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Review article

A scoping review of human health co-benefits of forest-based climate change mitigation in Europe

Matilda van den Bosch [a,b,c,d,e,f,*], María Lucía Bartolomeu [g], Sarah Williams [a,b,c], Corina Basnou [h], Ian Hamilton [i], Mark Nieuwenhuijsen [a,b,c], Joan Pino [h], Cathryn Tonne [a,b,c]

[a] ISGlobal, Barcelona, Spain
[b] Universitat Pompeu Fabra (UPF), Barcelona, Spain
[c] CIBER Epidemiología Y Salud Pública (CIBERESP), Madrid, Spain
[d] School of Population and Public Health, University of British Columbia, Vancouver, Canada
[e] Department of Forest and Conservation Sciences, University of British Columbia, Vancouver, Canada
[f] European Forest Institute, Biocities Facility Rome, Italy
[g] Dirección Nacional de Epidemiología del Ministerio de Salud de La Nación, Buenos Aires, Argentina
[h] CREAF, Cerdanyola del Vallès, Spain
[i] University College London, London, United Kingdom

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ABSTRACT

Climate change is a pressing global challenge with profound implications for human health. Forest-based climate change mitigation strategies, such as afforestation, reforestation, and sustainable forest management, offer promising solutions to mitigate climate change and simultaneously yield substantial co-benefits for human health. The objective of this scoping review was to examine research trends related to the interdisciplinary nexus between forests as carbon sinks and human health co-benefits. We developed a conceptual framework model, supporting the inclusion of exposure pathways, such as recreational opportunities or aesthetic experiences, in the co-benefit context. We used a scoping review methodology to identify the proportion of European research on forest-based mitigation strategies that acknowledge the interconnection between mitigation strategies and human impacts. We also aimed to assess whether synergies and trade-offs between forest-based carbon sink capacity and human co-benefits has been analysed and quantified. From the initial 4,062 records retrieved, 349 reports analysed European forest management principles and factors related to climate change mitigation capacity. Of those, 97 studies acknowledged human co-benefits and 13 studies quantified the impacts on exposure pathways or health co-benefits and were included for full review. Our analysis demonstrates that there is potential for synergies related to optimising carbon sink capacity together with human co-benefits, but there is currently a lack of holistic research approaches assessing these interrelationships. We suggest enhanced interdisciplinary efforts, using for example multideterminant modelling approaches, to advance evidence and understanding of the forest and health nexus in the context of climate change mitigation.

1. Introduction

1.1. Rationale

Climate change is one of the greatest threats to human health (Romanello, 2022). The consequences of climate change strike broadly and unequally and include, for example, fatalities and injuries due to extreme weather events, heat-related morbidity and mortality (Kovats and Hajat, 2008; Martínez-Solanas, 2021), and escalating spread and emergence of infectious diseases as well as population displacement, economic losses, exacerbated violence, reduced food security, and poor mental health and wellbeing (Crane et al., 2022).

However, addressing climate change can also be one of the greatest health opportunities of our time (Patz et al., 2014). Actions to adapt to and mitigate against climate change can result in co-benefits for human health beyond those realised through averted climate change (van Daalen, 2022). Reducing fossil fuel combustion reduces emissions of air pollutants; shifting to low-carbon, plant-forward diets can reduce

* Corresponding author.
E-mail address: matilda.vandenbosch@isglobal.org (M. van den Bosch).

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dietary risk factors; and reducing motorised transport demand can be achieved by increasing usage of active and public transport, leading to large health benefits as well as greenhouse gas (GHG) reductions (Haines, 2009; Landrigan et al., 2018; Landrigan, 2017). Climate change adaptation and mitigation is also addressed by so called nature-based solutions (NbS), defined as "actions to protect, sustainably manage, and restore natural and modified ecosystems that address societal challenges effectively and adaptively, simultaneously benefiting people and nature" (IUCN, 2023). Many NbS are also directly linked to health, especially in urban settings (van den Bosch and Ode Sang, 2017).

Europe plays a central role in the global response to addressing climate change(Romanello, 2021). The Land Use, Land-Use Change, and Forestry (LULUCF) sector is incorporated in the European Green Deal as a central component for achieving the European Union's (EU-27) climate neutrality goal by 2050 (Deal, 2023). European forests can function as NbS and contribute to climate change adaptation through, for example, cooling of the microclimate especially in cities. More important, though, is the key role forests play in climate change mitigation through sequestering and storing carbon (in combination called carbon sink) in vegetation and soil (Verkerk Delacote et al., 2022). Forests remove CO_2 from the atmosphere through photosynthesis and emit it back via decomposition and combustion (Cannell, 1996). Human activities can influence this balance and the relative carbon sink through various, activities.

