# A Comprehensive Framework for Forest Restoration after Forest Fires in Theory and Practice: A Systematic Review

**Article** *in* Forests · August 2022

DOI: 10.3390/f13091354



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# A Comprehensive Framework for Forest Restoration after Forest Fires in Theory and Practice: A Systematic Review

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**Abstract:** Incidences of forest fires have increased in recent decades largely as a result of climate change and human factors, resulting in great environmental and socioeconomic losses. Post-fire forest restoration is therefore indispensable for maintaining forest ecological integrity and for the sustainability of the affected forest landscapes. In this study, we conduct a systematic review of the available literature on forest restoration in the past two decades (2002–2022) and propose a comprehensive framework for consideration in forest restoration after the occurrence of forest fires. The Preferred Reporting Items for Systemic Reviews and Meta-Analyses (PRISMA) model was adopted for this study, where three academic literature databases (Scopus, CAB Direct, Web of Science), the Google Scholar search engine, and specialized websites were used for literature searches. A final list of 36 records from the initial 732 was considered for this study after the screening stage and subsequent inclusion/exclusion of articles as per the stipulated eligibility criteria. The study findings reveal a dearth of information in the field of post-fire forest restoration in an integrated, balanced, and comprehensive manner, as there was no single methodology or unified protocol that guides post-fire forest restoration. There was also a notable bias in the geographical distribution of the relevant studies in restoration as influenced by economic prosperity, political stability, and scientific and technical advancement. This study recommends a 6-criteria comprehensive framework with 29 indicators for post-fire forest restoration based on the reviewed studies. The criteria integrate environmental, economic, social, cultural and aesthetic, management, infrastructure, and education objectives in their design and implementation for better outcomes in achieving the restoration goals.

**Keywords:** fire regimes; Forest Landscape Restoration; restoration strategies; recovery factors; post-fire restoration



**Citation:** Alayan, R.; Rotich, B.; Lakner, Z. A Comprehensive Framework for Forest Restoration after Forest Fires in Theory and Practice: A Systematic Review. *Forests* **2022**, *13*, 1354. https://doi.org/10.3390/f13091354

Academic Editor: Chunying Ren

Received: 29 June 2022
Accepted: 22 August 2022
Published: 25 August 2022



## 1. Introduction

The global forest cover area is estimated at 4.06 billion hectares (ha), or a third of the total land area [1]. Forests provide multiple economic, environmental, social, and cultural benefits which are essential for human wellbeing and sustainable development [2–5]. Despite their significance, forests face a myriad of challenges ranging from deforestation due to Land Use and Land Cover (LULC) changes and disturbances from fire, diseases, insects, pests, and severe weather conditions as a result of climate change [6–9]. Wildfires are among the dominant disturbances in forests resulting in detrimental social, environmental, and economic impacts [10–12]. Forest fires influence the forest vegetation structure and species composition, affect the forest soil properties, affect forest succession, and influence biogeochemical cycles [13–16]. Forest fires also result in great economic losses due to the huge amount of resources used in fire suppression and prevention, the associated costs of the loss of non-market public services, and the loss of commercial value of the damaged wood products [17,18]. Forest fires greatly affect the carbon balance, as it is estimated that they contribute approximately 5–10% of the world's total greenhouse gas (GHG) emissions [16,19]. In recent decades, there has been an increase in the frequency and intensity of forest fires due to natural and anthropogenic causes, often resulting in great losses [15,20–23]. Scientific evidence shows that more than 90% of all wildfires are directly or indirectly linked to human activities such as arson, broadcast burning for pasture maintenance, and outdoor fire accidents [24]. The behavior and intensity of a forest fire depend on land cover dynamics and existing local conditions such as fuel type, fuel loading, humidity, wind, temperature, and terrain [25–27]. Fire-induced forest losses account for about 15% of forest losses globally, with a reported average of 67 million ha of forest area burned annually from 2003 to 2012 [6,28]. Forests in Africa, Australia, North America, Southeast Asia, and Amazonia are prone to fires on a frequent basis [22,29–31]. It is estimated that more than 50% of the global forest fires occur in Africa [32,33], while in Europe, about 45,000 forest fires occur annually, burning half a million hectares of forests [17]. Between 2019 and 2020, more than 23% of the temperate forests in southeastern Australia were burnt [23], whereas nearly 30.5% of South and Southeast Asian countries showed recurrent annual fires within fifteen years (2003–2017) [34]. The United States of America (USA) experienced an annual average of about 61,289 wildfires from 2012 to 2021, which impacted an estimated 7.4 million acres of land annually [35], while the Brazilian Amazon encountered an increase in fire incidences in the year 2015 by 36% compared to the preceding 12 years [36]. The impacts of fire in a region are dependent on the fire regime, which entails the severity of the fire and fire return interval [14,37]. Mapping of fire regimes is essential for a better understanding of how spatial processes (topography, vegetation, proximity to roads and settlements, and climate) influence fire dynamics [38–40]. The spatial characterization of forest fire distribution and their causes are critical in wildfire mitigation and suppression, including the establishment of preventive actions [41–43]. Characterizing the impact of forest fires further provides critical information that helps provide land managers with a starting point for decision-making in resource management [11,38,44]

