estimated at 294 million ha, representing 7% of the world's forest area. The commercial area of forest plantations spreads worldwide to supply the global demand for wood, fuel, and cellulose (Heilmayr, 2014). Unfortunately, the side effects on native forest areas (Liu et al., 2018) and ecosystem services (Paruelo, 2012) are large and may lead to homogenization of their structure (Bird et al., 2000). These natural areas also have great importance for ecological functions such as landscape connectivity (Cabarga-Varona et al., 2016), carbon sequestration, biodiversity (Vihervaara et al., 2012), water provision, and soil conservation (Dai et al., 2018). However, there are positive examples of forest management operations (Liu et al., 2018) with significant advances in global forestry and forest conservation (Begotti et al., 2018; Tavares et al., 2019; Pliscoff et al., 2020), forest fire damage (Lauer et al., 2017), and landscape conservation (Daniel and Schroeder, 1979; Angelstam et al., 2020). Forest management enables the use of degraded, unproductive, and underused land, usually unsuitable for agriculture (Rode et al., 2014; Guedes et al., 2018). Sustainable silvicultural practices are important to mitigate climate change, soil damage, and ecological losses (Jack and Long, 1996; Fonseca et al., 2009; Vides-Borrell et al., 2019). In addition, there are social and economic advantages for landowners and industries (Nambiar, 2019).

The policy and management of land use is a complex issue for government and private landowners due to the fact that forest projects are usually extensive. The monitoring process demands a high financial

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investment to guarantee legal compliance. An example of this type of effort is seen in Brazil's Rural Environmental Registry, or CAR (in Portuguese), which has a concise database of all rural properties (Jung et al., 2017) for environmental and territorial planning (Roitman et al., 2018). However, traditional log production focuses on reduced cost and maximum revenue, which is disconnected from the landscape's sustainable use context (Ewald, 2001). From the other end of this practice, society are looking for ecologically sustainable products and, as a consequence, forest managers are planning to consider multi-objective criteria (Bettinger and Sessions, 2003; Baskent and Keles, 2005), such as water pollution (Hughes and Quinn, 2019), soil erosion and losses (Fulton and West, 2002), biodiversity (Carnus et al., 2006), connectivity among forest reserves (Augustynczik et al., 2018), socio-ecological aspects (Fischer, 2018), recreational spaces, and the esthetic aspect value of the landscape (Panagopoulos, 2009).

Landscape modeling and optimization are promising areas of research (Kaya et al., 2016) and can lead to better production in the timber industry (Liu and Lin, 2015), considering stand spatial arrangement. In this sense, selecting species or clones within the site provides improvements in forest management efficiency (Fischer et al., 2019). The monodominance of a single species or clone is undesirable due to its lower resistance to diseases, often in the form of homogeneous mosaics (Martins et al., 2017).

The current paper presents a contextualization of the state of the art in landscape management in forest areas from the perspective of spatial forest planning. The main motivation of our work is the assumption that the esthetic value as a combinatorial output of a mathematical model can enhance public acceptance of forest activities and increase the perception of sustainability of forest enterprises. In this review, we also seek to establish a reflection on the use of more fragile landscapes and less productive sites to maximize landscape values and wood production and strengthen indicators of forest certification.

Recent studies have raised some important and frequent questions about this topic. Rönnqvist et al. (2015) have listed 33 open forest problems in operations research, including the challenge of modeling and solving spatial problems in harvesting, transport, roads, and wildlife conservation. De Pellegrin Llorente et al. (2017) present a set of spatial considerations in planning forest management focused on wildlife habitat, invasive species, and harvesting operation costs. Baskent et al. (2020) dedicated a state-of-the-art assessment of ecosystem services applied to forest management planning. We believe that our study answers undiscussed questions in these previous studies and contributes to building bibliographic knowledge still scarce on some points of this theme.

Some spatial forest planning problems are open and still theoretical, especially those aimed at achieving aesthetically pleasing and economically viable forests. In this study, we highlight a gap in the need for real commercial cases that assess the return on profits and economic benefits when investing in landscape and ecosystem attributes for timber production. These issues may be essential for companies and forest managers facing forest certification practices. Our study is one of the few in that it compiles a state-of-the-art assessment and bibliometric survey on spatial planning to obtain aesthetically, environmentally, and economically viable forests at the landscape scale. Bettinger and Chung (2004) report in a bibliographic survey between 1950 and 2001 that timber production and economic objectives still dominated the periodical article themes, but that despite this, forest management evolved with the inclusion of non-timber objectives. Shan et al., (2009) also report that in addition to economic and commodity production objectives, the proportion of ecological and social concerns in the objective functions of mathematical models increased notably. Obviously, there are many other important and interesting areas and questions that we have not included.

Part 1 presents a Literature Review aimed at tracing a baseline of forest science, industry, and sustainability considering the principles of forest landscape sustainable usage practices. Firstly, we report and contextualize the forest landscape management problems, challenges, trends, innovations, and scientific advances of the last decades. The review covers the world statistics of global forests, forest plantations, production, planning, decision support systems, landscape ecology, heuristics, meta-heuristics, and geospatial solutions.

In the second part of this paper, we provide an extensive review of worldwide qualitative and quantitative indices. We sought to answer the following questions: (1) what is the history of studies on forest landscape management? and (2) what strategies and techniques are used in different fields of forest landscape management research? Deep literature research is often applied to understand emerging trends (Huang et al., 2020), differently from traditional bibliographic research (Merediz-Solà and Bariviera, 2019). The bibliometric method is robust enough due to the mathematical and statistical metrics applied (Ball, 2018; Uribe-Toril et al., 2019), offering valuable indicators of global scientific research (Aleixandre-Benavent et al., 2017) and forestry research in recent years (Bonnel, 2012; Bullock and Lawler, 2015; Mourão and Martinho, 2020).

2. . Databases and research methods

Several indices from a set of journals and papers are available online, and they store thousands of millions of pieces of information regarding scientific advances. The most cited database research engines available are Scopus and Web of Science (WOS), with high-quality data and citable references (Mongeon and Paul-Hus, 2016; Guz and Rushchitsky, 2009; Huang et al., 2020). We outline this search to meet the connections among concepts, methods, countries, and authors based on scientific knowledge. The search interval was from 1980 to 2021.

Initially, we conducted a bibliographic search focusing on research papers containing the matched keywords: (*i*) "world forests"; (*ii*) "forest resource management"; (*iii*) "forest landscape management"; (*iv*) "visual landscape management"; (*v*) "spatial forest planning"; (*vi*) "forest regulation"; (*vii*) "spatial constraints"; (*viii*) "adjacency constraints"; (*ix*) "scenic quality and forest aesthetics"; (*x*) "wildlife conservation"; (*xi*) "green-up"; (*xii*) "geographic information systems," and (*xiii*) "spatial harvest scheduling". Later, we complementarily searched for institutional repositories, conference notes, specialized websites, and government reports.

Given the extensive document list, we divided the review into two parts: (1) a review addressing the themes of (a) global forest landscape management and (b) spatial forest planning with applications in forest landscape management; and (2) the bibliometric analysis. Zhao and Strotmann (2015) methodology was applied for bibliometric analysis, highlighting the most impactful studies and research topics. It combines (*i*) the definition of search keywords; (*ii*) data cleaning, filtering, and formating; (*iii*) preliminary analysis to ensure study compatibility; and (*iv*) statistical data analysis.

Finally, we used bibliometric analysis as a systematic review using the term search rule: TS = "forest planning" OR "spatial forest planning" AND "forest landscape management" OR "forest visual landscape management" OR "forest aesthetics" AND "spatial constraints" OR "adjacency constraints" OR "green-up" OR "gis" OR "operational research." The quotation marks guarantee the accuracy of the records managed by the bibliographic services for the exact expression. The keywords were included in a non-exclusive way, using the "OR" operator to retrieve all possible articles. We considered the period between 1980 and 2021 in the WoS and Scopus databases as search criteria. We also filtered searches for data articles and reviewed articles only in the English language in the following categories: Forestry, Remote Sensing, and Computer Science. We intended this bibliometric analysis to help recognize studies directly focused on spatial planning for landscape-scale management. To avoid inflating the search results, we did not address keywords associated with more specific themes. The documents obtained are unique, with no replicas containing an identification number in the database collected using BibTex format for RStudio version 1.2.5033

(RStudio Team 2019). The network patterns visualization uses the Bibliometrix R package (Aria and Cuccurullo, 2017), the most practical and comprehensive tool for scientific mapping (Camarasa et al., 2019). In addition, the Biblioshiny web interface application (Aria and Cuccurullo, 2017) was the tool used to generate the graphics and tables of the bibliometric survey.