As described in Verkerk et al. (2022) (Verkerk Delacote et al., 2022), human activities that influence forests' mitigation capacity can be categorised as (1) management (e.g., forest harvesting practices, such as thinning intensity, rotation length, and tree species selection); (2) restoration (e.g., forest recovery after die-back episodes, afforestation, or reforestation); (3) protection (e.g., avoiding deforestation); and (4) wood use (e.g., shifts in wood use). The relative climate mitigation capacity depends on how these different activities are applied. Rotation length is the time elapsed between two final fellings in a forested area and can refer to the practice of clear-cutting (i.e., the practice of uniformly cutting down all trees in an area (Sottosanti, 2023)) or continuous cover (i.e., the practice of maintaining forest stands nonuniformly and harvest trees individually (Mason et al., 1999) management. Less frequent and less intensive harvesting of trees tends to be most efficient for climate mitigation purposes (Verkerk Delacote et al., 2022). However, clear-cutting with short rotation periods is still the predominant management principle in Europe, especially in northern regions (Mauser, 2021), usually for timber harvesting objectives (Nyland Kenefic et al., 2016). While there is large variability and uncertainty in estimates of carbon sink-related mitigation capacity, evidence indicates that the activity with the strongest mitigation potential is management characterised by decreased harvesting (~78 million tonnes of carbon dioxide equivalent, $MtCO_2eq/yr$), followed by protection and restoration, which have similar potential (~54–58 $MtCO_2eq/yr$) (Verkerk Delacote et al., 2022). This means that, for example, decreased harvesting has the potential to counteract CO_2 emissions corresponding to 78 million tonnes.

A recent review by the European Forest Institute (EFI) (Verkerk Delacote et al., 2022) concluded that, compared to the current mitigation capacity by EU-27 forests (~380 $MtCO_2eq/y$, 10 % of EU-27′s total annual GHG emissions), an additional 143 $MtCO_2eq/y$ (40 % increase from current) could be sequestered or stored using combined strategies of forest conservation, decreased harvesting, and adapted management methods (Verkerk Delacote et al., 2022), approaching the EU-27 policy target of an additional 170 $MtCO_2eq$ removed annually by LULUCF by 2050 (European_Commission. Proposal for a Regulation of the European Parliament and of the Council Amending Regulations (EU), 2018).

Regarding forested land, the largest carbon sinks are provided by large forests outside cities, but urban forests (a forest or collection of trees that grow within a city (Konijnendijk, 1999; Konijnendijk et al., 2006) also play a role (Habib et al., 2023; Strohbach et al., 2012). In particular, *peri*-urban forests are central to mitigating part of the carbon debt of large cities, while simultaneously responding to recreational demands (Devisscher, et al., 2019).

Forest-based climate change mitigation also provides opportunities for human health co-benefits. A vast literature documents the beneficial health impacts associated with exposure to forests and other natural environments (Konijnendijk Devokta, D., Mansourian, S., Wildburger, C. (eds.), C. Forests and Trees for Human Health: Pathways, Impacts, Challenges and Response Options. A Global Assessment Report. . vol. 41, 2023; van den Bosch Bird and van den Bosch Bird, 2018) which are hypothesised to operate through a number of mechanisms (van den Bosch van den Berg, A., Dadvand, P., Feng, X., Morand, S., Remans, R., Tyrväinen, L., de Vries, S., M. Framing the Interrelations between Forests and Human Health. in Forests and Trees for Human Health: Pathways, Impacts, Challenges and Response Options. A Global Assessment Report (ed. Konijnendijk C D., Mansourian, S., Wildburger, C., D.) vol. 41 232 (IUFRO, Vienna, Austria, 2023; van den Bosch Cave et al., 2016). Several conceptual models for these mechanisms have been developed (Hartig et al., 2014; van den Bosch and Nieuwenhuijsen, 2017; van den Bosch and Ode Sang, 2017; Marselle et al., 2021) with the Ecosystem Services (ES) model from the Millennium Ecosystem Assessment (MA) being among the most recognised (MA. Millennium Ecosystem Assessment: Ecosystems and Human Well-Being. (Island Press, Washington DC, 2005). The ES model presents the supporting (e.g., nutrient cycling), provisioning (e.g., food), regulating (e.g., climate regulation), and cultural (e.g., recreation) services provided from biodiverse ecosystems as basic elements for various constituents of human health and wellbeing.

