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Pine afforestation on degraded lands: a global review of carbon sequestration potential

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Pine plantations on degraded lands play an important role in providing ecosystem services, among the most significant being soil and land protection against erosion, water source protection, carbon sequestration, and the restoration of landscape and biodiversity. In addition, these plantations also have a significant social and economic role. This study offers a comprehensive bibliometric and systematic analysis of publications on the use of pines in plantations on degraded lands and the environmental effects of these plantations, especially regarding soil, water, carbon storage, and more. The study's results include an assessment of research trends, key contributors, and their influence on scientific progress in forestry, ecological restoration, and environmental protection. A total of 281 publications on the use of pines in plantations on degraded lands were identified, published between 1983 and 2024. These publications mainly originate from the USA, China, and Spain, with additional contributions from European institutions. The research findings are published in top journals in the fields of forestry, ecology, and the environment, highlighting their global impact. These articles belong to the scientific fields of environmental science and ecology, forestry, agriculture, water sciences, and others. The research results have been published in numerous journals, with the most frequently cited being *Forest Ecology and Management*, *Forests*, and *Land Degradation & Development*. The most frequently used keywords include afforestation, forest, restoration, pine, and carbon. The analysis of publications on the use of pines for afforestation of degraded lands highlights the widespread use of pine species in reforestation, underlining the resilience and adaptability of these species in various degraded land conditions. Future research should focus on innovative techniques for ecological reconstruction and pine forest regeneration, measures to adapt these plantations to climate change, the impact of ecosystem management practices on degraded lands on their carbon storage potential, and the effectiveness of pine species in various ecological conditions.

KEYWORDS

afforestation, land restoration, forest management, carbon stock, ecosystem services

1 Introduction

Soil erosion is a major environmental issue, affecting more than 1,100 million hectares of land globally and redistributing approximately 75 billion tons of soil annually (Lavelle et al., 2005; Pimentel et al., 1995). The eroded soil contains 1.5–5% carbon, contributing significantly to global carbon loss (Lal, 2001). Soil erosion depletes nutrients, reduces soil depth, and leads to land degradation and desertification. It disrupts nutrient cycling and soil productivity, severely affecting agricultural systems and ecosystems. The consequences extend beyond on-site degradation, as off-site impacts include siltation of water bodies, water flow irregularities, reduced irrigation capacity, water pollution, and agrochemical runoff (Uri, 2001; Ananda and Herath, 2003). Global warming is expected to intensify the hydrological cycle, resulting in more total precipitation and an increased frequency of high-intensity rainfall events (Tudose et al., 2022; Marin et al., 2022). These climatic changes, in combination with shifts in temperature, solar radiation, and atmospheric CO_2 levels, are anticipated to significantly influence soil erosion processes (Nearing et al., 2004). The most immediate impact of climate change on erosion is the alteration in rainfall erosivity, which directly affects the detachment and transport of soil particles (Favis-Mortlock and Guerra, 1999; Mullan, 2013; Mihalache et al., 2020). Furthermore, modeling studies indicate that future climate scenarios will lead to higher rates of soil erosion and soil organic carbon loss, especially in areas with steep slopes, sandy soils, and fallow land (Mondal et al., 2016; Marin et al., 2024). Recent studies further support this, showing that climate-induced changes in erosion patterns and nutrient redistribution could intensify land degradation and food insecurity in vulnerable regions (e.g., Shen et al., 2015; Wang et al., 2024).

Under conditions of climate change and the expansion of environmental degradation processes, degraded lands present potential locations for tree plantations. When managed well, these plantations can restore landscapes and sustainably produce wood and non-wood resources (Dincă et al., 2015). Moreover, the use of highly resilient seedlings obtained in genetic breeding programs and the creation of favorable species mixtures composition could ensure the success of forest lands restoration programs (Budeanu et al., 2014; Apostol et al., 2020; Marcu et al., 2020; Budeanu et al., 2025). The benefits of afforesting degraded lands include biodiversity improvement, ecosystem stability, protection against soil erosion, provision of recreational activities, and increased carbon accumulation (Maestre and Cortina, 2004; Semwal et al., 2013; Moscatelli et al., 2017; Oprică et al., 2022). Nevertheless, in the beginning of 18th and the late of 20th century, resinous monocultures of Scots pine (*Pinus sylvestris*) and Norway spruce (*Picea abies*) were introduced well in Central Europe (Knoke et al., 2008; Heinrichs et al., 2019), resulting the forest composition of the current inventory, used to define the forest types (Simons et al., 2021). Moreover, conifer forests of Silver fir provide different ecosystem services such as productivity and resistance toward the disturbing factors as well as fulfill different types of both protective and ecological functions, especially at higher altitudes (Dincă et al., 2022).

Pine species have been and continue to be frequently used for restoration of forest vegetation on degraded lands (eroded, ravine-affected, rocky lands, mining dumps and so on), coastal areas, and low-productivity lands in many countries worldwide (United States, Brazil, India, China, Germany, Spain, and so on). Pine plantations have also been established to replace low-productivity or derived forests or to afforest lands outside their natural range (Constandache et al., 2021). The installation of protective forestry cultures made up of pine species had as its main purpose the reduction of degradation processes, the protection of socio-cultural objectives by reducing the intensity of torrential rain, soil, climate and development works in torrent control structures (Silvestru-Grigore et al., 2016).

Among the many pine species globally (187 identified species), the most commonly used for afforesting degraded lands have been Scots pine (*Pinus sylvestris* L.), black pine (*Pinus nigra* Arn.), and, less frequently, eastern white pine (*Pinus strobus* L.), ponderosa pine (*Pinus ponderosa* Laws.), and others. The first two species are known for their modest requirements regarding climatic and soil conditions (Șofletea and Curtu, 2007; Vlad et al., 2019), making them suitable for afforesting degraded lands (Untaru et al., 2008; Silvestru-Grigore et al., 2018) as well as other types of land outside their natural range (Enescu and Dănescu, 2013). Pine plantations have also been established to replace low-productivity forests (productivity classes IV and V) or derived forests (e.g., hornbeam forests, mixed stands) (Arhip, 1998) on lands outside their natural range (Constandache et al., 2021).

The effects of pine plantations on degraded lands include land restoration and making use of lands unsuitable for other purposes (Constandache et al., 2024), as well as mitigating climate change effects due to their high capacity for atmospheric CO_2 sequestration (Dincă et al., 2015). They also help prevent land degradation through soil stabilization and improvement (Nicolescu et al., 2018), reduce anthropogenic pressure on natural forest ecosystems, and provide an alternative for fossil fuel production (Spîrchez and Lunguleasa, 2016).

Several studies provide valuable insights on the ecological restoration or silvicultural management of specific pine species or regions (e.g., Pausas et al., 2004; Allen et al., 2002; Mechergui et al., 2022; Imanuddin et al., 2020; Wasserman et al., 2022). Compared with previous studies, our research differs in terms of scope, methodology, and contribution.

First of all, we provide a global perspective through systematically synthesized data on pine plantations across multiple continents, while previous papers focus on a specific region (e.g., Mediterranean, southwestern USA, Indonesia) or individual species (e.g., *Pinus pinea*, *Pinus merkusii*, ponderosa pine). Second, we integrate the quantitative bibliometric analysis (e.g., publication trends, co-authorship, keyword evolution) with traditional review on ecological restoration, carbon stocks, and land rehabilitation. In doing so, we were able to map the development of research on pines in restoration contexts and identify knowledge gaps, key collaborative networks, and emerging research themes through VOSviewer. Third, while other studies address biomass or carbon storage (e.g., Mechergui et al., 2022) we offer an updated analysis of carbon sequestration in pine plantations considering both above- and below-ground in varied ecological conditions and management practices. Finally, we conducted a cross-comparison of thinning and afforestation practices, as well as their environmental impacts, across species and ecosystems, thereby enabling comparative insights into best practices for degraded land restoration.

Considering the worldwide expansion of afforestation initiatives, particularly under climate policy and carbon credit frameworks, our research provides policy-relevant insights regarding the potential and limits of using pines on degraded lands. Moreover, our analysis serves as a baseline for further research and supports practitioners and researchers to improve their knowledge on the ecological trade-offs of pine-based restoration at a global scale. There are bibliometric studies on carbon stock (Jiang et al., 2022; Wu et al., 2024; Yu and Song, 2023). In recent years, bibliometric analysis has also been used in forestry studies (Bullock and Lawler, 2015; Ma et al., 2022; Sullivan, 2022; Santillán-Fernández et al., 2023; Oluwajuwon et al., 2024).

The goal of this study is to review and analyze the utilization of pine species for afforestation on degraded lands, focusing on their role in land restoration, soil stabilization, and carbon sequestration. Through a bibliometric and literature review approach, the study aims to assess the environmental benefits of pine plantations, evaluate their contribution to carbon stock accumulation, and identify key trends, challenges, and research gaps in this field. Additionally, it seeks to provide insights into the most frequently studied pine species, their effectiveness in different ecological conditions, and the impact of forest management practices on their carbon storage potential.

This study is significant because it synthesizes over four decades of global research on pine-based afforestation efforts, offering a comprehensive understanding of their ecological and climate-related benefits. By mapping the evolution of scientific knowledge and highlighting priority areas for future research, the study supports the development of informed policies and strategies for restoring degraded ecosystems and enhancing climate resilience through pine plantations.

2 Materials and methods

We used the Web of Science Core Collections from the Web of Science (WOS) platform (Web of Science, 2024) and Scopus platform to compile a bibliographic database on pine plantations established on degraded lands. Recognized for its reliability, WOS is a preferred resource among researchers and is extensively utilized in recent bibliometric studies (e.g., Dincă et al., 2024; Mi'raj and Ulev, 2024; Yardibi et al., 2024). Employing WOS's "Advanced Search" functionality, we performed searches using terms like *"Utilization of pines on degraded lands and carbon stocks"* and "*pines on degraded lands and carbon stocks,*" focusing on publications dated between January 1, 1983, and December 31, 2024.