Restoration is defined as the "process of assisting the recovery of an ecosystem that has been degraded, damaged or destroyed" [45]. Post-fire forest restoration is an intentional attempt to bring the forest ecosystem back to its historical state to regain its ecological integrity and resilience [46,47]. Post-fire forest restoration is therefore essential to conserve biodiversity, meet food security and livelihood needs, and reduce the economic losses and damage from wildfires [25,48,49] Reducing and responding to these adverse consequences requires a two-pronged approach: the first is to avoid or at least reduce degradation, and the second is to restore system's degraded ecological environment [50]. The restoration principles should be founded on a detailed understanding and proper integration of the ecological, economic, and social factors associated with the affected forest ecosystems [49,51,52] Consideration of environmental, social, and economic factors such as recovery rate, levels of degradation, land use matrix, topographic features, restoration objectives, potential constraints, and available resources is instrumental in selecting the appropriate restoration approach. Collaboration among relevant stakeholders such as local communities, government officials, and scientists is also important for a successful restoration of natural forests [53–55]. There are two common forest restoration approaches employed in the recovery of large deforested and degraded forest areas: passive restoration, where no action is taken apart from ceasing environmental stressors and relying on natural regeneration, and active restoration, which entails the implementation of management techniques such as planting seeds or seedlings [17,56,57]. While passive restoration methods are the most cost effective in the restoration of large areas, they are not without costs and can face unanticipated future expenses [58]. A combination of the above two restoration approaches which involves assisted natural regeneration forms the mixed approach [59]. Generally, however, there are very few efforts globally to restore forest landscapes after the occurrence of fires [60]. Ref. [61] further notes that post-fire management of burnt areas receives less attention in Europe and other parts of the world in comparison to fire prevention and suppression.

Systematic reviews provide an important means for scholars and practitioners to apply existing knowledge to further action in the form of policy, management decisions, and research [62–64]. Systematic reviews use a strict methodology that aims at maximizing transparency, repeatability, and objectivity [63,65]. Several scientists have employed systematic reviews in the field of forest research, including urban forest research, community forest management, mangrove forests, and forest governance [66–71]. Systematic review studies on post-fire forest restoration literature are, however, rare, and to our knowledge, this study is the first of its kind that frames post-fire forest restoration in an integrated framework. We, therefore, aim at filling this research gap by providing a comprehensive framework and an updated and integrated review of the latest developments in the field of forest restoration after the occurrence of fires. The specific research objectives of our study are: (a) carry out an up-to-date and comprehensive review of the latest developments in post-fire forest restoration through a systematic review of literature from the past twenty years (2002–2022); and (b) provide a comprehensive framework that will guide future post-fire forest restoration.

The main question of our research was: will the comprehensive framework for forest restoration after fires meet the multiple planning requirements and sustainable development goals? The components of the main question (PICO) are as follows:

Population/Theme: Burned forests.

Intervention: The integrated restoration of forests after fires and an attempt to understand all the direct and indirect aspects in this field (environmental, economic, social, cultural and aesthetic, and scientific objectives, management and decision-making sciences, planning, political and legal sciences).

Comparison: Integration is performed to understand all aspects of forest recovery after fires or focus on one aspect.

Outcomes: Healthy Forest restoration after fires and its impact on sustainable development.

Other relevant research questions are:

Will the comprehensive framework be successful and effective in the long term if implemented?

Will it reduce hesitation and bias among stakeholders and decision-makers while undertaking recovery actions?

Will the comprehensive framework fill knowledge gaps or identify the most urgent research needs in the area of recovery?

## 2. Materials and Methods

### 2.1. Search Strategy

Our review was guided by the PRISMA (Preferred Reporting Items for Systemic Reviews and Meta-Analyses) model [72,73]. The PRISMA protocol comprises a 27-item checklist that guides the identification, selection, appraisal, and synthesis of studies and is widely accepted as a standardized method for conducting systematic reviews [72]. It entails an initial database search for the identification of relevant literature, exclusion of duplicates, screening of titles and abstracts, and screening of full-text articles for eligibility as per the laid down eligibility criteria [72]. Three academic literature databases (Scopus, CAB Direct, Web of Science), the Google Scholar search engine, and specialized websites were used to conduct searches on potentially relevant scientific literature in the field of post-fire forest restoration. The specialized sites comprised:

International Union for Conservation of Nature (www.iucn.org); (accessed on 9 June 2022)
International Tropical Timber Organization (ITTO) (www.itto.int); (accessed on 13 June 2022)
Society for Ecological Restoration (www.ser.org); (accessed on 13 June 2022)
The Joint Research Center European Commission (ec.europa.eu/dgs/jrc); (accessed on 11 June 2022)
European Environment Agency (www.eea.europa.eu); (accessed on 11 June 2022)
United Nation Environment Program (www.unep.org); (accessed on 10 June 2022)

National Institute of Forest Science (www.eng-nifos.forest.go.kr); (accessed on 10 June 2022)
Food and Agriculture Organization (www.fao.org); (accessed on 12 June 2022)
World Wildlife Fund (WWF) (www.worldwildlife.org); (accessed on 9 June 2022)
Forest Service US Department of Agriculture (www.fs.usda.gov); (accessed on 12 June 2022)
National Wildfire Coordinating Group (www.nwcg.gov); (accessed on 9 June 2022)

The searches were restricted to studies conducted within the last two decades (4 February 2002–21 July 2022) for contemporary advances in the field. Only articles published in English were screened. Article types included research articles, review articles, book chapters, and status reports.

### 2.2. Search Strings

The following search strings were applied across all the databases under the respective topic subject covering the Title, Abstract, and Keywords. The search terms were kept consistent to allow for future search repetition: ((“forest fire*” AND “restor*” AND “development*” OR “burned forest” OR “reconstruct*” OR “regeneration” OR “recovery” OR “rehabilitation” OR “management*” OR “assessment” OR” evaluation” OR “strateg*”)).

In terms of research fields and areas the key disciplines included in the initial search results were: “Agriculture and Biological Sciences, Environmental Sciences, Earth and Planetary Sciences, Multidisciplinary, Social Sciences, Computer Sciences, Economics, Econometrics, Finance, Engineering, Mathematics, Business and Economics, Arts and Humanities”.

### 2.3. Eligibility Criteria

Two key predetermined eligibility criteria for our study were the field of study and language. First, the paper had to be in the field of post-fire forest restoration or related to planning and management sciences. Excluded fields of study comprised: (chemical environment–agriculture engineering + biophysics–wildfire management sciences: fuel-water containers–HR-history-fire analysis and behavior–Gas Analysis-technical ecology-climate management-satellite–images analysis-general natural disturbance except for forest fire–fire prevention except for restoration management-social risk management-environmental engineering–prescribed fire management–ecosystem services statics). The second criterion for selecting the papers was that the study had to be published in the English language. Table 1 shows a summary of the eligibility criteria used for this review.