Within the health sciences, health co-benefits have typically been attributed to mediating variables. These mediators, i.e., the links between forest exposure and eventual health impact, can be defined as exposure pathways. Such pathways have been conceptualised and tested in empirical studies, including those related to healthy behaviours (Wang et al., 2022), such as recreation, physical activity (Cardinali et al., 2024), stress relief (Stoltz, 2016), attention restoration (Ohly, 2016), and social interactions in urban forests or forests outside urban population centres. These exposure pathways can, to some extent, be conceptualised as cultural ES (van den Bosch van den Berg, A., Dadvand, P., Feng, X., Morand, S., Remans, R., Tyrväinen, L., de Vries, S., M. Framing the Interrelations between Forests and Human Health. in Forests and Trees for Human Health: Pathways, Impacts, Challenges and Response Options. A Global Assessment Report (ed. Konijnendijk C D., Mansourian, S., Wildburger, C., D.) vol. 41 232 (IUFRO, Vienna, Austria, 2023). Several studies have also analysed health impacts from exposure pathways related to regulating ES, such as reduction of heat (Iungman, 2023), noise (Klingberg et al., 2017), or air pollution (Diener and Mudu, 2021). Systematic reviews have concluded that these services and exposure pathways result in direct health impacts (van den Bosch and Ode Sang, 2017; Cheng et al., 2021), such as improved mental health (Watts and Jump, 2022) and reduced prevalence of cardiovascular illness (Donovan et al., 2015), respiratory diseases, diabetes, depression (van den Bosch and Meyer-Lindenberg, 2019; Yeon, 2023), cancer, dementia (Moyle et al., 2018), and mortality (Wolf, 2020; Dadvand de Vries et al., 2022). Some studies also indicate that exposure to biodiversity in forests has a positive impact on the human gut microbiome, resulting in improved immunoregulation (Rook, 2012; Rook, 2013). This has been postulated as one of the explanations for the lower prevalence of allergies and asthma among children growing up in forested environments compared to children in cities (Pakarinen, 2008; Kondrashova et al., 2013).

Much research on health benefits is conducted in urban forests, but there is also evidence related to the positive impacts of *peri*-urban forests and forests outside cities, particularly for those living nearby or having easy access through adequate transport options (Dadvand de Vries et al., 2022). These benefits include, for example, recreation and nature experiences (Lackey, 2021), including so-called forest bathing ("shinrin yoku") (Kotera et al., 2022) with assumed direct health benefits from forest air(Watts and Jump, 2022). In addition, dietary aspects, such as access to nutritious forest-sourced foods, such as edible leaves, seeds, wild fish, berries, or mushrooms, may prevent malnutrition. Some studies suggest that forest foods are key for food security because of their richness in micronutrients and diversity (Vira Wildburger et al., 2015; Rowland et al., 2017; Baudron, 2019).

The health co-benefits of climate change mitigation related to air quality, low carbon diets, and healthy, sustainable transport are well documented (Haines, 2009; Hamilton, 2021; Chang, 2017) and a recent Lancet review assessed a number of health benefits related to climate change mitigation actions (Whitmee, 2023), but the *extent* to which human health co-benefits have been assessed within research on forest-based mitigation strategies is unclear. Thus, we know that much research has been conducted on forest-based climate change mitigation, but we don't know if, how, or where human health co-benefits have been simultaneously analysed. To our knowledge, no previous review has synthesised research efforts on this interdisciplinary topic and while, as described above, a number of exposure pathways and health co-benefits have been ascribed to forest exposure, the literature has not been systematically assessed within the context of climate change mitigation activities. A scoping review is needed to identify relevant frameworks and disciplines, exposure pathways and health outcomes to evaluate whether and how human co-benefits of forest-based climate mitigation activities have been assessed to date. Additionally, the most appropriate methods and research questions to further investigate this emerging topic have not been established and should therefore be addressed.

1.2. Objectives

Our aim was to conduct a scoping review to systematically map recent research on this topic in Europe, identify the nexuses between forest-based climate change mitigation activities and exposure pathways or health co-benefits, and suggest methods for future research. We chose to focus on Europe in this first step to test our approach of quantifying the *proportion* of studies that assess human co-benefits within the context of forest-based climate change mitigation and also to make the results potentially more applicable for European policy-making. Given the broad and interdisciplinary topic, we decided to use a scoping review methodology rather than a systematic review to be able to provide a comprehensive overview of the field, which includes numerous disciplines, study designs, and methods. The aim was to contribute to a broad understanding of the interdisciplinary connections between forests, carbon sinks, and human health co-benefits rather than assessing effect sizes and quality of evidence, which would have been more typical for a systematic review. This research area is emerging and therefore a scoping review is more appropriate in that it aims to identify where and how future research efforts should be focused.

Our specific objectives were to:

1. Identify to what extent exposure pathways or health co-benefits of contemporary forest-based carbon sink management strategies or related factors (e.g. different forest types, tree species, and forest-related land use/cover change) have been scientifically assessed within the contemporary research agenda on forest-based climate change mitigation.
2. Assess whether the existing literature identifies win–win strategies that maximise forest carbon sink capacity alongside human co-benefits (contextualised or defined in the literature as either exposure pathway, human health outcome, or both).
3. Propose future research approaches to investigate the nature and scale of potential human co-benefits of forests-based climate change mitigation activities.

Based on previous literature and a recently published global assessment report on forests and human health (Konijnendijk Devokta, D., Mansourian, S., Wildburger, C. (eds.), C. Forests and Trees for Human Health: Pathways, Impacts, Challenges and Response Options. A Global Assessment Report. . vol. 41, 2023), we adapted existing frameworks to develop a conceptual model of the exposure pathways linking forest-based climate change mitigation and positive human health outcomes (Fig. 1). This model is meant as a very basic framework on which to possibly build future interdisciplinary studies. Various refinements would be required in such studies, such as consideration of different dimensions of health that may influence the perception of ecosystem services. Equally, forestry related factors like thinning intensity has a dynamic, non-linear relation to carbon sink potential and the impact depends also on, for instance, the frequency of thinning and the subsequent use of wood. Nevertheless, it is one factor that may be considered in further attempts to assess linkages between forest-based climate change mitigation activities, exposure pathways, and human health.