Data processing involved Web of Science Core tools (Clarivate, 2024), alongside Excel (Microsoft, 2024) and Geochart (Google, 2024). Visualization of maps and cluster analysis were carried out using VOSviewer version 1.6.20 (VOS Viewer, 2010). From the initial 1,489 records identified, we excluded duplicates (i.e., articles indexed in both Web of Science and Scopus), conference proceedings, book chapters, articles without abstracts, studies with unclear geographic origin, and those unrelated to the research topic (e.g., not focused on carbon stocks in pine forests). After applying these criteria, 281 articles remained for detailed analysis.

The bibliometric analysis aimed to uncover emerging themes, prominent contributors, and insights into articles, authors, and journals relevant to the topic. The study focused on 10 primary aspects: (1) publication types, (2) WOS Categories for Web of Science data and All Science Journal Classification codes for Scopus data, (3) publication years, (4) countries, (5) institutions, (6) language, (7) journals, (8) publishers, (9) authors, and (10) keywords.

The study's second phase adopted a traditional review methodology, providing an in-depth assessment of numerous articles (1,489 were examined). Results were grouped into two key categories: "Pines and Carbon Stock" and "Pines on Degraded Lands and Carbon Stock." The first category included four main themes: Carbon sequestration across Pine species; Allometric models for estimating Pine biomass and carbon stock; Carbon dynamics in mixed versus pure Pine stands and Effects of thinning on carbon allocation in Pine forests.

A schematic presentation of the adopted methodology is shown in Figure 1.

3 Results

3.1 Bibliometric review

The first article on this topic was published in a renowned scientific journal in 1983. After that, the number of published articles followed an increasing trend, with a significant rise especially after 2015 (Figure 2). Citations have followed a similar upward trend, in line with the number of published articles. Citation data: citing articles = 7,389, times cited = 8,058, average per item = 2,984 (Web of Science, 2024).

A total of 204 authors who have published at least one article on this topic were identified. The most prolific contributors in the area of pine use on degraded lands were Lucian Dinca and Cristinel Constandache (5 articles each), and John Stanturf (4 articles), reflecting a strong focus on 'degraded land' terminology in Romanian research. In contrast, the most productive authors in studies focusing on carbon stocks in pine stands were primarily from Finland and Spain—such as Seppo Kellomäki (18 articles), Keli Peltola (14), Miren del Río (13), and Ricardo Ruiz-Peinado (13 articles)—highlighting regional specialization. Although the largest number of articles originated from institutions in the USA and China, these contributions were more widely distributed among a larger pool of authors with fewer publications each.

The most well-represented countries are the USA (72 articles), China (41 articles), Spain (30 articles), Canada (16 articles), and Germany (15 articles) (Table 1).

The countries of origin of the authors who have published articles on this topic can be grouped into five clusters: the first cluster includes England, Ecuador, Belgium, France, and the Czech Republic; the second cluster includes Spain, Brazil, Mexico, Sweden, Italy, Poland, and Norway; the third cluster includes China, Russia, and Turkey; the fourth cluster includes the USA, Iran, Argentina, and Sri Lanka; the fifth cluster includes Germany, Chile, and South Korea (Figure 3).

The most representative institutions where authors publishing on this topic are active include: Chinese Academy of Science (with 18 articles), United State Department of Agriculture (with 17 articles), United States Forest Service (with 17 articles), Consejo Superior de Investigaciones Cientificas (with 10 articles), University of Wisconsin Madison (with 9 articles) and University of Wisconsin System (with 9 articles).

Articles on this topic have been published in 306 journals, with the highest number of articles appearing in: Forest Ecology and Management (25 articles), Forests (16 articles) and Land Degradation & Development (11 articles). However, when considering total link strength, the top three journals in the ranking are: Forest Ecology and Management, Catena, and Geoderma (Table 2).

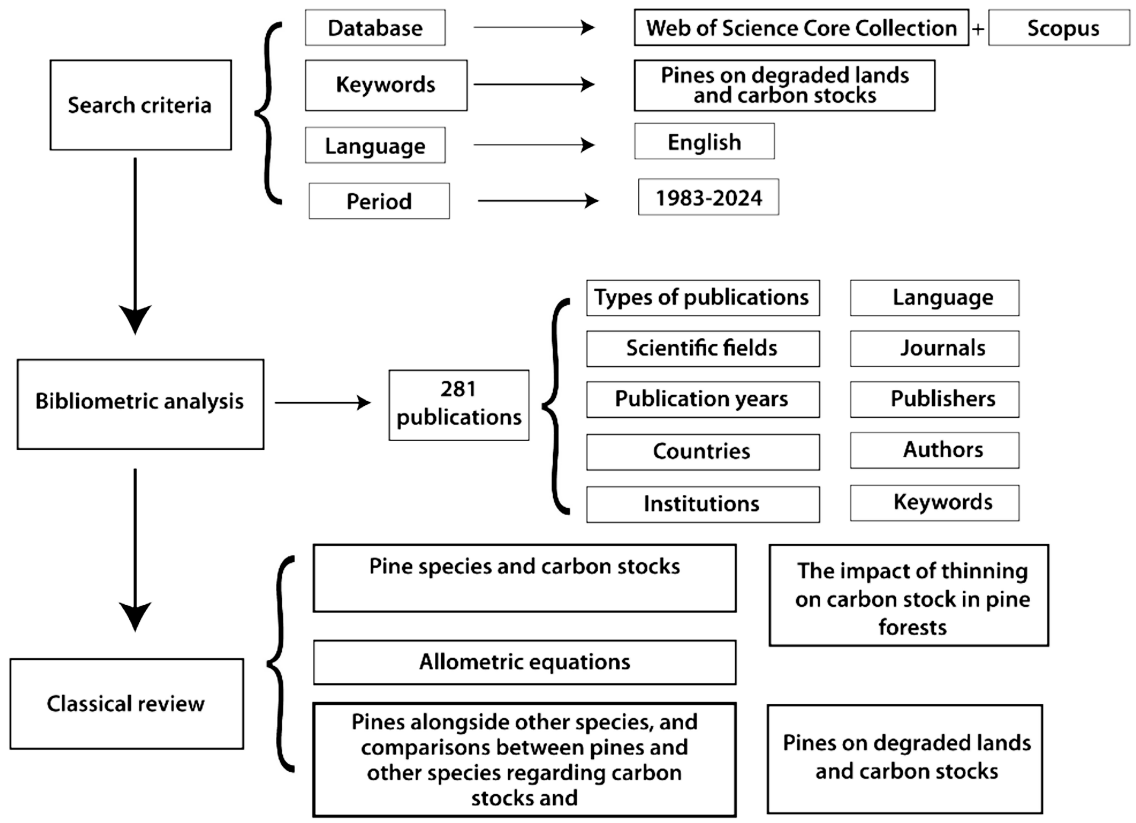

FIGURE 1
The scheme of the adopted methodology.

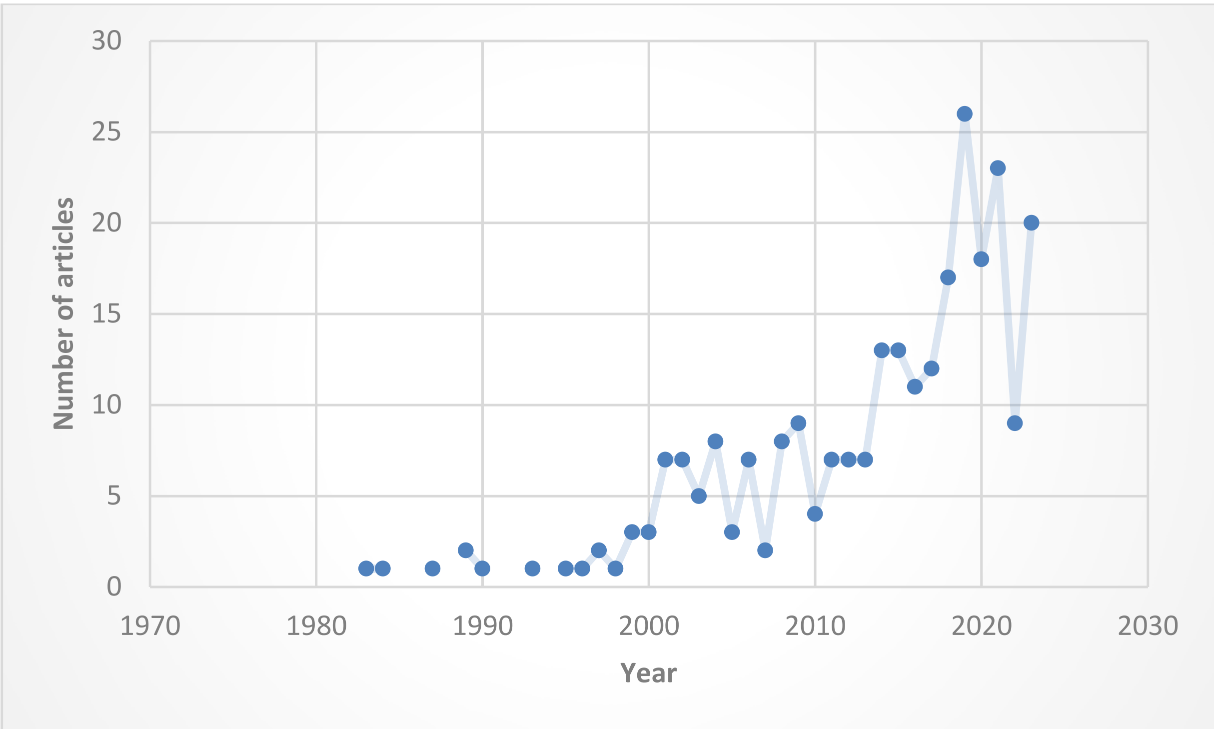

FIGURE 2
The distribution of the articles on years.

TABLE 1 The most representative countries where articles on the utilization of pines on degraded lands have been published.

