Bibliometric Analysis of the Structure and Evolution of Research on Assisted Migration

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Abstract
Purpose of Review Assisted migration is increasingly proposed as a proactive management strategy to mitigate the consequences of maladaptation predicted under climate change. Exploring the social and academic structure of the field, its research gaps, and future research directions can help further the understanding and facilitate the implementation of assisted migration strategies. Here we used bibliometric analysis to examine the intellectual, social, and conceptual structures of assisted migration research to identify gaps and opportunities for future research. Bibliometric data based on publications on assisted migration were collected from Scopus and Web of Science databases using assisted migration and climate change or their synonyms as queries. Metadata were merged, processed and several networks were constructed.

Recent Findings Co-citation and keyword co-occurrence networks identified three major clusters focused on (i) theory and risk of assisted migration of threatened and endangered species, (ii) impact of climate change on realized and fundamental climate and geographic niches, and (iii) assisted population migration. Collaboration network analysis identified three social core hubs: North America, Europe, and Australia, with the USA and Canada being the most productive and the most collaborative countries.

Summary We conclude that future research is expected to concern mainly the assessment of physiological response of species and populations to extreme climate events such as drought and frost, and the contribution of non-climatic factors and biotic interactions in local adaptation and population performance under climate change. Social core hubs distinguished in this work can be used to identify potential international research and training collaborators necessary to address gaps and challenges underlying assisted migration implementation.

Keywords Bibliometrics · Network analysis · Assisted migration · Climate change · Conservation biology · Ecological restoration

Introduction

Anthropogenic climate change is having substantial impact on the composition and structure of native biodiversity leading to shift associated with species distributions [1–3], and ecosystem functioning [4, 5, 6•, 7•, 8]. Some species have shifted their distribution as they track their changing climatic niche. These range shifts depend on species’ ability to track changing abiotic cues and biotic interactions, and may lead to range contraction, fragmentation, or expansion [1, 9••, 10–14]. However, while some species maintain the capacity to track a shifting ecological niche [2, 15, 16], the vast majority may not be able to keep pace under rapid climate change [17, 18].
Among the various strategies that have been proposed to manage species under climate change, assisted migration (AM) is a proactive conservation and restoration strategy that aims to limit species’ maladaptation by facilitating gene flow and transfer of genetic material that may be adapted to the climate of the recipient environment [9••. 19–21]. AM, also called “assisted colonization,” “managed relocation,” and “assisted gene flow” is defined as the intentional movement of species or populations to regions predicted to be suitable under future climate conditions [9••, 21, 22]. According to the literature above, there are three categories of assisted migration:

(i) **Assisted population migration**, also called assisted gene flow, is the intentional movement of seed sources or populations to locations within a species’ current natural distribution.

(ii) **Assisted range expansion** is the intentional movement of seed sources or populations to locations slightly beyond a species’ current natural distribution.

(iii) **Exotic translocation** is the intentional movement of species to locations that are predicted to be more suitable under future climate but distant from their natural geographic range.

Assisted migration could significantly reduce the expected negative impacts of climate change [23, 24]. However, devising and implementing a system of assisted migration that will be safe, effective, and readily adopted by practitioners requires multidisciplinary understanding of diverse fields including biology, climatology, geography, computer programming, and social science [25]. Bibliometric analysis can assist in identifying research gaps and individuals active in collaborative networks required for this work.

Bibliometric analysis involves a set of quantitative explorations that aims to provide insight into the evolution of a given discipline, detect research gaps, and describe the collaborative structure between academic institutions or countries [26–28]. It also allows identification of authors actively contributing to a research field and those that have established a collaborative foundation to build upon. Bibliometric analyses have become widely used in social and economic sciences and even in basic sciences [28–32], but few bibliometric analyses have been conducted within the field of forest science.

Bibliometric studies are categorized into three types: reviews, evaluative, and relational studies [28, 30, 33•]. Review studies often include literature reviews or meta-analyses, called “review methods” [28]. Evaluative studies measure the academic impact of articles or authors associated with a given research field using various metrics (collaboration index, productivity index, impact metrics, and hybrid metrics) (see Aria and Massimo [33•] for additional details). Relational studies examine the relationships between units of analysis (article, author, institution, journal, reference, and keyword) within a research field and can be divided into four types of analyses: co-citation analysis, bibliographic coupling, co-authorship analysis, and co-word analysis. Collectively, these four approaches allow assessment of the intellectual, social, and conceptual structure of a research area [34–37]. In this way, relational studies can identify changing trajectories of research themes within a scientific field and the collaborative networks associated with those research themes [32, 36]. These analyses can be used to visually illustrate the intellectual structure of a field of research by identifying and quantifying the influence of authors, sources (journals), and articles in this field [34, 35]. The social structure examines the relationships (the levels of scientific collaboration) between individual actors at different scales (authors, institutions, and countries) based on jointly published documents [27]. The conceptual structure examines the relation among keywords in a field, with aims to (i) structure knowledge into the research domain or topic and (ii) identify potential knowledge gaps and future research themes. The latter are identified through evaluation of implicit gaps (identified in the literature) that have low co-occurrence [32].