**Table 1.** Summary of the criteria used in the systematic literature review.

| Criteria | Details |
|---|---|
| Literature sources | Databases, search engine, specialized websites |
| Fields | Post-fire forest restoration, planning, and management sciences |
| Study period | 2002–2022 |
| Language | English |
| Document types | Research articles, review articles, books, book chapters, and status reports |
| Keywords | “Forest fire*” AND “restor*” AND “development*” OR “burned forest” OR “reconstruct*” OR “regeneration” OR “recovery” OR “rehabilitation” OR “management*” OR “assessment” OR” evaluation” OR “strateg*” |

### 2.4. Article Screening

The initial search returned a total of 732 records from which 37 duplicates were removed, leaving 695 records for screening. Each article was read individually and carefully to determine its suitability for inclusion. The titles and abstracts of articles were first checked by two reviewers and for the doubtful cases, a full-text evaluation was performed to confirm its fulfillment of the eligibility requirements for a final decision on inclusion. An example of an article that was excluded after reading the title:

*A review of environmental droughts: Increased risk under global warming* [74]?

This article did not meet the first eligibility criteria since it fell outside the field of post-fire forest restoration and hence was excluded.

An example of an article that was excluded after reading the abstract:

*Effects of fire-derived charcoal on soil properties and seedling regeneration in a recently burned Larix gmelinii/Pinus sylvestris forest* [75].

This article examined the relationship between biochar and plant regeneration in post-fire forests and determined the contribution of biochar to soil properties. We found that this article examined the effects of forest-fire-derived charcoal on post-fire seedling regeneration and soil properties and delved into chemical detail (it did not meet the third pre-specified review eligibility criteria).

After the above exercise, 628 articles did not meet the eligibility criteria and were excluded as an initial screening stage. Subsequently, the full texts of the 67 remaining studies were downloaded and assessed for eligibility, out of which 31 articles were excluded for failure to meet the inclusion/exclusion criteria.

An example of an article that was excluded after reading the full text:

*Incorporating economic valuation into fire prevention planning and management in Southern European countries* [76].

The article did not address post-fire forest restoration, but rather focused on how to prevent fires and link them to the social aspect. It did not meet the first criterion of eligibility criteria, but rather provided thoughtful guidance to decision-makers and local administrative bodies to develop the best scenario for preventing fires or reducing burning areas through proven firefighting practices that are effective in controlling fire.

Another example of an article excluded after going through the full text:

*Assessment of the post-fire forest restoration dynamics in the Olekminsk state nature reserve (Russia) according to data of Landsat satellite images* [77].

Despite the title and abstract of the article being in English and the article meeting the first criteria of being within the field of post-fire forest restoration, the article was excluded for failing to meet the second criteria as the main text was in the Russian language.

An example of an article that was included after reading the full text:

*Post-fire ecological restoration in Latin American forest ecosystems: Insights and lessons from the last two decades* [78]. This article was included in the final list as it met all three eligibility criteria.

In the end, 36 articles met the eligibility criteria and were included for the systematic review.

### 2.5. Data Extraction

Data were extracted from each of the 36 included studies separately, and a database table was created on the MS Excel sheet to manage, classify, sort, and evaluate the extracted data. Information related to the research topic was recorded as follows: article title, author/authors, publisher, publication date, article type, study area, methodology, results and discussion, and funding sources for the study.

### 2.6. Statistical Analyses

Statistical analyses were conducted using Microsoft Excel (version 2016, New York, NY, USA). Summary statistics were carried out to characterize retrieved data from literature searches and the results were presented in form of tables, map, and graphs. Mapping of the global distribution of the studies was performed using QGIS software (version 3.16.10, Hannover, Germany).

### 2.7. Bias and Certainty Assessment

Bias was evaluated manually in an MS Excel sheet. This was performed by reading and analyzing the full text and by comparing the characteristics, hypothesis/question, and results of each article in an integrated manner to help identify if there are any biases in the study. Bias occurs at any stage of article writing/study, due to insufficient studies, and consequently, the lack of enough integrated information to be used in general at all stages and steps of forest restoration after fires. It may be the result of a spatial bias (i.e., tropical forests—western United States). This bias can be associated with a country's economic status, the country's stability, and interest in developing a general protocol for forest restoration after fires (funding sources and resources). Bias may also result from conflicting interests by the local authorities on the ground due to a lack of defined management priorities or restrictions on funding.

Certainty was evaluated manually in an MS Excel sheet after reading and analyzing the full text and comparing the methodology, method and tools of research, scale and size of the study, its impact area, and evidence used to reach the results.

## 3. Results

### *3.1. Study Selection*

The initial search returned a total of 732 records of which 553 were articles from the databases and 179 from the specialized websites. Next, 37 duplicates were removed from the initial search, leaving a total of 695 records for screening. After screening, 628 records were excluded for failing to meet the eligibility criteria, hence the remaining 67 articles were downloaded and full text read for eligibility. A total of 31 from the 50 downloaded articles did not meet the inclusion/exclusion criteria and were excluded. In the end, 36 articles (Appendix A) were eligible and used for this systematic review. Figure 1 gives a summary of the systematic review process.