Crt. no.	Country	Documents	Citations	Total link strength
1	USA	72	3,291	35
2	China	41	1,042	24
3	Spain	30	880	19
4	Germany	15	318	15
5	Ecuador	7	339	10
6	Australia	10	256	9
7	Belgium	5	291	9
8	Scotland	6	153	9
9	Canada	16	210	8
10	England	5	130	8
11	France	6	380	8
12	Czech Republic	6	81	7
13	Italy	11	140	6
14	Argentina	7	86	5

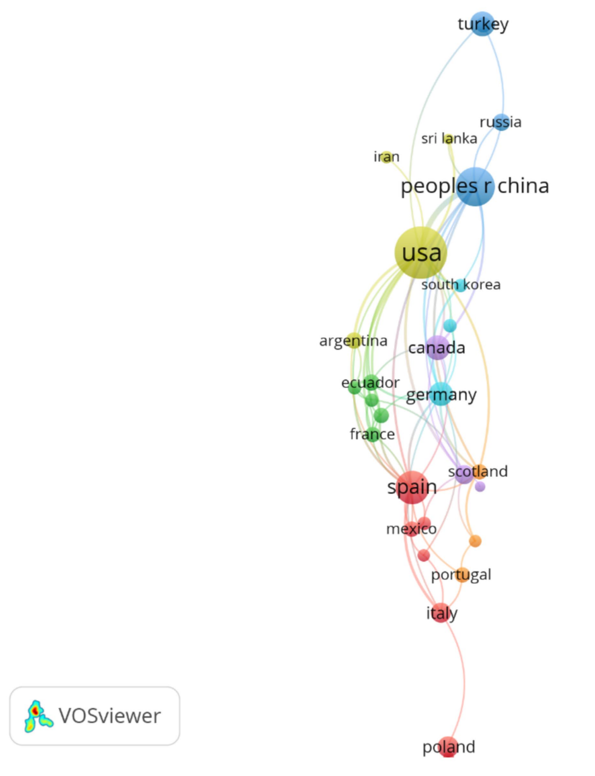

FIGURE 3
Clusters of countries with authors who have published articles on the utilization of pines on degraded lands. The node size and the thickness of the connecting lines are proportional to the number of documents assigned to each country. The connections represent the collaboration network among research institutions.

TABLE 2 The most representative journals where articles on the utilization of pines on degraded lands have been published.

Crt no.	Review	Documents	Citations	Total link strength
1	Forest Ecology and Management	25	1,446	16
2	Catena	7	335	13
3	Geoderma	4	130	8
4	Restoration Ecology	6	183	7
5	Land Degradation and Development	11	176	6
6	Science of the Total Environment	3	26	6
7	Agriculture Ecosystems and Environment	2	213	5
8	Forests	16	119	5
9	Journal of Hydrology	4	221	5
10	Ambio	2	110	4
11	Biodiversity and Conservation	2	469	4
12	Biotropica	2	65	4
13	Ecological Engineering	5	122	4
14	European Journal of Forest Research	2	24	4
15	Fresenius Environmental Bulletin	2	3	4
16	iforest-Biosciences and Forestry	2	15	4

The journals can be grouped into six clusters: Cluster 1: Applied Soil Ecology + Agriculture, Ecosystems & Environment + Ecological Engineering; Cluster 2: Journal of Hydrology + Ecological Indicators + Science of the Total Environment + Agricultural and Forest Meteorology; Cluster 3: Forest Ecology and Management + Land Degradation + Ambio; Cluster 4: Restoration Ecology + Ecological Applications + New Forests + Plant and Soil; Cluster 5: Catena + European Journal of Forest Research + Geoderma + Biodiversity and Conservation + Land Degradation & Development; Cluster 6: Forests + iForest-Biogeosciences and Forestry + Bioenergy Research + Scientific Papers Series E-Land (Figure 4). Journals were grouped into clusters using co-citation analysis and the VOSviewer clustering algorithm based on their bibliographic coupling strength (VOS Viewer, 2010).

The most frequently used keywords are *forest*, *afforestation*, *nitrogen*, and *plantations*, highlighting the central themes in the

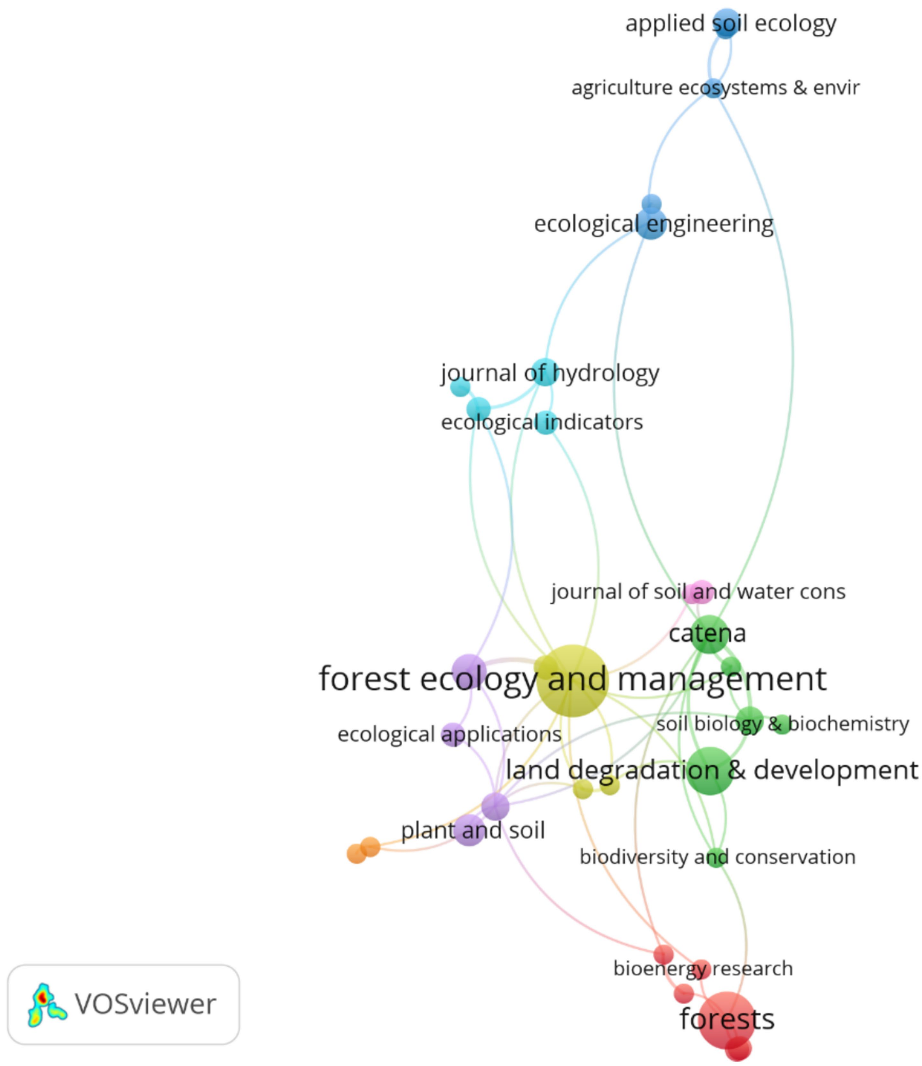

FIGURE 4
The main journals where has been published articles about the utilization of pines on degraded lands.

literature on pine-related restoration. The keywords are grouped into four distinct clusters, each reflecting different thematic emphases in the field. The first cluster includes 16 words, such as *forest*, *nitrogen*, *management*, *organic carbon*, and *sequestration*, indicating a strong focus on soil nutrient dynamics and carbon management in forested systems. This cluster underscores the ecological processes underpinning carbon sequestration and nutrient cycling in pine-based restoration efforts. The second cluster consists of 15 words, including *biodiversity*, *growth*, *restoration*, *reforestation*, *land*, and *succession*. These terms suggest a broader ecological restoration narrative, where biodiversity recovery and vegetative succession are central outcomes of reforestation, particularly with pine species, especially when planted in their native range or in admixtures. The third cluster, comprising 10 words such as *biomass*, *land use*, *plantations*, *Scots pine*, and *climate change*, reflects the intersection of land-use change, biomass productivity, and climate mitigation potential—highlighting pine plantations' role in sustainable land management. Lastly, the fourth cluster includes 7 keywords like *pine*, *soil*, *erosion*, and *impact*, pointing to the role of pine species in controlling land degradation, particularly through soil stabilization and erosion reduction. Together, these clusters provide a multifaceted view of how pine species contribute to degraded land recovery, linking soil health, biodiversity, carbon cycling, and climate resilience. This clustering helps structure the ongoing scientific conversation and identifies integrated themes across ecological and management domains (Table 3 and Figure 5).

While in the 2012–2013 period the keywords used were *plantations*, *vegetation*, *reforestation*, and *dynamics*, in the years 2014–2016, the most used were *nitrogen*, *land-use*, *restoration*, and *growth*. In more recent years (2017–2020), the most common keywords have been *biodiversity*, *communities*, *pine plantations*, and *climate change* (Figure 6).

3.2 Pines and carbon stock

3.2.1 Pine species used in afforesting degraded lands for carbon

Many published articles refer to different pine species and their relationships with carbon stock (Table 4). These studies show that pine

TABLE 3 The most frequently used keywords in articles published on the utilization of pines on degraded lands.

