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Review

Forest Vulnerability to Climate Change: A Review for Future Research Framework

Roshani [1], Haroon Sajjad [1], Pankaj Kumar [2,*], Md Masroor [1], Md Hibjur Rahaman [1], Sufia Rehman [3], Raihan Ahmed [4] and Mehebub Sahana [5]

[1] Department of Geography, Faculty of Natural Sciences, Jamia Millia Islamia, New Delhi 110025, India; roshnisingh1405@gmail.com (R.); haroon.geog@gmail.com (H.S.); mdmasroor1994@gmail.com (M.M.); hibjuronline@gmail.com (M.H.R.)
[2] Institute for Global Environmental Strategies, Kanagawa, Hayama 240-0115, Japan
[3] Department of Civil Engineering, National Institute of Technology, Surathkal, Mangalore 575025, India; srfpinky@gmail.com
[4] Department of Geography, Nowgong College, Nagaon 782001, India; raihan.geog@gmail.com
[5] School of Environment, Education and Development (SEED), University of Manchester, Manchester M13 9PL, UK; mehebubsahana@gmail.com
* Correspondence: kumar@iges.or.jp; Tel.: +81-046-855-3858 (ext. 3058)

Abstract: Climate change has caused vulnerability not only to the forest ecosystem but also to forest-dependent communities. Therefore, its management is essential to increase forest ecosystem services and reduce vulnerability to climate change using an integrated approach. Although many scientific studies examined climate change impact on forest ecosystems, forest vulnerability assessment, including forest sensitivity, adaptability, sustainability and effective management was found to be scant in the existing literature. Through a systematic review from 1990 to 2019, this paper examined forest vulnerability to climate change and its management practices. In this paper, descriptive, mechanism and thematic analyses were carried out to analyze the state of existing research, in order to understand the concept of vulnerability arising from climate change and forest management issues. The present study proposed a framework for integrated forest assessment and management for addressing such issues in future research. The conversion of forest land into other land uses, forest fragmentation, forest disturbance and the effects of climate change on the forest ecosystem are the existing problems. Forest vulnerability, effective adaptation to forest ecosystems and long-term sustainability are priority areas for future research. This study also calls for undertaking researchers at a local scale to involve communities for the effective management of forest ecosystems.

Keywords: climate change; forest management; forest vulnerability; literature review; future framework

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1. Introduction

Climate change continues to be the primary stressor of the planet and is projected to be a great challenge for the 21st century in view of high emission conditions. Increased fossil fuel combustion, increased use of fertilizers, deforestation and land use/land cover change have driven up the concentration of greenhouse gases in the atmosphere. All these processes have resulted in the alteration of the earth's climate [1]. Forest acts as an essential resource for regulating the earth's climate, sequestering a significant amount of carbon from the atmosphere and maintaining ecological stability [2–4]. This important resource is constantly degraded due to anthropogenic activities and climate change. Climate change has adversely affected the environment's state at spatial scales [5–7]. The Intergovernmental Panel on Climate Change (IPCC) has reported that if the global temperature continues to increase at the present rate, it may increase by 1.5 °C between 2030 and 2052, altering the frequency and severity of natural disturbances and having potentially profound impacts

on forest resources and species composition [8]. The recent IPCC (2022) report projected the risk for the near-term (2021–2040), mid-term (2041–2060) and long-term (2081–2060) at different levels and 1.5 °C across multiple decades [9].

Climate change has had several effects on forests and will likely lead to a rise in temperature in the near future. Indigenous communities living in forest regions are particularly vulnerable to climate change as they lack the sufficient adaptation capacity to cope with climate variation and extremes, and have limited access to alternative sources of income [10,11]. Hence, monitoring and assessing the climate change impact on forests is a prerequisite in lessening its effects and making suitable adaptation strategies. The US Government conducted the first global assessment in the earlier part of this century [12]. In addition, several international organizations or institutions, such as the Food and Agriculture Organization (FAO), UN Framework Convention on Climate Change (UNFCCC), Convention on Biological Diversity, and World Wildlife Fund (WWF) are aiming to combat climate change and its effects on forest dynamics [13]. After UNFCCC concern, a policy was laid for reducing emissions arising due to deforestation and degradation. The convention also stressed the sustainable utilization and management of forest and increased forests' carbon stocks [12].

Several approaches were utilized to assess and monitor the health of the forest, such as forest fragmentation [10,14–19], household dependency [10,20–24] and forest susceptibility [25–28]. Previous research has examined the climate change impact on forest [18,29–41]. The focus of study has now shifted from a general impact assessment to a vulnerability assessment involving all its components (exposure, sensitivity and adaption). Researchers and practitioners are now highly interested in understanding the dynamics of forest vulnerability assessment [42–44]. The IPCC has defined vulnerability as the susceptibility to adverse effects. It involves three essential components, viz. exposure, sensitivity and adaptation [45]. Two main approaches to vulnerability assessment, i.e., contextual and outcome have been distinguished. The contextual approach is applied to assess the current impacts, while the outcome approach is utilized to assess future impacts. The contextual approach is participatory, where social and ecological impacts are assessed using qualitative data. The outcome approach assesses biophysical impacts by employing modelling [46].

Forests differ significantly around the world. The regional disparities in climatic effects and adaptation capability significantly impact forest vulnerability [47]. Approximately 240 million people live in tropical forests in developing nations, including some of the world's poorest and most marginalized people who rely on the forest for their livelihood [48]. Local-scale studies allow a deep understanding of the system and dynamics at a local level and are helpful in deciding priorities for vulnerability reduction. Forest vulnerability assessment at the local level primarily reveals communities' actual responses to climate impacts, thus, employing their knowledge and abilities for developing and implementing appropriate strategies is highly valued [49]. The local level approach helps to identify and assess climatic threats and their implications on community livelihoods. This assessment, however, necessitates a comprehensive understanding of forest dynamics and how numerous structural changes influence them. As a result, a participatory or "bottom-up" method must be adopted for local-level vulnerability assessments. Furthermore, local scale studies directly link monitoring and broader notions of sustainable forest management, such as biodiversity protection and livelihood assistance. They also enhances local people's ability to care for their immediate environment by raising awareness and knowledge about the present state of the forests and surrounding regions [50]. A plethora of methods, approaches and models have been utilized in earlier studies to evaluate forest vulnerability to climate change. However, these studies mainly emphasized the forest ecosystem vulnerability to climate change on the global scale [51–53]. Some studies have also attempted to examine the vulnerability of forest-dependent communities to climate change [54–56]. Despite a great deal of information on climate change and forest vulnerability, certain aspects are still unexplored. The climate change-induced forest vulnerability