Based on our conceptual model, we formulated the following research questions:

- Are human co-benefits included in research analysing forest-based carbon sink potential from different mitigation activities? (Objective 1)
- If so, what exposure pathways and health outcomes have been included and how have they been analysed? (Objective 1)
- Can synergies between carbon sink capacity and human co-benefits be quantified? (Objective 2)
- What interdisciplinary research methods and study designs are most promising to advance understanding of the synergies and trade-offs related to human co-benefits of forest-based climate change mitigation? (Objective 3)

2. Methods

2.1. Protocol

We developed a review protocol in accordance with the Joanna Briggs Institute (JBI) methodology for scoping reviews (Peters, 2022) and used the Preferred Reporting Items for Systematic reviews and Meta-Analyses extension for Scoping Reviews (PRISMA-ScR) checklist to develop our search and the charting of results (Tricco, 2018). Because this scoping review wanted to address outcomes related to any exposure pathway or related health co-benefit across various populations, *Participants* were considered as the entire European population without any predefined characteristics or criteria. The *Concept* ("intervention") examined was any type of forest-based climate change mitigation activity or factor affecting carbon sink potential. The review *Context* refers to the aim of identifying human co-benefits of forest management strategies and forest characteristics (e.g., tree species, biodiversity) that affect carbon sink potential. For the purpose of this study, we defined human health in its broadest possible sense referring to social, mental, physical, and spiritual wellbeing and also included exposure pathways to health.

We adapted the methods for study inclusion to be able to provide assessments of the *proportion* of studies on forest-based carbon sink strategies that acknowledge human co-benefits and the *proportion* of those that quantified these co-benefits. Since one of our objectives was to identify to what extent human co-benefits are considered in forest-based climate change mitigation research at all, we developed a hierarchical inclusion criteria system:

- Category 1: All papers that met primary eligibility criteria (see below). From this category, we made general conclusions about strategies and factors of importance for carbon sink potential.
- Category 2: Proportion of papers in Category 1 that acknowledged human co-benefits. From this category, we made conclusions about to what extent this literature can be placed within a human health research context.

