Review

https://doi.org/10.1590/1678-992X-2023-0186

ISSN 1678-992X

SCIENTIA AGRICOLA

100 Years on Boron Research in Plants – Forestry Science

A gist of current understanding about soil-plant boron nutritional status in eucalyptus: a bibliometric review

Matheus da Silva Araújo[1]*, Rafael Otto[1], José Lavres Junior[1], Vitor Corrêa de Mattos Barretto[2], Maurício Roberto Cherubin[1]

[1]Universidade de São Paulo/ESALQ – Depto. de Ciência do Solo, Av. Pádua Dias, 11 – 13418-900 – Piracicaba, SP – Brasil.
[2]Universidade Estadual Paulista - Câmpus de Dracena, Rod. Comandante João Ribeiro de Barros, 651 – 17915-899 – Dracena, SP – Brasil.
*Corresponding author <agroaraujomatheus@gmail.com>

Edited by: Tiago Tezotto

Received August 15, 2023
Accepted May 13, 2024

ABSTRACT: A bibliometric study was undertaken to analyze the spatiotemporal distribution of works related to managing boron (B) in *Eucalyptus* spp. from 1970 to 2022. This analysis was based on the Web of Science and Scopus databases, and 121 documents were retrieved. The eight main aspects analyzed were (1) annual scientific production, (2) most relevant research sources, (3) world scientific production, (4) association between countries, (5) most relevant affiliations, (6) indexed terms, (7) most relevant authors, and (8) most cited documents. The results indicated that publications of studies about B in eucalyptus have increased significantly over the last decade (2010-2020). Brazil has produced the most studies relating to the nutritional management of B in eucalyptus, as is mainly reflected in the numbers of researchers, research institutions, and journals that have published on the subject. Our study found that most works have been developed regionally, with little international collaboration between countries although researchers from the United States are the most frequent partners in international collaborations. The majority of the articles analyzed focused on studying the influence of B doses on the growth and rooting of eucalyptus seedlings. Finally, one significant gap in the literature is the need for studies on sources of B via soil and leaves, and new studies on this subject should be commissioned. Thus, the bibliometric review was an efficient approach for observing the main advances in managing B in eucalyptus in recent decades and identifying the leading research groups and future opportunities for scientific advances in this area.

Keywords: bibliometric indicators, fertilization, forest species, micronutrient

Introduction

The genus *Eucalyptus* spp. originates from Australia, Tasmania, and other islands in Oceania, and its expansion into other countries has made this genus important worldwide. An estimated 20 million hectares of eucalyptus have been planted worldwide, of which 22 % are in India, 20 % in Brazil, 14 % in China, and the remainder in other countries, which have less than 5 % each (IBÁ, 2020; IBGE, 2021). Species of this genus move the booming market for wood, charcoal, panels, cellulose, and paper, in which Brazil is the leading exporter of raw materials, generating approximately 7.4 billion US dollars a year (IBÁ, 2020).

With the expansion of eucalyptus plantations in recent decades, especially in soils of the Brazilian Cerrado which naturally have low fertility, several studies have analyzed the nutritional management of these plants (Malavolta et al., 1997). Among these studies, boron (B) was found to be the most limiting nutrient for species' productivity (Silveira et al., 2000). In addition to the loss in productivity, B is directly related to the quality of the wood. Plants deficient in B throughout the cycle can suffer irreversible symptoms including apical meristem death and trunk bifurcations (Faquin, 2005).

Boron is one of the elements essential to adequate plant growth and development. B is classified as a micronutrient because it is required in only small amounts. The structural function of B is as a component of complex polysaccharides present in the pectin of the plant cell wall - rhamnogalacturonan-II; thus, B is available to the plant throughout the crop cycle (Marschner, 2012). However, the levels of deficiency and toxicity of B are very close, which requires special attention in the management of doses and sources applied with different solubilities in water (Ferrando and Zamalvide, 2012).

To better understand the breadth of a specific area of science, such as the management of B in eucalyptus, systematic analyses of global scientific production should be carried out to verify the history of the works and future trends (Song and Zhao, 2013). Recently, many scientists have used this strategy to direct their research (Romanelli et al., 2018; Martíni et al., 2020; Valani et al., 2021). In this context, bibliometric analysis plays an essential role in information management and supports decision-making in the scientific field.

No published reports have applied this integrated assessment tool to analyze issues relating to the management of B in eucalyptus. Thus, we seek to fill this gap through bibliometric analysis over the last 52 years (1970-2022). Specifically, the objective of this bibliometric study was to analyze the temporal and geographic evolution of publications relating to the management of B in eucalyptus and to identify the main advances obtained in the last five decades, the leading

research groups working on this theme and the possible aspects relating to the management of B that future research still needs to consider.

Materials and Methods

Data collection

The Web of Science - Clarivate Analytics Platform and Scopus were used to collect the bibliographic data. The survey was conducted in Jan 2022, with the help of the "Topic Field", which considers the "Title", "Summary", and "Keywords plus" of each record. The search was limited to scientific articles and literature reviews. The search terms used in both databases were "boron" AND "eucalyptus" ((TS (Search Terms) = ((boron)) AND TS = ((eucalyptus))) AND (DT (Types of Documents) = ("ARTICLE" OR "REVIEW")) during the period from 01/01/1970 to 31/12/2022, because in the 1970s, forestry cultivation expanded in Brazil with the introduction of eucalyptus and pine.

The search in the Web of Science database resulted in 45 documents in the sub-areas: "Forestry", "Soil Science", "Agronomy", and "Plant Sciences". In the Scopus database, the research resulted in 85 documents from the sub-area: "Agricultural and Biological Sciences". The results were exported in the "BibTex" format and the files from the two databases were compiled into a single file employing the R studio program using the "bibliometrix" package. The two databases resulted in 130 documents, of which nine were duplicates and excluded from the analysis. Consequently, 121 documents were analyzed.