assessment allows for raising awareness about climate change among communities and local stakeholders [57]. However, the lack of empirical data poses a great challenge for implementing vulnerability assessments at the community and local levels. Furthermore, forests are simultaneously exposed to numerous climatic and non-climatic stressors. Further, approaches to vulnerability assessment that adequately account for this condition are currently inadequately mentioned in the existing literature. Thus, determining the susceptibility of forest ecosystems is difficult in the absence of reliable data for analyzing sensitivity. The review also identified a lack of adaptation strategies and sustainability in forest management. Thus, an integrated forest management approach involving vulnerability assessment, devising suitable adaptation strategies and long-term sustainability is essential in the era of climate change. This study noticed the lack of a holistic approach for analyzing the vulnerability of forest and forest-dependent communities, adaptation and the sustainability of forest management practices. Thus, a concerted effort has been made in this study to explore the missing links between vulnerability assessment and forest management practices.

2. Methodology

This section elucidates the synthesis of metadata and literature survey. It described the selection of scientific articles on forest vulnerability to climate change and management.

2.1. Synthesis of Metadata

The present systematic review is based on meta-analysis and thematic analysis [58]. A master table in the Microsoft Excel datasheet was prepared to categorize all the research papers into publication year, keywords, authors, study area, the dataset used, methodology applied, conclusions and suggestions. A comprehensive literature search was directed through three processes, i.e., search strategy, identification and screening. A total of 315 articles were downloaded from Web of Science (206) and Google Scholar (109). Two keywords, 'climate change' and 'forest vulnerability', were used as the selection criteria for the literature survey of scientific research papers. The downloaded articles were further screened by reading their abstracts and eliminating the repetitive articles and articles revealing climate change impact on forests in terms of exposure, sensitivity and adaptation. For the final analysis, a total of 160 articles were selected (Supplementary Materials). The detailed framework of the study is presented in Figure 1.

2.2. Literature Survey

The study utilizes extensive literature mining on forest vulnerability to climate change and forest management from 1990 to 2019. The generated database was analyzed using descriptive and statistical methods to assess the spatio-temporal dynamics of earlier studies. The perspective of the studies, approaches and adaptation strategies were also discussed in detail. The data were statistically analyzed in MS Excel and graphically represented through Node XL, Gephi 0.9.2 and Origin Pro 2018 software. ArcGIS 10.3 was utilized for mapping the geographical location of the studies. The final database was further analyzed to evaluate the trend and approaches in forest vulnerability research and climate change and to suggest future studies.

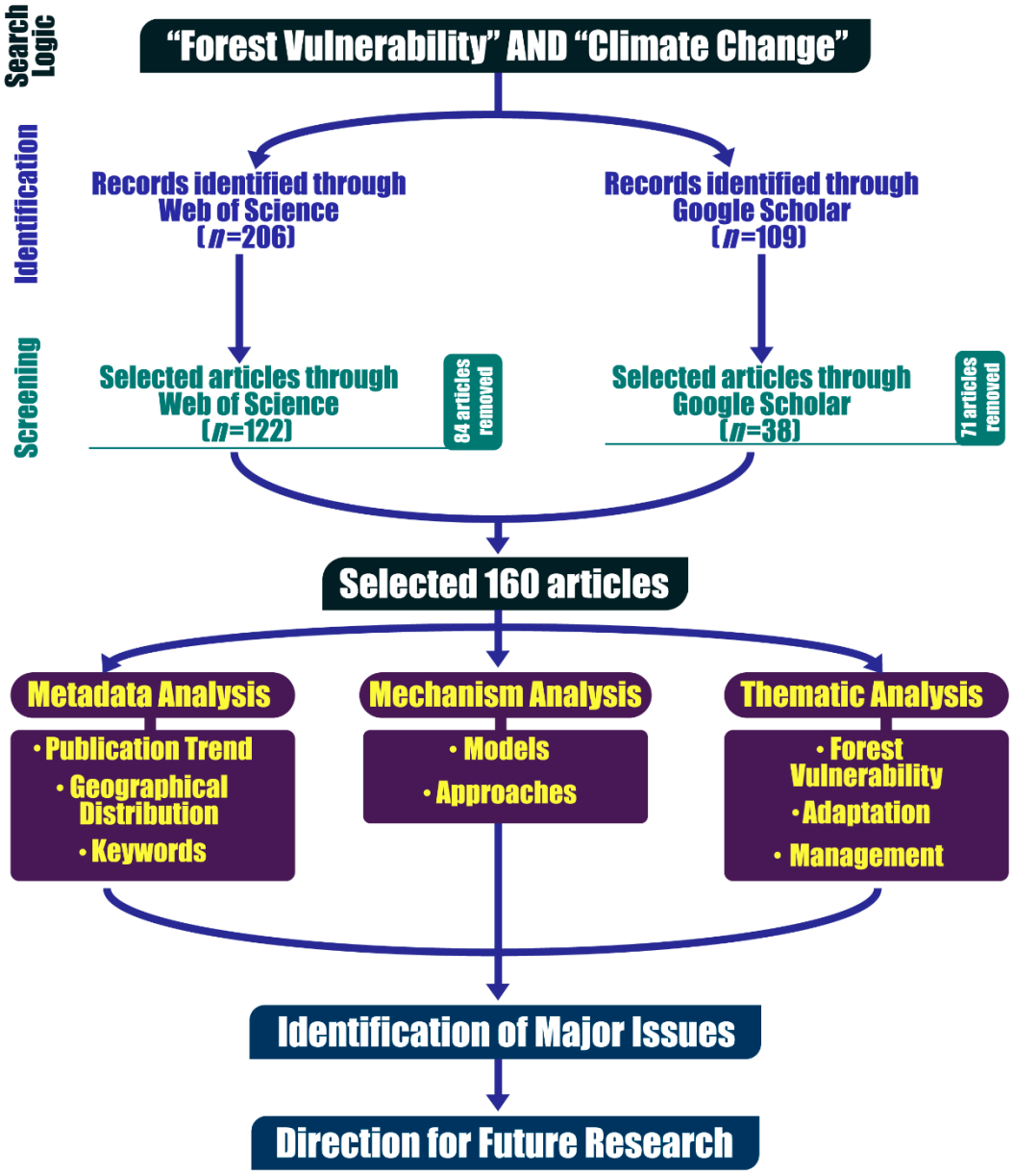

Figure 1. The methodological framework of the systematic review.