3. . Result and discussion

3.1. . An overview of global forests

The world forest surface is about 4.06 billion hectares smaller than 25 years ago (FAO, 2020). Natural forests cover 3.7 billion hectares, and planted forests are nearly 294 million ha (United Nations, 2021) (Fig. 1). Planted forests have increased by over 123 million hectares since 1990 (FAO, 2020). Despite this, planted areas in East and Southeast Asia, North and South America, and Europe decreased by 1.2% between 2010 and 2015 (FAO, 2015; FAO 2018, 2020). However, this value is lower than the 2.4% necessary to supply the global demand for wood and fibers (Payn et al., 2015). South America's planted forest estimates have risen to 26.7 million hectares by 2050 (McEwan et al., 2019). Tree growth rates and land costs affect their expansion significantly. In general, the mean annual increment is 3 to 4 times in the southern hemisphere compared to the north (Siry et al., 2005; McEwan et al., 2019). East Asia and Europe have reached the largest planted forest areas, followed by North and South America and Southeast Asia. China has 91.8 million hectares of planted forest area, the United States has 26.4 million hectares, the Russian Federation has 19.8 million hectares, and Canada has 15.8 million hectares (Payn et al., 2015). Brazil reached 9.0 million hectares (2019) while 6.97 million hectares of *eucalyptus* species had 35.3 m^3/ha./year (IBÁ, 2020). More details on tree growth patterns can be found in Schulze et al. (2019).

The forestry sector has a relevant contribution to the world's trade and economy. Social impacts are also positive, employing over 18.21 million people directly and another 45.15 million indirectly (Li et al., 2019). In addition, the sector's gross world product (GWP) was $ 1298 billion (Li et al., 2019). Recently, the United Nations 2030 Agenda for Sustainable World Development (United Nations, 2015) highlighted the economic growth, quality of social life, and environmental sustainability under forest system production in various ways (Li et al., 2019). Concerns about sustainability are increasing, which has been incorporated into policymakers' agendas and corporate strategies. The term "sustainability" itself and its conception have their origins in forestry (Geissdoerfer et al., 2017). Based on forestry principles, the amount of harvested wood must not exceed the growth rate in volume units. This postulate dates back to the beginning of the 18th century and is from "Sylvicultura Oeconomica" (von Carlowitz, 1713).

Managing forests for multiple purposes is the challenge of the 21st century (Burger, 2009). Several forest products are associated with a range of wood and non-wood services from extensive areas across the landscape (Pretzsch et al., 2015). Generally, these areas affect the pools of carbon storage and balance (Winjum and Schroeder, 1997). Moreover, forest managers may have to simultaneously work on wood production, energy, recreation, biodiversity, flood control, water quality, and wildlife habitat protection. There are many desirable reasons for considering a mixed-species plantation, which include ecological benefits (Scherer-Lorenzen et al., 2005), arid and semi-arid soil conservation (Gong et al., 2020), and increased soil diversity, structure, and their natural function (Pereira et al., 2019). This system holds many vital ecosystem functions and services and has been preferred to single-species plantations (Pretzsch and Schutze, 2014), although it is not economically viable for global demands on a large production scale.

The challenges for forest management worldwide are directly related to new regional demands and integration with technological innovations. Forestry companies have been diversifying and expanding their portfolios through the addition of new non-timber forest products

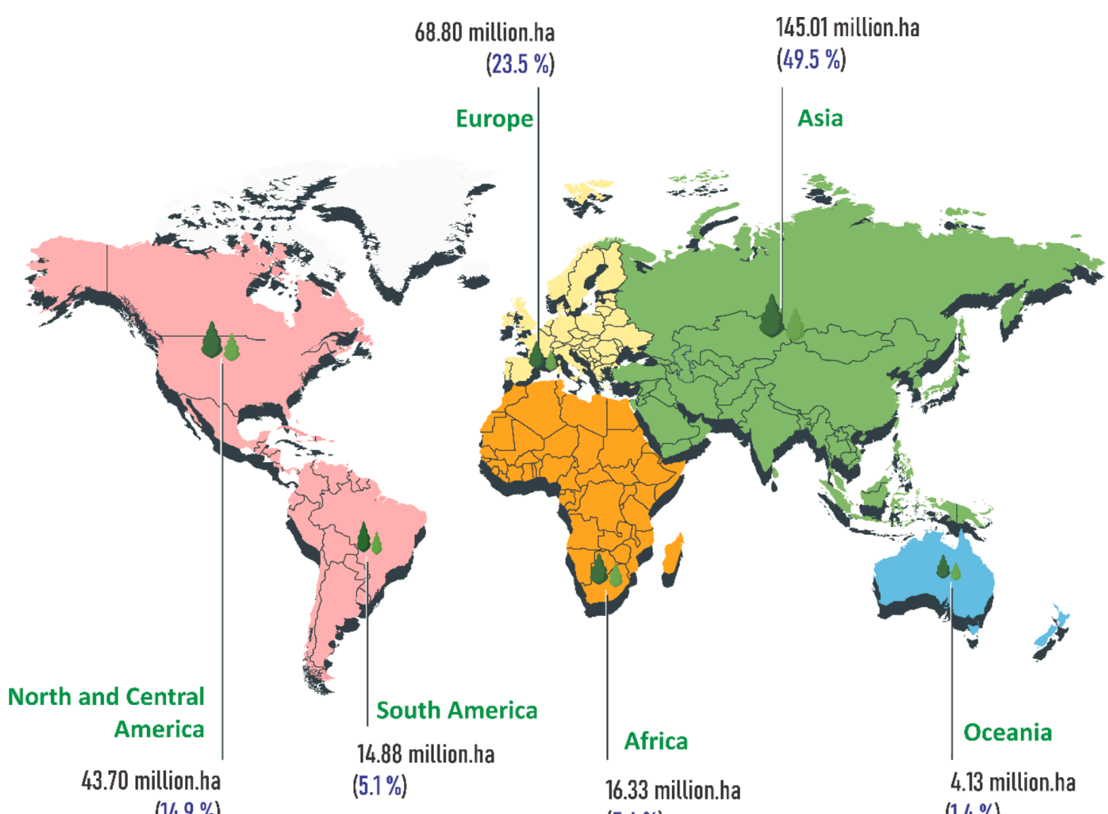

Fig. 1. World forest plantation by region and countries (adapted from FAO, 2015; FAO, 2020).

and services (Zivojinovic et al., 2017); cellulose and paper industries are investing in biorefineries for commercial residual usage (Lynd et al., 2017; Mandeep et al., 2020); tree clones are pest-resistant and disease-resistant, with optimized water use and a high growth rate (Bouvet et al., 2020); decision support systems and big data for better choices in forest planning (Bettinger et al., 2017); and currently, automated machines for forest transportation are getting involved, especially for future work (Rien and Francis, 2021). Forest harvesting operations in the restricted area adhere to sustainable forest management principles (Marchi et al., 2018; McEwan, 2019).

3.2. . A complete link between the landscape and the forest

Large-scale design and landscape practices have influenced land-use planning for many decades. The British Forestry Commission had a program to overcome the straight and square lines on the slopes in the early 1960s. Previously, the project status of non-native conifer plantations was ruled for forests and woodlands in England, Scotland, and Wales (Crow, 1966). Building on British initiatives, the US Forest Service introduced a formal landscaping program in 1971 (USDA, 1974). British Columbia, Canada, introduced visual landscape management strategies in 1980, and a decade later, they emphasized the new landscape design (BC Ministry of Forests, 1981, 1994). The analysis of esthetic values at the forest planning level was published in “Landscape Management Strategies” for Alberta (Alberta, 1986). They describe rules for forest harvest planning and visual landscape resources, especially for stand design and layout forms (line, shape, pattern, size, time, and cutting systems), operations, maintenance, and monitoring. Similar concerns about the spatial structure and forest plantations were adopted in the Mediterranean region (González-Moreno, 2011).

Since the mid-1980 s, landscape planning and forest harvest operations have been connected enough at the spatial level and away from each other’s principles and goals. At this moment, the sparse published research considers the visual impact assessment of forest activities and sustainability (Panagopoulos, 2009; Ribe, 2009; Jenkins, 2018). In Ireland, for example, the public participation campaign decided the forest decision courses for timber production and recreation purposes (Kearney and O’Connor, 1993; Dhubháin and O’Connor, 2009). The social perception of forest harvest production was evaluated in the United States (Palmer, 2008) and New Zealand (Roche, 2017; Edwards et al., 2018). Generally, all these actions depend on visual quality and sustainable forest operations for rural communities (Brown et al., 2016). Vodak et al. (1985) carried out the first studies on the scenic impacts of forest management. They measured the private forest landowner’s perceptions of scenic beauty at various management regime levels. Brush (1979) also evaluated the attractiveness of commercial forests in the perceptions of forest owners in Massachusetts. Anderson (1981) pointed out the land use issues and their effects on scenic beauty in forest landscapes.

Naturally, the landscape is straightly related to the recreation and beauty scene (e.g., Europe and North America) and later absorbed by multipurpose forest management plans (Panagopoulos and Hatzistathis, 1995; Panagopoulos, 2009). Therefore, the tradeoff between production and environmental quality has started as a new forest management version. The document entitled “visual guide for sustainable forest management practices and landscape quality” (USDA, 1994) was proposed by the U.S Forest Service and contributors as a program for forest-based industries. These guidelines help ensure that timber harvesting has a minimum impact on esthetic quality through the so-called “visual quality BMPs” (Best Management Practices) (USDA, 1994). Individual states in the United States have mainly developed BMP’s as guides to forest management activities when state laws are lacking. Even before that, the United States Forest Service had already developed the National Forest Landscape Management Program (Bacon, 1979) due to public demands about forest plantation impacts. Bell (2001) reveals a detailed visual landscape analysis of public participation in forest planning.