Crt no	Keyword	Occurrences	Total link strength
1	Afforestation	35	127
2	Forest	36	122
3	Nitrogen	31	119
4	Plantations	30	117
5	Restoration	26	110
6	Vegetation	24	89
7	Dynamics	26	83
8	Carbon	22	73
9	Organic-matter	23	72
10	Pine	22	71
11	Management	22	64
12	Reforestation	14	63
13	Biomass	15	62
14	Land-use change	15	62
15	Land-use	25	61
16	Sequestration	16	59
17	Soil	22	56
18	Growth	21	55
19	Regeneration	14	53

species have been widely investigated across a range of geographic zones, with notable concentrations in China, Mexico, and the United States. China appears most frequently, with at least seven different species studied, indicating significant interest in pine afforestation for carbon sequestration. Similarly, multiple species from Mexico and the USA highlight the ecological and silvicultural relevance of pines in North American carbon strategies. Some species, such as *Pinus sylvestris* and *Pinus radiata*, are examined in multiple continents, reflecting their global use in plantation forestry and carbon projects. Several Pinus species, including *P. taeda*, *P. massoniana*, *P. densata, P. pinceana, P. cembroides, P. occidentalis, P. caribaea*, and *P. halepensis*, are mentioned in research articles related to carbon stocks on degraded lands. These studies explore the potential of Pinus species to sequester carbon in various degraded ecosystems, including abandoned agricultural lands, degraded forests, and sites affected by erosion (Li et al., 2024). The pine species plays a role in carbon sequestration and can help stabilize slopes and reduce erosion on degraded lands (Torres et al., 2021). Thematically, research spans natural forests, degraded lands, and commercial plantations, showing that pines play a versatile role in both ecological restoration and climate mitigation.

3.2.2 Allometric models for estimating pine biomass and carbon stock

Generally, tree allometry establishes quantitative relations between some key characteristic dimensions of trees (usually fairly easy to measure) and other properties (often more difficult to assess). In this paper, allometric equations refer to total tree-level aboveground biomass and are necessary for predicting carbon stock. These equations use different variables, the most commonly used being *diameter at breast height (DBH)* and *height (H), and, in case additional or distinctive elements appear – not found in other works (ex. geometric equations, etc.), we have also completed the presentation with the equations adjacent to the models, for the beauty of the exhibition.* For clarity of the exposition, we have presented in each case, within the limits of possibilities, the structure of the generic equations. An exposition cannot be made without presenting the structure of the generic equations. Examples of allometric equations for different pine species are provided in Supplementary Table S1. The table is structured as follows: section (a) generic allometric equations – for a clear and clever presentation – in this way we include the generic, the results could be exposed more obviously; –(b) the connected geometric, graphical fitted or supplementary variable equations etc. in connection with the anterior expression for completeness or clearer presentation; – (c) the allometric identified equations' parameters with eventually R –square or other coefficients of determination. For a faithful presentation, we kept the notations and names of the variables in accordance with the authors' presentation method. Having respect for the authors, we included most of the models presented in the articles.

3.2.3 Carbon dynamics in mixed versus pure pine stands

Organic carbon stock dynamics have been extensively studied in various forest ecosystems, with particular attention to pine (*Pinus* spp.) due to its ecological and economic significance. In many cases, pine species have been examined both in monoculture and in combination with other tree species, allowing for insights into their relative performance in carbon sequestration.

In southern boreal forests, a comparative study between *Jack pine* (*Pinus banksiana* Lamb.) and *trembling aspen* (*Populus tremuloides* Michx.) demonstrated that extending the rotation age beyond 90 years does not necessarily enhance carbon sequestration (Wang et al., 2012). This finding challenges the assumption that older stands always contribute to higher carbon storage, particularly in boreal environments.

In forestry shelterbelts, a combination of *Scots pine* (*Pinus sylvestris*) and *red cedar* (*Juniperus virginiana*) significantly increased soil organic carbon (SOC) in the topsoil layer (0–15 cm) compared to cultivated fields (3.994 g m^{-2} vs. 3.623 g m^{-2}) (Sauer et al., 2007). Similarly, in a 34-year-old plantation in Mozambique, *Loblolly pine* (*Pinus taeda* L.) combined with *Eucalyptus grandis* Hill showed improved SOC storage in the 0–50 cm soil profile (Guedes et al., 2016), highlighting the benefits of mixed-species afforestation in tropical and subtropical regions.

In China, the introduction of *Pinus massoniana* in mixture with *Castanopsis hystrix* contributed to an increase in ecosystem carbon stock (You et al., 2018). Furthermore, modeling projections for the period 2000–2,100 in Spain found that mixed plantations of *Scots pine* (*Pinus sylvestris* L.) consistently outperformed pure stands in terms of CO_2 accumulation across all biomass fractions (aboveground and belowground) (Rodríguez de Prado et al., 2023).

Contrasts between pine and broadleaf species are also notable. In northern Germany, thinned *Scots pine* forests demonstrated lower carbon sequestration potential compared to naturally developing *beech* (*Fagus sylvatica*) forests (Förster et al., 2021). However, soil carbon storage was, on average, approximately 80% higher under pine than under beech. The total soil organic carbon (SOC) stock in the soil

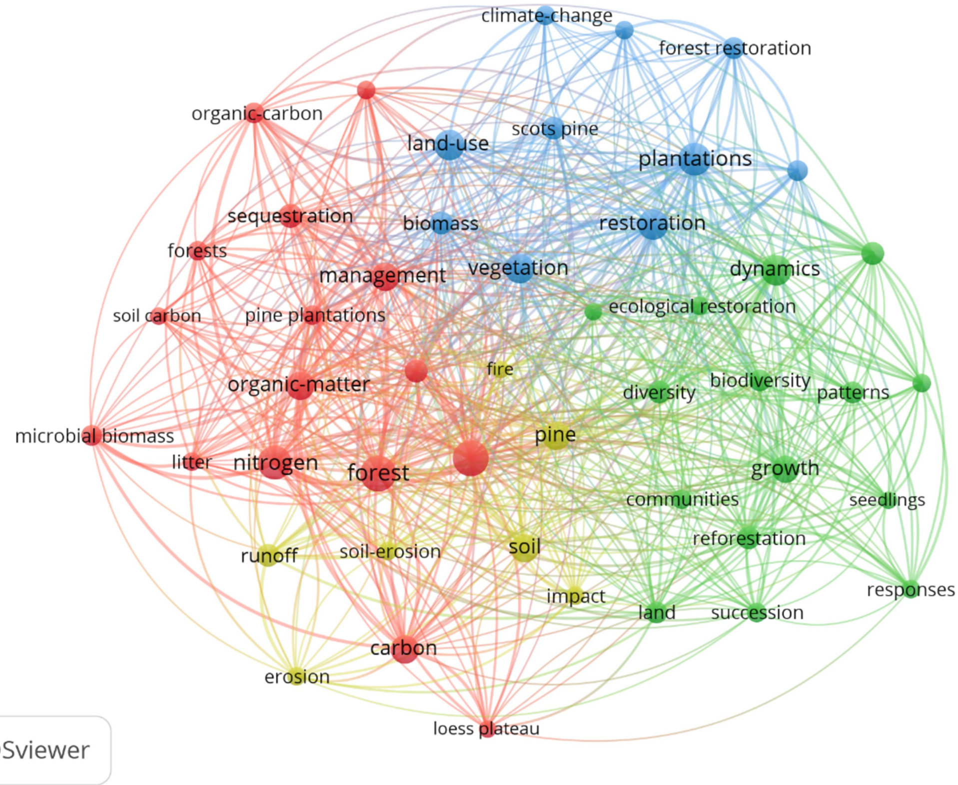

FIGURE 5
Authors' keywords concerning the utilization of pines on degraded lands. The node size and thickness of the connecting lines are proportional to the number of documents in which the keyword appears. The colors indicate the cluster the item belongs to, and the connection line between nodes represents co-occurrence; the shorter the distance between the different nodes, the stronger the relationship between the keywords.

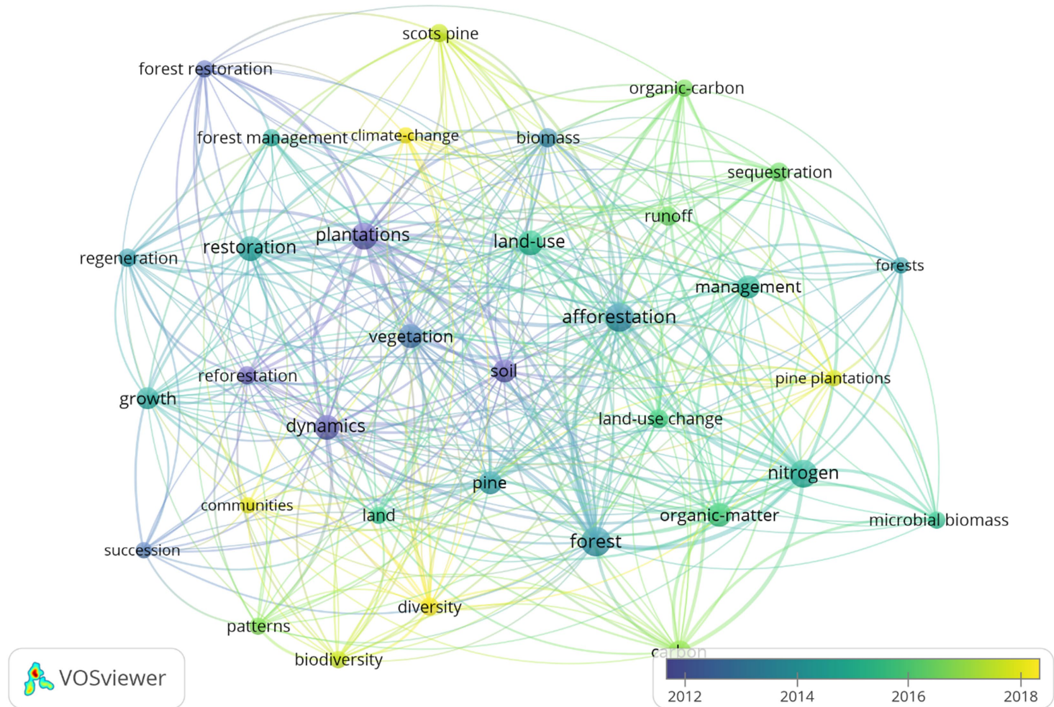

FIGURE 6
Yearly distribution of keywords regarding the utilization of pines on degraded lands. The node size and thickness of the connecting lines are proportional to the number of documents in which the keyword appears. The colors indicate the cluster the item belongs to, and the connection line between nodes represents co-occurrence; the shorter the distance between the different nodes, the stronger the relationship between the keywords.