3. Results

After the final selection of scientific papers, the literature was analyzed to identify the descriptive analysis, mechanism analysis and thematic analysis.

3.1. Metadata Analysis

After the further classification of the final document database, descriptive analyses were performed to classify a publication trend analysis, the geographical distribution of the studies and a keyword analysis.

3.1.1. Publication Trend Analysis

A total of 17 articles were published during 1990–2000. During this phase, the literature's main focus was on climate change-induced forest vulnerability and forest health assessment. Several authors have also utilized the modelling approaches as general circulation models and long-term forest monitoring plots [29,59,60] and the impact of CO_2 fluxes [61] to ascertain forest vulnerability. An increasing trend in the publication was

observed during 2001–2010, i.e., 32 articles. This phase saw momentum in the concept of sustainable forest management. The most focused areas were forest health status assessment, forest vulnerability and forest-based adaptation measures. A shift from climate change-induced forest impact assessment to mitigation and adaptive measures was also observed during 2001–2010.

An analysis of the publication trend revealed an upsurge after 2010 (Figure 2). A paradigm shift in the focus from conceptual to model-based forest vulnerability assessment to climate change was observed during 2011–2019. In this phase, the maximum number of articles (111) were published using advanced methods and techniques. The scientific community is now more oriented towards empirical and modelling-based forest vulnerability assessment rather than analyzing the overall impact of forest ecosystems [32,33,35,62]. Adaptation at the individual, national and regional levels was more emphasized by the scholars [44,63]. Indicator-based assessments prominently figured in recent studies and helped to identify the intrinsic factors of forest vulnerability [12,33,64,65].

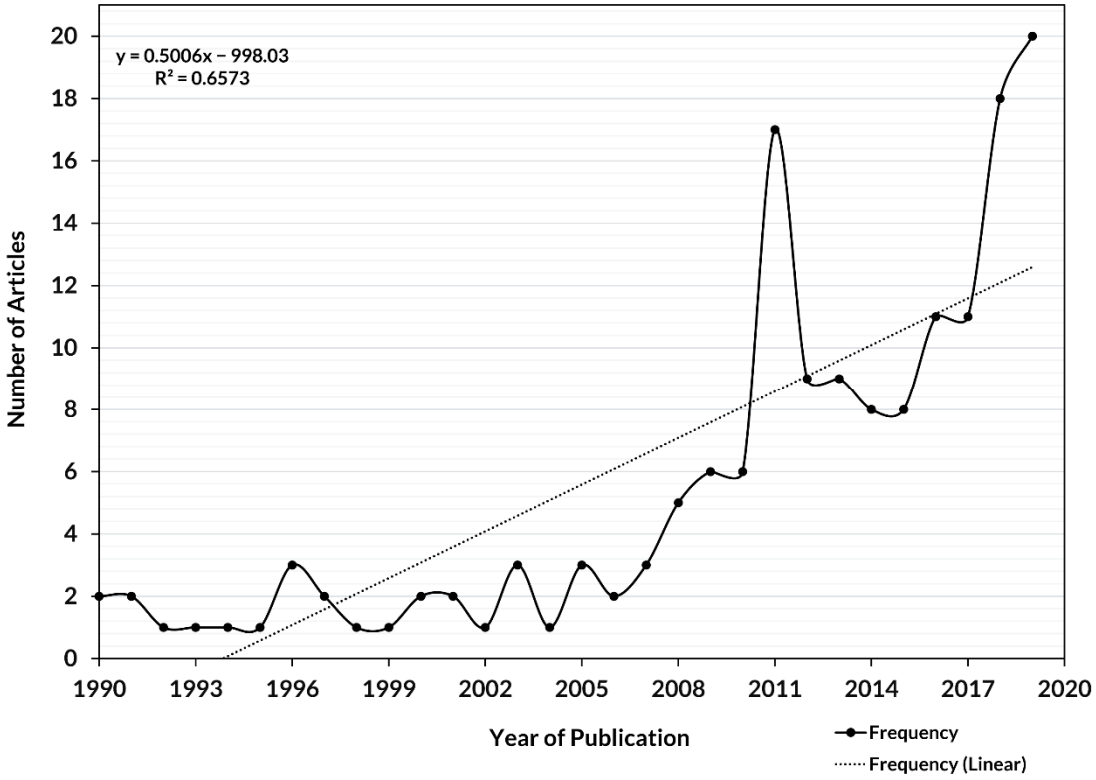

Figure 2. The trend in the publication of forest studies (1990–2019).

3.1.2. Geographical Distribution of the Studies

The geographical distribution of the articles was carried out to ascertain the spatial pattern of forest vulnerability assessment (Figure 3). Of the total articles (160), the highest number of articles were found in European countries (33 articles), followed by the USA (25 articles), Canada (15 articles), India (10 articles), China (four articles) and countries of Latin America (seven articles), respectively. Most of the global research was conducted on various forest types, including temperate forest, boreal forest, and alpine forest which are mostly confined in the higher latitude areas as these are the most vulnerable forest type to climate change [32,44]. The majority of forest studies were conducted in developed nations; however, inadequacy in the availability of datasets has been identified as a reason for less forest research in China, India and a few countries in South-East Asia [30,33,66]. As a result, information and assessment on forest degradation in these nations are scant [67].