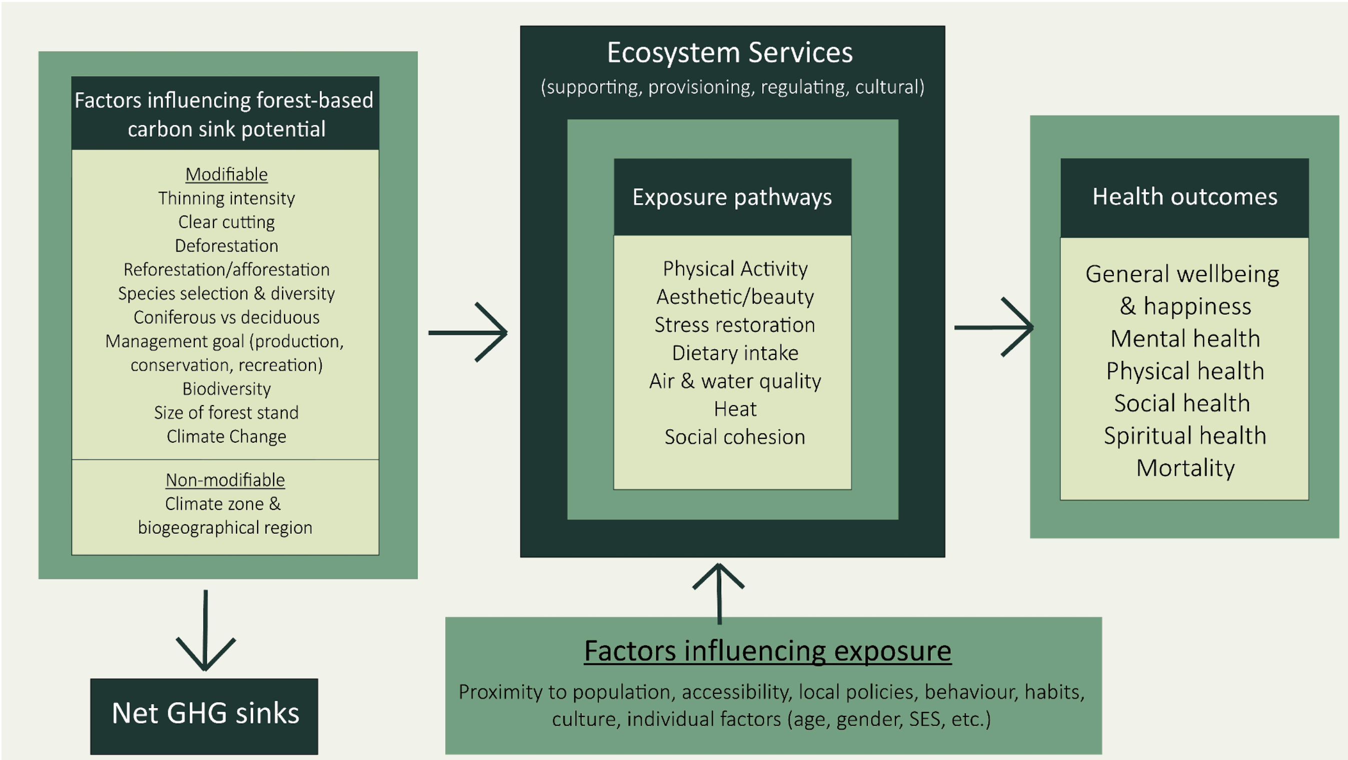

Fig. 1. Conceptual framework of how forest-based climate change mitigation through carbon sink potential can result in positive health outcomes through a number of exposure pathways related to ES. The various factors (strategies, activities, and characteristics such as the size of the forest stand and the above-ground biomass) that influence carbon sink potential determine the relative impact on exposure pathways and attributable health co-benefits (e.g. general wellbeing, happiness, mental health, and physical health – all related to each other). In addition, a number of spatial and sociodemographic factors predict the level of impact.

- Category 3: Proportion of papers in Category 2 that quantified human co-benefits. For this category, full data extraction took place.

We used the three categories to (1) obtain an understanding about recent forest-based climate change mitigation strategies and how it has been assessed in the literature (Category 1); (2) identify whether human co-benefits have been considered within this research context at all (category 2); and (3) to assess methods and whether synergies between carbon sink capacity and human co-benefits can be understood and calculated (Category 3).

2.2. Eligibility criteria

The eligibility criteria for the respective categories are presented in Table 1

Exclusion criteria:

- Studies reporting on forest management strategies without any mitigation goals
- Studies reporting on carbon payment strategies or other economic incentivising tools
- Studies conducted outside Europe
- Published before 2013 or reporting results based on data collected before 2013.
- Studies merely reporting on methods for measuring carbon sink capacity
- Woody vegetation types other than forests (e.g., hedges)
- Studies that evaluate the impact of climate change on carbon sink capacity, but not vice versa

Table 1
Eligibility criteria for inclusion in the review for category one, two, and three respectively.

Eligibility criteria	Category 1	Category 2	Category 3
Addressing forest-based climate change mitigation through carbon sink potential, reporting on strategies and/or factors that influence carbon-sink capacity	√	√	√
Publications on forests (including urban)	√	√	√
Studies conducted in Europe (UN-definition)	√	√	√
Quantitative observational, quasi-experimental, or experimental studies. Modelling and scenario-based studies as well as systematic reviews and *meta*-analyses	√	√	√
Published (or pre-print) in English	√	√	√
Published (or pre-print) in peer reviewed scientific articles, textbooks, chapters, policy documents, or other grey literature	√	√	√
Acknowledging exposure pathway or health co-benefits	–	√	√
Measuring or systematically assessing exposure pathways or health co-benefits	–	–	√

2.3. Information sources and search strategy

The search strategy aimed to locate both published and unpublished studies conducted in Europe. An initial limited search of Scopus was undertaken to identify articles on the topic to develop a preliminary search strategy. Relevant terms contained in the titles and abstracts of identified articles and the index terms used to describe the articles were then used to develop a full search strategy for two electronic databases, Scopus and Web of Science, which were searched through the 7th of March 2023. The search strategy was supported by a librarian, and search syntax was broadly aligned with that of Verkerk et al. (2022) (Verkerk Delacote et al., 2022). The keywords included, for example, forest, wood, carbon, CO_2, sink, substitution, stock, change, and sequestration and were combined with Boolean operators in relevant search sets. We did not include keywords related to health or exposure pathways because one of the aims was to identify the proportion of studies on European forest-based carbon sinks that also acknowledged health; thus, we initially needed to estimate the total number of studies conducted on the topic. For a full description of the syntax and screening process, see supplementary material.

2.4. Selection of sources of evidence

Initially, one member of the research team screened the title or abstract of the total number of records for inclusion in Category 1. Two independent reviewers then screened the remaining records for eligibility to be included in Category 2 and 3. To make the process as streamlined and synchronised as possible, we independently pilot screened 10 studies, carefully evaluated the respective screening approaches, and had iterative discussion to obtain an as homogenous method as possible for inclusion in Categories 2 and 3. In case of disagreement, all authors discussed and we used a consensus-based approach to identify the final articles to be eligible for full data extraction (i.e. Category 3).