For example, by investigating the evolution of ecological restoration using a bibliometric analysis, Guan et al. [38•] highlighted the need to develop more international academic collaborations, together with techniques of management and monitoring of restored ecosystems, and the social issues associated with this field. In a bibliometric analysis of remote sensing applied in forest management, Abad-Señura et al. [39] found that ecological sensitivity assessment, satellite fire mapping, topological acoustic sensing, unsupervised treetop detector, and air pollution mitigation would be the predicted hotspots of future research in this research domain. A recent bibliometric analysis of temporal trends in frequencies of title words revealed a shift in research away from sustained-yield-based forestry and towards a more interdisciplinary view of forests as ecologically important and dynamic systems [40].

The objectives of the study were to (i) examine the intellectual, social, and conceptual structures of AM research using bibliometric relational methods; (ii) examine the pattern and evolution of AM research; (iii) identify knowledge gaps and future research directions. Together, these results will provide a roadmap for ongoing research and implementation of AM, and identify gaps in the field that will benefit from new collaborative research programs.
Materials and Methods

1. Data Collection and Processing

Bibliometric data were collected from the Web of Science (WOS) and Scopus databases, the two largest multidisciplinary scientific databases. Previous studies have indicated substantial complementarity between these databases, arguing the importance of using both to conduct a single integrated bibliometric investigation [31, 41]. We retrieved bibliometric metadata related to assisted migration from these two databases between 1900 to 2020 using the following strings to query across titles, abstracts, and keywords: (“assisted migration” or “assisted population migration” or “assisted gene flow” or “assisted colonization” or “assisted colonization” or “managed relocation”) and (“climate change” or “global change” or “climate-change” or “climatic change” or “global warming”) and (Language = all) and (document type = All document types). This query syntax was used to identify articles where assisted migration is proposed as a climate change adaptation strategy, while avoiding documents on assisted migration from other fields such as chemistry, physics, and social sciences. The search yielded 561 and 425 publications in WOS and Scopus, respectively, and the data were downloaded as BIBTEX and CSV files, respectively.

Bibliometric data were processed and analyzed in R version (4.0.0) [42]. First, metadata files associated with each database (WOS or Scopus) were loaded, transformed into a data frame, and merged in one step using the function `bib2df` of the Bibliometrix R package [43]. Second, variables within the two datasets (WOS and Scopus) were shortened to 18 common and relevant variables (“Authors,” “Author Keywords (ISI),” “Index Keywords (Scopus),” “Affiliations,” “Document Type,” “Source title,” “Cited by,” “Bibliographic Database,” “References,” “Abstract,” “Correspondence Address,” “Title,” “Year,” “Country of affiliation for the first author,” “Country of affiliation for co-authors,” “University of affiliation for each co-author and the corresponding author,” “Language”, “ISSN”), and the two data frames were merged. Duplicated documents were removed from the merged data frame using `duplicatedMatching` function of the Bibliometrix R package [33•]. The abstract was used as the tag variable to identify the duplicates due to special characters and those were inspected and deleted (n = 17) using a VBA custom script following [31], leaving 622 publications (194 and 64 exclusively from WOS and Scopus, respectively and 364 shared between WOS and Scopus). A final step to accept or remove published material (eligibility) was performed using the following criteria: (i) non-English language publications were accepted if keywords, title, and abstract were provided in English (n = 22); (ii) documents without ISSN (International Standard Serial Number) were removed (n = 1); and (iii) document types such as errata notes, conference papers, and short surveys were excluded (n = 8) [32, 44]. Conference papers are often the initial product of ongoing research or synthesis of published material. As such, their impact is generally lower than original research papers. Although editorial material is usually excluded from bibliometric studies, we included this type of document (n = 13) since they are relevant for the dissemination of scientific knowledge [45] (Table 1). The final dataset contained 614 articles (Fig. 1).