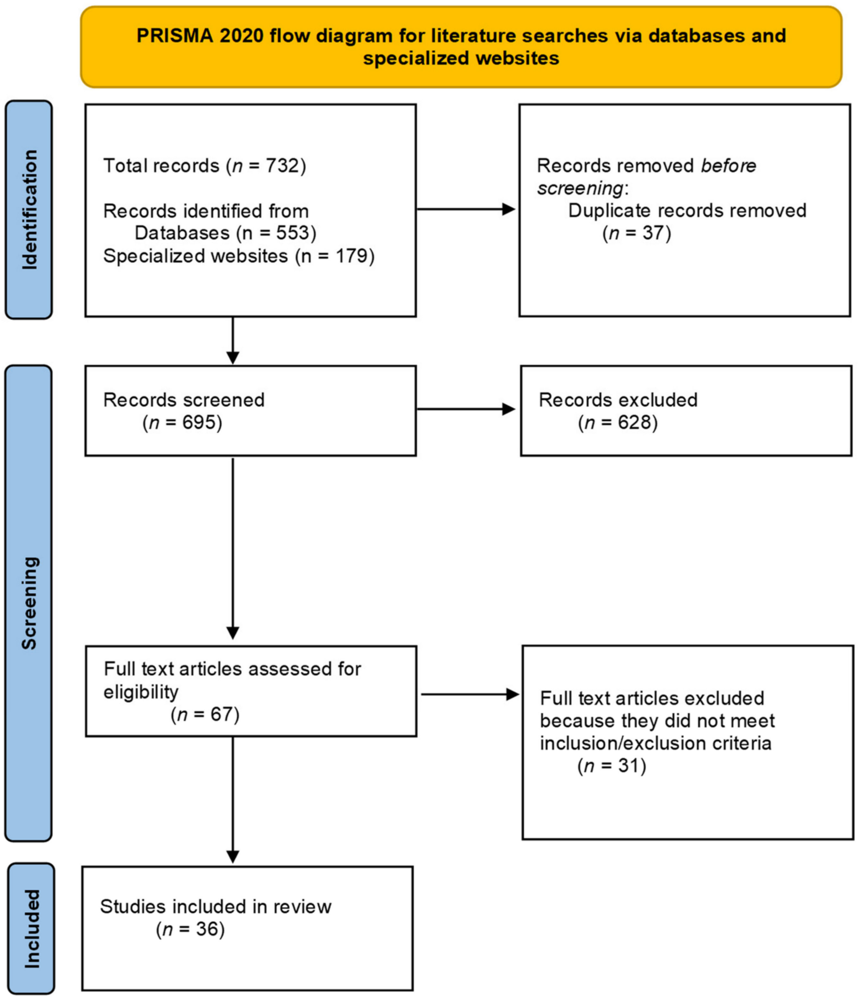


**Figure 1.** Flowchart showing the study selection process [72].

### *3.2. Study Characteristics*

There were variations in the geographical distribution of the relevant studies (Figure 2). Nearly half of the studies (14) were from North America (United States of America $n = 13$, Canada $n = 1$), 8 from Europe (Southern Europe $n = 7$, Greece $n = 1$), 3 from Asia (South and North Korea $n = 1$, South Korea $n = 1$, China $n = 1$), 1 from South America (Argentina), 1 from the tropical humid regions, 1 from the Middle East (Lebanon), and 8 were general papers without geographical association.

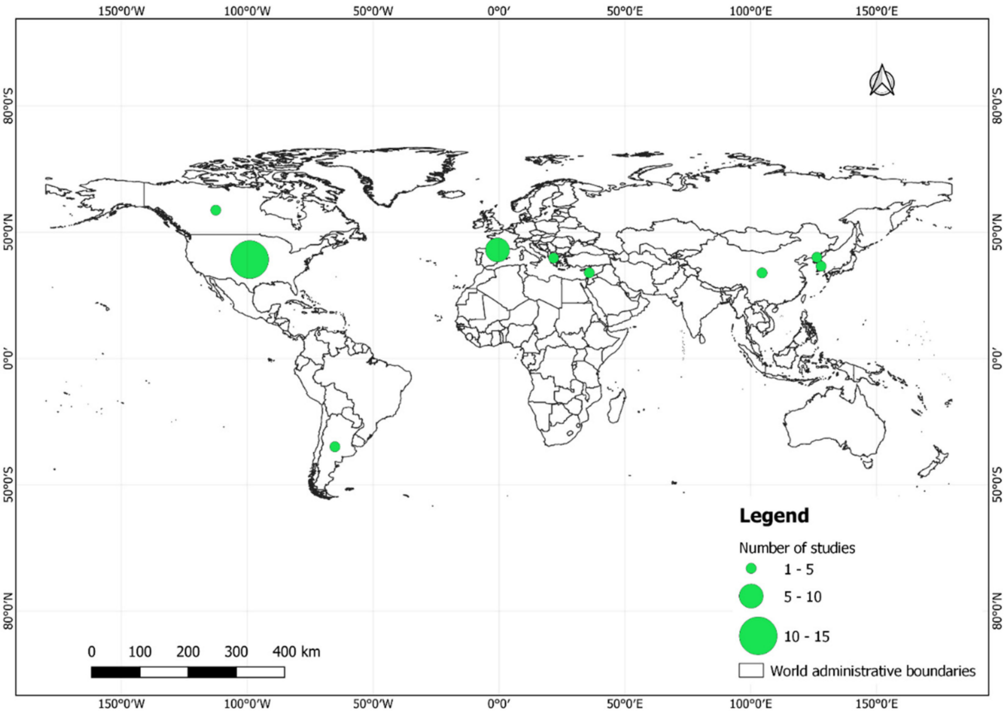


**Figure 2.** Map of the world showing the geographical distribution of the selected studies.

In terms of the literature sources, 12 articles were sourced from Web of Science, 10 from Google Scholar, 7 of the articles we sourced from Scopus, 5 from CAB direct, and 2 from specialized websites (IUCN and FS-USDA). Peer-reviewed journal articles formed most of the final articles. More than half (24) of the selected literature were review articles, 4 research articles, 5 book chapters, and 3 reports. The research themes and focus area of the selected studies (Figure 3) revolved around forest and forest fire management [11,17,61,79–88], fire ecology [89–91], forest and landscape restoration [25,49,53,59,92–94], post-fire forest monitoring [26,95–98], ecological restoration [99–101], technical post-fire management [102,103], and traditional fire knowledge [46,103,104].