2.5. Data items and charting

For Category 1, we identified publications on any European forest-based climate change mitigation strategy or factor that corresponded to the eligibility criteria. From the retrieved records, we reviewed whether human co-benefits were acknowledged to identify articles eligible for Category 2. We then screened these articles and collected data on potential factors influencing impact on both carbon sink potential and human co-benefits, such as age of forest, tree size, species diversity, and distance to population. If the articles reported quantification of human co-benefits, they were included for full data extraction (Category 3). We conducted a pilot data extraction based on a priori identified data items to chart. Three reviewers blindly extracted items from eight papers, compared and discussed results, and refined the data extraction process. The following information was finally charted: authors' scientific affiliation, study type and aim, design and methods, time period for data collection, region of study, geographical/climatic context, forest-related strategy details (e.g. management, species, Land Use Land Cover (LULC) change, size, distance to population), comparison with other environments, carbon sink capacity, exposure pathway/health co-benefit, other co-benefits or ES, whether impact of climate change on the forest was considered, and conclusion/summary of results. When specific data were lacking, such as year of data collection, corresponding authors were contacted. Category 3 studies were reviewed by at least two authors and data were extracted by the authors independently.

2.6. Synthesis of results

We summarised and tabulated charted data and synthesised the findings to illustrate trends, geographical scope, and interdisciplinary patterns. Exposure pathways and health outcomes were categorised and described within the context of forest-based climate change mitigation. Finally, an attempt was made to identify win–win strategies by comparing different forest-based mitigation activities and their relative impact on carbon sink and human co-benefits respectively.

3. Results

After removing duplicates, a total of 862 search results were screened based on their titles and abstracts. Seven studies were excluded because we were unable to access the article, despite efforts to contact authors. Hence, 855 records were retrieved and after assessing them against eligibility criteria for the three different categories respectively, a total of 349 articles were included for Category 1. Of those, 97 (28 %) acknowledged exposure pathways or health co-benefits (Category 2), and 13 (4 %) quantified them and were hence included for full review (Category 3). A flow diagram of the process is presented in Fig. 2.

Category 3 papers, included for full review (n = 13), were all published articles in peer-reviewed, scientific journals. A summary of the information extracted from the included papers is presented in Table 2. Papers were mainly primary research, with one evidence synthesis (Pérez-Silos et al., 2021). Many studies used scenario modelling, relying on available data and various forecasting methods or trend analyses (Başkent and Kašpar, 2022; Berglihn and Gómez-Baggethun, 2021; Pukkala, 2018; Schaubroeck, 2016), sometimes in combination with case studies (Pukkala, 2022; Pukkala, 2016; Thrippleton, 2023; Thrippleton, 2021). One study applied the i-Tree software to calculate potential health co-benefits from increasing urban tree coverage, estimating reduction in air pollutant related adverse health effects as a quantitative indicator (Oliveira, 2022). Three studies applied experimental designs to assess the impact of different management regimes (Moghli et al., 2022; Paletto, 2021; Paletto et al., 2017).

The number of studies that acknowledged exposure pathways or health co-benefits within the context of forest-based climate change mitigation increased over the last decade (Fig. 3), although this was merely a consequence of an increased number of publications in total (values actually ranging from 67 % of the papers in 2013 to 40 % in 2022). Neither could we identify any upwards trend in the number of studies that quantify human co-benefits. Thus, in spite of novel concepts such as NbS, the exploration of exposure pathways and health co-benefits within forest-based climate change mitigation research is still in at an early stage.

3.1. Journals, scientific fields, and keywords as indicators of interdisciplinarity

The included articles were published in eight unique journals, five of which mentioned human health in their Aims and Scope section (Ecosystem Services (Berglihn and Gómez-Baggethun, 2021), Science of the Total Environment (Moghli et al., 2022), Land (Oliveira, 2022), Landscape Ecology (Pérez-Silos et al., 2021), and Frontiers in Forests and Global Change (Thrippleton, 2021). The remaining three journals lacked this interdisciplinary aspect in their Journal information.

The author affiliations demonstrated a disciplinary breadth, although notably, no direct health discipline was represented (Fig. 4), and there was a strong dominance of environmental- and forest-related disciplines. Social sciences were represented through an affiliation with an economy institute in two papers (Paletto, 2021; Paletto et al., 2017). Life sciences were represented in four papers (Berglihn and Gómez-Baggethun, 2021; Schaubroeck, 2016; Thrippleton, 2023; Moghli et al., 2022) but referred to ecology and biology and not health.

We identified an interdisciplinary pattern by analysing the keywords of the included articles (Fig. 5). Carbon sequestration took a central position, but the most prominent term was "ecosystem services" (ES). This would support a potential framework for interdisciplinary research as outlined in our initial model (Fig. 1), where exposure pathways to health co-benefits can be, at least partly, understood in the context of ES.