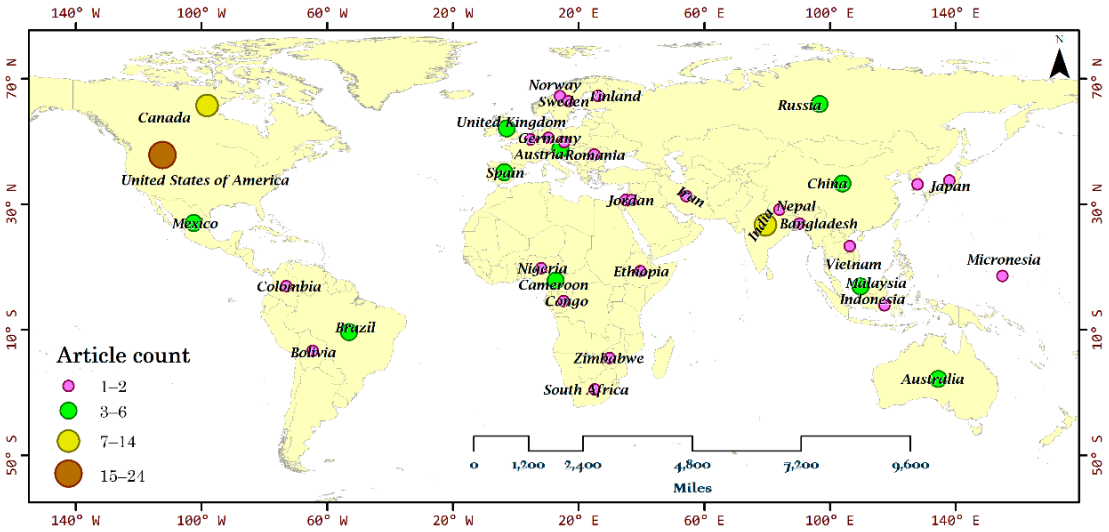

Figure 3. Geographical distribution of forest research.

An author analysis was also carried out to identify the eminent authors of different countries for forest assessment. A total of 721 authors and co-authors together have worked on forest vulnerability in response to climate change. The notable authors that were identified throughout the review to be working on climate change-induced forest vulnerability were MJ Lexer, R Seidl, AP Fischer, DJ Sonwa, RJ Keenan, CR Nitschke, J Sharma, S Upgupta, M Lindner, etc. The author distribution analysis (Figure 4) revealed that forest vulnerability was primarily carried out by scholars of the USA (26%), followed by Canada (11%), India (7%), China (4%) and European countries (23%). Lines connecting between the countries and authors portray the significant collaborations among authors. Inaccessibility, inadequacy, and a lack of information related to climate change implications on the forest are considerable barriers to vulnerability assessment in developing nations. Despite the formulation of various policies, their ground implementation is still far from becoming a reality [11]. A lack of collaboration among the scientific community, policymakers, and local bodies impedes forest management practices and makes the outlook for sustainable forest management bleak.

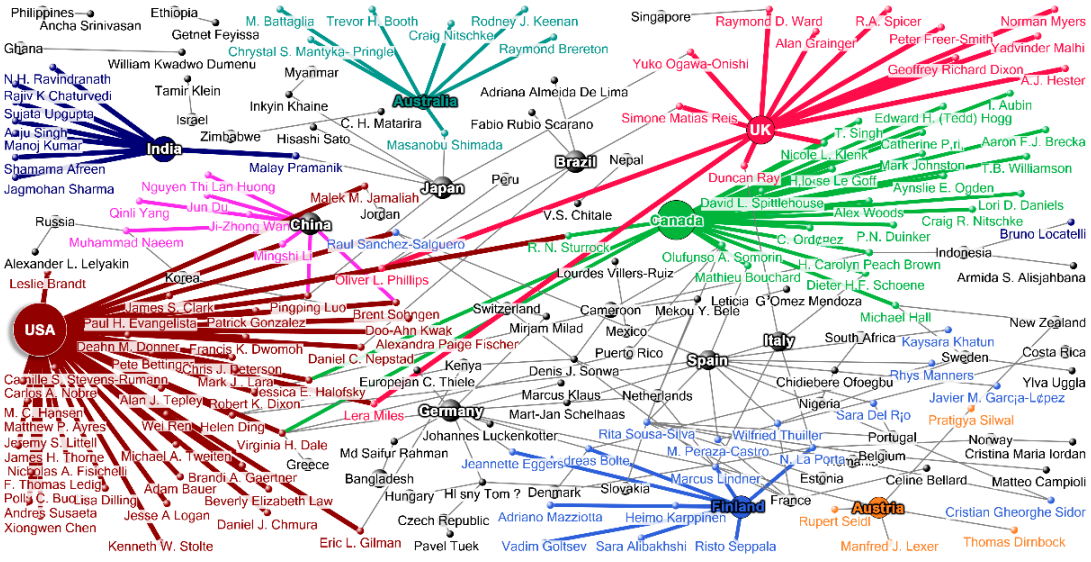

Figure 4. Global distributions of author collaboration.

3.1.3. Keyword Analysis

Keywords were retrieved to analyze the various knowledge domains in forest vulnerability assessment. A total of 781 keywords were identified from the collected document database. A frequency table was created after analyzing all the keywords and eliminating the repeated ones. Finally, 425 keywords were utilized for further analysis. A total of 92 keywords were identified which occurred more than twice. The prominent keywords in the first phase (1990–2000) were climate change [68,69], forest ecosystem [70], mitigation [29], climate models [59] and forest epidemiology [69]. Fewer keywords were found in this phase, and the scholars attempted to conceptualize forest vulnerability. During 2001–2010, the most occurring keywords were related to climate change [71,72], functional diversity and species richness [73], forest vulnerability [71,74], vegetation modelling [75,76] and conservation [77,78]. Scholars in this phase shifted their attention from general conceptualization to modelling-based forest vulnerability assessment. The number of keywords focusing on adaptation, datasets, and models increased in later phases (Figure 5).