Further analysis

To gather information on B management in species of the genus *Eucalyptus* spp., articles that did not consider the genus were eliminated. One hundred twenty-one documents were read analyzed individually, and 77 were excluded.

Finally, the dataset containing 44 scientific articles were analyzed using the web interface "biblioshiny for bibliometrix" (Aria and Cuccurullo, 2017). This interface allows for the creation of maps and tables for easy visualization and exploration of interactions on the subject discussed between authors, countries, research institutions, journals, and keywords (Romanelli et al., 2018). Within the interface, the following tools were used: "annual scientific production", "most relevant sources", "world scientific production", "association between countries", "most relevant affiliations", "indexed terms", "most relevant authors", and "most cited documents".

Results

Dynamics of boron in soil and plant

The studies analyzed addressed the dynamics of B in the soil and plant. Figure 1 illustrates the proportion (%) of each compartment of the soil-plant system, which was addressed in the respective publications. The authors emphasized the importance of this micronutrient for plant development, increased productivity, and biogeochemical cycling. The following sections will present the evolution of publications over the years, the main countries, institutions, and authors who research B in eucalyptus, the primary sources of research and works, and the gaps in the literature.

Evolution of publications over the years

The application of B in eucalyptus plantations is important for guaranteeing stress resistance, high yields, and wood quality (Hodecker et al., 2014). However, the subject is relatively recent in the scientific field. The first scientific works began to appear in the early 1990s (Mhando et al., 1993; Dell and Malajczuk, 1994; Trindade and Pais, 1997; Poss et al., 1999), with a significant increase in the last 12 years (Figure 2).

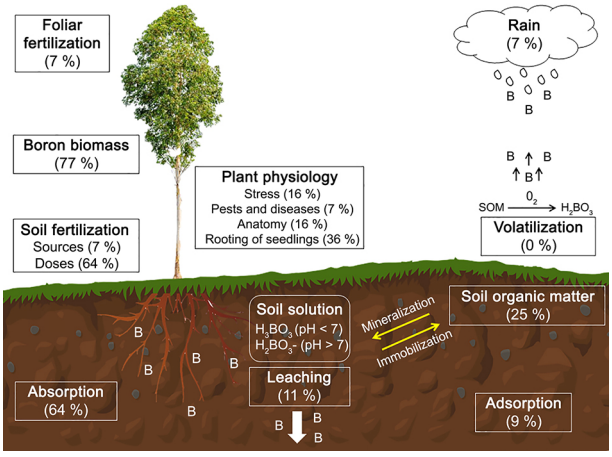

Figure 1 – Dynamics of boron (B) in the soil, and the relative and absolute proportion of publications in each compartment of the system.

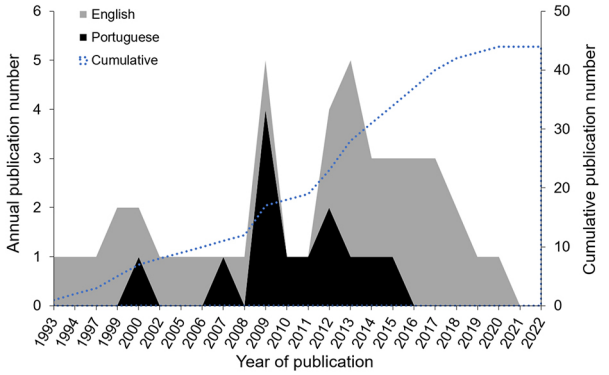

Figure 2 – Number of publications per year relating to boron management in eucalyptus.

Main countries, institutions and authors

In international scientific production on studies related to the management of B in eucalyptus, Brazil is the leader with 59.5 %, followed by Australia (14.5 %), the United States (7.5 %), China (2.9 %), Chile (2.3 %), and other countries that together account for 13.3 % (Figure 3). The scientific contribution of Brazil is associated with an increase in the planted area with the species, along with the growth and investment of pulp and paper companies in the country. Many works on the subject have also been confirmed in Australia, where eucalyptus originates.

Several collaborations between countries were verified in the development of works related to the management of B in eucalyptus plantations (Figure 4). Although several countries produce scientific papers on the subject, the few scientific collaborations between research groups from different countries show that the subject is still being researched regionally. The collaborations that stand out are Australia-Indonesia (2), Australia-New Zealand (1), Brazil-USA (1), Chile-Colombia (1), Chile-Costa Rica (1), China-USA (1), USA-Chile (1), and USA-Colombia (1). Thus, the USA, Chile, Australia, and Colombia are the countries that work most in partnership with other countries.

The leading institutions responsible for publications related to B management in eucalyptus worldwide are Brazilian (Table 1). Ninety institutions were involved and, of the top 15 ranked institutions, eight are Brazilian, located in the southeast (São Paulo and Minas Gerais states) and the south (Paraná and Rio Grande do Sul states) regions. These states add up to 3.86 million hectares planted with eucalyptus, which represents 55.4 % of all eucalyptus production in Brazil (IBÁ, 2020).