From the general keyword analysis, we can conclude that there is a dominance of forestry or environmentally related themes, for example, continuous cover forestry, forest management, and soil organic carbon. Climate change is also well represented in the terminology. Many keywords refer to various designs and methods, such as cost-benefit

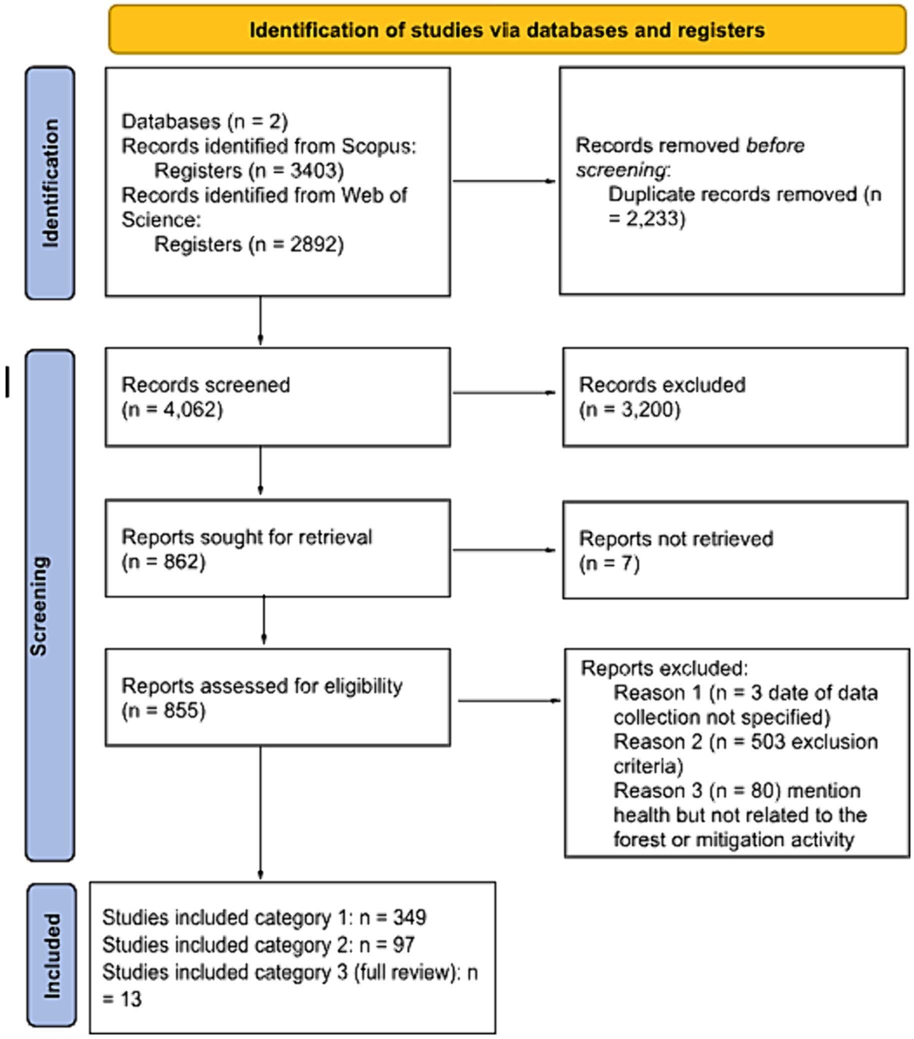

Fig. 2. Flow chart of article screening and selection process. After the initial title and article scanning we sought to retrieve 862 reports, but seven were not possible to obtain despite efforts to contact authors, hence in total 855 reports were assessed for eligibility.

analysis, stakeholder analysis, InVEST, i-Tree tool, trade-off analysis, multiple-criteria decision analysis, responsibility analysis, environmental impact assessment, data envelopment analysis, economic analysis, forest modelling, life cycle assessment, and simulation. The keywords also indicate the relative lack of emphasis on health or methods from the health sciences, with few terms referring to health-relevant exposures, health outcomes, or methods related to environmental exposure science, epidemiology, or health impact assessment.

Altogether, the analysis of these interdisciplinarity indicators, suggests that further integration between the fields is needed.

3.2. Results of individual sources of evidence

Key results from the data extraction are presented in Table 2. During the review process, additional data were extracted for contextual information (for details, see Table S2, supplementary material).

3.3. Exposure pathways or health co-benefits

Most of the quantified benefits related to exposure pathways rather than direct health co-benefits. Using an ES framework, these pathways could be predominantly categorised as cultural services, including recreation, spending time in nature, and aesthetic experiences(Pérez-Silos et al., 2021; Başkent and Kašpar, 2022; Berglihn and Gómez-Baggethun, 2021; Pukkala, 2022; Pukkala, 2016; Thrippleton, 2023; Thrippleton, 2021; Paletto, 2021; Paletto et al., 2017), typically measured by bespoke surveys or questionnaires (see Table S3).

Specific activities, such as honey production (Moghli et al., 2022), collection of edible plants, fishing, and hunting (Pukkala, 2018; Pukkala, 2022) were also analysed, using proxy measures (e.g. number of fish permits sold). These outcomes can be categorised as either provisioning or cultural (via recreation) ES.