TABLE 4 *Pinus* species mentioned in articles published on their carbon stocks.

Cur. no.	Species	Geographic zone	Cited by
1	*Pinus banksiana* Lamb.	China; Canada; USA	Wang et al. (2013), Foster and Morrison (2002), Rothstein et al. (2004), Fradette et al. (2021)
2	*Pinus brutia* Ten.	Turkiye	Bulut (2023)
3	*Pinus bungeana* Zucc. ex Endl.	China	Li C. et al. (2013) and Li X. et al. (2013)
4	*Pinus caribaea* Morelet	Venezuela	Gómez et al. (2008)
5	*Pinus cembra* L.	Austria	Jandl et al. (2018)
6	*Pinus cembroides* Zucc.	Mexico	Rios-Carrasco et al. (2009)
7	*Pinus contorta* Engelm.	USA	Chatterjee et al. (2009) and McIntire et al. (2022)
8	*Pinus densiflora* Siebold & Zucc.	South Korea	Baek and Kim (2024), Li C. et al. (2013), Li X. et al. (2013), and Kim et al. (2011, 2017)
9	*Pinus durangensis* Martinez	Mexico	Hernández-Vera et al. (2017)
10	*Pinus elliottii* Engelm.	China	Wang et al. (2015) and Fu et al. (2017a)
11	*Pinus halepensis* Mill.	Spain; Tunisia	Navarrete-Poyatos et al. (2019) and Rezgui et al. (2024)
12	*Pinus koraiensis* Siebold & Zucc.	Korea	Li et al. (2011)
13	*Pinus leiophylla* Schiede ex. Schltdl. & Cham.	Mexico	Hernández-Vera et al. (2017) and Valerio Hernández et al. (2024)
14	*Pinus massoniana* Lamb.	China	Bai and Ding (2024) and Fu et al. (2017b)
15	*Pinus merkusii* Jungh. & de Vriese	Indonesia	Hartiningtias et al. (2020)
16	*Pinus nelsonii* Shaw	Mexico	Rios-Carrasco et al. (2009)
17	*Pinus palustris* Mill.	USA	Markewitz et al. (2002), Samuelson et al. (2017), and Gonzalez-Benecke et al. (2018)
18	*Pinus patula* Schltdl. & Cham.	Zimbabwe; Ecuador	Mujuru et al. (2014), Quiroz Dahik et al. (2021), and Hofstede et al. (2002)
19	*Pinus pinaster* Aiton.	Turkey; Portugal	Ozdemir et al. (2013), Nunes et al. (2010), and Durkaya et al. (2019)
20	*Pinus pinceana* Gordon	Mexico	Rios-Carrasco et al. (2009)
21	*Pinus pinea* L.	Portugal; Italy	Correia et al. (2010) and Cutini et al. (2013)
22	*Pinus ponderosa* Douglas ex C. Lawson	USA; Argentina	Hicke et al. (2004), Araujo and Austin (2020), and Zhang et al. (2021)
23	*Pinus pumila* Pall.	China	Zhao et al. (2023)
24	*Pinus radiata* D. Don	New Zeeland; Australia; Spain	Mohan et al. (2020), Guo et al. (2008), and Balboa-Murias et al. (2006)
25	*Pinus resinosa* Ait.	Canada	Ouimet et al. (2007)
26	*Pinus roxburghii* Sarg.	Pakistan; India	Ali et al. (2020), Khan et al. (2021), Amir et al. (2018), Kumar et al., 2021, and Ali et al. (2023)
27	*Pinus sylvestris* L.	Sweden; Estonia; Poland; Latvia	Jörgensen et al. (2021), Uri et al. (2022), Pietrzykowski and Daniels (2014), Węgiel and Polowy (2020), and Kenina et al. (2018)
28	*Pinus sylvestris* var. *mongolica* Litv.	China	Chen et al. (2010), Khan et al. (2020), and Siqing et al. (2022)
29	*Pinus tabulaeformis* Carr.	China	Cheng et al. (2014), Zhao et al. (2014), and Cao et al. (2012)
30	*Pinus taeda* L.	USA; Brazil	Thomas et al. (2017), Cassol et al. (2019), and Gonzalez-Benecke et al. (2014)

profile (organic layer plus mineral soil, measured up to 60 cm and extrapolated to 100 cm) was about 40 and 20% higher under pine, respectively (Diers et al., 2021), indicating a significant belowground advantage for pine in certain contexts.

Simulation studies further support the role of pine in carbon dynamics. Vallet et al. (2009) modeled the conversion of *sessile oak* (*Quercus petraea*) stands to *black pine* (*Pinus nigra* subsp. *laricio*), revealing a potential increase in carbon storage of 1.6 tC ha^{-1} yr.$^{-1}$ over a 64-year rotation period of the conifer plantation.

Nevertheless, pine is not universally superior in terms of carbon sequestration. Recent research from Spain found that *Quercus* forests stored more total carbon than *Pinus halepensis* plantations. Notably, *Pinus* sequestered 55% of its carbon in aboveground biomass, while *Quercus* stored approximately 60% belowground, in roots and soil (Bor et al., 2023). These findings underscore the importance of considering both aboveground and belowground carbon pools when assessing forest management strategies for carbon mitigation.

In South Korea, *Pinus densiflora* and *Quercus* var*iabilis* stands exhibit similar carbon stock distributions, with limited influence from interspecific differences such as litterfall and decomposition rates. However, *P. densiflora* shows significantly higher total carbon input from litterfall, and litter-derived organic carbon is decomposed more rapidly compared to *Q.* var*iabilis* (Baek and Kim, 2024).

Consequently, although pine monocultures may have certain economic advantages (higher productivity), mixed pine forests with deciduous trees often demonstrate greater potential for carbon storage and ecosystem restoration on degraded lands.

3.2.4 Effects of thinning on carbon allocation in pine forests

Thinning plays a crucial role in modifying carbon dynamics in pine forests, though its effects on carbon stock are highly context-dependent. Outcomes vary based on thinning intensity, species-specific traits, site conditions (e.g., climate, soil, and topography), stand age, forest structure, and the carbon accounting approach used (i.e., whether off-site storage in harvested wood products is included).

3.2.4.1 Thinning intensity and species-specific responses

Heavier thinning intensities often promote individual tree growth by reducing competition for light, water, and nutrients, which can lead to increased aboveground biomass. In Masson pine (*Pinus massoniana*), for instance, heavy thinning increased diameter growth and reduced the height-to-diameter ratio, improving stand stability and biomass accumulation (Deng et al., 2019). Similar trends were observed in young *Pinus halepensis* in Spain and *P. pinaster* in Mediterranean regions, where growth improvements translated to increased carbon sequestration, especially when harvested wood carbon was included (Lull et al., 2024; del Río et al., 2017).

Different pine species exhibit contrasting responses in carbon allocation. In heavily thinned stands of *P. halepensis* and *P. sylvestris*, soil organic carbon (SOC) increased post-treatment, while no such effect was seen in *P. nigra* (Navarro-Cerrillo et al., 2022). In southern Italy, *P. laricio* responded positively, with intense thinning significantly enhancing SOC (Settineri et al., 2018), suggesting that thinning can stimulate belowground carbon processes in some species.

3.2.4.2 Site conditions: climate, soil, and topography

Environmental context modulates the impact of thinning. For example, in the Southern Carpathians of Romania, higher altitude and specific site types correlated with increased wood mass production and carbon accumulation (Murariu et al., 2021; Crişan et al., 2024). Soil carbon responses, however, varied geographically. In Norway, *P. sylvestris* forests showed increased soil carbon stocks following thinning (Pohjola and Valsta, 2007), whereas in Turkey, thinning in *P. brutia* plantations had no significant effect on soil or biomass carbon pools (Erkan et al., 2023). In some Spanish *P. pinaster* stands, thinning did not significantly alter soil carbon, highlighting the role of site-specific variables such as soil texture, nutrient availability, and moisture (Ruiz-Peinado et al., 2016).

3.2.4.3 Stand age and forest structure

The developmental stage of a forest stand influences its response to thinning. Younger stands often exhibit compensatory growth and biomass accumulation, while older stands may respond with reduced growth and lower carbon gains (Meyer et al., 2021). In Germany, forest plots with higher mean diameter at breast height (DBH) stored more carbon overall, though structural traits and wood density also played a role (Springer et al., 2024). Thinning strategies should therefore consider both stand age and structural characteristics to optimize carbon outcomes.

3.2.4.4 Carbon allocation and accounting approaches

The impact of thinning on total carbon stock is also shaped by how carbon is measured. Some studies report declines in biomass carbon post-thinning, as seen in *P. sylvestris* (Ruiz-Peinado et al., 2013; Bravo-Oviedo et al., 2015), yet soil carbon often remains stable or may increase due to changes in microclimate, litter input, and root turnover. In the western US, Powers et al. (2012) highlighted that thinning primarily altered the distribution of carbon among above- and belowground pools, rather than the total carbon stock itself.

In summary, thinning can enhance or reduce carbon stock in pine forests, depending on its intensity, species involved, local site conditions, stand development stage, and how carbon is accounted for. Soil carbon dynamics, though less frequently emphasized than aboveground biomass, play a vital role in long-term carbon sequestration. Integrating both biomass and soil responses, and considering harvested wood products, provides a more comprehensive view of the carbon implications of thinning. Particularly on degraded lands, pine thinning practices that are context-sensitive can support carbon goals while contributing to ecosystem restoration.

3.2.5 Soil carbon dynamics in pine afforestation and management

Soil carbon plays a critical role in the long-term carbon sequestration potential of pine afforestation and forest management practices. Across the literature, pine plantations on degraded or marginal lands have shown variable yet often positive impacts on soil organic carbon (SOC) accumulation, depending on species, site conditions, and silvicultural interventions.