Similarly, the authors who published the most works related to B's management in eucalyptus are also from Brazil. Of the fifteen main authors listed in Table 2, nine are Brazilians associated with the leading

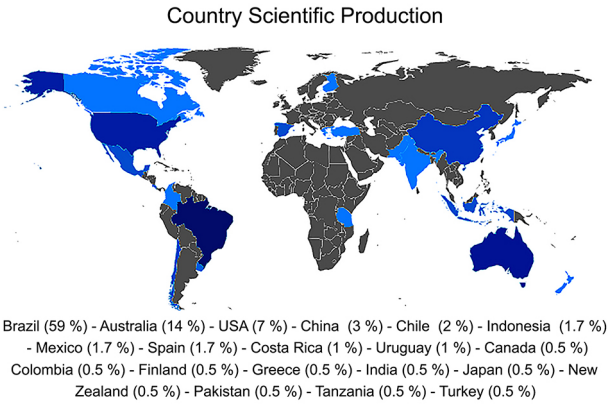

Figure 3 – Geographical distribution (country level and quantity) of scientific publications relating to the management of boron in eucalyptus from 1970 to 2022. The countries in blue produced some studies in this area.

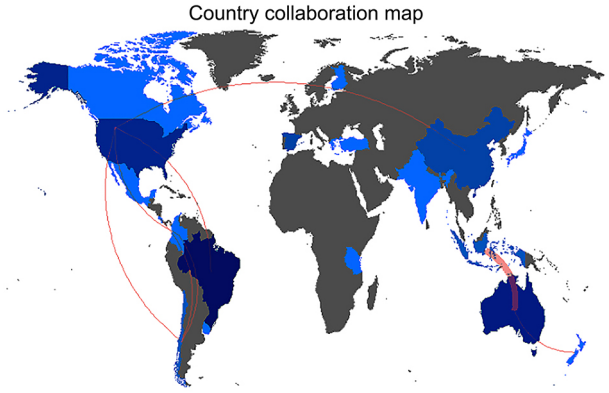

Figure 4 – Map of the collaborations between countries on publications related to the management of boron in eucalyptus.

Table 1 – Institutions responsible for the largest number of publications related to the management of boron in eucalyptus.

Ranking	Institution/Country	Publications	%
1st	Universidade Federal de Viçosa/Brazil	28	15.3
2nd	Universidade de São Paulo/Brazil	11	6.0
3rd	Universidade Federal Lavras/Brazil	8	4.4
4th	Universidade Estadual Paulista/Brazil	7	3.8
5th	University of the Sunshine Coast/Australia	6	3.3
6th	Murdoch University/Australia	5	2.7
7th	Universidade Federal de Santa Maria/Brazil	5	2.7
8th	[1]USDA-ARS U.S. Salinity Laboratory/USA	5	2.7
9th	Southern Cross University/Australia	3	1.6
10th	Universidade Estadual do Centro-Oeste/Brazil	3	1.6
11th	Universidad Concepción/Chile	3	1.6
12th	Bahauddin Zakariya University/Pakistan	2	1.1
13th	North Carolina State University/USA	2	1.1
14th	Universidade Federal de São Carlos/Brazil	2	1.1
15th	Universidade Federal do Pampa/Brazil	2	1.1

[1]United States Department of Agriculture, Agricultural Research Service.

Table 2 – Authors responsible for the largest number of publications related to the management of boron in eucalyptus.

Ranking	Author	Institution/Country	Publications	%
1st	Barros NF	Universidade Federal de Viçosa/Brazil	8	18.2
2nd	Almeida M	Universidade de São Paulo/Brazil	4	9.1
3rd	Bristow M	Charles Darwin University/Australia	3	6.8
4th	Brondani GE	Universidade Federal de Mato Grosso/Brazil	3	6.8
5th	Silva IR	Universidade Federal de Viçosa/Brazil	3	6.8
6th	Faquin V	Universidade Federal de Lavras/Brazil	3	6.8
7th	Grattan S	University of California/USA	3	6.8
8th	Grieve CM	[1]USDA-ARS U.S. Salinity Laboratory/USA	3	6.8
9th	Leite FP	Celulose Nipo-Brasileira/Brazil	3	6.8
10th	McMahon TV	University of the Sunshine Coast/Australia	3	6.8
11th	Novais RF	Universidade Federal de Viçosa/Brazil	3	6.8
12th	Poss JA	[1]USDA-ARS U.S. Salinity Laboratory/USA	3	6.8
13th	Hodecher BER	Universidade Federal de Viçosa/Brazil	3	6.8
14th	Trueman SJ	University of the Sunshine Coast/Australia	3	6.8
15th	Neves JCL	Universidade Federal de Viçosa/Brazil	2	4.5

[1]United States Department of Agriculture, Agricultural Research Service.

Brazilian institutions. The other authors are from Australia and the USA, countries that, together with Brazil, have the largest number of publications and the greatest subject domain (Table 2).

The authors explored several lines of research on the management of B in plants and soil, highlighting the main functions of B. Among the various subjects and variables studied, the most discussed subareas of the 44 studies were "doses" (26.6 %), "rooting" (24.4 %), "salt and water stress" (13.3 %), "pest and disease resistance" (8.8 %), "nutrient cycling" (8.8 %), "plant mobility" (6.6 %), "deficiency" (6.6 %), "sources" (4.4 %), and "anatomy" (2.2 %).

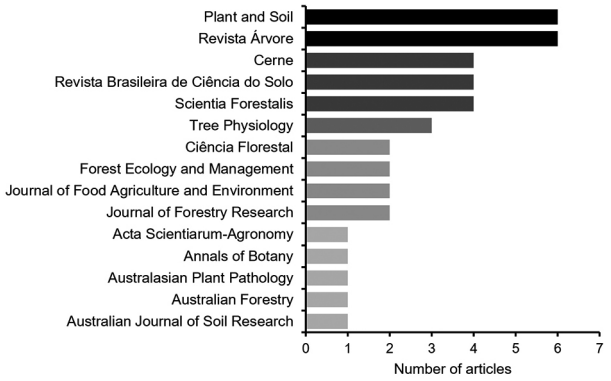

Figure 5 – Most relevant scientific journals and respective numbers of publications related to the management of boron in eucalyptus.