2. Thesaurus Construction

Text data mining and the construction of a thesaurus are crucial to keyword co-occurrence-based analysis.

| Table 1 | Descriptive statistics of the database |
|---------|--------------------------------------|
| Description | Results |
| Main information | |
| Sources (journals, books, etc.) | 220 |
| Documents | 614 |
| Average number of citations per document | 28.52 |
| Average number of citations per year per document | 3.35 |
| References | 29,406 |
| Document type | |
| Article | 493 |
| Book chapter | 21 |
| Editorial material | 13 |
| Letter | 10 |
| Proceedings paper | 10 |
| Review | 67 |
| Document content | |
| Keywords Plus (ID) | 2002 |
| Author’s Keywords (DE) | 1814 |
| Authors | |
| Authors | 1952 |
| Author appearances | 2759 |
| Authors of single-authored documents | 47 |
| Authors of multi-authored documents | 1905 |
| Author’s collaboration | |
| Average co-authors per document | 4.49 |
| Collaboration index | 3.39 |
The use of plural or singular (e.g., range shifts/range shift; ecosystem/ecosystems; provenance test/provenance tests) or different synonyms for the same keyword (e.g., climate change, global change, global warming, climatic change/climate-change) is a common issue that directly affects both the frequency and co-occurrence of keywords.

We constructed a thesaurus file manually by grouping all synonyms and plural or singular forms of keywords under the same word, except synonyms for assisted migration to show their co-occurrence. We also merged keywords containing two or three words that were wrongly separated by removing semicolons to create uniformity among multi-word keywords. For example, we replaced “range; shift” by “range shift,” “local; adaptation,” by “local adaptation,” and “assisted migration,” by “assisted migration”.

3. **Analysis Using Bibliometrix and VOSviewer**

Descriptive statistics (average number of publications per year, most productive author, most productive institutions, most productive countries, and most cited author) were calculated using Bibliometrix R package [33•], and network analyses were conducted to assess the social, intellectual, and conceptual structure of our final dataset (Fig. 1) using VOSviewer software [37, 46].

The co-authors per document index was calculated as \( \frac{\text{The number of co-authors per document}}{\text{The number of documents}} \), and the collaboration index (CI) was calculated as \( \frac{\text{Total authors of multi-authored articles}}{\text{Total multi-authored articles}} \) [33•].

For each network illustration, clusters are distinguished by color, while the size of each node reflects its occurrence. The shorter the distance between two nodes, the more closely connected they are. Finally, the thickness of the connection between two nodes indicates the strength of their relationships [33•].

Clustering was performed using the LinLog algorithm and the modularity clustering technique, where the weighted sum of the squared Euclidean distances with all pairs of nodes is minimized [47]. Nodes were then assigned to clusters based on their similarities (related to co-occurrences).

The intellectual structure of a discipline can be assessed by examining the influence of authors or articles and their connectivity, which is quantified by examining the relationship between pairs of authors (or articles) based on the frequency of their co-citation in other articles. We constructed distance-based co-citation networks [37] in VOSviewer to identify the most active authors in the research field, based on
the number of papers published, the number of local citations (citation of a given author within the field of AM) as well as their influence in structuring the knowledge on AM. The minimum number of citations for authors or articles was set to 10 during network construction.

The social structure of AM research was assessed using the co-authorship network to identify connections between authors, institutions, or countries based on jointly authored publications [37].

The conceptual structure examines the relations among words in the bibliometric database. This analysis aims to (i) structure the knowledge into the research domains or topics and (ii) highlight the most frequently covered topics and identify trends that may allow prediction of possible future lines of research. We assessed keyword co-occurrence network using author keywords in VOSviewer [37, 46]. The minimum occurrence of a keyword was set to four. Web of Science provides another category of keywords named “KeyWords Plus” which are generated using algorithms based on the title of references cited in an article. The overlap between KeyWords Plus and titles of papers may reach 50% [47]. Similarly, Scopus provides “Indexed keywords” which are chosen by content suppliers. The use of KeyWords Plus or Indexed keywords to complement the author keywords may consolidate author keyword-based analysis [48, 49]. However, the similarity between Index keywords and KeyWords Plus has not yet been documented, making their use in merged databases not recommended.

Results and Discussion

Since the first publications on assisted migration as a climate change adaptation strategy in 2007, the number of publications per year increased rapidly from 4 to 75 between 2007 to 2015 thereafter fluctuated moderately (Fig. 2), the average publication per year was 43.8. Research articles and reviews account for 91% of the total publications (Table 1). Multi-authored documents contained an average of 4.5 authors, with only 6% of the documents being single-authored. The collaboration index (CI) averaged 3.4 (Table 1) and was highest during the 2017–2020 period (CI = 4.49) compared with the 2007–2011 (CI = 3.66) and 2012–2016 (CI = 3.48) periods. The same temporal pattern in collaboration was observed in the field of biodiversity research [50]. These results point towards the growing emphasis on collaboration for assisted migration research.