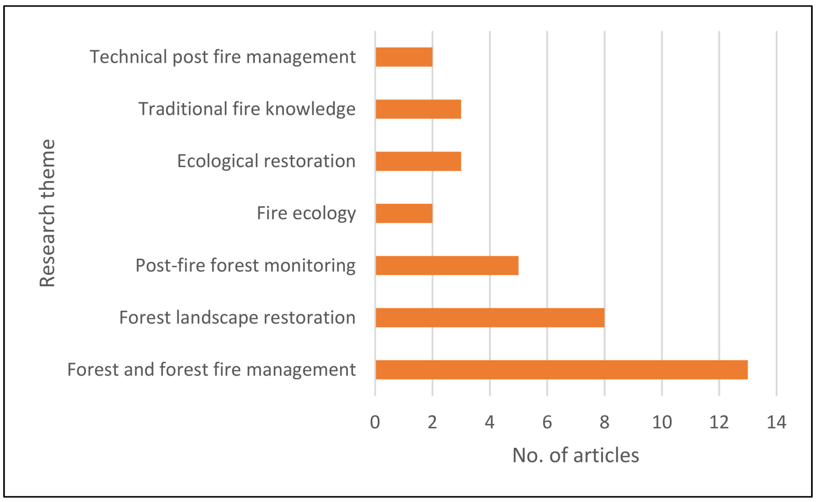


**Figure 3.** Number of articles based on research themes ($n = 36$).

More than three quarters ($n$ = 30) of the 36 relevant studies were from the second decade (2010–2022) of the selected study period. The year 2012 recorded the highest number of publications ($n$ = 6), with the lowest number of articles ($n$ = 1) recorded for each of the years 2004, 2010, 2014, 2016, and 2020 (Table 2).

**Table 2.** Number of articles based on the study years.

| No. | Year | Number of Articles ($n$ = 36) |
|---|---|---|
| 1 | 2004 | 1 |
| 2 | 2006 | 3 |
| 3 | 2008 | 2 |
| 4 | 2010 | 1 |
| 5 | 2012 | 6 |
| 6 | 2014 | 1 |
| 7 | 2015 | 2 |
| 8 | 2016 | 1 |
| 9 | 2017 | 4 |
| 10 | 2018 | 2 |
| 11 | 2019 | 4 |
| 12 | 2020 | 1 |
| 13 | 2021 | 5 |
| 14 | 2022 | 3 |

### *3.3. Risk of Bias in Studies*

Bias (with reasons stated) was found in 12 out of 36 included studies (33.3%). The bias was either in the information or the method of analysis. This classification was based on whether the study dealt with the restoration of forests after fires in an integrated manner or not, that is, the integration and comprehensiveness of the factors that must be addressed when managing forest restoration. These factors include environmental, social, economic, administrative, and scientific (information bias). Another classification basis was the type of recovery that was focused on in the study and whether the study achieved the intended goal or whether it exaggerated the description of the results (bias in the analysis). After evaluating the bias of each included study, we found that most of the included studies had a common bias, i.e., not linking the goals and management of forest restoration after fires with the aforementioned factors (environmental, social, economic, administrative, scientific) which helps to analyze restoration in full. This was observed in 8 out of 36 articles (4 articles did not refer to these factors at all, while 4 articles mentioned one or two factors at most). The other reasons for bias were the focus of the study on a specific geographical location and funding foundation(s).

## 4. Discussion

### *4.1. Characteristics of the Selected Literature on Post-Fire Forest Restoration*

From the analysis of the selected studies (Appendix A), it was noted that economic prosperity, political stability, and scientific and technical progress are among the factors influencing studies and projects on post-fire Forest Landscape Restoration (FLR) [59,104]. This was evident from the review, as most of the selected literature was from North America, Europe, and some the East Asian countries, such as North Korea, South Korea, and China. Post-fire forest restoration studies in Africa were scarce, yet this region experiences more than half of the global forest fires [33,105].

Funding is critical in post-fire forest restoration, as sufficient funding allows for use of the latest equipment and technologies in restoration. It also allows for the creation of a comprehensive database to help show the extent of fire damage and the use of spatial data in facilitating and weighing the optimal administrative decision and determining the restoration priorities. The United States (US) Forest Service of the US Department of Agriculture spends nearly 50% of its annual budget on extinguishing fires [82,106]. Nine of the ten studies in the USA were funded by the US Department of Agriculture.

Over the past three decades, forest and ecological restoration have experienced significant growth globally, along with an increase in research publications. Our study showed that a majority of the selected articles were from the second decade of the study period (2010–2022). This can be attributed to the marked increase in interest in the subject after the first World Conference of Environmental Restoration Society in 2005 [107].

This review, however, revealed a dearth of information in the field of post-fire forest restoration in an integrated, balanced, and comprehensive manner, as there is no single methodology or unified protocol that combines post-fire forest restoration projects. Out of the included 36 studies, 22.2% focused on the multiple aspects of forest restoration while 80.5% of the studies were within specific geographical locations.

More than half of the studies dealt with unilateral forest restoration or a single factor. This implies insufficiency or failure to design strategies or forest restoration plans within an integrated framework to meet the requirements or goals in the medium- or long-term. Even studies defined by a geospatial framework (case studies), such as this review article, were conducted to raise awareness of restoration and factors that affect the management of natural resources, wildfires, and climate changes, and to identify scientific gaps and raise awareness at the national level [82,83,93,95]. Through this example, it is not possible to generalize and deduce from these case studies a one-size-fits-all approach to restoration outside this geographical framework; therefore, it is important to expand the geographical focus of post-fire forest restoration studies. It has become necessary to conduct a new review that is more comprehensive and realistic in its results to serve as a general framework that can be applied to any study of forest restoration after fires, regardless of the type of forest, its location, the intensity of the fire, or its area.