Main sources of research, works, and gaps in the literature

Articles related to B and eucalyptus were published in 32 scientific journals. The major journals were "Plant and Soil" (10.5 %), "Revista Árvore" (10.5 %), "Cerne" (7 %), "Revista Brasileira de Ciência do Solo" (7 %), and "Scientia Forestalis" (7 %) (Figure 5). Of the five leading journals, four are Brazilian, and together, they represent 31.5 % of the total production. Thus, Brazil's dominance on the subject is evident in research sources, publications, research institutions, and authors.

As for the impact factor of journals, "Plant and Soil" has the highest factor (3.29), followed by "Revista Brasileira de Ciência do Solo" (1.2), "Cerne" (0.77), "Revista Árvore" (0.38), and "Scientia forestalis" (0.33).

Among the most cited works, Brazilian journals are highlighted in several citations; of the seven most cited journals, five are Brazilian. However, Brazilian authors have few citations compared to authors from other countries (Table 3). In addition to the quality of the work, an important point that explains the higher number of citations of authors from other countries is that these articles are in English. Many works published in Brazil were written in Portuguese, which limits the interest and access of people who need to learn Portuguese. As time passes, published scientific articles are more likely to be cited. The ten most cited works were published between 1997 and 2014, with an average of 16.3 years since publication (Table 3).

Figure 6 provides the most used sources available on the market. The choice of the source to be applied is due to solubility, mode of application (via soil or foliar), and market price. More soluble sources make the nutrient available to plants more quickly, so they can be absorbed in high concentrations, which could cause toxicity and/or losses from leaching depending on the soil profile.

Discussion

Boron is absorbed by the plant as boric acid (H_3BO_3) and borate anion ($B(OH)_4^-$) at high pH values (Berger and

Table 3 – Top ten articles ranked based on number of citations.

Articles	Journal	1st Author	Quotes
1st - Mineral nutrition and adventitious rooting in microcuttings of *Eucalyptus globulus*	Tree Physiology	Schwambach J	60
2nd - Changes in soil chemistry in effluent-irrigated *Pinus radiata* and *Eucalyptus grandis* plantations	Australian Journal of Soil Research	Falkiner RA	56
3rd - Stable carbon isotope discrimination: an indicator of cumulative salinity and boron stress in *Eucalyptus camaldulensis*	Tree Physiology	Poss JA	32
4th - Production of cuttings in response to stock plant temperature in the subtropical eucalypts, *Corymbia citriodora* and *Eucalyptus dunnii*	New Forests	Trueman SJ	27
5th - Response of *Eucalyptus camaldulensis* Dehnh., *E. globulus* Labill. ssp. globulus and *E. grandis* W.Hill to excess boron and sodium chloride	Plant and Soil	Marcar NE	23
6th - Production of *Eucalyptus cloeziana* cuttings in response to stock plant temperature	Journal of Tropical Forest Science	Trueman SJ	17
7th - Characterization of leaf boron injury in salt-stressed *Eucalyptus* by image analysis	Plant and Soil	Poss JA	17
8th - Mini-cutting of *Eucalyptus benthamii*: effect of the genotype, IBA, zinc, boron and shoots collection	Cerne	Brondani GE	15
9th - Nutrient partitioning among the roots, hedge and cuttings of *Corymbia citriodora* stock plants	Journal of Soil Science and Plant Nutrition	Trueman SJ	13
10th - Physiological characteristics and dry matter production of eucalyptus in response to boron	Revista Árvore	Mattiello EM	11

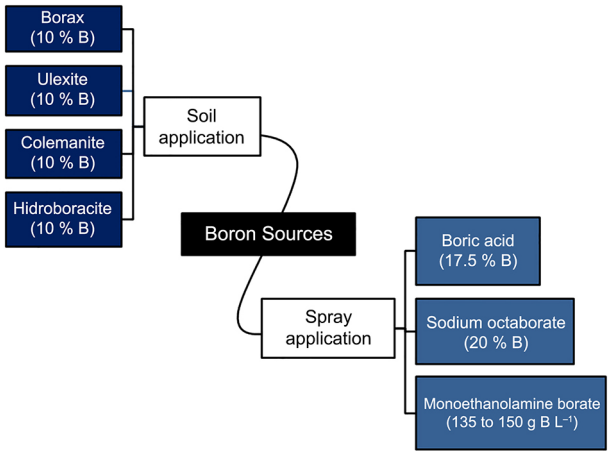

Figure 6 – Scheme of the most used sources of boron (B) via soil and leaves.

Truog, 1946). In the soil solution, B moves to the roots through mass flow. When equilibrium occurs between the contents in the roots and the solution, the nutrient is passively absorbed, depending on the transpiration flow of the plant (Marschner, 2012).

Organic matter is an essential source of B for the plant; however, its contents depend on the mineralization rate and its constitution in the original organic material (Malavolta et al., 1997). Despite being a significant source, the levels available in the soil solution for plant absorption are still low. Furthermore, under dry conditions, the mineralization of organic matter is reduced. Thus, the availability of B is affected, and the plants are incapable of absorbing the nutrients in the most superficial layers, requiring the application of fertilizers via the leaves. In eucalyptus cultivation areas in the Brazilian Cerrado, it is essential to apply B to the leaves to avoid loss of productivity and wood quality (Faquin, 2005).