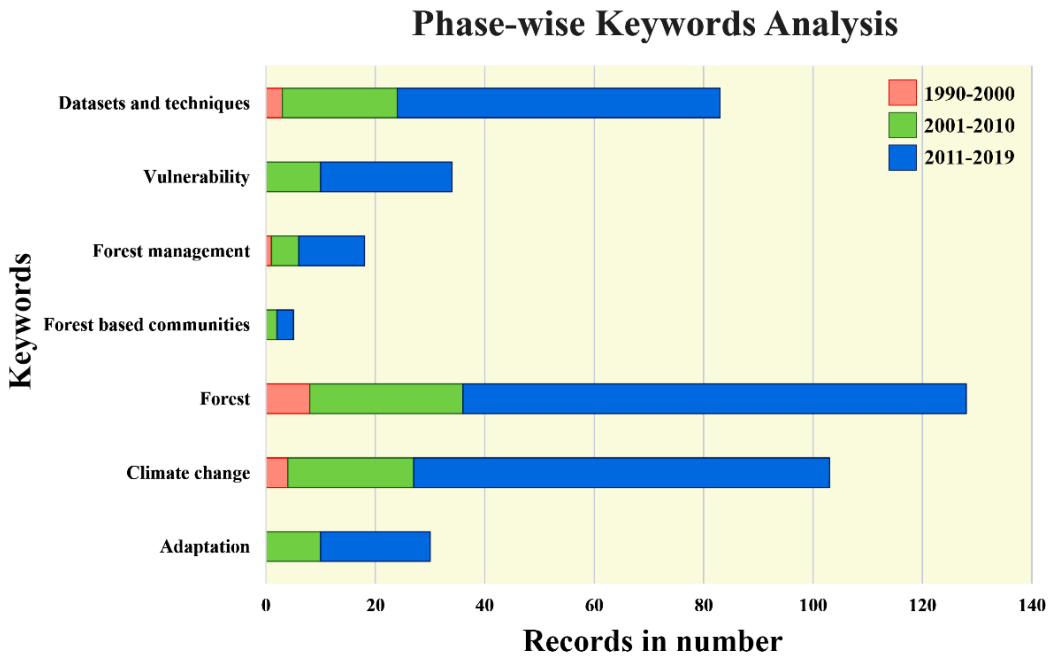

Figure 5. Keywords analysis during a different phase of systematic review.

Social vulnerability [55], inherent vulnerability [30], wildfire/forest fire [65], remote sensing [33], sustainable forest management [79,80], adaptation [81,82], plant pathogens [83,84], forest fires [66], forest carbon [80,85] and forest modelling [86,87] were found consistently in the literature during 2011–2019. The overall analysis highlighted the most frequently used keywords as climate change (85), adaptation (25), vulnerability (16), forest fire (13), forest fragmentation (12), forest management (12), drought (11), sustainable forest management (9) and adaptive capacity (8).

The keywords analysis insinuated that the scientific community has widely acknowledged climate change since the 1990s. The central theme of most studies was found to be climate-change-induced forest vulnerability. After 2010, numerous studies shifted their focus from the general overview of forest degradation and climate change impacts on forest products and services to geospatial and machine learning-based forest vulnerability analyses [26,33,36,62,69,88–93].

3.2. Mechanism Analysis

Recent research has attempted to study the consequences of climate change on forests and forest-dependent communities and their adaptation potential to these changes. The primary focus of these studies has been proper preparedness, best management technique, mitigation of the climate change impacts, adaptation of the changes, and resilience. Further, advancement in remote sensing techniques has enabled the researchers to achieve accurate results and analysis. The high-resolution satellite data have facilitated scholars to research remote areas with spatio-temporal information. Our analysis revealed that most of the papers used Landsat and MODIS datasets, and some of them were a blend of field datasets and DEM. The authors have adopted modelling techniques since the advent of forest studies. Models have improved the capability to make accurate forecasts and consistently monitor forest health. Accordingly, models have been developed to assess future climate change projections and their impacts. The most widely used models for estimating future climate change were global climate models (HadRM3, HadCM3), dynamic global vegetation models and generalized models. The species distribution model and habitat suitability model are recently used models to predict species distribution across geographic space and time. Wan et al. [18] employed a species distribution model combined with an endemics–area relationship (EAR) to assess forest susceptibility to climate change in China. It is a powerful tool to support forest management strategies, analyze species richness changes and estimate species composition changes from current climate change to the future [94]. Some models used primary datasets, such as field surveys, while others used secondary data, such as forest inventories or satellite data. In recent years, the MaxEnt program, based on the maximum-entropy technique, has become increasingly popular for modelling species niches and distributions. The Holdridge life zones classification system is a global bioclimatic scheme for the classification of land area and is utilized in assessing the possible changes due to global warming. Climate models, dynamic global vegetation models and bioclimatic envelope models are conventional models that are still in use and rely on quantitative techniques [60,81]. However, the auto-regression model, HyTAGs, SWAT Model, MaxEnt modelling approach, fuzzy models and geospatial indices were more dynamic in forest vulnerability assessment [78,95,96].

The development of computational algorithms (machine learning) and software (R, MaxEnt software, NVivo data analysis software, frag stats) provided an accurate analysis of forested areas and validation of the ground reality. Various authors used several methods and tools for assessing forest vulnerability to climate change during 1990–2019 which are identified and demonstrated in Table 1. Advancements in methods and tools were mainly identified from the second phase of the review, i.e., post-2001. Models using the secondary datasets of forest inventories and reports from weather and meteorological stations were crucial in forest studies. Scholars were implicitly assisted in analyzing forest risk and susceptibility using a modelling approach that included the Hadley Centre regional climate model (HadRM3), dynamic global vegetation model (IBIS), species distribution model, The Lund–Potsdam–Jena (LPJ) model and maximum entropy modelling algorithm (MaxEnt), SWAT model, and bioclimatic envelope model (BEM). Recently, scholars have oriented their attention towards adaptation of the forest communities and discerning individual resilience. Challenges that were associated with the studies of past and present were also identified in the present review. However, overcoming these challenges requires integrated forest assessment using advanced datasets, techniques and adequate ground intimation.

Table 1. Methods, models and tools employed for assessing forest vulnerability to climate change.