The most ambitious works of forest landscape management are presented in “*The Design of Forest Landscape, UK*” (Lucas, 1991); the guidelines for forest design in British Lowland landscapes, UK (Bell and Britain, 1992); “*Creating and managing woodlands around towns, UK”* (Hodge, 1995); “*Visual quality best management practice, USA”* (USDA, 1994); and “*Designing sustainable forest landscape, Country”* (Bell and Apostol, 2008). Bell (1999) published a protocol study on the commercial plantations’ management in Britain. The author reveals the great local concerns about the negative impact of the extensive forest on the landscape. The work exposes new challenges for forest managers to develop new compliance and practices for reshaping commercial stands over cutting age. In Spain, for example, Cabarga-Varona et al. (2016) analyzed the importance of extensive areas with *Eucalyptus globulus* plantations as a mechanism for improving connectivity between patches of native forests. Since the late 20th century, the commercial forests of Central European countries (e.g., Austria, the Czech Republic, Germany, and Slovenia) have had multi-objective management goals based on policy and planning tools, with emphasis on the role of forest land beyond only wood production (Koch and Skovsgaard, 1999; Bončina et al., 2019). Ewald (2001) highlighted the need for landscape improvement in Switzerland.

In South America, only three countries, Brazil, Chile, and Uruguay, are working on landscape issues to guide sustainable forest management. The first country has environmental legislation (Oliveira et al., 2020) for exotic species plantations and recognizes the negative landscape impacts after harvest operations. In addition, as an example, there is an experiment called “ecological bands” that preserves native forest strips (25×500 m) within eucalyptus plantations (Fig. 2). These strips are connected by multiple-purposes such as firebreaks, fauna, and species corridors (Zanuncio et al., 2016; Vallourec, 2019). In Chile, the certified forest plantations cover around 1.5 million hectares, and the landscape quality (aesthetics and connectivity) is still incipient (Salas et al., 2016), requesting new forest policy instruments (Mery, 1996). Vihervaara et al. (2012) described some perceptions among stakeholders (industry and communities in Uruguay) on integrating land use and ecosystem services.

The Finnish government has a payment system for ecosystem services entitled “Landscape and Recreational Values Trading” (LRVT). It is a compensatory program for voluntary forest owners that adopt landscape and leisure values on their lands (Tyrväinen et al., 2014; Tikkanen et al., 2017). Mäntymaa et al. (2019) highlight the advances of LRVT applied to tourism in hotspot zones. The program conciliates a range of ambiguous goals for local economic benefits. Today, nature-based tourism is a promissory “green industry” in the European economy (Tyrväinen et al., 2014; CBI Ministry of Foreign Affairs, 2020) and forest management practices should mitigate the landscape impacts (Mäntymaa et al., 2019). A detailed description of practices on scenic and recreational values in private forests can be seen in Tyrväinen et al. (2021). For example, people tend to prefer old-mature forests with high conservation stage and short rotation practices (Gundersen and Frivold, 2008; Ribe, 2009; and Mäntymaa et al., 2018). Therefore, the rotation delays have financial and production effects on forest owners, and the government should pay or reduce taxes as a compensatory policy (Mäntymaa et al., 2019). Zabel et al. (2018) suggest a self-sustaining landscape involving a system of tax resource funds. According to Haines et al. (2019) and Fischer et al. (2019), forest fragmentation and spread habitats may be minimized in such cases.

Fig. 3 describes the common forest landscape mosaics and their visual impacts. They should be mitigated following some recommendations: (i) the creation of ecological corridors and permanent biodiversity protection areas; (ii) spatial stand arrangement and layouts (scale, size, organization, location, shape, pattern, proportion, edge, margin, texture, and road network); (iii) forest harvest limits across the relief; and (iv) heterogeneous stands of trees in terms of density, age classes, species, and structure.

Fig. 2. Ecological bands or corridors between eucalyptus plantations in Brazil. Sources: Public Summary of the Forest Management Plan – Vallourec (2020) and Arcgis online satellite imagery.

Currently, the advances in forest landscape management focus on the variable retention forestry (VRF) method, an alternative to traditional forest management (Martínez Pastur et al., 2020). According to the author, this method is widely applied throughout the world, integrating environmental, economic, and cultural objectives. Its benefits include forest biodiversity and improved harvesting operations (Gustafsson et al., 2012; Gustaffson et al., 2020). VRF is a practical effort to address global challenges related to biodiversity loss in forest areas and compensation for climate change (Shorohova et al., 2019; Franklin and Donato, 2020). In Finland, the Program for the Endorsement of Forest Certification (PEFC) and the Forest Stewardship Council (FSC) require the VRF technique application (Kuuluvainen et al., 2019).

Worldwide, forest certification increases faster due to customers' demands for sustainability, health, and socioeconomic viability (Garzon et al., 2020). The Green Tag Certified Forestry Certification Programme (American Resources, Inc., 2013) requests the esthetic quality of planted forests. Further, the FSC certification stimulates forest protection, restoration, and conservation of natural forests, including wildlife corridors, mosaics of age classes, and rotation to define the plantation layout at large scales.

The environmental issues of the landscape are the new frontier of knowledge for forest management and planning. Clear-cutting area limits and the connectivity of vegetation problems are frequently described for landscape management in the literature (Moreira and Rodrigues, 2010). The opening areas have esthetic negative impacts after large-scale harvest operations. In certain circumstances, the mathematical formulation with spatial constraints is desirable to solve forest planning tasks. Chamberlain and Meitner (2009) corroborate the increase in esthetic design quality and timber production. The authors have modeled a forest harvest scheduling problem aiming at the visual impacts.

Maximizing the esthetic environmental quality of the forest landscape is a relative action according to the criteria and objectives of companies, regions, and socioeconomic realities. These challenges can be discussed from the perspective of spatial forest planning.

3.3. . Forest planning and landscape design challenges

In this section, we address what is often applied to forest landscape management correlated with spatial forest planning techniques. Global environmental requirements have driven important changes in forest planning models. They merge spatial forest stands with wildlife habitats, scenic beauty, soil conservation, and water protection (Weintraub and Murray, 2006). These interactions are constrained by a range of problems involving stand shape, management regimes, adjacency, maximum and minimum opening sizes, connectivity to natural ecosystems, landscape fragmentation, and road problems. Spatial or landscape structure refers to the relative spatial arrangement of patches and interconnections between them (Baskent and Keles, 2005), and spatial forest planning is conceptualized as a solid forest modeling approach that accommodates spatial requirements and various management objectives. According to Boyle et al. (2016), the sustainable silviculture conception has disseminated in forest industries motivated by ecological issues. In addition, the new silvicultural practices have incorporated social-ecological aspects within forest management regimes. Changes in forest management prescription quickly outdate the operational level and reduce the landscape impacts. However, the early conception of forest regulation provides a sustainable principle for forest management and planning.

Linear programming can accommodate forest management problems that have wood flow and sustainability concerns, with one of the first works applied to forestry published by Curtis (1962). In general, there is a linear programming model to solve the forest regulation problems by defining the harvest scheduling and future management practices (Hennes et al., 1971). Therefore, the results are integrated for wood supply and silvicultural tasks. Roth (1914) reinforced the challenge faced by forest regulation not only to order the forestry work in time and space with the stands' planting or reform, but also to plan an orderly harvest, road construction, and environmental conservation. It requires an appropriate distribution of forest ages, yield, size, and wood quality (Leuschner, 1990). There are two classical models widely applied to solve the wood supply chain described by Johnson and Scheurman (1977). Type I and Type II models were used to portray the forest

Fig. 3. (A) Illustration of the visual impact of forest harvesting in a sloping area; (B) Area with a harvested forest cover generating great scenic impact; (C) Forest area also harvested with little regard to local topography compliance in Scotland; (D) Mountainous slope with harvested areas reducing the visual quality of the landscape; (E) Harvesting plots in the shape of a chessboard in Canada; (F) Forested area considering a mosaic with natural forest in Brazil; (G) Forestry technique in a mosaic of equine eucalyptus "blocks" interspersed with native vegetation in Brazil; (H) Planted and harvested areas with high disagreement and local topography in Great Britain; (I) Harvest in a sloping area, generating a negative visual effect in the USA; (J) Visual impact on the harvest pattern in a mountainous forest area in Canada; (K) Significant visual impact of size and harvest on a sloping terrain in Canada; (L) Plots planted in natural forest mosaic in Chile. (*the sources of the images are available in "supplementary materials").

regulations. Both are widely used in natural resource management planning problems. A Model I linear programming problem uses decision variables that track the history of a field or stratum over the entire planning horizon, regardless of when the area will be cut. It is mostly used at the level of spatial forest planning. A Model II linear programming problem tracks the history of a field only until the final crop is examined. According to Bettinger et al. (2017), Model II is best suited for age-matched management regimes. Table 1 shows several examples of functions and constraints applied to forest planning and landscape management.