### *4.2. Forest Landscape Restoration Approaches and Strategies*

Post-fire FLR is a multi-stage process, which typically includes the planning, design, implementation, monitoring, and evaluation phases. The success of FLR is determined by the choice of the restoration approach [59,108]. Sound restoration of affected forest areas is critical for the restoration of its ecological functions and provision of economic incentives to the locals [49]. Several forest restoration strategies and approaches can be used depending on the multiple aspects of restoration, including specific environmental, social, and economic characteristics [25,94,102]. Active, passive, and mixed restoration approaches can be adopted depending on the severity of the damage, available resources, and objectives of restoration [59,93,108,109].

In less severe degraded lands, natural regeneration is the most appropriate and effective cost-wise for the improvement and conservation of biodiversity. The natural recovery processes, however, may take years to produce favorable improvements; therefore, a change to more resource-intensive options, such as active restoration through careful cultivation that aids natural regeneration, could hasten the restoration of ecosystem functions and produce a variety of advantageous FLR economic and social effects [59]. Ref. [108] proposes the adoption of active restoration via artificial regeneration in cases where the post-fire recovery goal is timber production, while passive restoration in the form of natural regeneration can be utilized if the restoration focus is species richness and canopy vertical density.

Ref. [110] notes that the social demands for preserving and improving ecological values in addition to advances in fire and restoration ecology in most Mediterranean countries over the last few decades have led to new forest management and post-fire restoration approaches. These changes have led to the development of new restoration objectives encompassing mitigation and adaptation to climate change, combating desertification, biodiversity conservation and recovery, fire prevention, and recreational and cultural use [111]. The restoration of degraded ecosystems also requires new technologies for seed handling, production of seedlings, seedling planting, and management. However, most nations lack the infrastructure necessary to set up such regeneration systems, and there is still little understanding of how to use ideas and frameworks that enable plant community management, such as the "response and impact" characteristic framework [82]. In cases where the goal is to restore a forest ecosystem to its original state, priority ought to be given to the reintroduction of native species [25]. The achievement of long-term restoration goals, therefore, requires scientific and technological insights, appropriate legislation, and funding [112–115].

Actively involving local communities in decision-making processes, supporting multi-level cooperation, establishing and maintaining collaborative capacity by national or regional contexts, fostering multi-level cooperation and looking into investment opportunities to build value chains based on restoration, and setting priorities for effective resource allocation are necessary for a successful forest restoration [86,93,116,117]. The contribution of traditional knowledge to the ecological restoration of fire-affected forests cannot be ignored, and its inclusion can complement modern techniques of restoration. Most forest communities have rich traditional knowledge which can be integrally linked to biodiversity conservation and sustainable management of natural resources [118,119]. Traditional knowledge and science complement each other and should therefore be used concurrently in ecological restoration projects [46]. It is also vital to encourage the creation of inexpensive, effective alternatives, prioritizing places above alternatives already available [25,95]. Consideration may be given to the following factors while creating restoration goals and objectives: current and projected environmental capacities; environmental safety; and climate change expectations, including the environment, environmental responses, and the landscape level [92].

Ref. [59] lays out a six-step plan for achieving sustainable FLR. Enhancing environmental knowledge to support FLR, adaptive FLR management, modeling, social improvements and adaptations, implementation considerations, participatory monitoring for long-term FLR outcomes, and improving communication, collaboration, and multidisciplinary at the local, regional, and global levels are some of the areas that are covered.

Spatio-temporal information on the distribution and characteristics of forest fires can aid in risk reduction efforts and guide the formulation of integrated fire management policies [120–122]. Understanding the dynamics of the ecosystem after a fire further helps predict the regeneration capacity of the burned area, so that decision-makers know whether to invest in restoration practices and how to allocate their resources. Remote Sensing (RS) is an effective tool in the prevention and monitoring forest fires, in addition to being a potential tool for understanding how forest ecosystems respond to wildfires [123]. A number of the selected studies highlight the significance and application of RS in post-fire forest restoration and monitoring [87,95–98]. Ref. [96] notes that RS is a powerful analytical, synthesis, and reporting tool that provides insights on forest fires and contributes to informed restoration decisions in Spanish forests. RS aids in estimating burnt forest areas to check the extent of the damage, assess the natural recovery ability of forest ecosystems after fires, support the planning of restoration interventions, and monitor the restoration outcomes [97]. Landsat time series analysis has also been utilized to describe and analyze post-fire vegetation recovery across the temperate forests of western North America and in the Iberian Peninsula Mediterranean region of Spain [10,89]. The use of long time series data in the Hinggan Mountain Ranges revealed that topography and climatic factors have a significant impact on the restoration of forest vegetation in burned areas [124]. are essential, as they provide an understanding of forest ecosystems' successional pathways after the occurrence of fires and enable the managers to plan appropriate restoration actions accordingly. Post-fire forest monitoring and evaluation is also instrumental in the re-direction of restoration actions in an adaptive management context [61].

### *4.3. Post-Fire Forest Restoration Challenges*

From the review, it was found that lack of stable or sufficient funding was a key limitation to forest restoration after fires [81]. Funding for purposes of forest restoration emanates from specific funds allocated at the national or regional level. Most developing countries report a lack of funding as one of the leading constraints to the effective implementation of forest restoration action [102]. This challenge can be overcome through integrated spatial planning by preparing a national restoration program to manage limited funding or resources and setting priorities according to the existing situation of forest burning and fuel processors (adaptive management). Budgetary allocation for forest fire management also ought to be increased in respective regions. A report by The Nature Conservancy [106] notes the need for a paradigm shift in wildfire risk reduction and resilience. It recommends setting aside additional annual investments of around USD 5 billion to USD 6 billion in the USA to address the ever-increasing threat of wildfires [106].