3.2.5.1 Pine afforestation impacts on degraded soils

Numerous studies demonstrate that afforestation with pine species enhances SOC, especially in the upper soil layers (0–30 cm), through increased litterfall, root biomass, and organic matter inputs. For example, afforestation with *Pinus sylvestris* in boreal and temperate zones has led to a gradual build-up of organic matter, particularly in formerly cultivated or degraded lands (Pohjola and Valsta, 2007). In China, *Pinus massoniana* plantations improved SOC and microbial biomass in subtropical degraded lands, indicating the ecological restoration potential of pines (You et al., 2018).

3.2.5.2 Effect of species composition and stand type

Mixed stands of pine and broadleaved species may enhance SOC compared to monocultures, by diversifying litter inputs and modifying decomposition rates. For example, mixed *Pinus densiflora* and *Quercus variabilis* stands in Korea had higher total carbon input through litterfall and faster decomposition under pine, reflecting species-specific dynamics (Baek and Kim, 2024). Similarly, *Pinus taeda* mixed with *Eucalyptus grandis* increased SOC in tropical regions (Guedes et al., 2016).

3.2.5.3 Soil response to thinning

Thinning effects on SOC are highly context-dependent. In some studies, such as those involving *Pinus halepensis* and *P. sylvestris*, soil carbon increased post-thinning due to enhanced root turnover and understory development (Navarro-Cerrillo et al., 2022). Conversely, in *Pinus brutia* stands in Turkey, thinning had no significant impact on SOC (Erkan et al., 2023), highlighting the importance of local soil texture, nutrient availability, and climatic conditions.

3.2.5.4 Vertical distribution and long-term storage

The vertical distribution of SOC varies among species. *Scots pine* stands typically accumulate substantial organic matter in the upper mineral soil and forest floor layers. However, in mixed forests with beech (*Fagus sylvatica*), SOC tends to be distributed deeper in the soil profile, suggesting different implications for long-term carbon stability (Diers et al., 2021).

We can conclude that soil carbon dynamics under pine afforestation and management are influenced by species traits, site conditions, and stand treatments. Restoration strategies that incorporate pine afforestation should consider these dynamics to maximize both ecological and carbon sequestration benefits.

3.3 Afforestation with pines on degraded lands: carbon recovery and soil enhancement

Plantations with different pine species (pure or mixed with deciduous trees) were established on degraded or abandoned lands, contributing to the restoration of the ecosystem and biodiversity. Restoring and preserving forest carbon (C) stocks in subtropical and tropical regions is an effective way to capture atmospheric CO_2 (Griscom et al., 2020; Koch and Kaplan, 2022). Afforesting degraded soils is essential for ecosystem recovery (Lamb et al., 2005; Coban et al., 2022). Reforestation with loblolly pine on degraded lands can restore soil carbon stocks to levels similar to subtropical natural forests within 30 years (Veloso et al., 2018).

3.3.1 Carbon sequestration in mined and degraded lands

Reclaiming mined lands accelerates post-mining ecosystem recovery and enhances carbon sequestration. In Poland, afforestation with Scots and black pine restored 20 and 27% of carbon stocks, respectively, after 35 years (Woś et al., 2022). Young forest ecosystems also showed relatively high C-sequestration compared to unmined managed pine forests (Pietrzykowski and Daniels, 2014). In Estonia, Scots pine stands in reclaimed oil shale mines accumulated 7.8 t·ha^{-1} of carbon by 1990, 34.5 t·ha^{-1} by 1983, and 133.4 t·ha^{-1} by 1968, with increasing C allocation to tree stems over time (Karu et al., 2009).

3.3.2 Pine afforestation in semi-arid regions

Mongolian Scots pine (*Pinus sylvestris* var. mongolica) has been widely used for vegetation restoration and windbreaks in Horqin Sandy Land, Northern China, due to its resilience to climate stress (Khan et al., 2022). Afforestation of active sand dunes with Mongolian Scots pine significantly increased soil carbon sequestration, with soil C levels 6.1 times higher in 25-year-old plantations and 10.2 times higher in 35-year-old plantations compared to active sand dunes (Li et al., 2012). However, in Keerqin Sandy Lands, afforestation of grasslands with Mongolian Scots pine did not significantly affect soil organic carbon (SOC) in the 0–100 cm layer, with C sequestration mainly attributed to tree biomass (Zhang et al., 2023).

In northeastern Mexico, three pinyon pine species (*Pinus cembroides, Pinus pinceana*, and *Pinus nelsonii*) are recommended for large-scale reforestation due to their high organic carbon storage (Rios-Carrasco et al., 2009). In China, planting Mongolian Scots pine on degraded grasslands initially decreased bulk topsoil (0–15 cm) carbon but increased as forests matured (Chen et al., 2010).

3.3.3 Afforestation and soil carbon improvement

Afforestation with various pine species enhances soil organic matter and atmospheric carbon sequestration (Panagopoulos and Hatzistathis, 1995; Ouimet et al., 2007). In Mozambique, *Pinus* and *Eucalyptus* plantations replacing degraded mountain miombo woodlands significantly increased carbon sequestration. Miombo woodlands stored ~116 Mg ha^{-1} of C, while *Pinus taeda* stands stored 363 Mg ha^{-1} (Guedes et al., 2018). Similarly, in the Himalayas, *Pinus roxburghii* plantations on degraded lands increased carbon storage (Jina et al., 2008).

In Nepal, pine-dominated forests on degraded lands had higher total carbon stock per hectare than mixed forests due to greater tree biomass, although mixed forests had higher litter and soil organic carbon (Aryal et al., 2013). In Ecuador, *Pinus patula* plantations had the highest aboveground and belowground carbon storage across most locations (Quiroz Dahik et al., 2021).

3.3.4 Carbon recovery in afforested lands

In southeastern China, *Pinus massoniana* ecologically managed forests significantly contributed to forest carbon density and soil carbon recovery in degraded landscapes, especially during the period of 2000–2015, when the C density rate was higher (25–48%) than the intermission period during 1989–2000 (only 9–18%) (Xu et al., 2019). In Spain, large-scale afforestation efforts since the 1950s helped restore severely eroded soils. In the Central Spanish Pyrenees, afforestation with *Pinus sylvestris* and *Pinus nigra* led to increased soil organic carbon (SOC), the results have revealed that more than 50 years after the land abandonment, the composition of SOC was largely similar across the different land-cover types, with significant differences observed under *P. nigra* afforestation, both in the topsoil and at depth (Campo et al., 2019).

In Chile, *P. radiata* plantations on degraded lands accumulated 181–212 Mg ha^{-1} of carbon in aboveground biomass, with total carbon stocks reaching 343 Mg ha^{-1}, showing a 138% increase in above-ground biomass C and carbon stock from age 10 to 20, with accumulation continuing beyond its 22–24-year economic rotation (Olmedo et al., 2020).

3.4 Ecological benefits of pine plantations in restoration

Beyond carbon sequestration, pine plantations contribute to a suite of ecological functions that make them valuable tools in the restoration of degraded landscapes. Their roles in soil stabilization, hydrological regulation, microclimate amelioration, and biodiversity enhancement support ecosystem recovery and resilience (Chirino et al., 2006; Martín-Peinado et al., 2016; Cifuentes-Croquevielle et al., 2020).

Soil stabilization and erosion control: Pine root systems, particularly those of species like *Pinus halepensis* and *P. pinaster*, are effective in stabilizing soils on slopes and erosion-prone areas (Danjon et al., 2005; Pérez-Rodríguez et al., 2007). Their dense root mats reduce surface runoff and enhance soil cohesion, critical in restoring degraded hillsides and preventing landslides or gully formation.

Hydrological regulation: Pine plantations can influence hydrological processes through canopy interception, evapotranspiration, and improved infiltration. In semi-arid and Mediterranean environments, *Pinus halepensis* plantations have shown mixed effects, with some studies indicating reduced runoff and better water infiltration due to improved ground cover, while others highlight potential water consumption trade-offs (Voltas et al., 2015; Vicente et al., 2018). Site-specific planning is thus essential to avoid adverse water balance impacts.

Microclimate improvement: Pines contribute to the amelioration of local microclimates by providing shade, reducing temperature extremes, and increasing air humidity (Castro et al., 2002; Gómez-Aparicio et al., 2008). This can foster the re-establishment of understory vegetation and soil microbial activity, creating favorable conditions for broader ecosystem development.

Biodiversity enhancement through admixtures: Although monoculture pine plantations often support lower biodiversity than natural forests, mixed-species plantations or those managed for structural heterogeneity can enhance habitat value (Carnus et al., 2006). Integrating broadleaved species such as *Quercus*, *Populus*, or native shrubs with pine increases vertical and horizontal complexity, promoting faunal and floral diversity (Barbaro and Rossi, 2006; Arnold and Larsson, 2017; Constandache et al., 2016). For instance, mixtures of *Pinus sylvestris* with native species in Europe have been shown to support higher bird and insect diversity compared to pure stands (Felton et al., 2010).

Ecological legacy and resilience: Over time, pine plantations can serve as ecological scaffolds—facilitating the return of native species, improving soil fertility, and enabling transitions toward more diverse forest systems. Their adaptability to poor soils and harsh conditions makes them particularly useful as pioneer species in restoration trajectories (Parrotta et al., 1997; Ruiz-Jaen and Aide, 2005).

In sum, the ecological benefits of pine plantations go beyond carbon to encompass multiple ecosystem functions vital for landscape rehabilitation. When designed with ecological principles and long-term goals, pine plantations can be a cornerstone of integrated restoration strategies.

4 Discussion

4.1 Bibliographic analysis

Most of the publications on this topic are articles (90%), distributed across 30 research areas, of which the most representative are Environmental Science, Ecology, Forestry, and Agriculture.