For adsorption in soils, B can be fixed on the positive charges of clay minerals and aluminum oxides and hydroxides and secondarily on iron oxide, which have variable charge (pH dependent charges) (Gupta et al., 1985). On the one hand, the availability of B increases from pH 4.7 to 6.7 due to the increase in the electronegativity of soil charges. On the other hand, it decreases from 7.1 to 8.1 due to the formation of calcium borates (Ca) in the soil solution (Berger and Truog, 1946).

In the soil-plant system, B can be lost via leaching due to high rainfall conditions, since B in the form of H_3BO_3 has zero charge and can be easily leached. Leaching loss is closely related to soil texture, as this micronutrient is easily leached in sandy soils due to its high mobility (Azevedo et al., 2001). In forest plantations, losses due to leaching are negligible because of the deep root system and the species cycle. Little information is available about losses due to volatilization; however, with the burning of organic matter, B can be lost in the form of H_3BO_3 (Redin et al., 2011). The entry of B into the soil can be via organic matter, source material, rain, or fertilizer application.

This can be explained by the expansion of forest plantations in Brazil, especially in areas of the Brazilian Cerrado, where greater attention is required to applying B due to the local edaphoclimatic conditions (Figure 2). Soils with low levels of organic matter and long periods of water deficit have low nutrient availability, which damages eucalyptus plants, including killing the apical bud, better known as the "dry tip" (Dias et al., 2017).

Generally, the journals that publish on the studied subject have a relatively low impact factor. This can be explained by the depth of studies relating to the management of B in eucalyptus, as well as the location of the studies. The management of this nutrient is highly influenced by the edaphoclimatic characteristics of a given region, which could be an obstacle to its entry into high-impact international journals (Figure 5).

Specifically, the most cited works address the positive influence of B on the rooting of several species of the genus (Schwambach et al., 2005; Trueman et al., 2013a, b, c; Brondani et al., 2014). This was followed by work on stress caused by toxicity and salinity (Falkiner and Smith, 1997; Poss et al., 2000), in which eucalyptus showed satisfactory tolerance to high levels of B in the soil, with high levels of leaf B, with no adverse effect in plant growth (Marcar et al., 1999; Mattiello et al., 2009) (Table 3) and evaluated the leaf area affected by injuries caused by excess B (Poss et al., 1999). Although eucalyptus presents a wide range between deficiency and toxicity compared to other crops, the excess can cause symptoms of "purpleness" followed by necrosis in the leaf margins, thereby decreasing the leaf area and harming the photosynthesis process (Silveira et al., 2000) (Table 3).

Among the subareas, most of the articles analyzed focused on the influence of B doses on eucalyptus species' growth and morphological parameters. Thus, several field studies have been undertaken (Rodríguez-Juárez et al., 2014; Celestrino et al., 2019; Ferrando and Zamalvide, 2012; Lu et al., 2020; Albaugh et al., 2015; Mhando et al., 1993) as well as assays in greenhouse pots (Ferreto et al., 2016; Silveira et al., 2000; Barretto et al., 2007; Ramos et al., 2013; Sakya et al., 2002; Mattiello et al., 2009; Leite et al., 2010). The doses studied in the greenhouse pot assays ranged from 0.13 to 10 mg dm^{-3} of B, while in the field studies, they ranged from 0.5 to 12 kg ha^{-1} of B (Table 3).

Among the doses studied, the authors generally recommend the application of up to 4 mg dm^{-3} of B in pot assays since values above these can cause toxicity in the plants. B must be applied several times in the field, with a part of the nutrient demand at planting (about 50 to 70 % of the total dose) and the rest in the canopy at 6 and/or 12-18 months. For planting, doses of up to 2.5 kg ha^{-1} are recommended. In the canopy, apply 4 to 6 kg ha^{-1} in areas with water deficits and 2 to 3 kg ha^{-1} in regions without water deficits. Doses between 135 and 450 mg L^{-1} are recommended for foliar applications. The doses can vary according to the nutrient content in the soil, texture, organic matter, precipitation, and requirements of the cultivated species (Table 3).

Few works have studied the response to different sources of B. In this bibliometric survey, only two works (Ferrando and Zamalvide, 2012; Celestrino et al., 2019) emphasize the use of different sources, including the ulexite (17.8 % B), sodium borate (20.8 % B), borogran (10 % B), and boric acid (17 % B) (via soil and foliar). Among the studied sources, the most promising results were with the ulexite source, which has medium solubility, gradually releasing B to the plants, thereby avoiding leaching losses and toxicity symptoms in the plant due to excessive absorption (Table 3).

Several studies were restricted to quantifying the levels of B present in the biomass of the species (Carvalho Neto et al., 2012; Albaugh et al., 2017; Dick et al., 2017; Chu et al., 2018) and its correlation with the contents of other nutrients. These works found positive correlation between the B and Ca contents (Trevizam et al., 2011). These nutrients are directly related to cell wall formation, especially in cell elongation and division. In other words, the root meristem requires them for cell multiplication, an effect found in other studies in which the roots of seedlings were evaluated (Brondani et al., 2014; Cunha et al., 2009; Wheeler and McComb, 2006). Thus, if there is a nutritional imbalance of B and Ca, the growth of the root system is limited. During drought or low rainfall in areas of the Cerrado, the plants will display severe symptoms, such as the death of the apical meristem.

Studies have specifically emphasized the influence of B on resistance to pests and stresses (water and saline) (Nageli et al. 2016; Silva et al. 2018; Scott et al. 2015). Boron is directly related to the integrity of the plasma membrane. Thus, plants deficient in B can present high sugar and potassium efflux values. This is very harmful to the plants because, in addition to reducing the efficiency of potassium fertilization, they release sucrose and amino acids in the apoplast, serving as food for plant pests and pathogens.