The co-citation network consisted of 81 nodes forming three clusters (Fig. 4), with each node representing one co-cited document (Fig. 4a) or one co-cited author (Fig. 4b). Node size is proportional to its number of citations. The green cluster (Fig. 4b) consisted primarily of plant and animal conservation ecologists who have focused on theory, foundation, and risk of AM. This group was comprised of at least five authors: Ove Hoegh-Guldberg (University of Queensland, Australia), Jason S. McLachlan (University of Notre Dame, USA), Anthony Ricciardi (McGill University,
Canada), David M. Richardson (Stellenbosch University, South Africa), and Mark W. Schwartz (University of California at Davis, USA) who initiated the debate of using AM as a conservation strategy to mitigate the consequence of climate change on the distribution of species [19, 21, 22, 54]. Authors within the blue cluster (Fig. 4b) were mostly ecologists who have assessed the impact of climate change on species’ geographical distributions and range shifts (Fig. 4a). The authors Camille Parmesan (University of Plymouth, USA) and Chris D. Thomas (University of York, UK) were the prominent members of this cluster [3]. The red cluster (Fig. 4b) was comprised of forest geneticists who have conducted population genetics studies, often using provenance trials and molecular data for commercial forest trees (Fig. 4a). The most prominent authors within this cluster were Sally N. Aitken (UBC, Canada) and Gerald E. Rehfelt (US Forest Service, USA). Ten additional authors in this cluster (red) focused on assisted population migration for forest tree species with an emphasis on modeling growth and ecophysiology. Together, the foundational theory underlying the shift of the ecological niche and its evolutionary consequences for species under climate change are represented by authors in the blue cluster (Fig. 4b) with empirical testing, monitoring, and application of assisted migration research to conservation and restoration by authors in the green and red clusters (Fig. 4b).

To examine the evolution of intellectual influence in structuring knowledge of assisted migration research for each cluster, the data collected between 2007 and 2020 were divided into three time periods. During the first period (2007–2011), the green and blue clusters (Fig. 5a) were the most prominent communities producing publications on the theoretical foundation of species range shifts due to climate change. This research provided a framework for assessing ecological benefits and risks associated with AM as a conservation option [3, 19, 21, 22]. During the second period (2012–2016), based on the size and position of the node, some prominent authors (e.g., Schwartz M; Thomas CD; Hunter ML) within the first period (Fig. 5a) became less influential relative to other authors (e.g., Ricciardi A; Hewitt N; Pedar JH) (Fig. 5b). The blue cluster narrowed while the red cluster expanded and became more structured with reduced distance between members. The red cluster, an intellectual community dominated by forest geneticists [20, 55, 57], became more numerous with strong linkages among its members. During the third period (2017–2020), the pattern observed in the second period was accentuated for all groups (Fig. 5c). Shifts in authorship suggest that research on assisted migration is expanding into new research areas with an influx of new authors (e.g., Isaac-Renton MG, Valladares F; Hamann A; Gray LK; Jump AS) from different disciplines, such as ecophysiology, growth modeling, and seedling production, to complement existing theory (Fig. 5c). Over time, the three clusters had distinct trajectories and dynamics, and highlight the following aspects: (i) the green cluster (working mainly on long-distance AM) had a slower evolution with limited empirical data needed to shift to a new structure; (ii) the blue cluster might disappear in the next few years as the theoretical foundations of AM (e.g., the shift in species ecological niche under climate change) now appear to have sufficient empirical support; (iii) inversely, the dynamic evolution observed within the red cluster is more likely to quickly achieve a new structure and might dominate the AM research for the coming years. The rapid evolution of the red cluster may originate from (i) the economic impact of climate change on forest productivity and (ii) the long history of growing trees in provenance trials established many decades ago (starting from the 40 s for some species) which provides a laboratory to test the impact of climate change and assisted population migration.
on species’ success [9••, 55, 56]. The data from these trials has been essential in the development of seed transfer models and the implementation of assisted migration [23, 25, 57, 58].

Moreover, the intellectual structure of AM research might yet change since research on AM is still relatively new (15 years) with limited publications when compared with other similar research fields. Furthermore, securing funds to support extensive research on AM is still challenging. This may reflect the fact that both stakeholders and funders are not informed or sufficiently convinced of the potential benefit of AM research, or that natural sciences funding cycles are unable to support long-term research needed on assisted migration [59].