The inability to evaluate wildland fire incidents and identify trends within and between countries due to the inconsistent and incomplete documentation of these events also curtails post-fire forest restoration [91]. Administrative obstacles in the form of lack of coordination between all stakeholders were also a notable challenge. Other limitations to effective forest restoration after fires emanated from management practices. They include fragmentation of responsibility, lack of a specific coordinating mechanism, lack of a transparent strategy for setting restoration priorities, as well as constraints related to restoration operations [125]. In addition, there were social and cognitive constraints in the field of forest restoration, which negatively affect the implementation of optimal forest restoration. A major challenge in fire management is the coordination of managers and landowners, given that wildfires can easily move across different land ownerships. Reducing the scope and number of high-risk wildfires, therefore, requires cross-border cooperation among managers and land owners [80].

Landscape heterogeneity in relation to their physical, ecological, and social characteristics also poses a challenge to FLR efforts. Social constraints to restoration include the unwillingness of landowners to allocate land for restoration, general lack of awareness, and conflicts over dwindling natural resources [126,127]. The broader scope is also unclear regarding biophysical, governance, and socioeconomic barriers. There are also complexities of integrating multiple benefits, competing interests, scales, and priorities in balancing biodiversity, livelihoods, and ecological environments. These challenges are further worsened by rapid population growth, extreme climatic conditions, increased frequency and impact of wildland fires, and the ever-changing land use patterns, which in turn increase the importance of rethinking how to restore degraded ecosystems [59,91,128]. The lack of awareness of the significance of agroforestry practices and insufficient incentives for the same are key to the widespread lack of incorporation of agroforestry practices into FLR planning [82]. Misleading fire management practices such as cutting down trees create structural changes that reduce the dominance of fire-tolerant species. Livestock grazing in affected forests impedes natural regeneration and delays recovery [87,100]. Policy and legal constraints may hinder the success of implementing forest restoration programs. For effective forest restoration, negotiation and reconciliation at multiple scales through social and ecological dimensions and minimization of power imbalances are critical [114].

### *4.4. Implications for Practice, Policy, and Future Research*

Post-fire forest restoration treatments have improved the overall health of forests, their resilience to drought, and future fire risks [129]. Measuring success in Forest Landscape Restoration is a complex matter that requires trying to assess social impacts and environmental indicators at different scales and across different spatio-temporal scales [50]. Spatial patterns and long-term trends are useful in current and future restoration therapies and to better guide remediation strategies [129]. There is a need to integrate spatial planning in preparing a restoration program on a national scale that manages limited funding or resources and sets priorities that must be consistent with the multiple restoration goals in a balanced and ideal manner. The plan should meet the requirements of the future, consider the characteristics of the place and the forest, make trade-offs between the desired outcomes, and find the most effective paths [93]. This undoubtedly needs a monitoring and control system to assess the micro- and macro-outcomes at each stage of forest restoration and enhance access to adaptive management for long-term resilience. There is also a need to take into account the complexity and changing nature of ecosystems, site conditions, and diverse social and political systems [130]. Other potential goals of forest restoration may include the provision of aesthetic amenities or accommodation for activities with social impacts, such as strengthening the community through the participation of individuals in the restoration project while promoting sustainable economic development through adaptive reuse of site infrastructure [54,131]. There is no systematic multi-functional and multi-benefit compilation of post-fire FLR projects globally; therefore, the need to address the drivers of forest loss and degradation remains a challenge in most cases, especially when the main direct drivers such as those related to agricultural progress, infrastructure development, mining and urbanization, and security of tenure or marginalization of already vulnerable groups are similar and may ultimately have impacts that are significant to the success of forest restoration itself [50]. It is therefore important to have legislation that is inclusive to all stakeholders and is adaptable to the new science [82].

The corresponding decisions for optimal post-fire management and restoration measures should be based on environmental, social, legal, and economic aspects [102]. The adoption of a more holistic approach that considers multiple response variables is therefore essential for the quantification of ecosystem recovery [100,132]. Globally, several forest restoration targets have been set, but most land managers and policymakers lack guiding principles on how to achieve them [56]. Based on the 36 reviewed studies, shortcomings of the previous restoration projects, and recommended best restoration practices from existing studies, we compiled a comprehensive framework encompassing 6 key criteria from which 29 indicators were derived to guide forest restoration after fires (Table 3).

**Table 3.** Criteria and indicators for inclusion in the comprehensive framework for post-forest fire restoration.

| Criteria | Indicators | References |
|---|---|---|
| Economic | Economic benefits (productions: NTFP + TFP)<br>True yield (outputs–inputs)<br>Restoration costs and budget<br>Funding and investment<br>Labor force<br>Ecotourism | [17,102] |
| Environment | Landscape structure and condition<br>Soil: erosion and fertility<br>Hydrology: water sources and volume<br>Environmental services: carbon sequestration<br>Disturbance types, frequency, and history<br>conservation | [83,101] |
| Social | Community services and social engagement<br>Livelihood opportunities<br>Life quality<br>Stakeholders | [86] |
| Infrastructure and Educational | Infrastructure networks and services<br>Land use<br>Technical ability and support<br>Research and educational purposes (training and programs) | [99,133] |
| Culture and Aesthetic | Culture and entertainment values<br>Spiritual values<br>Local knowledge and awareness | [46,118,119] |

**Table 3.** *Cont.*

| Criteria | Indicators | References |
|---|---|---|
| Management and Legal | Governance process management (communications, collaborative participation, and restoration of silviculture practices)<br>Services to local communities<br>Monitoring and feedback<br>Policy process and key actors (sustainable restoration plans)<br>Empower laws and regulations (restoration aids, tenure disputes)<br>Institution's outcomes and plans | [53,80,102] |

### 4.5. Limitations

The main limitation encountered in this review was the integration of the various models into a single framework that can be adopted at regional and national levels for planning and decision-making. There was heterogeneity in the results of the included studies, which are sometimes not without contradictions more than similarities among them. This limitation was overcome by ensuring there is a balance and in the inclusion of the fundamental and core criteria proposed by the various researchers for the successful restoration of forests after fires. The scarcity of scientific studies on forest restoration in an integrated manner may constitute an obstacle to subsequent systematic reviews in this field unless the scope of interest in restoring forests after fires is expanded, as this systematic review is the only one so far that deals with the restoration of forests after fires in an integrated manner.