We verified two main gaps for future studies based on the works analyzed. The first would be to evaluate the anatomy and biochemistry of injuries caused by the toxicity of B to discover the stresses caused on the plant. Second, studies should be developed related to the application of other or new sources of B since of the 44 studies evaluated, only two works (Ferrando and Zamalvide, 2012; Celestrino et al., 2019) studied sources of B in the growth of eucalyptus in the field. Furthermore, in these studies about the sources and doses of B, more information is needed about the recovery of the element by plants, as well as the physiological efficiencies of absorption and use of B.

The sources of B currently on the market have different solubilities and B levels, as well as the association or complexation of algae and sugars to increase retranslocation via the phloem. Although studies prove this retranslocation of B only in species that produce natural polyols (Leite et al., 2008; José et al., 2009), new studies are essential to evaluate the behavior of other sources in species of the genus *Eucalyptus* spp.

Final Remarks

Studies on B fertilization in eucalyptus have increased in the last ten years; however, this subject is still treated regionally among countries. In this context, Brazil has conducted the most research on the management of B in eucalyptus, particularly in institutions in the south and southeastern regions. Despite this, research conducted in Brazil still has a very local scope, reducing international interest and citations of the published articles.

Most of the analyzed articles focused on studying the influence of B doses on field growth and rooting of eucalyptus seedlings. For pot trials, doses of up to 4 mg dm^{-3} of B are recommended, and for field studies,

doses of up to 6 kg ha^{-1}. This review revealed the need for further studies to evaluate new sources of B via soil and leaves, and in-depth studies that elucidate the influence of B on plant anatomy.

Finally, it is important to mention that the bibliometric review is a valuable tool for identifying the current lines of research of several authors, institutions, and countries and, above all for guiding decisions related to future research.

Acknowledgments

Thanks to the Programa de Pós-Graduação em Solos e Nutrição de Plantas of the Departamento de Ciência do Solo at the Universidade de São Paulo and the Fundação Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES) for the doctoral scholarship granted to the first author. The second author thanks Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) for the research productivity grant (process no. 31811/2023-0).

Authors' Contributions

Conceptualization: Araújo MS, Cherubin MR, Otto R. **Data curation:** Araújo MS, Otto R, Lavres Junior J, Barretto VCM, Cherubin MR. **Formal analysis:** Araújo MS, Cherubin MR, Otto R. **Funding acquisition:** Otto R. **Investigation:** Araújo MS, Cherubin MR. **Methodology:** Araújo MS, Cherubin MR, Otto R. **Project administration:** Araújo, MS. **Supervision:** Araújo MS, Cherubin MR. **Writing-original draft:** Araújo MS, Cherubin MR, **Writing-review & editing:** Araújo MS, Otto R, Lavres Junior J, Barretto VCM, Cherubin MR.

Conflict of interest

The authors declare no conflict of interest.

Data availability statement

Not applicable.

Declaration of use of AI Technologies

No technologies were used.

References

Albaugh TJ, Rubilar RA, Fox TR, Allen HL, Urrego JB, Zapata M, et al. 2015. Response of *Eucalyptus grandis* in Colombia to mid-rotation fertilization is dependent on site and rate but not frequency of application. Forest Ecology and Management 350: 30-39. https://doi.org/10.1016/j.foreco.2015.04.030

Albaugh TJ, Rubilar RA, Maier CA, Acuña EA, Cook RL. 2017. Biomass and nutrient mass of *Acacia dealbata* and *Eucalyptus globulus* bioenergy plantations. Biomass and Bioenergy 97: 162-171. https://doi.org/10.1016/j.biombioe.2016.12.025

Aria M, Cuccurullo C. 2017. *Bibliometrix*: an R-tool for comprehensive science mapping analysis. Journal of Informetrics 11: 959-975. https://doi.org/10.1016/j.joi.2017.08.007

Azevedo WR, Faquin V, Fernandes LA. 2001. Boron adsorption in lowland soils from the South of the State of Minas Gerais, Brazil. Pesquisa Agropecuária Brasileira 36: 957-964 (in Portuguese, with abstract in English).

Barretto VCM, Valeri SV, Silveira RLVA, Takahashi EN. 2007. Boron use efficiency on growth by *Eucalyptus* clones in pots. Scientia Forestalis 76: 21-33 (in Portuguese, with abstract in English).

Berger KC, Truog E. 1946. Boron availability in relation to soil reaction and organic matter content. Soil Science Society of America 10: 113-116. https://doi.org/10.2136/sssaj1946.03615995001000C00018x

Brondani GE, Baccarin FJB, Bergonci T, Gonçalves AN, Almeida M. 2014. Mini-cutting of *Eucalyptus benthamii*: effect of the genotype, IBA, zinc, boron and shoots collection. Cerne 20: 147-156 (in Portuguese, with abstract in English). https://doi.org/10.1590/S0104-77602014000100018

Carvalho Neto JP, Silva EB, Santana RC, Grazziotti PH, Fernandes JSC, Freitas JPX, et al. 2012. Partition of dry biomass and nutrient in ministumps of *eucalyptus* influenced by NPK fertilization. Ciência Florestal 22: 467-476 (in Portuguese, with abstract in English). https://doi.org/10.5902/198050986615

Celestrino TS, Buzetti S, Teixeira Filho MCM, Gazola RN, Gazola RPD, Silva AC, et al. 2019. Management of boron fertilization in eucalyptus cultivated in the low altitude Cerrado region in Entisol. Revista Brasileira de Ciências Agrárias 14: e5634. https://doi.org/10.5039/agraria.v14i2a5634

Chu S, Jacobs DF, Sloan JL, Xue L, Wu D, Zeng S. 2018. Changes in soil properties under *Eucalyptus* relative *to Pinus massoniana* and natural broadleaved forests in south China. Journal of Forestry Research 29: 1299-1306. https://doi.org/10.1007/s11676-017-0546-9