Kaya et al. (2016) published a recent worldwide review of forestry optimization, and they concluded that landscape modeling and optimization are promising new research areas. Computational challenges have generated research in two directions for solving harvest scheduling problems, accounting for spatial and environmental concerns. One research direction is heuristic solution development. Another research focus is exact solution approaches (Rönnqvist et al., 2015). In this context, we highlighted several studies connected with forest landscape management. Önal and Briers (2006) formulated a mixed-integer linear programming model for establishing spatial connections between forested areas. Könnyű et al. (2015) applied a similar study to guarantee temporal connectivity within mature forest habitats over time. The edge effects were also investigated using spatial optimization and wood production constraints (Ross and Tóth, 2016). Wei and Hoganson (2007) formulated mixed integer programming (MIP) to describe core area production in a forest management programming model. Augustynczik et al. (2018) developed a model to integrate ecological connection corridors by maximizing the Net Present Value (NPV). They found a 4.2% reduction rate in NPV, and Moreira et al. (2013) only found 0.051% in Brazil. Sessions (1992) used a heuristic function for ecological corridors between wildlife areas.

The ecological corridors for species habitats are often found in literature, and it is still a challenge for decision-makers. The main advantage of formulating habitat protection problems such as Integer Programming (IP) models with an array of objectives and constraints is site-specific policy guidance, including habitat protection activities that efficiently achieve wildlife conservation goals and tradeoffs between conservation goals and protection costs (Rönnqvist et al., 2015).

Table 1
A brief description of some forest landscape problems and the mathematical model structure.

Authors	Description	Mathematical formulation
Barahona et al. (1992)	**Objective:** A model for forest planning that considers habitat dispersion objectives. **Constraints:** the model is subject to constraints related to habitat dispersion.	$Maximize \sum Zc_{ij}x_{ij}$
Williams (1998)	**Objective:** Network wildlife corridor (NWC) model – A two-objective zero–one programming model was formulated for the problem of selecting land for a system of wildlife corridors that must connect a known set of existing reserves or critical habitat areas. The objectives are to minimize corridor land costs and minimize the amount of unsuitable land within the corridor system. **Constraints:** a model subject to "flow balance" restrictions related to the delimitation of viable regions to connect habitats and link "islands" of native forest fragments.	$MinZ1 = \sum_{j\in J} c_j(\sum_{k\in A_j} x_{jk})$ $MinZ2 = \sum_{j\in J} a_j(\sum_{k\in A_j} x_{jk})$
Murray (1999)	**Objective:** models for solving forest harvest planning problems with spatial landscape restrictions. This means that the analysis incorporates specific objectives and considerations aimed at minimizing forest activity impacts. **Constraints:** A model subject to constraints that limit the treatment activities in a unit to occurring at most once ensures a minimum level of treatment activity each time; ensures a maximum level of treatment activity results each time; provides uniform or non-declining timber supplies; and restricts the treatment activity of neighboring units, allowing at most one neighboring unit to be treated; and constraints that impose integer requirements on decision variables.	$MaxZ = \sum_i \sum_t a_{it}x_{it}$
Öhman (2000)	**Objective:** A planning model designed to maximize the net present value and create continuous patches of old forests (connectivity problems).	$Max \sum_{i=1}^{I} \sum_{j=1}^{J_i} (D_{ij} + \overline{D_{ij}} Y_i) X_{ij}$ $-\alpha \sum_{p=1}^{P} (\overline{C_p} - \sum_{i=1}^{1} C_{ip})^{2}_{>0}$ $-\beta \sum_{p=1}^{P} (\sum_{i=1}^{1} G_{ip} - \sum_{i=1}^{1} C_{ip})^2$
	Constraints: model subject to the constraints related to a certain amount of 'core area' in the landscape.	
Graetz (2000)	**Objective:** The SafeD model is a spatially explicit hybrid simulation or optimization model that allows achieving multiple resource goals at both the stand and landscape levels while recognizing stochastic disturbances and management behavior. The SafeD model designs planning problems such as Model I nonlinear integer problems, where individual stands are tracked through time as they are regenerated or disturbed. **Constraints:** model subject to constraints related to the landscape scale context.	$Maximize \sum_{k=1}^{m} \sum_{j=1}^{q} \sum_{t=1}^{n} r_{k,j,t}x_{k,j,t}$
McDill et al. (2002)	**Objective:** (MILP ARMS) presented two mixed integer-linear-programming harvest-scheduling formulations that include adjacency constraints in the context of ARM. **Constraints:** model subject to adjacency constraints but which allows the simultaneous harvesting of contiguous plot groups whose combined areas are below the predefined limit.	$Max \sum_{m=1}^{M} \sum_{t=1}^{T} c_{mt}.A_m.X_{mt}$
Moreira et al. (2013)	**Objective:** a mixed-integer linear programming model that guarantees minimal connectivity among fragmented natural areas while maximizing the profit or production of the managed industrial forest plantations. **Constraints:** model subject to constraints related to field integrity, periodic production (minimum and maximum annual volume), renovation/replanting, annual budget, the flow of the ecological corridor, and connectivity of existing fragments.	$MaxZ = \sum_{i=1}^{n} A_t \sum_{j=1}^{m} D_{ij}x_{ij}$
Almada (2018)	**Objective:** multi-objective model that combines the URM for harvest scheduling and a model for connected and compacted reserves known as RCC-nR species protection.	$Max \sum_{t\in T} \sum_{i\in L} \ell_{it}x_{it}$ $Min \sum_{i\in L} D_{i\gamma}x_{i\gamma}$

(*continued on next page*)

Table 1 (*continued*)

	Constraints: model subject to constraints requiring a position to be harvested at most in a single period; guarantee that a certain volume of wood is obtained in each harvest period and the constraint that imposes the adjacency constraint that identifies the URM model so that no restrictions are repeated.	
Augustynczik et al., (2018)	**Objective: The** optimization model was to maximize forest Net Present Value (NPV) while creating new forest reserve areas, respecting a minimum area requirement, and connecting them through a corridor of extensively managed stands. **Constraints:** model subject to constraints such as ensuring that plots are forest reserves, connecting plots, or managed plots; adhering to a minimum area; adhering to a set of conservation flow restrictions; and meeting total wood production with the inclusion of forest reserves and connection corridors.	$MaxZ = \sum_{i\in S} npv_i x_i + \sum_{i\in S} npvExt_i z_i - \sum_{i\in FR} per_i y_i Dc + \sum_{(i,j)\in E_{FR}} 2edge_{ij} n_{ij} Dc$

Nevertheless, most landscape optimization problems consider the harvest scheduling problem at the tactical level (Könnyu and Tóth, 2013; Tóth et al., 2013). Although IP is relevant for habitat maintenance and development, tactical planning is still widely used. Tactical planning is, in fact, the planning level where these types of problems are recognized.

Generally, spatial harvest scheduling is associated with the managed area's environmental, ecological, and social aspects while seeking to optimize objectives economically. Nevertheless, it is reasonable to note the negative impact of wood production due to ecological-landscape constraints in most mathematical models. Landscape changes are easy to measure after forest harvest simulation (McGarigal and Marks, 1995; Baskent and Jordan, 1995). Franklin and Forman (1987) presented the ecological consequences of using only harvest patterns practiced in the western United States. The authors suggest changing the spatial configuration to create an alternative landscape. These changes improve the lower-risk disturbances such as pests and diseases, forest fires, and wind destruction. Kurttila (2001) presents other spatial ecological aspects in more detail.

There are two different approaches to mathematically managing the size of harvest units within a harvest scheduling model, the Unit Restriction Model (URM), which restricts the cutting of adjacent harvest units in the same period, and the Area Restriction Model (ARM), in which the adjacency restriction is controlled by maximum harvest opening sizes (Baskent and Keles, 2005). These two different approaches are for handling clear-cut adjacency constraints within a mathematical programming system. That is, it seeks to ensure that the maximum predetermined cut size is not exceeded. These restrictions prevent large contiguous cutting areas from being formed (Kurttila, 2001). URM and ARM were proposed by Murray (1999), who presented a formulation of Integer Linear Programming (ILP) for URM and considered heuristic and dynamic programming to solve ARM. The ARM proposal is the same as the URM, except for expanding the cutting area in the landscape in the neighboring units. They are two models for solving crop planning problems with spatial landscape restrictions. There are still some computational obstacles to the effective use of exact methods for these problems. Constantino et al. (2008) proposed a Mixed-Integer Programming Model for the Harvest Scheduling Subject to Maximum Area Restrictions with Stand-clear-cut Variables (ARMSC). The approach uses a polynomial number of variables and constraints to better obtain solutions in a short computational time.

Adjacency constraints require crop organization in space and time to achieve a landscape goal, assessing the problem mathematically before activities are implemented on the ground (Bettinger and Sessions, 2003). For example, clear-cut plots can increase erosion, visual impacts, and habitat disturbance (Church et al., 1998). The basic mathematical representation of adjacency constraints (Murray, 1999) applied to spatial harvest planning problems includes (i) restrictions on the adjacency and exclusion period, which restricts the harvest of adjacent stands during a specified exclusion period, and (ii) restrictions of whole variables and other restrictions related to sustainability and the uniform flow of removals (Kurttila, 2001). Essentially, there are two main approaches for optimization techniques: (i) integer linear programming and mixed-integer linear programming, and (ii) heuristics.