2. Social Structure

Collaborations between countries were explored by examining co-authorship networks (Fig. 6). Our results identified clusters representing four collaborative groups:

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**Fig. 4** Co-citation network of assisted migration research based on a articles and b authors. Each cluster is represented by a color. The size of a node (author or article) reflects the number of received citations.
the blue cluster was composed of North American countries (USA, Canada, and Mexico) and China, and within this group, the most prolific teams were from Canadian and US institutions. The green cluster included Australia, South Africa, and New Zealand, and was led by Australia according to the size of the nodes. The red and yellow clusters included European countries identifying German and British research groups as the most active (Fig. 6).

Substantial collaboration was observed between the USA and Canada relative to all other countries (Fig. 6). Interestingly, the network also identified collaborations between North America and Europe, with greater collaboration between Canada and Germany, and groups in the USA collaborating primarily with the UK. Collaborations between North America and Europe were more frequent than collaborations within Europe. The same pattern was observed with the green cluster where collaborations between USA and Australia were more frequent than collaboration within the group led by Australia. In Europe, most frequent collaborations were observed between the UK and Germany (Fig. 6).

Greater productivity of Canadian and US authors and institutions might be due in part to the awareness of rapid climate change of northern countries relative to tropical or southern countries, their substantial economic dependence on forestry, and the greater amount of research resources available in the global North than in the global South.

Fig. 5 The network map of authors’ co-citation for a the period from 2007 to 2011, b the period from 2012 to 2016, and c the period from 2017 to 2020. Each cluster is represented by a color.

Fig. 6 The network map of country collaborations based on corresponding author affiliations of assisted migration research. Each cluster is represented by a color. The size of the node represents the productivity of the country (the number of publications in collaboration with other countries). The shorter the distance between two nodes, the more closely connected they are (based on co-authored articles).
3. Conceptual Structure

Seventy-one keywords that occurred at least 4 times were identified. They were grouped into three distinct clusters (Fig. 7) based on their co-occurrence. The blue cluster (11 keywords) was mainly represented by the following terms: species distribution, distribution model, and range shifts. This cluster was mainly focused on the shift in species distribution as a response or a consequence of climate change and on different approaches to model the ecological niche. The green cluster (23 keywords) was dominated by the terms: climate change adaptation, conservation, biodiversity, assisted colonization, managed relocation, translocation, and ecological restoration. This cluster corresponded to research on AM of species as a proactive conservation and management strategy under climate change. This cluster focused on the theoretical conceptualization, debate, and arguments on the impact of action or inaction regarding the deployment of such a strategy for endangered and vulnerable species (Fig. 7). The red cluster (37 keywords) was dominated by the terms: assisted migration, climate change, populations, adaptation strategies, plasticity, genecology, and local adaptation. These terms referred to assisted population migration used for forest tree species. We noted that ecologists have been mostly working on the second and third categories of AM (green cluster), usually using the terms assisted colonization or managed relocation rather than assisted migration.

4. Research Gaps and Future Directions

The temporal scaling of the keyword co-occurrence network (Fig. 7) showed different patterns of research evolving within each cluster (Fig. 8). The terms in blue are linked to early research done before 2014 (average publication year) (Fig. 8). They are generally from the green and blue clusters in Fig. 7 and correspond to the second and third categories of AM. The emerging terms from these clusters were vulnerability (assessment),
ecological restoration, range shift, and species distribution models (Fig. 8), and each exhibited linear to exponential growth as keywords over time (Fig. 9). Within these clusters, terms such as conservation, biodiversity, and species distribution showed a quadratic pattern with a decrease in their occurrence from 2015. As a conservation strategy, assisted migration for threatened and endangered species has been controversial [19, 21, 22, 54, 60]. Traditional conservation failed for several species reintroductions [61] because species establishment was likely limited by the ontogenetic niche rather than the climatic niche [62]. Species establishment is a complex ecological process which depends on different biotic and abiotic factors and their interactions, such as presence of pollinators, mycorrhizas, herbivory pressure, pathogens or competitors, and habitat physico-chemical parameters required for seeds germination and seedling establishment. Conservation-oriented restoration appeared to be the optimal strategy because it integrates both climate and ontogenetic niches in the process of species translocation [62]. The linear increase of research on ecological restoration (Fig. 9) suggests an increased interest in both biodiversity conservation and habitat restoration. In addition, research assessing biotic interactions of the introduced species in their new ecosystem is needed for effective species translocation. For example, assisted migration of forest trees should consider above- and below-ground interactions, including existing flora, predominant pests, pollinators, and grazing fauna alongside below-ground communities.