The most prominent research areas and journals are directly linked to the causes and consequences of land degradation and the outcomes of pine plantations on different land categories. Moreover, the keywords used in recent years align with modern trends in research on this topic and with management methods for pine stands. As some researchers point out, an analysis of the keywords used by authors reflects research trends (Onan et al., 2016). In the early years (2012–2013), the research focus was primarily on practical aspects of land recovery, reflected in keywords such as *plantations*, *vegetation*, *reforestation*, and *dynamics*. During the mid-period (2014–2016), studies increasingly addressed ecological processes, with prominent terms like *nitrogen*, *land-use*, *restoration*, and *growth*. More recently (2017–2020), the attention has shifted toward broader environmental concerns, with keywords including *biodiversity*, *communities*, *pine plantations*, and *climate change*, indicating a growing integration of ecological and climate-related themes into pine-related land restoration research. The keywords chosen for the article titles are among the top keywords used by the authors who published on this topic: pine ranks 10th, reforestation 12th, and management 11th. However, afforestation ranks 1st, and forest 2nd, highlighting the crucial role that afforestation and forests play in improving degraded lands. Other top keywords include plantations (4th), dynamics (7th), and carbon (8th). Keywords related to land use also occupy a special place (14th and 15th), and if combined, would likely rank 2nd.

The number of published articles as well as citations has increased significantly after 2015. The growing trend of published articles, observed in other bibliometric studies (Liu et al., 2019), also applies to the topic of pines on degraded lands. This phenomenon can be explained by two main factors: a recent substantial increase in the number of journals and scientific publications, along with a growing level of interest among researchers in this topic. Furthermore, the average annual number of scientific publications is expected to increase, driven by the growing demand for strategies that enhance carbon uptake, particularly in forest and grassland ecosystems, given their significant role in reducing greenhouse gas emissions (Ma et al., 2025). The increase in publications reflects the growing attention given to pines, especially in regions such as the Mediterranean Region, the Alps, and the USA. Our analysis identified authors from 66 countries across five continents who have contributed to this topic (Figure 7). We included only 23 countries out of 66, because we have considered only the most representative clusters (those with at least 5 countries).

Out of a total of 187 known pine species (World Flora Online, 2024), our bibliographic study identified 38 species (20% of the total number of pine species) for which articles have been published regarding afforestation and carbon stocks, with *Pinus banksiana* Lamb. being the most cited. The most commonly used species for afforestation of degraded lands, especially in Europe, has been the black pine (*Pinus nigra* Arn.), known as a species with modest requirements regarding climatic and soil conditions (Şofletea and Curtu, 2007; Vlad et al., 2019), with good results in halting soil erosion and landscape degradation. Various pine species (*Pinus sylvestris* L., *Pinus cembra* L., *Pinus ponderosa Douglas* ex C. Lawson) have been used both for afforestation of degraded lands (Untaru et al., 2008; Silvestru-Grigore et al., 2018) and on other land categories outside their natural range or to replace poorly productive stands (Enescu and Dănescu, 2013).

Since the chosen topic also refers to pines in mountainous areas, some review articles address this component (Vallauri et al., 2002; Hofstede et al., 2002). Other articles focus on plant inventory methods, such as monitoring (Traci and Untaru, 1986), remote sensing (Mapuru

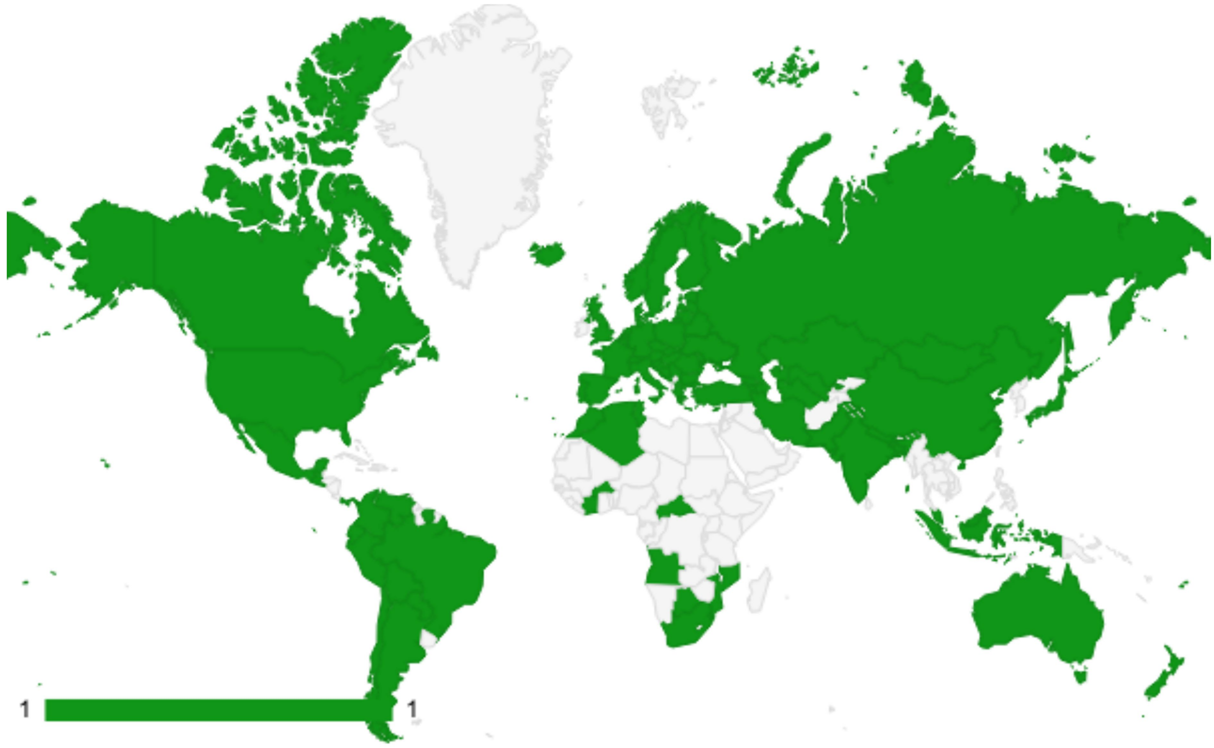

FIGURE 7
Distribution of countries where the utilization of pines on degraded lands is addressed in research articles.

et al., 2023), stand structure in specific geographical regions (Thanasis et al., 2007), or the evolution of plantations under different climatic and soil conditions (Constandache et al., 2024). Also, some articles focus on the examination of scientific literature about agroforestry practices and their role in enhancing agricultural productivity (Enescu et al., 2025) as well as the influence of climatic factors on health and sustainability (Bratu et al., 2025; Tudor et al., 2023). Review articles analyzing the influence of climate change on pine plantations on degraded lands are also well represented (Vlad et al., 2019).

Since this topic concerns areas of afforested degraded lands, it is natural that the authors come from countries with significant afforested areas, such as the USA, China, and Germany. Regarding the journals in which articles on this topic have been published, many have titles including terms such as forest, ecology, environment (e.g., Forest Ecology and Management, Forests, Restoration Ecology, Science of the Total Environment, Agriculture Ecosystems & Environment) or include restoration, aligning with the primary scientific fields discussed above.

4.2 Ecological and environmental benefits of pine afforestation

Afforestation with pines on degraded lands serves as an effective strategy for soil stabilization, nutrient retention, and landscape restoration. The results indicate that pine plantations enhance soil organic carbon (SOC) levels, particularly in severely degraded and mined lands. Studies from Poland and Estonia demonstrate that afforested lands with Scots and black pine show a marked increase in carbon sequestration over time, aligning with findings from previous research on carbon recovery in forested ecosystems (Woś et al., 2022; Karu et al., 2009). Moreover, pine species such as Mongolian Scots pine have proven particularly effective in semi-arid regions for mitigating desertification and improving soil carbon content. In most European countries, afforestation of degraded lands began at the end of the 19th century, with the main goal of conserving soil and landscapes. Pines were widely used in afforestation efforts in Greece, France, and Hungary. Afforestation was primarily carried out with black pine (*Pinus nigra* ssp. *nigra* and *P. nigra ssp. laricio*), with plantations needed to stop soil erosion and landscape degradation in hilly areas. This species is much more tolerant to maritime influences, such as salt-laden winds, than Scots pine (*Pinus sylvestris*), which is why it often grows closer to the sea. In Mediterranean Region, during the second half of the 20th century, many large reforestation projects were conducted in the south of Europe (Villar-Salvador, 2016). Several reforestation programs were undertaken in degraded areas where different pine species were planted, focused on reducing erosion and increase the forest productivity (Pausas et al., 2004).

In France, in the southwestern Alps region Haute-Provence, at 120 years after the first tree plantings, the plant communities are still early seral assemblages for the most part, with Austrian black pine occurring alone in the canopy. In contrast, most of the marly soils have physically recovered part of their total depth, with layers of fragmented and altered material equal to 50 cm, but their structure and chemical fertility are still poor (Vallauri et al., 2002). *Pinus nigra* Arnold var. *austriaca* has been widely used in reforestations in Greece. The use of *P. nigra* to restore the degraded ecosystems around Mt. Olympus was deemed as successful (Thanasis et al., 2007).

In Hungary, black pine, being quite drought-resistant and heat-tolerant, was used to improve lands characterized by dolomitic and sandy soils, where vigorous stands resulted (Tamas, 2003). In Bulgaria, the first afforestation efforts date from 1884 to 1887, when anti-erosion afforestation was undertaken on about 4,000 hectares. Forest plantations were established, predominantly of coniferous tree species [*Pinus sylvestris* L., *Pinus nigra* Arn., *Pseudotsuga menziesii* (Mirb.) Franco and so on] (Aleksandrov and Tonchev, 2021).

In the Southern United States, by the end of the 20th century, there were 32 million acres of pine plantations on cutover forest land and degraded agricultural land, and this region is now the woodbasket of the world (Fox et al., 2004).

In the Himalayan sub-tropical region, Chir pine (*Pinus roxburghii*), is the predominant tree species (Champion and Seth, 1968; Forest Survey of India, 2019), distributed within an altitude range of 450–2,300 m above mean sea level, covering nearly all major valleys and slopes in the region (Forest Survey of India, 2019) having the ability to mitigate soil erosion, improve soil quality and promote sustainable ecosystems (Razafindrabe et al., 2010).