Studies on adjacency constraints are important for forest harvest planning in line with aspects of environmental quality (Weintraub et al., 1994; Kurttila, 2001; Baskent and Keles, 2005). Therefore, Murray and Weintraub (2002) show that heuristic approaches, such as tabu search and simulated annealing algorithms, were widely used.

Spatial restrictions such as these control the timing, placement, and size of planned harvest areas (e.g., Fig. 3-E). The regulation of the harvesting activity's spatial impacts promotes higher quality forests and long-term sustainability (Weintraub and Murray, 2006). Könnyu and Tóth (2013) emphasize that restrictions on the size of the opening in the forest harvest are requirements for forest certification standards such as the Forest Stewardship Council (FSC) (FSC, 2010) and Sustainable Forestry Initiative (SFI). The impacts generated on the landscape after forest harvest in reforestation are visible and may contain extensive areas of soil exposure, breaking the continuity and shredding the landscape and increasing risks caused by gales (Gomide et al., 2013). Forest certification is designed to guarantee consumers that the wood products they purchase come from managed forests that maximize aspects of environmental quality in forest management (Van Deusen et al., 2010).

In the models of spatial harvest planning that incorporate maximum restrictions on the size of the harvest opening (URM or ARM) (Murray, 1999; Könnyu and Tóth, 2013), the greening or exclusion period is also inherent. This is the period, generally expressed in years, which must pass before harvesting activities are allowed in adjacent areas (Bettinger et al., 2017). Also, restrictions that prohibit final harvesting in areas before the regeneration of harvested areas are known in forest planning as "green-up constraints" (Borges et al., 2015).

In North America, where adjacency constraints are particularly common, green-up constraints regulate the simultaneous harvesting of neighboring plots (Murray and Weintraub, 2002; Tóth et al., 2012). Adjacency and green-up restrictions address the juxtaposition of crops and habitat and are perhaps the most widely used spatial restrictions in forest planning today (Kadioğullari et al., 2015). In addition to the adjacency restrictions and green-up problems restrictions (Boston and Bettinger, 2001), there are also limitations designated for maintaining ecological corridors (Fischer and Church, 2003). Some of them are linked to landscape indexes (Heinonen, 2007); they block restrictions to facilitate harvest (Nelson, 2001), among others (Gomide et al., 2010).

Block-cutting restrictions are widely used in countries with fast-growing forests. These restrictions, depending on the size of the harvest blocks in large areas, can have a significant impact on the landscape, which, considering the scenic value and environmental quality, can have a negative impact, despite the proportions and despite generating greater positive economic effects for forest owners. Classic approaches to optimizing forest planning to model harvest scheduling problems with block size constraints can be seen in Lockwood and Moore (1993), Clements et al. (1990), and Augustynczik et al. (2017).

In Fig. 4, we present an illustration of the spatial dynamics of the influence of adjacency restrictions (Fig. 4a) in an illustrative forest area, with a demonstration of valid and viable harvest units for cutting according to established maximum sizes and harvest scheduling scenarios in a planning horizon. Scenarios related to restrictions in blocks with green-up requirements (Fig. 4b) and an ecological corridor between the stands (Fig. 4c) are also illustrated. In the harvest schedule, it is common to protect wildlife and their habitat to ensure a connected nature reserve whose stand has a minimum time before being harvested (Almada, 2018).

There has been progress in the use of heuristic techniques to solve spatial forest planning problems. The integer designation of decision variables (potential harvests) can come with a high computational cost. Therefore, using traditional techniques of mathematical programming does not make sense, and a range of successful methods such as heuristics and meta-heuristics are suitable (Bettinger and Kim, 2008; Gadow and Pukkala, 2008). In contrast, a given landscape-level planning model has single or multiple objective functions and traditional or advanced techniques to solve it (Bettinger and Kim, 2008). They have been widely used in forestry and territorial planning policies and studies (Hayes et al., 2004). The search for better management of environmental aspects, resources, and economic benefits has led to the concept of managing the forest landscape (Baskent and Jordan, 1996). There is still a lot to be done in this research area, as most of the spatial problems and environmental processes presented in this section are stochastic, with significant economic, mathematical, and computational challenges.

Generally, it is necessary to convince and engage within the companies to implement one more restriction on harvesting and transport planning, which will divide the harvest blocks and probably make the operation difficult. One of the main challenges is the cultural issue of companies that only aim at short-term profit. Developing this shift in mindset can be a problem in the case of developing or underdeveloped countries. Certifications value landscape planning actions, but do not oblige them to do so; thus, it is up to the company to implement it or not.

3.4. *Support decision systems for spatial (SDSS) analysis*

Spatial forest planning is causally related to geovisualization and the processing of geographic data. What is frequently applied to forest landscape management and is correlated with SDSS techniques?

Geographic Information Systems (GIS) are another important research field in forest science, and maps are essential for data visualization. The spatial structure of trees, stands, roads, and forest is essential for wood supply chain control (Bettinger and Sessions, 2003). The idea behind forest planning and GIS is to melt over decades (Kyem, 2002; Gomide, 2009). The authors Baskent and Jordan (1991), Jordan and Baskent (1992), Baskent and Jordan (1996), Jamnick and Walters (1993), and Pukkala et al. (1995) emphasize the benefits of this forest management technology. In addition, the resource provides valuable information for spatial analysis (Baskent and Keles, 2005).

Spatial Decision Support Systems (SDSS) combine spatial and non-spatial data within GIS technology for problem management and solutions. In addition, the SDSS has many advantages for evaluating the trade-off goals (Keenan and Jankowski, 2019), including landscape management and spatial forest planning. One of the most complete publications is the FORSYS report (Borges et al., 2014) 'Forest Management Decision Support Systems', which brought together almost a hundred authors and approaches related to twenty-six countries in Europe, North and South America, Africa, and Asia. The authors present an overview of computational tools for forest management planning in several countries. They also describe methods and technologies based on multicriteria and objective functions, GIS, computer programming, and

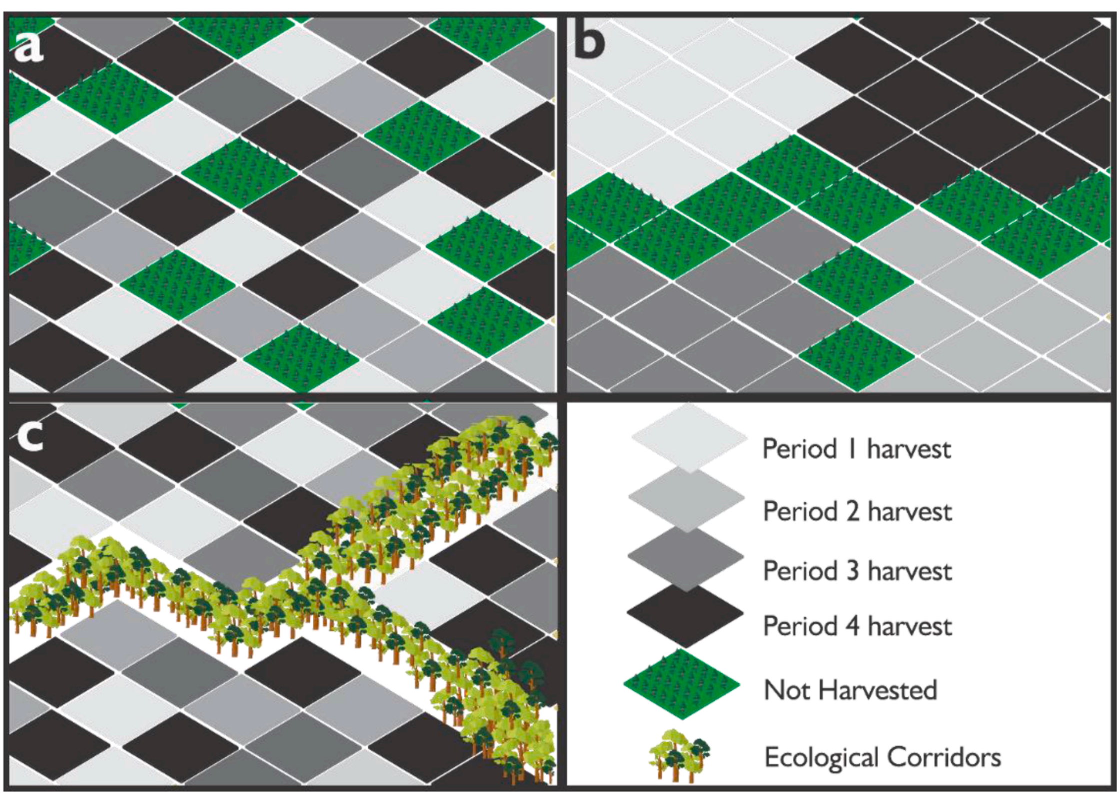

Fig. 4. Hypothetical illustration of ideal or alternative forest harvesting programs in the contexts of forest regulation and landscape quality: (a) harvesting for periods with the imposition of adjacent restrictions on spatial dynamics; (b) block harvesting modeled to comply with green-up requirements; and (c) harvest condition integrating the ecological corridor environmental restriction. Source: The authors, 2021.

communication tools and spatial visualization. In general, SDSSs are essential tools for solving complex forest decision-making problems (Segura et al., 2014). Bettinger and Sessions (2003) point out a robust database to extract correct spatial information. This critical alert affects the final decision and landscape response. Forest management companies need to create management plans to balance the environmental, social, economic, and operational aspects of their harvesting plans (Walters et al., 1999).