Research related to assisted population migration was more recent compared to the second and third categories of assisted migration (Fig. 8). Within the red cluster (assisted population migration), research was focused initially on the genetic structure of species populations (2015 on average), followed by the investigation of growth-climate relationships, which was facilitated by the availability of growth data from old provenance tests (2016). More recently (2017 to 2020), research on assisted population migration focused on forest management, local adaptation, plasticity, and drought and frost-related traits (bud burst, bud set and cold hardiness) where research on local adaptation and mortality has grown linearly, and exponentially for drought (Fig. 9). The growing interest of research in local adaptation and plasticity of functional traits were related to their...
crucial role in species adaptation to climate change and therefore to resilience capacity [9••, 20, 63]. The fifth report of Intergovernmental Panel on Climate Change [5] highlighted an increase in the frequency and severity of extreme climate events (frost and drought) under climate change which represents an additional challenge for the implementation of assisted migration [64, 65]. This may have contributed to stimulate research on adaptation to frost and drought events. Then, we expect intensive research on the assessment of the specific responses of
species populations to both drought and frost events in the future. An important additional issue in the response of tree populations to climate change is the noticeable increase of mortality of forest trees (Fig. 8) which is attributable mostly to the effect of more frequent extreme drought events [66, 67]. Finally, more research on the role of microbiome and epigenetics in the adaptation to climate change and the development of a new generation of seed transfer models is needed. This research should consider growth-climate relationships, drought and frost tolerance, and interactions between the translocated species and their biotic environment.

**Study Limitations**

We acknowledge two limitations to our analysis which likely resulted in our failing to locate all articles dealing with AM. First, our search could not detect articles that focused on AM but did not explicitly use “assisted migration” or its synonyms. For example, Mátyás and Yeatman (1992) [68], who developed a seed transfer model for jack pine and discussed its use to define safe ecological transfer distance, and Ledig and Kitzmiller (1992) [69], who recommended establishing plantations with populations from climates that are warmer than the plantation site climate, are not included in our study because they did not use the term “assisted migration” or any of its synonyms. Despite not being recorded in our database, the authors Mátyás and Ledig figured in the intellectual structure (Fig. 5). The second limitation is related to the standard search engines used, which looked at the term “assisted migration” or its synonyms in titles, article keywords, and abstracts, but not in the text. This limitation likely excluded some articles, such as Andalo et al. (2005) [70], who developed a seed transfer model for white spruce. The article did not use the term “assisted migration” in the title, keywords, or abstract but evoked its potential use in the discussion section. More accurate search tools using novel approaches like machine learning would be more efficient in detecting articles in the “blind spots” of conventional search engines.

**Conclusion and Perspectives**

This study showed that much of the research on assisted migration has been carried out in North America, where Canada and the USA have established strong collaborative networks. Canada–USA collaborations have emphasized research related to assisted migration of populations for forest trees, compared to other research categories, including assisted range expansion and exotic translocation, which may largely be contingent on economic interest. The network analysis demonstrated that the knowledge was structured in three intellectual and conceptual groups working on species distribution, exotic translocation, and assisted population migration.

Our work provides new insights into the development of research on assisted migration of forest trees under climate change. For example, to minimize the mortality and vulnerability of forest trees, our bibliometric analysis indicates that the research on the consequences of extreme climatic events like drought and frost anomalies is a promising avenue. Therefore, the development of research on the physiological basis of drought and frost tolerance in trees and the interaction with increased atmospheric CO₂ is crucial. In addition, assessing the potential role of epigenetic memory to traits variation may help improve the prediction of drought and frost impacts to plant fitness. In addition, new research themes linked to the observed growing interest in ecological conservation may include the contribution of soil properties (physics, chemistry, and microbiome) and the impact of biotic interactions on local adaptation patterns for different tree species. Overall, this bibliometric analysis points towards the need to establish new, long-term experiments that expand international collaborations and foster development of interdisciplinary toolkits to fill existing and evolving knowledge gaps that are important to assisted migration and its application to conservation and restoration.

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**Data Availability** The datasets generated for this study are available upon request to the corresponding author.

**Code Availability** R codes are available upon request to the corresponding author.

**Declarations**

**Conflict of Interest** The authors declare no competing of interests.

**Human and Animal Rights and Informed Consent** This article does not contain any studies with human or animal subjects performed by any of the authors.