Year of Publication	Author	Methods, Models and Tools
2002	M.J. Lexer	Bayesian probability theory
2006	Wilfried Thuiller	BIOMOD framework, Simpson's diversity index
2009	M.J. Lexer	PROMETHEE outranking method
2010	Yuko Ogawa-Onishi	Multiple linear regressions
2010	Patrick Gonzalez	Correlation coefficient
2011	Paul H. Evangelista	Jackknife testing
2011	Marcus Klaus	Logistic regression analysis, Wald-test
2011	Wei Ren	leaf area index (LAI)
2011	N. H. Ravindranath	PCA, agricultural vulnerability index (AVI), water vulnerability index (WVI), forest vulnerability index (FVI)
2012	Doo-Ahn Kwak	Inverse distance squared weighting (IDW), Non-linear regression analysis
2012	Rupert Seidl	ANOVA, significance of the squared Mahalanobis
2014	Mingshi Li	NDVI, normalized burn ratio (NBR)
2014	Jun Du	Kriging method
2014	Pavel Tucek	Multivariate statistical techniques, PCA
2014	Nicholas A. Fisichelli	Pearson's correlation coefficient
2014	Adrianon Mazziotta	Habitat suitability index (HSI), generalized estimating equations (GEEs) Methods
2014	V.S. Chitale	Geographic weighted regression (GWR)
2015	Sujata Upgupta	Forest vulnerability index (FVI)
2016	Adam Bauer	Regression analysis
2016	Alan J. Tepley	Non-parametric multiplicative regression
2016	Rauls Anchez-Salguero	COFECHA program, ARSTAN program
2016	Mark J. Lara	Regression analysis, maximum likelihood algorithm, error matrix and Kappacoefficient
2017	Ji-Zhong Wan	MaxEnt software
2017	Jan C. Thiele	Site index, leaf area index (LAI), Kolmogorov–Smirnoff test
2017	Craig R. Nitschke	Linear regression, Program Dendroclim, Kalman filtering, multiple regression, Kappa coefficient
2017	Rhys Manners	fuzzy cognitive mapping
2017	Alexandra Paige Fischer	Z-Scores, PCA
2017	Duncan Ray	Pearson correlation method
2017	I. Aubin	Climate moisture index (CMI), drought sensitivity index
2017	Camille S. Stevens-Rumann	Z-score, Chi-square test
2018	Alexandra Paige Fischer	NVivo data analysis software
2018	Qinli Yang	CCDC algorithm, F-mask algorithm, ANUSPLIN software, simple linear trend (SLT) method, Mann–Kendall, correlation analysis
2018	Rita Sousa-Silva	Kruskal–Wallis test, Spearman's correlation analysis
2018	Malay Pramanik	Pearson correlation coefficient, PCA
2018	Simone Matias Reis	Fragstats software, Mann–Kendall, Kruskal–Wallis test
2018	Chidiebere Ofoegbu	SPSS, Chi-square, Bonferroni tests, logistic regression model
2018	Xiongwen Chen	Simpson's index, *t*-test
2018	Nguyen Thi Lan Huong	Livelihood vulnerability index (LVI) and livelihood effect index (LEI), *t*-tests
2018	Getnet Feyissa	Diversity index
2018	M. Peraza-Castro	Differential split-sampling test (DSST), linear regressions
2018	Manoj Kumar	Climate data operator (CDO) software, correlation coefficient
2019	Cristian Gheorghe Sidor	Basal area increment (BAI), CooRecorder software, COFECHA software, XLSTAT software, QGIS software
2019	Brandi A. Gaertner	Asymmetric Gaussian function, Penman–Monteith equation, Mann–Kendall, PCA
2019	Tamir Klein	Global forest watch (GFW) analysis tool, standardized precipitation evapotranspiration index (SPEI), ANOVA
2019	Adriana Almeida de Lima	Maximum entropy algorithm
2019	Mathieu Bouchard	Poisson distribution
2019	Sara Alibakhshi	Leaf area index (LAI)
2019	Muhammad Naeem	MaxEnt software, Pearson's correlation coefficient, Markov chain analysis
2019	A.J. Hester	*t*-tests, Bray–Curtis distance matrix, ANOVA
2019	Francis K. Dwomoh	Relative delta normalized burn ratio (RdNBR)

4. Discussion

There has been extensive research on forest and climate change focusing primarily on evaluating the potential effects, responses and vulnerability of various species and ecosystems to climate change. Forests' susceptibility to climate change has been emphasized in scientific study, which has focused on assessing and comprehending the vulnerability of forests and associated systems, as well as forest and dependent populations' adaptation capacity. Our review has identified four critical issues that are relevant to climate change-induced forest vulnerability assessment and management which may be addressed in future research. These issues have been explicitly discussed in the following sub-sections.

4.1. Climate Change Impact and Forest Vulnerability

The concept of vulnerability has its origin in natural hazard studies [97] and has been defined as an outcome of exposure, sensitivity and adaptive capacity. Over time, vulnerability became a multi-dimensional topic among the scientific community. Forest exposure to climate change is a highly complex problem to be understood because current and future climate changes are affecting forest adaptability along with their dependent communities [98]. Climate change impact and forest vulnerability assessments have occupied an important place in recent scientific studies. Proxy measures, such as temperature variables or indicators which typically recognize critical processes to assess forest inherent vulnerability were used to reduce the implications [40,43]. Thus, the vulnerability assessment's structure must be revised to account for its multidimensionality in space and time [99]. Climate change has a major influence on forests globally and has been deliberated by several literatures. It affects the forestry habitat structure and plays a critical role in forest health conservation. However, the temperature is fluctuating worldwide. There were influential factors influencing forests, such as temperature, precipitation, relative humidity and photosynthesis-active radiation (PAR) [33]. The long seasonal extension has important implications for forestry growth and productivity. Climate change is predicted to affect forest disturbance frequency, and goods and services, according to their locations and habitats. Climate change has reduced the forest ecosystem's regulating capacity and created severe consequences for flora and fauna, particularly at the regional and local scale. Persistent forest loss has negatively affected communities' livelihoods and posed a significant challenge to the sustainability of the forest ecosystem. Many studies have touched upon the structure and function of the forest ecosystem, covering the distribution of species, fragmentation of forest, canopy density and habitat suitability using scientific models. However, the global community seems to be reaching a critical juncture, with recent commitments and initiatives, such as the Paris Agreement, Sustainable Development Goals (SDGs), and UN Strategic Plan for Forests 2017–2030 (UNSPF) contributing to a positive trajectory of progress. These organizations aid countries in overcoming these challenges by imparting policy advice, capacity building and technical support [13]. Sustainable forest management involves optimizing the benefits of forest resources to satisfy the needs of society by conserving and maintaining forest ecosystems for both present and future generations. Several studies on the influence of climate change on forest cover have found that shifting patterns of vegetation cover varied across areas due to spatiotemporal changes in climate change and eco-environmental factors [100]. It is also evident that changes in forest dynamics are not only due to climate change but are also accelerated by several anthropogenic disturbances [18]. Thus, ecological and inherent vulnerability assessments are significant for examining the exposure and sensitivity components.