3D visualization is often used for architectural modeling systems, realistic simulators, virtual computer reality, and other applications (Favorskaya and Tkacheva, 2013). Real-time rendering of forest landscape scenes is also possible for better esthetic management in large forest plantations (Bao et al., 2012). A 2D and 3D visualization model applied to landscape harvest plans can be seen in Chamberlain and Maitner (2009). Falcão et al. (2006) developed a real-time 3D visualization module for forest landscapes based on heuristics, mathematical programming techniques, and GIS. The construction of virtual landscapes allows real-time navigation through the forest in each period of the planning horizon of a scenario. The technology explores a range of views to support forest activities and certification programs (Domingo-Santos et al., 2011). Today, rendering technology has been made easier with Light Detection and Ranging (Lidar) (Wulder et al., 2012) for the land surface with detailed high-resolution (Pierzchała et al., 2018; Ozkan et al., 2020). The cost of the dataset is still high but should decrease over time (Bettinger et al., 2017).

Forest landscape-planning includes economic, ecological, and social aspects to guide the decisions. These virtual results may concern stakeholders' views and goals. Some examples can be observed in Meo et al. (2013) with a GIS of public participation (PPGIS) in forest landscape planning; Vopěnka et al. (2015) with a developed GIS extension for forest harvest scheduling problems with spatial and temporal design aspects; a GIS-based model to assess the impact on recreation areas caused by harvesting activities in a commercial forest (Harshaw and Sheppard, 2013); and based on a Multicriteria Decision Analysis (MCDA) methodology, Ezzati et al. (2016) found optimal locations of viable harvest zones in mountainous areas. In MCDA and spatial forest planning, the tool AHP (Analytic Hierarchy Process) methodology (Saaty, 1980) has been widely used to model problems of assessing preferences for multiple criteria (Alho et al., 2002; Kangas and Kangas, 2002; França et al., 2020; Morandi et al., 2020).

Spatial forest planning using meta-heuristic techniques, associated with SDSS and developed in multiple programming languages, should be explored. In the microplanning and optimization of stands, an important current challenge for forestry companies is to achieve greater homogeneity in their stands. The forest plot definition can be explored through the 'Nesting Problem' method (Bennel and Oliveira, 2008), which performs ordering and better arrangement of geometric pieces (Lo Valvo, 2017), in this case at the level of the forest landscape.

In 1996, with the possibility of using ESRI Shapefiles (Environmental Systems Research Institute) in forestry decision support systems with resources for spatial planning, the Canadian company Remsoft Inc. launched the Stanley software (Spatial Optimizer), which uses sets of heuristics for the automatic insertion of spatial constraints in strategic forest-planning models with multi-objective linear programming (Goals programming). It was an important step in dealing with the inclusion of new sustainability criteria in forest management planning. Heuristics-based shapefiles applying the imposition of adjacent and green-up constraints on spatial parameters help the planner to better control the minimum, average, and maximum size of the cutting units and the green-up period between adjacent areas.

Finally, statistical models have also been developed to analyze the scenic beauty of plantations in forest landscapes. The model inputs are associated with tree density, species, harvested volume, and vegetation cover (Schroeder and Daniel, 1981). Brown (1987) also analyzed a statistical model, including scenic quality and net present value. Generally, most models developed predicted the perceived scenic quality of the sites.

Therefore, statistical or mathematical models and geospatial support of SDSS provide forest landscape management more comprehensively, creating an effective link between strategic and operational levels.

3.5. Bibliometric results

Scientific production related to the approach of spatial forest planning and landscape management aimed at the scenic and environmental quality forest is not a much-researched area compared to other areas in forest engineering (e.g., forest carbon stock, ecosystem services). Nevertheless, these studies have a great impact on society and the environment because they involve extensive production areas. The bibliometric analysis allowed identifying trends observed in the topics, terms, and sub-fields of the analyzed theme. The overall spatial forest planning and landscape management articles were present and obtained.

We summarized 2022 articles from 129 sources (journals) over the 1980–2021 timeline. Of those, 1959 are data articles, and 63 are literature reviews. The average calculated collaboration rate was 2.77 authors, which indicates a high degree of predominance of collaborative research. A collaboration network between authors is strategic to increase the impact of scientific production, especially international collaborations (Koseoglu, 2016). Publications with single authorship represent only 7.96% (161 single-authored documents) of the 5245 authors involved in the survey. The total of 5084 documents is from authors in multiple authorships, confirming the high collaboration among researchers in this line of study and demonstrating that, although the theme is still not much studied compared to other themes, there are many people involved and interconnected in these studies. We also found 5942 different keywords used by these authors to provide the central idea of their manuscripts. There is scientific production related to the theme before 1980 in different parts of the world. However, according to our methodological rules for searching for keywords and production time scale, these works were not examined in bibliometrics. Despite this, a large portion of these records prior to that decade were included in the critical review of the subject's state of the art. Most were books, technical reports, guides, or local productions.

The bibliographic review indicates an increasing rate of publication (Fig. 5). In this regard, the temporal evolution confirms the relevance of the theme over the last two decades. In addition, the dataset records suggest a strong correlation between our research theme and global sustainable agendas, also including forest certification, land use, and climate change (Sánchez and Croal, 2012; Leemans and Vellinga, 2017; https://s3.sa-east-1.amazonaws.com/cop25.cl/documents/es-p/ACUERDO%20DE%20PARIS.pdf. ; COP 25, 2019; Maamoun, 2019). The most relevant journals are Forest Ecology and Management (237 articles), Forests (155 articles), International Journal of Applied Earth Observation and Geoinformation (150 articles), Spatial Information Research (117 articles), and Forest Science (99 articles) in global publishing (Fig. 6A). The maximum point observed is between 2017 and 2021, reinforcing that the topic has gained more focus recently, and this trend suggests a hot topic study for the coming years (Fig. 5). The regression analysis supports our findings from the coefficient of determination (0.76%).

The most relevant affiliations were with the Swedish University of Agricultural Sciences (Sweden), the Finnish Forest Research Institute (Finland), and Oregon State University (USA). As for the most producing countries, the United States (1145 articles), China (521), Finland (449), and Canada (415) stand out as the origin of affiliation of the main author's working with the themes (Fig. 6C). Considering the ratio of citations and published articles, the most relevant countries are the United States, Canada, and Finland, with an average article citation of 19,56 and a total citations of 7102 in the USA, 3121 in Canada, and 2938 in Finland. This may be because these countries have large forest areas and a long tradition of using forest resources. For example, Finnish forest-

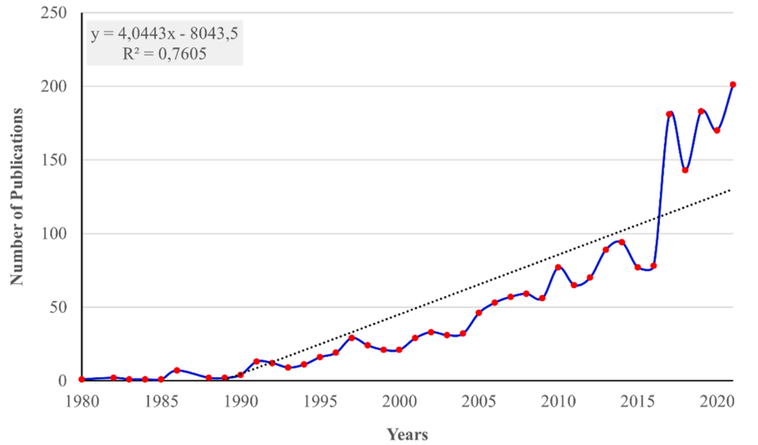

Fig. 5. Annual publishing production of articles from Web of Science (WOS) and Scopus.