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References

Papers of particular interest, published recently, have been highlighted as:
• Of importance
•• Of major importance

1. Davis MB, Shaw RG. Range shifts and adaptive responses to Quaternary climate change. Science. 2001;292:673–9.
2. Chen I-C, Hill JK, Ohlemüller R, Roy DB, Thomas CD. Rapid range shifts of species associated with high levels of climate warming. Science. 2011;333:1024–6.
3. Parmesan C, Ryrholm N, Stefanescu C, Hill J, Thomas C, Descimon H, Huntley B, Kaila L, Kullberg J, Tammaru T, et al. Poleward shifts of species’ ranges associated with regional warming. Nature. 1999;399:579–83.
4. Williams JW, Jackson ST, Kutzbach JE. Projected distributions of novel and disappearing climates by 2100 AD. Proc Natl Acad Sci USA. 2007;104:5738–42.
5. IPCC: Climate change 2014: Impacts, adaptation, and vulnerability. Part a: Global and sectoral aspects. Contribution of working group ii to the fifth assessment report of the intergovernmental panel on climate change. Edited by. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press; 2014:1132.

•• Buttn Chauvenet ALM, Adams VM, Beger M, Gallagher RV, Shanahan DF, Ward M, Watson JEM, Possingham HP: importance of species translocations under rapid climate change. Conservation Biology 2020. This paper presents practical recommendations to advance assisted migration as a conservation tool.
6. Clark JS, Andrus R, Aubry-Kientz M, Bergeron Y, Bogdziewicz M, Bragg DC, Brockway D, Cleavitt NL, Cohen S, Courbaud B, et al. Continent-wide tree fecundity driven by indirect climate effects. Nat Commun. 2021;12:1422.
7. Aitken SN, Yeaman S, Holliday JA, Wang TL, Curtis-McLane S: Adaptation, migration or extirpation: climate change outcomes for tree populations. Evolutionary Applications 2008; 1:95–111. In this review, the authors highlighted the question of the fate of forest tree populations and identified three potential responses to a rapidly changing environment: migration, adaptation, or extinction.
8. Moir ML, Veski PA, Brennan KEC, Poulin R, Hughes L, Keith DA, McCarthy MA, Coates DJ. Considering extinction of dependent species during translocation, ex situ conservation, and assisted migration of threatened hosts. Conserv Biol. 2012;26:199–207.
9. Thomas LF, Rehfelt GD, Sáenz-Romero C, Flores-López C. Projections of suitable habitat for rare species under global warming scenarios. Am J Bot. 2010;97:970–87.
10. Parmesan C, Hanley ME. Plants and climate change: complexities and surprises. Ann Bot. 2015;116:849–64.
Scientometrics Recent Advances; IntechOpen: Rijeka, Croatia, 2019; p. 13. ISBN 978-1–78084–713–0.

33. Arias, Massimo: bibliometrix: An R-package for comprehensive science mapping analysis. Journal of Informetrics 2017; 11:959–975. This paper propose an R-package that help to perform a comprehensive science mapping analysis of scientific literature.

34. Boyack K, Klavans R. Co-citation analysis, bibliographic coupling, and direct citation: which citation approach represents the research front most accurately? J Am Soc Inform Sci Technol. 2010;61:2389–404.

35. Cobo M, López-Herrera AG, Herrera-Viedma E, Herrera F. Science mapping software tools: review, analysis, and cooperative study among tools. J Am Soc Inform Sci Technol. 2011;62:1382–402.

36. Benckendorff P, Zehrer A. A network analysis of tourism research. Ann Tour Res. 2014;43:121–49.

37. van Eck NJ, Waltman L. Visualizing bibliometric networks. In: Ding Y, Rousseau R, editors. Measuring scholarly impact: methods and toolbox. Wolfram D: Springer International Publishing; 2014. p. 285–320.

38. Guan Y, Kang R, Liu J. Evolution of the field of ecological restoration over the last three decades: a bibliometric analysis. Restoration Ecology 2019; 27:647–660. This paper uses bibliometric approach as a systematic and quantitative analysis of the evolution of the field of ecological restoration.

39. Abad-Segura E, González-Zamar M-D, Vázquez-Canó E, López-Meneses E. Remote sensing applied in forest management to optimize ecosystem services: advances in research. Forests. 2020;11:969.

40. Polinko A, Coupland K. Paradigm shifts in forestry and forest research: a bibliometric analysis. Canadian Journal of Forest Research 2020; 51.

41. Mongeon P, Paul-Hus A: The journal coverage of Web of Science and Scopus: a comparative analysis. Scientometrics 2015; 106.

42. van Eck NJ, Waltman L. Visualizing bibliometric networks. In: Ding Y, Rousseau R, editors. Measuring scholarly impact: methods and toolbox. Wolfram D: Springer International Publishing; 2014. p. 285–320.

43. Ottolinger P: bib2df: Parse a BibTeX File to a Data Frame. R package version 1.1.1. 2019. https://CRAN.R-project.org/package=bib2df.