In tree plantations in the Ecuadorian Andes, in extreme climatic and site conditions and soils developed in recent volcanic ashes, pine-based forestry programs are still promoted, using arguments such as the future demand for timber, the social acceptance of exotic species, and the possible ecological benefits of forest plantations in general (Hofstede et al., 2002).

Environmental factors, especially temperature and precipitation, significantly influence the results of studies on the behavior of pine trees in different areas. Temperature affects growth and development, while precipitation influences water availability and, therefore, the health and vitality of trees (Köse et al., 2025; Ramírez-Valiente et al., 2021) having an impact in biomass accumulation and carbon stock (Wu et al., 2025). In regions experiencing moderate increases in precipitation, carbon stocks may be sustained as long as moisture availability does not constrain vegetation growth, while elevated temperatures, can negatively affect biomass accumulation and carbon uptake, acting as a stress factor that may limit soil organic carbon storage (Murphy et al., 2025). Spatial and temporal variations in these factors can lead to different growth responses among pine populations, even within the same species (Zhao et al., 2024).

The impact of pine plantations cannot be generalized but should be evaluated case by case while care is taken in implementing plantations until more knowledge is obtained about the effects on the ecosystem as a whole, especially considering their ecological importance.

In conclusion, pine plantations can be a valuable way for both carbon sequestration and ecological reconstruction of degraded lands, but their effectiveness depends on the composition of the forest, the management practices applied and the intervention of damaging factors, requiring permanent long-term monitoring.

4.3 Carbon sequestration and stock accumulation

Many published articles refer to various pine species and their relationship with carbon stocks (Wang et al., 2012), to growth dynamics using allometric equations with different variables, and to the effect of silvicultural practices on plantations and carbon stocks (del Río et al., 2017).

A key focus of the reviewed studies was the assessment of carbon sequestration capacity of various pine species. The results indicate that different pine species contribute differently to carbon stocks depending on site conditions, forest management practices, and climatic variables (Navarro-Cerrillo et al., 2022; Wang et al., 2013; Węgiel and Polowy, 2020). Additionally, some authors used the cluster related to the "forest floor" to estimate biomass, including both total carbon and litter carbon storage, while assessing the effects of tree species (Huang et al., 2020). Their findings indicated that pine species exhibited higher carbon stocks in both the forest floor and soil organic layers (Usuga et al., 2010). The comparison between pure pine stands and mixed-species forests suggests that while pine plantations accumulate significant aboveground biomass carbon, mixed forests may provide a better balance of belowground and aboveground carbon storage (Rodríguez de Prado et al., 2023). Furthermore, thinning interventions were found to have variable impacts on carbon sequestration, influenced by several interacting factors. These include thinning intensity (Deng et al., 2019; del Río et al., 2017), tree species (Navarro-Cerrillo et al., 2022; Pohjola and Valsta, 2007), stand age (Lull et al., 2024; Powers et al., 2012), and site conditions such as soil type, elevation, and climate (Murariu et al., 2021; Crişan et al., 2024). Heavier thinning often promotes individual tree growth and increases carbon allocation to fewer, larger trees, potentially enhancing long-term biomass carbon stock (Deng et al., 2019; del Río et al., 2017). However, it can also temporarily reduce total ecosystem carbon due to biomass removal (Bravo-Oviedo et al., 2015; Ruiz-Peinado et al., 2013). Soil carbon responses are equally variable: thinning has been shown to increase soil organic carbon in some pine species and regions (Settineri et al., 2018), while in others, the changes were negligible or absent (Erkan et al., 2023; Ruiz-Peinado et al., 2016). Other relevant factors include the presence of understory vegetation, post-thinning regeneration, and whether the harvested biomass is stored in long-lived wood products (Alfaro-Sánchez et al., 2015; del Río et al., 2017). Therefore, the impact of thinning on carbon storage is highly context-dependent and must be evaluated within specific ecological and silvicultural frameworks.

4.4 Challenges and considerations in pine afforestation

Most articles analyzed environmental conditions and their effects on pine plantations, their structure, yield, and functions, to provide insights on estimating the success of reforestation or ecological restoration and on selecting optimal planting, maintenance, and stand management techniques about the species used and the environmental conditions.

Despite the benefits, challenges associated with pine afforestation must be acknowledged. The ecological impact of pine plantations, particularly regarding biodiversity, soil properties, and long-term sustainability, requires careful management. This suggests that afforestation efforts should consider the trade-offs between rapid biomass accumulation and long-term soil carbon stability.

Additionally, the selection of pine species is crucial for afforestation success. While Scots pine and black pine have been extensively used due to their adaptability to poor soils and harsh climates, other species such as *P. taeda* and *P. radiata* have demonstrated high productivity in specific regions.

After 1950, afforestation with coniferous species was widespread in the lower forest belt, which is outside their natural range. Now, due to the already advanced age of the artificial plantations established in the 1960s and 1970s, as well as the initiated processes of intensive degradation, their great ecological and economic value requires taking timely decisions on their future management (Aleksandrov and Tonchev, 2021).

For example, *P. hartwegii* exhibits more than 70% mortality due to water stress (Flores et al., 2021). Under such conditions, pine species will face adaptation difficulties and will not achieve the intended ecological reconstruction and protection goals. In recent years, there has been growing concern about restoring degraded ecosystems with pines and hardwood species, with various models being promoted to optimize their structure at acceptable costs (Vlad et al., 2019).

4.5 Future research directions

Future research should explore the long-term impacts of different pine species on soil condition and carbon cycling to optimize afforestation strategies.

The bibliometric analysis indicates an increasing trend in research on pines and carbon sequestration, yet gaps remain. Future studies should focus on the long-term monitoring of carbon stocks in pine afforestation projects, integrating remote sensing and modeling techniques to improve carbon estimation accuracy. Additionally, comparative studies between pine afforestation and other land-use strategies (e.g., agroforestry, mixed-species plantations) are needed to determine the most effective approaches for maximizing carbon sequestration and ecosystem resilience.

Moreover, climate change projections should be incorporated into afforestation planning, as changing precipitation patterns and temperature extremes may affect pine growth, survival, and carbon sequestration potential (Vasile et al., 2017; Mustăţea et al., 2022; Tudose et al., 2023a, 2023b). Research on adaptive management strategies, including species selection, thinning regimes, and soil amendments, will be critical for ensuring the long-term viability of pine afforestation on degraded lands.

Studies on artificially planted pine forests analyzing their structure, yield and function are needed to provide answers about site suitability for each tree species used and for the estimation of reforestation success (Thanasis et al., 2007). Future research should focus on innovative techniques for ecological restoration and regeneration of pine forests, measures to adapt them to climate change, the impact of forest ecosystem management practices on degraded lands', carbon storage potential, and the effectiveness of different pine species under various ecological conditions.

This study highlights how the authors of existing studies analyze the impact of environmental factors on pine forests, using modeling, statistical analysis or experimental approaches. These methods help to understand how variations in environmental factors, such as temperature and precipitation, affect the state and evolution of pine forests, especially those on degraded lands, but also their ecosystem functions, in the context of climate change. In conclusion, pine forests are sensitive to changes in temperature and precipitation, and these factors can influence their distribution, growth, and health. Understanding these relationships is essential for predicting future forest dynamics and developing effective management strategies in the context of climate change.

There are also some gaps and limitations of our study: Limited geographic scope – While the study covers a broad range of regions where pine plantations have been used for degraded lands restoration, some areas with significant afforestation efforts may be underrepresented due to data availability constraints. Lack of long-term data – Many studies focus on short- to medium-term effects of pine afforestation, while the long-term ecological impacts, including biodiversity shifts and soil nutrient cycling, remain less explored. Exclusion of unpublished data and local case studies – The review primarily relies on published scientific literature indexed in databases such as Web of Science. Important local studies, government reports, and unpublished research may be missing. Lack of socioeconomic analysis – While the study focuses on ecological and carbon sequestration benefits, it does not comprehensively address economic and social aspects, such as cost-effectiveness, local community involvement, and policy implications of pine plantations on degraded lands.

To address these limitations, future studies should: Incorporate long-term ecological research/monitoring of pine plantations; Integrate socio-economic factors into afforestation analysis; Investigate the ecological trade-offs between pine afforestation and native species conservation.

5 Conclusion

This study presents a bibliometric and systematic review of publications on pine plantations, focusing on their role in the afforestation of degraded lands and their contribution to carbon stock accumulation. The analysis demonstrates that pine species are frequently utilized for ecological restoration, particularly due to their adaptability to degraded soil and climate conditions. The bibliometric data reveal a marked increase in research interest after 2015, especially in countries like the United States, China, and Spain.

Our findings underscore the potential of pine plantations to support soil stabilization, landscape restoration, and aboveground carbon sequestration in certain contexts. However, the ecological effects of these plantations vary depending on species selection, site conditions, and management practices. Although technological advances have improved establishment and monitoring methods, further research is needed to fully understand the long-term ecological outcomes, especially belowground carbon dynamics and biodiversity implications.

While the study synthesizes a large body of literature on pines and degraded lands, it does not provide original field data or meta-analytical effect sizes. Therefore, the conclusions should be interpreted as reflecting broad trends in the literature rather than definitive ecological outcomes. Future interdisciplinary research should explore these themes with empirical field validation to better inform land restoration strategies using pine species.

Author contributions

CT: Conceptualization, Formal analysis, Funding acquisition, Writing – original draft, Writing – review & editing. CC: Data curation, Funding acquisition, Investigation, Project administration, Writing – original draft. LD: Formal analysis, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. GM: Data curation, Resources, Software, Visualization, Writing – review & editing. NB: Conceptualization, Methodology, Supervision, Writing – review & editing. NT: Funding acquisition, Writing – review & editing. MM: Funding acquisition, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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