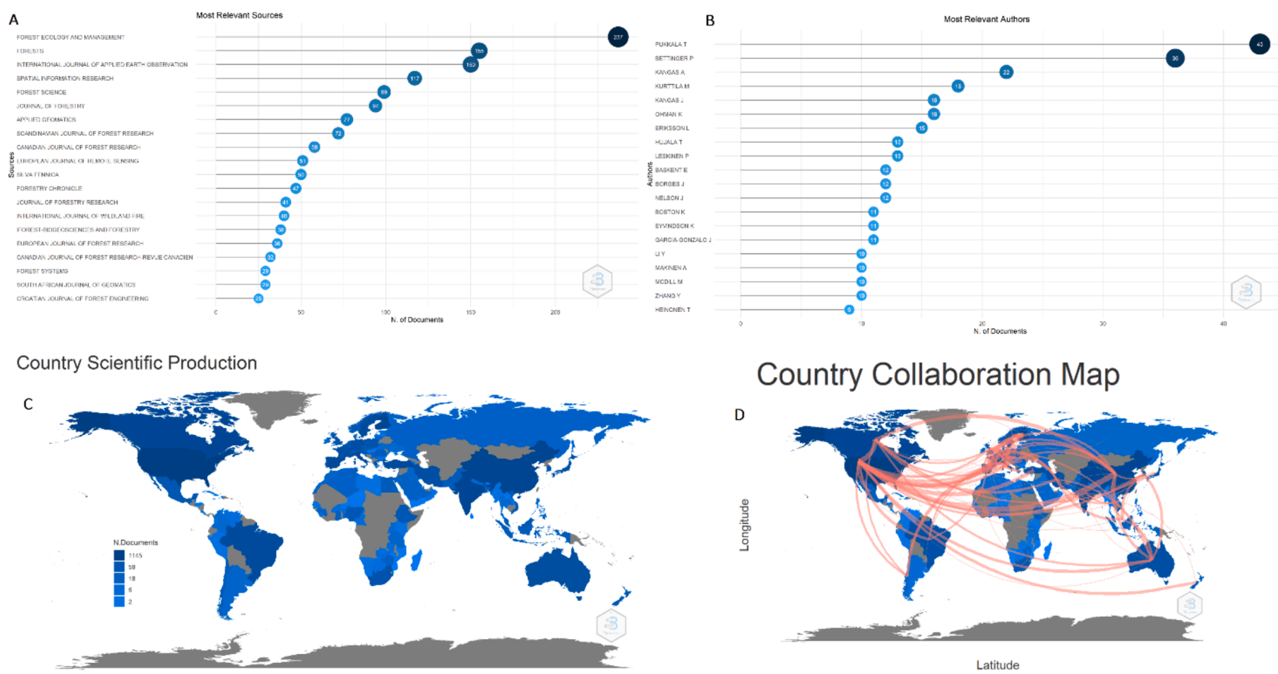

Fig. 6. (A) Most relevant sources; (B) Most relevant authors; (C) Country scientific production; and (D) Country collaboration map.

based companies are among those most concerned with sustainable growth and are precursors to the circular bioeconomy (Näyhä, 2019) and forest certification with advanced strategies for sustainable forest management (Kuuluvainen et al., 2019).

Çağlayan et al. (2018) define the United States and Finland as leading countries in forest management optimization. They have commercial systems, spreadsheet applications, and tools based on linear programming and heuristic techniques for spatial forest planning (Bettinger and Sessions, 2003). The forest certification processes are the internal factors that encourage this research. 48% (207 million hectares) of the certified forest area globally is in North America, and 25% (107 million hectares) is in Western Europe (UNECE, 2015). On the map of collaboration between countries (Fig. 6D), we observe a significantt interaction flow between North America and Europe.

Pukkala T. (43 articles) and Bettinger P. (36 articles) dominate the high number of article publication relevance. Although these authors present the highest productivity according to our bibliometric search rules, in our state-of-the-art survey, they are also identified as the authors of the main works related to forest landscape management and spatial forest planning, with a hundred other studies with broader approaches on the subject. Timo Pukkala and Pete Bettinger are associated with universities in Finland and the USA, respectively. We also observed that these authors were frequently cited in other articles. Moreover, the second important group of authors is Kangas, A. (22 articles), Kurttila, M. (18 articles), Kangas, J. (16 articles), and Ohwan, K. (16 articles), among others (Fig. 6B).

According to our selected keywords for the search procedure, the most researchable terms or most relevant words were "gis", "remote sensing", "forest planning", "forest management," and "optimization" in this sequential order (Fig. 7A). The dendrogram (Fig. 7B) shows the similarity groups, highlighting the formation of two main clusters, one related to optimization (group in blue color) and another to landscape management and forest resources (group in red color).

Finally, the Sankey diagram (Fig. 7C) matches three objects (countries, authors, and keywords) according to their relevance and frequency in a longitudinal data structure. The output describes an interactive flux of information and inferences within levels. It has been widely used to visualize and compare the flow patterns of simultaneous topics (Davis

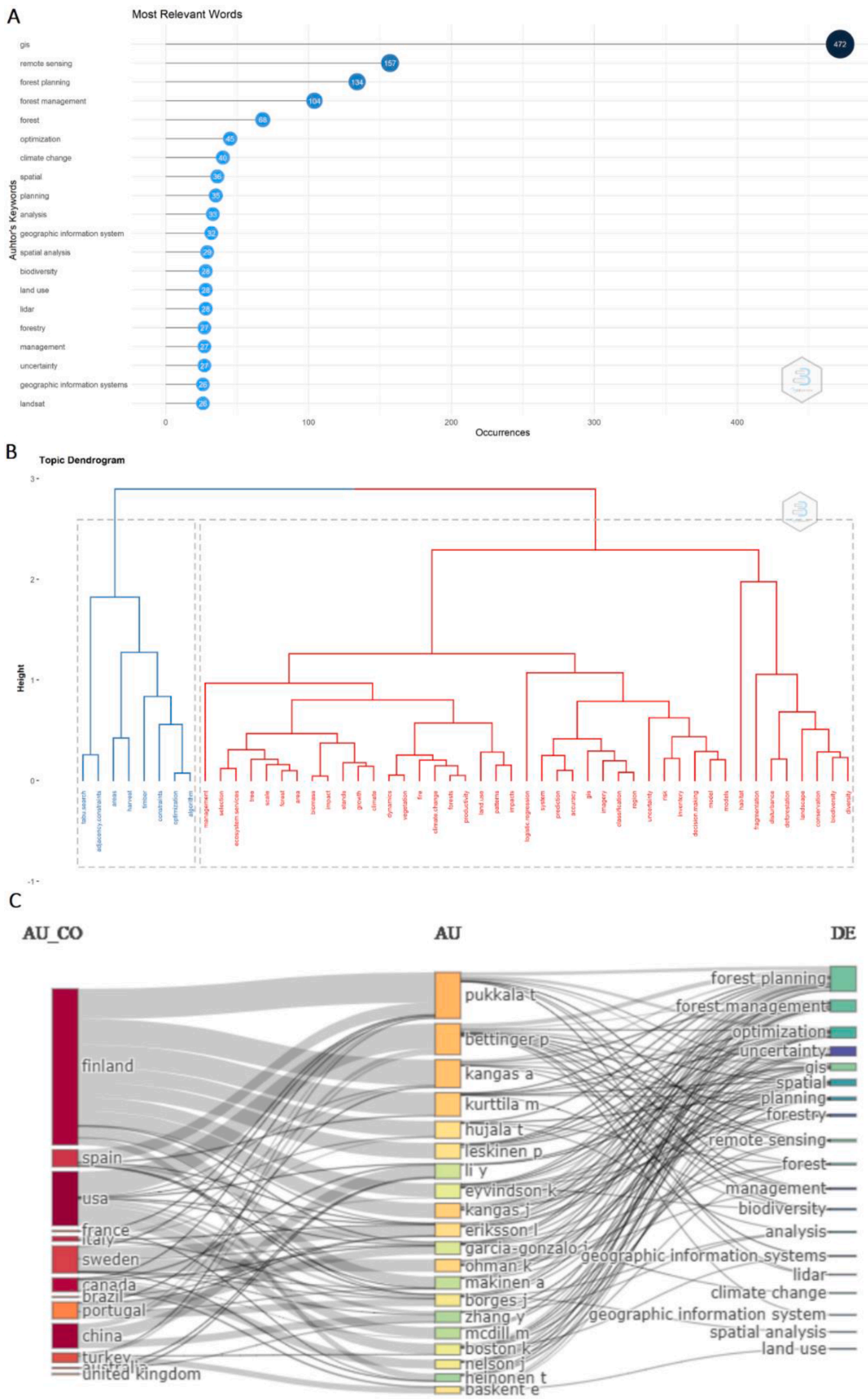

Fig. 7. (A) Most relevant words; (B) Topic Dendrogram; and (C) Sankey diagram, the interaction map between countries, authors, and keywords.

et al., 2018) and multidimensional data dimensions (Lupton and Allwood, 2017). Our findings suggest a plural pattern of actors and studies. With this result, we observe that the central theme is essentially multidisciplinary and broad. It is important to note the rectangles' size at any given level (Fig. 7C) that reflects the weight of the element proportionality of occurrence (Chao et al., 2020) and the lines are proportional to the index inclusion between connected themes or levels. Today, the scenic quality continues to be a hard task for the wood supply chain on a large scale. The case studies consider that the simulation approach and mathematical modeling are crucial for landscape management and its effects. Solving this proposal model is usually complex due to its combinatorial complexity (Weintraub and Murray, 2006).

The group of words "forest planning," "forest management," and "optimization," together with the group of words "GIS," "remote sensing," and "spatial analysis," represent the motor themes or themes of greater relevance and centrality in this subject. Other word combinations are organized in the graphs development degree and relevance degree (Fig. 8).