Current forecasts of future temperature and rainfall changes cover a broad spectrum, making forests' future climate, particularly regional and local, challenging to predict. Further, uncertainty is produced by the ecological trends which connect forest distribution and productivity to climate change. Most of the research concentrated on a timeframe that is impossible to understand as the only consequence of climate change. The principal challenge to the interpretation of such findings is the unpredictability of future climate projections. Thus, inventories of long-term vegetation data are indispensable for effectively

tracing climate change impacts on the forest. The ecosystem services of forests differ with the composition of site-specific species, influenced by forest governance. A thorough understanding of forest dynamics and their driving factors, either climate change or anthropogenic activities, can lead to forest management strategies. With vast ecological uncertainty and worldwide geological uncertainty, more research and evaluations are needed in the present context, including threats and potential opportunities in likely climate change scenarios. It is important to remember that additional research activities are required for long-term planning to improve forest products and services to meet the know-how gap. This may help in reducing livelihood vulnerability.

4.2. The Adaptive Capacity and Strategies of the Forest and Dependent Communities

Despite the realization about resilience and adaptive capacity, wide knowledge gaps still exist due to their complex nature and dynamic ecosystem functioning. Resilience, adaptation and vulnerability are found to be related to each other. The conversion of forest land and population dynamics have contributed enormously in shaping the existing patterns of forest distribution across the world [30]. Adapting forest management to climate change entails monitoring and forecasting changes to mitigate adverse impacts or maximize potential benefits [12]. In addition, forest vulnerability and ecological resilience research have significant implications for regeneration and sustainable forest management [67]. Although forest ecosystems are naturally robust, many species and ecosystems have adapted to historically changing climatic settings. Still, the extent and rate of future change may exceed the potential adaptive capacity of forest dynamics. Forest disturbances can affect forest composition and structure, which has ramifications for forest functionality and resistance. Hence, there is an urgent need to prevent and reduce the likely upcoming declines in forested areas to increase individual species adaptation. Forest vulnerability assessments are thus critical for determining which species are at risk due to climate change.

Previous literature has discussed the management theories relating to how local communities adapt to the changes occurring in forest ecosystems conceptually. However, Seidl and Lexer [79] have remarked on the prevalence of discontinuity in the policy initiatives that have been designed and enforced to improve the forest's adaptive capacity. Well-managed forest will considerably minimize local communities' climate change vulnerability. Societies that are directly or indirectly dependent on certain forms of forest typically find ways of adapting to current and potential climatic threats, as forests supply a broader array of ecosystems in different stressed scenarios. Therefore, forest-dependent community adaptation assumes significance, particularly in developing nations. Several options for adaptation may include community awareness, forest fire prevention, forest conservation, and livelihood diversification. However, forest and dependent communities still face several social, economic, political, and environmental problems. Policy interventions which combine adaptation with coping are non-efficient; instead, they promote temporary short-term changes rather than a permanent solution [101]. Thus, climate change adaptation should be considered a risk management component of a long-term forest management plan [52]. A micro-scale implementation of such an approach would be required for its sustainability.

4.3. Forest Management and Its Scope

Forests face a kind of disturbance that adversely affects their health and vitality. The uneven distribution of forests leads many different organizations to formulate forest policies and suggestions to enhance forest dynamics worldwide. Promoting regeneration, afforestation, forest stability, and trees' resilience to various kinds of disturbance should be practiced to sustainably preserve forest cover. Oak-dominated broadleaved forests in many parts of the world have been transformed into pine forests, mainly by human activities. These pine forests are more vulnerable to climate changes and should be transformed into mixed forests [85,102]. In some regions, forest managers turn the climatically sensitive forest into a diversified forest by gradually replacing species to enhance the forest's biological

diversity. This habitat conversion ultimately enhances the forest's adaptive capacity to a great extent [75,91,103]. There are very few studies concerning fundamental research into climate change vulnerability and extinction of flora, posing a great challenge for forestry managers aiming for long-term adaptation measures. Furthermore, there is a severe lack of clear scientific information regarding forest species' response to climate change. Therefore, local indigenous communities' expertise should be promoted and integrated to design solutions for climate change adaptation and reduce climate change impact on forest environments. Community forest management may play an essential part in the sustainable management of forests under the climate change scenario.

Local dependent communities protect various forest regions; however, they are not well-recognized and well-documented, risking the loss of political and financial support. In many countries, stakeholder involvement in the forest has resulted in the restoration of endemic flora and fauna [79,96]. Indigenous communities also advocate the use of trees and forestry tools in various land management scenarios which encourages them to participate in community-based land conservation activities, carbon sequestration programmers and other CFUGs, for example, REDD+ initiatives or CDM (Clean Development Mechanism) [30,104]. Such community participation will help forests to meet the indeterminate effects of climate change by preserving species that have become critically endangered or face risks. This kind of forest management improves forests' ecological variability, thus enhancing their capacity to adapt. Substantial community efforts to sustainable forest resource management guarantee improved natural resources, controls on indiscriminate and non-scientific degradation, and poverty reduction among several vulnerable communities. Further, combining knowledge of system vulnerabilities is imperative for devising management strategies involving risk and uncertainty to promote long-term sustainability [105].