Cunha ACMCM, Paiva HN, Leite HG, Barros NF, Leite FP. 2009. Influence of the nutritional status of ministumps on the rooting of eucalypt minicuttings. Revista Árvore 33: 607-615 (in Portuguese, with abstract in English). https://doi.org/10.1590/S0100-67622009000400003

Dell B, Malajczuk N. 1994. Boron deficiency in eucalypt plantations in China. Canadian Journal of Forest Research 24: 2409-2416. https://doi.org/10.1139/x94-311

Dias LPR, Gatiboni LC, Miquelutti DJ, Brunetto G, Campos DJP. 2017. Boron in preventing of shoot dieback on *Eucalyptus benthamii* grown in soil with different water regimes. Revista Scientia Agraria 18: 37-43. https://doi.org/10.5380/rsa.v18i3.52921

Dick G, Schumacher MV, Momolli DR, Guimarães CC, Souza HP, Ludvichak AA. 2017. Micronutrients and biomass in *Eucalyptus dunnii* Maiden stand. Revista Árvore 41: e410113. https://doi.org/10.1590/1806-90882017000100013

Falkiner RA, Smith CJ. 1997. Changes in soil chemistry in effluent-irrigated *Pinus radiata* and *Eucalyptus grandis* plantations. Australian Journal of Soil Research 35: 131-148. https://doi.org/10.1071/S95080

Faquin, V. 2005. Plant Mineral Nutrition = Nutrição Mineral de Plantas. UFV, Lavras, MG, Brazil (in Portuguese).

Ferrando MG, Zamalvide JP. 2012. Application of boron in eucalyptus: comparison of sources = Aplicación de boro en eucalipto: comparación de fuentes. Revista Árvore 36: 1191-1197 (in Spanish). https://doi.org/10.1590/S0100-67622012000600020

Ferreto DOC, Rodrigues JP, Ibarr MA, Oliveira CS, Vieira RCB, Weber MA, et al. 2016. Boron fertilization and liming for *Eucalyptus urograndis* cropped on sandy arenosol of Brazilian pampa. Journal of Plant Nutrition 39: 399-409. https://doi.org/10.1080/01904167.2015.1047517

Gupta UC, Jame YW, Campbell CA, Leyshon AJ, Nicholaichuk W. 1985. Boron toxicity and deficiency: a review. Canadian Journal of Soil Science 65: 381-409. https://doi.org/10.4141/cjss85-044

Hodecker BER, Barros NF, Silva IR, Diola V, Sarkis JES, Loureiro ME. 2014. Boron delays dehydration and stimulates root growth in *Eucalyptus urophylla* (Blake, S.T.) under osmotic stress. Plant and Soil 384: 185-199. https://doi.org/10.1007/s11104-014-2196-4

Indústria Brasileira de Árvores [IBÁ] 2020. Annual report. Available at: https://iba.org/datafiles/publicacoes/relatorios/relatorio-iba-2020.pdf [Accessed Apr 13, 2022]

Instituto Brasileiro de Geografia e Estatística [IBGE]. 2021. Technical Notes, Plant Extraction and Forestry Production = Notas Técnicas, Produção da Extração Vegetal e da Silvicultura. IBGE, Rio de Janeiro, RJ, Brazil (in Portuguese).

José JFBS, Silva IR, Barros NF, Novais RF, Silva EF, Smyth TJ, et al. 2009. Boron mobility in eucalyptus clones. Revista Brasileira de Ciência do Solo 33: 1733-1744. https://doi.org/10.1590/S0100-06832009000600022

Leite SMM, Valle CF, Bonine CAV, Marino CL. 2008. Boron influence on concentration of polyols and other sugars in *Eucalyptus*. Revista Árvore 32: 815-820. https://doi.org/10.1590/S0100-67622008000500005

Leite SMM, Marino CL, Bonine CAV. 2010. Response of *Eucalyptus grandis* and *E. grandis* x *E. urophylla* clones to boron suppression. Scientia Forestalis 38: 19-25 (in Portuguese, with abstract in English).

Lu H, Xu J, Li G, Liu W. 2020. Site classification of *Eucalyptus urophylla* x *Eucalyptus grandis* plantations in China. Forests 11: 871. https://doi.org/10.3390/f11080871

Malavolta E, Vitti GC, Oliveira SA. 1997. Assessment of the Nutritional Status of Plants: Principles and Applications = Avaliação do Estado Nutricional das Plantas: Princípios e Aplicações. POTAFOS, Piracicaba, SP, Brazil (in Portuguese).

Marcar NE, Guo J, Crawford DF. 1999. Response of *Eucalyptus camaldulensis* Dehnh., *E. globulus* Labill. ssp. *globulus* and *E. grandis* W. Hill to excess boron and sodium chloride. Plant and Soil 208: 251-257. https://doi.org/10.1023/A:1004594028069

Marschner P. 2012. Mineral Nutrition of Higher Plants. 3ed. Academic Press, London, UK.