We set up a network of keyword interaction and co-occurrence analysis (Fig. 9). The network linkage between nodes (keywords) associates the frequency and correlation of pairwise terms. Generally, this connected graph defines the relationship between the keywords used within articles (Chen et al., 2016). The networks represent the interrelationship of countries working together (Fig. 9A), the groups of researchers (Fig. 9B), and the group of keywords in their respective niches (Fig. 9C).

In contrast, the keywords that are close to each other influence the next keywords quickly, and so on. This analysis (Fig. 9A) combined four-color groups by theme (red, green, blue, and purple subnets). The grouping of countries in the red subgroup is dominated by the United States of America. In particular, there is a connection between all the clusters. In Fig. 9B, the authors are seen in their networks of collaboration and scientific production together. We observed that there is a collaboration network between the groups dominated by the authors Pukkala T. and Kangas A. (red and green clusters, respectively). The same happens for the connection network between the keywords (Fig. 9C), where "gis" and "remote sensing" dominate the largest word cluster (the red cluster), and "forest planning" and "forest management" dominate another large word cluster (the blue cluster). There is a direct relationship among all the clusters.

These results confirm a link with what was observed in the state of the art seen in the previous topics. The clusters and connection networks between the keywords call attention to the relationship with the temporal chronology of the studies developed on the central theme. Spatial forest planning has increasingly considered issues related to the maintenance and improvement of scenic and landscape aspects of forest areas. The esthetic value of the landscape as a result of a mathematical model can increase the sustainability perception of forest enterprises and improve the landscape structure conditions for biodiversity.

Despite the challenges, forest industries are faced with the problem of spending a lot of time and resources to achieve better strategies. In fact, we expected high interest from research institutions, companies, and governments concerning the subject. Our findings suggest that environmental issues are already incorporated into industry production, guiding international trade agreements. The positive rate indicates that North America and Europe comprise the majority of scientific publications. Although the esthetic and environmental merits of forest planning increasingly demand the attention of forest planners, more research needs to be encouraged for other regions with forest production on the rise worldwide, such as South America.

4. Conclusions and key recommendations

- In this study, the emphasis of spatial forest planning is on esthetic or visual quality concerns. We contextualize spatial forest planning and landscape correlation on a global scale. The challenges, trends, and advances were pointed out as an important theoretical framework for further discussion. This review links sustainable, aesthetically pleasing, and economically viable productive forests for forest certification purposes and global demands for ecological services.
- We identified research trends on the topic from 1980 to 2021 and observed clear evidence of an increase in publications, especially in the last decade, highlighting the spatial forest management of the landscape as a research area in full expansion.
- To aid decision making, scientific advances in spatial forest planning consider multi-objective functions and environmental constraints. These mathematical models should also integrate transportation routes and road investments (maintenance, adequacy, and/or construction) according to technical, economic, environmental, and social criteria at the three hierarchical levels (operational, tactical, and strategic). Currently, this research area has been associated with remote sensing, GIS databases, and computer programming.
- There are differences in public perception and landscape importance around the world. The high suitability of commercial forests is found in Europe and North America. In this sense, the long rotation of these forests has the possibility of exploring the visual resource for tourism. Moreover, wildlife corridors, Multiple species, and age mosaics of forests should be easily adopted in commercial plantations.
- The integration of forest planning and landscape management has been encouraged to take place after the spread of forest certification programs in the last three decades. These forests for biomass, timber, charcoal, and cellulose production have improved their protocols to mitigate the socio-environmental impacts of their operations.
- Business cases and applied research are necessary to analyze the economic benefits of keeping the landscape attributes and ecosystem

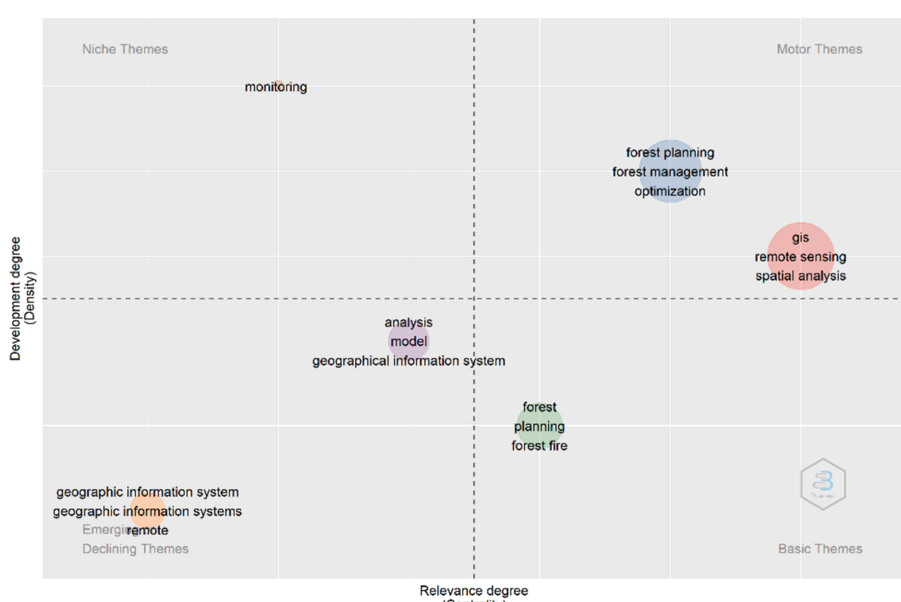

Fig. 8. Thematic map of relevance degree and theme development.

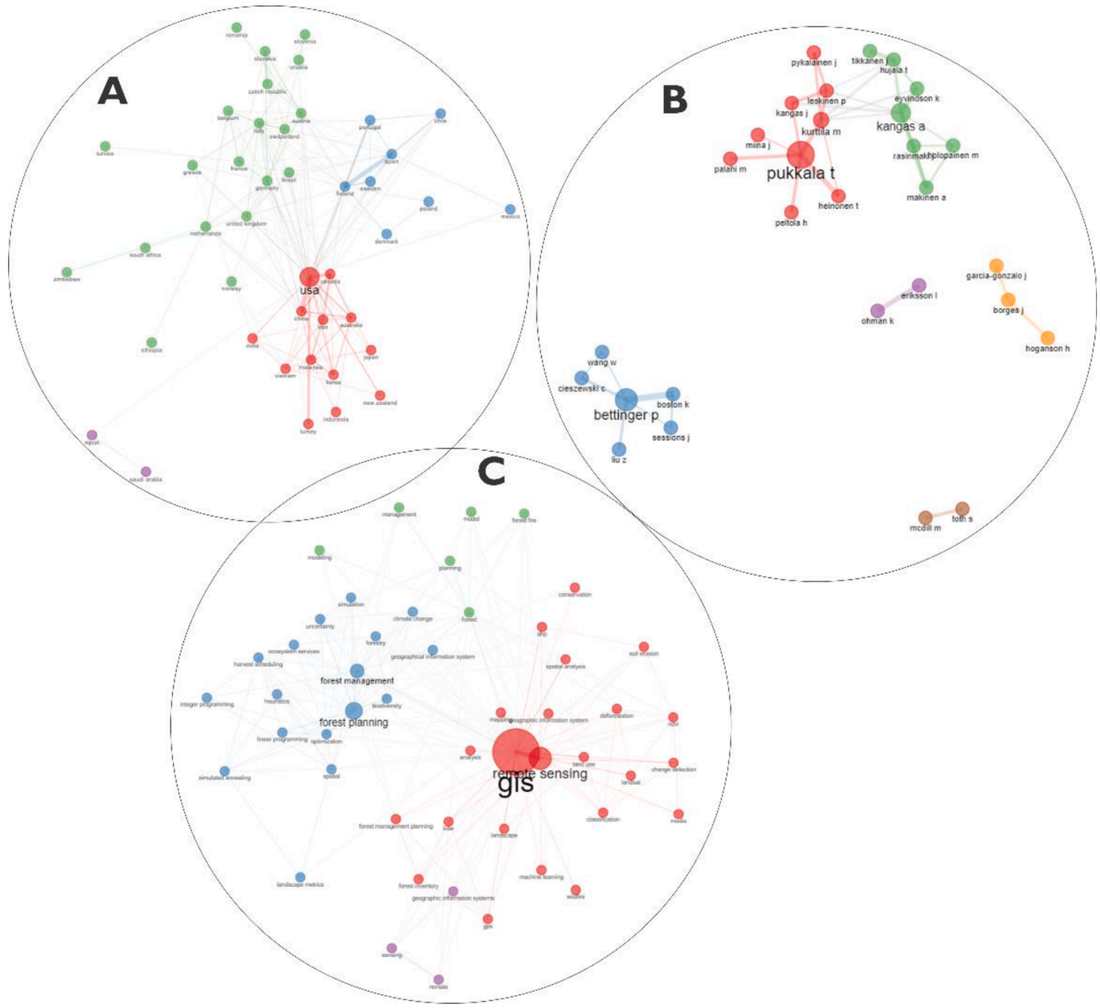

Fig. 9. (A) Interrelationship between countries working together; (B) The groups of researchers; and (C) the group of keywords in their respective niches.

services over timber production. Furthermore, fragile landscape areas should be more carefully regarded for damage by applying simulation techniques to minimize them.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.tfp.2022.100275.

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