## 5. Conclusions

The purpose of this study was to examine recent developments and literature on post-fire forest restoration and in the end, provide a comprehensive framework that will guide future post-fire forest restoration. A final list of 36 articles met the eligibility criteria and thus was used for this review to frame post-fire forest restoration in an integrated framework. Our analysis revealed a scarcity of literature in the field of post-fire forest restoration in addition to the lack of a unified protocol that guides post-fire forest restoration.

There is, therefore, a need to update the old restoration approaches and management strategies related to post-forest fire restoration by ensuring that restoration incorporates environmental, economic, social, cultural and aesthetic, scientific, political, and legal objectives in the planning, decision-making, and implementation stages.

The long-term goal of this comprehensive framework is to balance the multiple goals of forest restoration and management, and thus it can be modified and adjusted to suit the local conditions. Further research on the traditional knowledge and practices on forest restoration after fires should be upscaled to complement scientific approaches for better restoration outcomes. We also propose more post-fire restoration studies in the less studied yet among the most affected geographical areas such as Africa to have insights into the impacts of wildfires on forest landscapes, restoration approaches, and the outcomes of restoration.

**Registration:** This review was not registered, and methods were presented according to the PRISMA protocol and checklist guidelines, 2020.

**Author Contributions:** Conceptualization, R.A.; methodology, R.A.; software, B.R.; validation, R.A. and B.R.; formal analysis, B.R.; resources, Z.L.; data curation, R.A.; writing—original draft preparation, R.A. and B.R.; writing—review and editing, Z.L.; visualization, B.R.; supervision, Z.L. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research received no external funding.

**Acknowledgments:** This publication was supported by the Hungarian University of Agriculture and Life Sciences (MATE). Our gratitude also goes to the reviewers for their valuable comments and suggestions.

**Conflicts of Interest:** The authors declare no conflict of interest.

## Appendix A

**Table A1.** Details of the articles selected for this review (*n* = 36).

| NO. | Research Focus | Document Type | Study Area | Publication Year | Database/Source | Reference |
|---|---|---|---|---|---|---|
| 1 | Forest fire management | Book chapter | USA | 2004 | Google Scholar | [88] |
| 2 | Post-fire forest monitoring | Review | General | 2006 | Google Scholar | [98] |
| 3 | Forest and forest fire management | Review | General | 2006 | Web of Science | [85] |
| 4 | Forest and forest fire management | Review | USA | 2006 | Scopus | [79] |
| 5 | Post-fire forest monitoring | Review | General | 2008 | Google Scholar | [97] |
| 6 | Forest and forest fire management | Report | Lebanon | 2008 | Specialized websites | [84] |
| 7 | Forest and forest fire management | Report | Europe | 2010 | Google Scholar | [17] |
| 8 | Traditional fire knowledge | Review | General | 2012 | Scopus | [46] |
| 9 | Forest and forest fire management | Book chapter | Europe | 2012 | Google Scholar | [61] |
| 10 | Forest and landscape restoration | Review | USA | 2012 | Scopus | [53] |
| 11 | Technical post-fire management | Book chapter | Europe | 2012 | Google Scholar | [102] |
| 12 | Ecological restoration | Book chapter | Europe | 2012 | Google Scholar | [101] |
| 13 | Post-fire forest monitoring | Book chapter | Europe | 2012 | Google Scholar | [26] |
| 14 | Post-fire forest monitoring | Review | China | 2014 | CAB Direct | [95] |
| 15 | Ecological restoration | Review | Argentina | 2015 | Web of Science | [99] |
| 16 | Forest and landscape restoration | Research | USA | 2015 | CAB Direct | [93] |
| 17 | Fire ecology | Review | USA | 2016 | Web of Science | [90] |
| 18 | Traditional fire knowledge | Review | General | 2017 | Web of Science | [119] |
| 19 | Forest and forest fire management | Review | USA + Spain | 2017 | Google Scholar | [11] |
| 20 | Forest and landscape restoration | Review | South Korea | 2017 | Google Scholar | [49] |
| 21 | Forest and forest fire management | Research | USA | 2017 | Web of Science | [81] |
| 22 | Forest and forest fire management | Review | General | 2018 | Web of Science | [86] |
| 23 | Technical post-fire management | Review | Canada | 2018 | Scopus | [103] |
| 24 | Forest and landscape restoration | Review | USA | 2019 | Web of Science | [89] |
| 25 | Ecological restoration | Review | USA | 2019 | Web of Science | [100] |
| 26 | Post-fire forest monitoring | Review | Spain | 2019 | Web of Science | [96] |
| 27 | Forest and forest fire management | Review | USA | 2019 | CAB Direct | [82] |

**Table A1.** *Cont.*

| NO. | Research Focus | Document Type | Study Area | Publication Year | Database/Source | Reference |
|---|---|---|---|---|---|---|
| 28 | Forest and landscape restoration | Research | North + South Korea | 2020 | Scopus | [94] |
| 29 | Fire ecology | Review | Europe | 2021 | Web of Science | [91] |
| 30 | Forest and forest fire management | Review | Greece | 2021 | Web of Science | [87] |
| 31 | Forest and landscape restoration | Review | General | 2021 | Scopus | [59] |
| 32 | Forest and landscape restoration | Review | Humid tropics | 2021 | Scopus | [25] |
| 33 | Forest and landscape restoration | Report | USA | 2021 | Specialized website | [92] |
| 34 | Traditional fire knowledge | Review | General | 2022 | CAB Direct | [118] |
| 35 | Forest and forest fire management | Research | USA | 2022 | CAB Direct | [80] |
| 36 | Forest and forest fire management | Review | USA | 2022 | Web of Science | [83] |

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