44. Garza-Reyes JA. Lean and green – a systematic review of the state of the art literature. J Clean Prod. 2015;102:18–29.

45. van Leeuwen T, Costas R, Calero-Medina C, Visser M. The role of editorial material in bibliometric research performance assessments. Scientometrics. 2013:95:817–28.

46. van Eck NJ, Waltman LR: VOSviewer: A computer program for bibliometric mapping. Erasmus Research Institute of Management (ERIM), ERIM is the joint research institute of the Rotterdam School of Management, Erasmus University and the Erasmus School of Economics (ESE) at Erasmus Uni, Research Paper 2009.

47. Newman MEJ. Modularity and community structure in networks. Proc Natl Acad Sci. 2006;103:8577–82.

48. Small H, Garfield E. The geography of science: disciplinary and national mappings. J Inf Sci. 1985;11:147–59.

49. Zhang J, Yu Q, Zheng F, Long C, Lu Z, Duan Z. Comparing keywords plus of WoS and author keywords: a case study of patient adherence research. Journal of the Association for Information Science and Technology 2015; 67.

50. Liu X, Zhang L, Hong S. Global biodiversity research during 1900–2009: a bibliometric analysis. Biodivers Conserv. 2011;20:807–26.

51. Singh D: Publication bias - a reason for the decreased research output in developing countries. Afr J Psychiatry 2006; 9.

52. Mulimani P. Publication bias towards Western populations harms humanity. Nat Hum Behav. 2019;3:1026–7.

53. Huang J, Gates AJ, Sinatra R, Barabási A-L. Historical comparison of gender inequality in scientific careers across countries and disciplines. Proc Natl Acad Sci. 2020;117:4609.

54. Ricciardi A, Simberloff D. Assisted colonization is not a viable conservation strategy. Trends Ecol Evol. 2009;24:248–53.

55. Mátys C. Modeling climate change effects with provenance test data. Tree Physiol. 1994;14:797–804.

56. Mátys C. Climatic adaptation of trees: rediscovering provenance tests. Eurphytica. 1996:92:45–54.

57. O’Neill GA, Hamann A, Wang T. Accounting for population variation improves estimates of the impact of climate change on species’ growth and distribution. J Appl Ecol. 2008;45:1040–9.

58. Pedlar JH, McKenney DW, Aubin I, Beardmore T, Beaulieu J, Iverson L, O’Neill GA, Winder RS, Ste-Marie C. Placing forestry in the assisted migration debate. Bioscience. 2012;62:835–42.

59. Hughes B, Beaus-Luna R, Barner AK, Brewitt K, Bramble DR, Cerny-Chipman EB, Close SL, Coblentz KE, de Nesnera KL, Drobnitch ST, et al. Long-term studies contribute disproportionately to ecology and policy. Bioscience. 2017;67:271–81.

60. Sandler R. The value of species and the ethical foundations of assisted colonization. Conserv Biol. 2010;24:424–31.

61. Maschinski J, Haskins KE: Plant reintroduction in a changing climate: promises and perils. 2012.

62. Volis S: Conservation-oriented restoration – a two for one method to restore both threatened species and their habitats. 2019.

63. Benomar L, Lamhamedi MS, Rainville A, Beaulieu J, Bousquet J, Margolis HA: Genetic adaptation vs. ecophysiological plasticity of photosynthetic-related traits in young Picea glauca trees along a regional climatic gradient. Front Plant Sci 2016; 7.

64. Aitken SN, Bemmels JB. Time to get moving: assisted gene flow of forest trees. Evol Appl. 2016;9:271–90.

65. Wadgymar S, Cumming M, Weis A: The success of assisted colonization and assisted gene flow depends on phenology. Glob Change Biol 2015; 21.

66. Almeida SEdS, Farnese FS: Different ways to die in a changing climate: promises and perils. 2012.

67. Kitto M, Stagg K: Using functional traits to optimize ecosystem services: advances in research. Forests. 2020;11:969.

68. Menezes-Silva PE, Loram-Lourenço L, Alves RDFB, Sousa LF. Climate change and forest management: a systematic review. Forests. 2009;6:1382–402.

69. Kitto M, Stagg K: Using functional traits to optimize ecosystem services: advances in research. Forests. 2020;11:969.

70. Schubert O, Wadgymar S, Cumming M, Weis A: The success of assisted colonization and assisted gene flow depends on phenology. Glob Change Biol 2015; 21.

71. Almeida SEdS, Farnese FS: Different ways to die in a changing climate: promises and perils. 2012.