Martíni AF, Valani GP, Boschi RS, Bovi RC, Silva LFS, Cooper M. 2020. Is soil quality a concern in sugarcane cultivation? A bibliometric review. Soil & Tillage Research 204: 104751. https://doi.org/10.1016/j.still.2020.104751

Mattiello EM, Ruiz HA, Silva IR, Guerra PC, Andrade VM. 2009. Physiological characteristics and dry matter production of *Eucalyptus* in response to boron. Revista Árvore 33: 821-830 (in Portuguese, with abstract in English). https://doi.org/10.1590/S0100-67622009000500005

Mhando ML, Maliondo SM, Mugasha AG. 1993. Early response of *Eucalyptus saligna* to site preparation and fertilization at Sao Hill, Tanzania. Forest Ecology and Management 62: 303-311. https://doi.org/10.1016/0378-1127(93)90056-S

Nageli P, Grant J, Nichols JD, Sheil D, Horton B. 2016. Bell miner associated dieback: nutrient cycling and herbivore crown damage in *Eucalyptus propinqua*. Australian Forestry 79: 74-82. https://doi.org/10.1080/00049158.2015.1123565

Poss JA, Grattan SR, Grieve CM, Shannon MC. 1999. Characterization of leaf boron injury in salt-stressed *Eucalyptus* by image analysis. Plant and Soil 206: 237-245. https://doi.org/10.1023/A:1004488331737

Poss JA, Grattan SR, Suarez DL, Grieve CM. 2000. Stable carbon isotope discrimination: an indicator of cumulative salinity and boron stress in *Eucalyptus camaldulensis*. Tree Physiology 20: 1121-1127. https://doi.org/10.1093/treephys/20.16.1121

Ramos SJ, Faquin V, Ávila FW, Ferreira RMA, Araújo JL. 2013. Biomass production, B accumulation and Ca/B ratio in Eucalyptus under various conditions of water availability and B doses. Cerne 19: 289-295. https://doi.org/10.1590/S0104-77602013000200013

Redin M, Santos GF, Miguel P, Denega GL, Lupatini M, Doneda A, et al. 2011. Impacts of burning on chemical, physical and biological attributes of soil. Ciência Florestal 21: 381-392 (in Portuguese, with abstract in English). https://doi.org/10.5902/198050983243

Rodríguez-Juárez MI, Velázquez-Martínez A, Gómez-Guerrero A, Arnulfo A, Domínguez-Domínguez M. 2014. Boron fertilization in plantations of *Eucalyptus urophylla* S. T. Blake in tabasco. Revista Chapingo Serie Ciencias Forestales y del Ambiente 20: 204-213 (in Spanish, with abstract in English). https://doi.org/10.5154/r.rchscfa.2013.09.038

Romanelli JP, Fujimoto JT, Ferreira MD, Milanez DH. 2018. Assessing ecological restoration as a research topic using bibliometric indicators. Ecological Engineering 120: 311-320. https://doi.org/10.1016/j.ecoleng.2018.06.015

Sakya AT, Dell B, Huang L. 2002. Boron requirements for *Eucalyptus globulus* seedlings. Plant and Soil 246: 87-95. https://doi.org/10.1023/A:1021589029492

Schwambach J, Fadanelli C, Fett-Neto AG. 2005. Mineral nutrition and adventitious rooting in microcuttings of *Eucalyptus globulus*. Tree Physiology 25: 487-494. https://doi.org/10.1093/treephys/25.4.487

Scott PM, Barber PA, Hardy GESJ. 2015. Novel phosphite and nutrient application to control *Phytophthora cinnamomi* disease. Australasian Plant Pathology 44: 431-436. https://doi.org/10.1007/s13313-015-0365-4

Silva AG, Machado PS, Barros NF, Fonseca S, Alfenas AC. 2018. Severity of *Xanthomonas axonopodis* leaf blight on eucalypt cuttings under different levels of nutrients. Forest Pathology 48: e12412. https://doi.org/10.1111/efp.12412

Silveira RLVA, Takahashi EN, Sgarbi F, Camargo MAF, Moreira A. 2000. Development and nutrition of *Eucalyptus citriodora* tree sprouting under boron rates in nutrient solution. Scientia Forestalis 1: 53-67 (in Portuguese, with abstract in English).

Song Y, Zhao T. 2013. A bibliometric analysis of global forest ecology research during 2002-2011. Springer Plus 2: 204. https://doi.org/10.1186/2193-1801-2-204

Trevizam R, Brondani GE, Nery FU, Gonçalves AN, Almeida M. 2011. Morphological characterization of calli of *Eucalyptus urophylla* S. T. Blake subjected to concentrations of boron and calcium. Cerne 17: 215-222 (in Portuguese, with abstract in English). https://doi.org/10.1590/S0104-77602011000200009

Trindade H, Pais MS. 1997. In vitro studies on *Eucalyptus globulus* rooting ability. In Vitro Cellular & Developmental Biology-Plant 33: 1-5. https://doi.org/10.1007/s11627-997-0032-8

Trueman, SJ, McMahon TV, Bristow M. 2013a. Nutrient partitioning among the roots, hedge and cuttings of *Corymbia citriodora* stock plants. Journal of Soil Science and Plant Nutrition 13: 977-989. https://doi.org/10.4067/S0718-95162013005000077

Trueman SJ, McMahon TV, Bristow M. 2013b. Production of cuttings in response to stock plant temperature in the subtropical eucalypts, *Corymbia citriodora* and *Eucalyptus dunnii*. New Forests 44: 265-279. https://doi.org/10.1007/s11056-012-9315-y

Trueman SJ, McMahon TV, Bristow M. 2013c. Production of *Eucalyptus cloeziana* cuttings in response to stock plant temperature. Journal of Tropical Forest Science 25: 60-69.

Valani GP, Martini AF, Silva LFS, Bovi RC, Cooper M. 2021. Soil quality assessments in integrated crop-livestock-forest systems: a review. Soil Use and Management 37: 22-36. https://doi.org/10.1111/sum.12667

Wheeler MA, McComb JA. 2006. *In vitro* pollen viability and pollen storage in *Eucalyptus marginata* (Myrtaceae). Australian Forestry 69: 32-37. https://doi.org/10.1080/00049158.2006.10674985