4.4. Framework for Future Research

The earlier studies tended to focus on a particular aspect of forest vulnerability, while less attention was given to a comprehensive evaluation of climate change-induced forest vulnerability assessment. Therefore, we proposed a vulnerability, adaptation and sustainability (VAS) framework for analyzing the intrinsic forest characteristics at various levels (Figure 6). The present review has contributed to formulating the scientific amelioration of the concepts of vulnerability, forest sustainability and adaptation in forest studies. It has now become a common consensus among the scientific community to analyze vulnerability as a component of exposure, sensitivity and adaptation. Exposure and sensitivity have far-reaching implications for forest vulnerability. Such assessments require site-specific indicators at various scales. The indicators of exposure and sensitivity differ with various kinds of vulnerabilities. The forest ecosystem is exposed to multiple hazards. Exposure refers to the degree of stress and is to a greater extent determined by the hazard's nature and magnitude. Ground slope, canopy density and biological richness are greatly exposed by climate change exposure. Sensitivity determines how the livelihood of forest-dependent communities is sensitive to various kinds of exposures. These vulnerabilities have several facets involving different levels of resilience and adaptation. Therefore, adaptation assessment at an individual as well as community-level must be carried out. Societal adaptation is considered a domain of sustainability and must be taken into account. Adaptation assessment can help in decision-making processes and improve the capacity to attain sustainable forest management objectives. Conservation, protection and potentiality can help in achieving forest sustainability. Interaction among stakeholders, researchers, forest managers and dependent communities would yield fruitful discussion for prolific planning and management. Various studies have contributed to the productive implementation of forest adaptation strategies. For example, Silva et al. [63] indicated that the genetic information of different plant species helped in forest management and adaption in Belgium. Similarly, Liu et al. [105] proved that some selected plants and species have the capacity to adapt to climate change-related impacts. France implemented a national plan for adaptation to climate change in 2011 which helped to increase forest cover in the country [63]. Collective

action on adaptation to climate change has been successfully implemented in the North River watershed spanning Vermont and Massachusetts by the Massachusetts Department of Conservation and Recreation, and the Knife River project on Minnesota's North Shore of Lake Superior by the Minnesota Department of Natural Resources and the University of Minnesota-Duluth [106]. Thus, forest vulnerability and sustainability assessment using an outcome approach, indicators and multicriteria decision-making models are imperative for effective forest management.

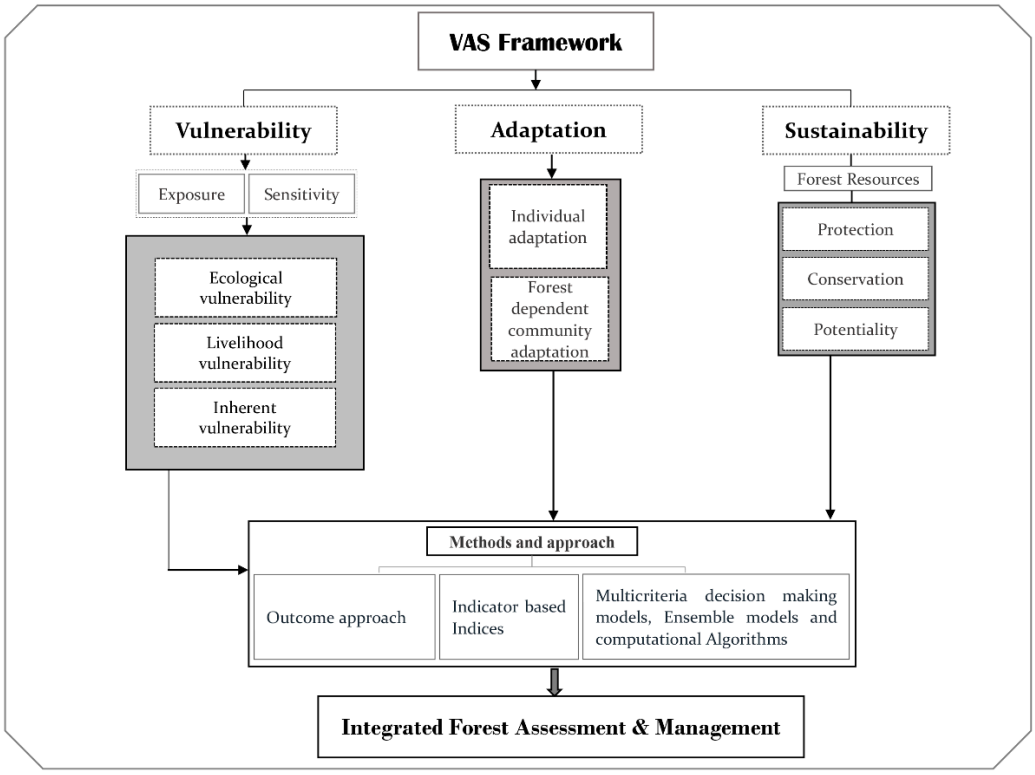

Figure 6. Proposed frameworks for future research.

5. Conclusions

Through a systematic review, this paper examined the current state of forest vulnerability to climate change and management issues. Though many types of research have touched upon the various aspects of climate change, forest vulnerability and management, a holistic approach for assessing climate-change-induced forest vulnerability and management is scant in the existing literature. From an in-depth analysis of our literature review and understanding of forest vulnerability to climate change management, we proposed an integrated framework involving the assessment of forest vulnerability, adaptation and sustainability. We also suggested using the outcome approach, indicator-based indices, and various decision-making models for such comprehensive assessment and management. Most strategic initiatives regarding forest conservation are taken at the macro-level system, which lacks the inclusion of local planning about forest services in adaptation processes that contribute to multiple policy decisions. Hence, it is expected that research could be carried out locally, focusing on a participatory approach. It is also imperative to implement flexible adaptation strategies for various stakeholders to provide forests' goods and services. Government efforts and policies should be accessible down to local levels in the forested region. Such strategies would enable the policymakers to proactively plan and prioritize mitigation and adaptation measures for the sustainable management of forests and their resources along with dependent communities under various climate change scenarios.

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