Finally, two studies evaluated regulating ES in the context of modelled air pollution reduction (Oliveira, 2022; Schaubroeck, 2016) and these studies also provided estimates of direct health co-benefits. Oliveira et al. (2022) (Oliveira, 2022) used the i-Tree Canopy scenario software (i-Tree. i-Tree Canopy - References. 2006; Paletto et al., 2017) in combination with a life cycle assessment (LCA) (Pennington et al., 2004) to assess the impact of increased urban tree coverage on carbon storage and reduced air pollution-related illness They reported that a 50 % increase in urban tree coverage in Naples, Italy, would result in an increased lifetime carbon storage capacity of almost 4,300 kT/yr. Using the Air Pollution Estimates of the i-Tree tool (Nowak et al., 2008; Nowak et al., 2006), they also estimated that the reduced incidence of pollution-related illness would correspond to a monetary value of almost 4,100,000 USD. Schaubroeck et al. (2016) (Schaubroeck, 2016) assessed the impact of different thinning regimes in a Belgian forest situated in the vicinity of a residential area using monetary ecosystem service

Table 2
Summary characteristics of included articles. *Acronyms explained at the bottom of the table.

Author (Year)	Design and methodology	Study aim	Country (and area if indicated)	Urban/rural/ geographical/ climate context/ type/distance to population/size	"Intervention". Forest related factors, e.g. management strategy, LULC change, species	Carbon sink capacity – absolute or relative	Exposure pathway or health outcome	Outcome metric (see Table S3 for details) and result	Other co-benefits or ES	Conclusion/ summary of results
1. Baskent & Kaspar (2022)	Scenario modelling with forecasting tool	To explore the impact of various management strategies on long-term provisioning of select ES	Turkey, South-eastern Plateau	Remote rural plateau (elevation range 880 – 3060 m). Mediterranean drought climate. Temperate forest type: Mainly black and red pine. 19,000 ha	Compares four modelled scenarios of varying intensity: BASE (Current management), LMI, MMI, HMI	Cumulative storage ($MtCO_2eq/yr$): BASE: 1.60LMI: 2.45MMI: 3.03HMI 2.82	Aesthetic value for recreation	RAFL index.**Results:** BASE: 0.51LMI: 0.49MMI: 0.47HMI 0.42(Range 0 – 1)	Timber production, habitat for biodiversity, soil loss prevention, water provision	The impact on ES supply varied between scenarios. MMI provided most carbon sink potential; BASE provided relatively higher value for recreation. However, differences were small.
2. Berglihn & Gomez-Baggethun (2021)	Mixed method. Quantitative data for trend analyses + qualitative data for interpretation.	To assess multiple ES from a *peri*-urban forest and the drivers of ES change and trends	Norway, Oslo (Oslomarka)	Peri-urban (5–40 km from Oslo city centre), mainly managed for recreational purposes. Surrounded by area comprising > 1.2 million people. Area: 1,700 km^2.	Current state and trend analyses based on historical data (1970 – 2020) to assess impact of the "great acceleration" – rapid global change.	Current state (2016): 1.75 $MtCO_2eq/yr$ stored.Trend: increased carbon sink over the period due to 75 – 93 % increase in forest volume	Cultural services:1. Spending time in nature2. Fishing3. Hunting4. Collection of edible plants	Proxy variables:1. Share of population visiting the area/year2. Number of fish permits sold3. Number of felled moose and roe dear,4. Share of users picking wild berries and mushrooms per year**Results**: Rising trend of visits, fishing, and hunting. No trend in plant collection	Food, water provision, timber, habitat provision. Other cultural services, e.g. education and sense of place	Increasing trend of cultural services and carbon sink. Legal regulations and evolving policy frameworks are major drivers of ES change.
3. Moghli et al. (2022)	Experimental. Full-factorial design.Field sampling and lab analysis	To assess long term (10y) effects of two different thinning regimes and plantation on multiple ES	South-eastern Spain	Remote mountain ranges. Mediterranean climate, sub-humid. Overstocked pine stands (75,000 – 220,000 trees/ha)	Three management strategies/ treatment:1. Low thinning2. High thinning3. Plantation of *Quercus faginea*.4. Control (unmanaged, with original tree density)	Relative (unitless): No difference in carbon sequestration between treatments.	Food production	Honey production potential. **Results**90 % increased potential following low thinning regime and with plantation of *Quercus faginea*.	Biodiversity, habitat complexity, forage, disturbance regulation, fire vulnerability, supporting services	Combination of thinning (low) and plantation maximise food production (and disturbance regulation). However, no impact on carbon sequestration.
4. Oliveira et al. (2022)	Modelling study. i-Tree software and LCA	To assess impact of tree increase on environmental, social, and economic benefits	Italy, metropolitan city of Naples	Urban forest. 1,200 km^2. 3,000,000 inhabitants	LULC change, i.e., potential increase of tree coverage (percentage) in select area. The model estimated a potential of approximately 50 % more urban forest cover	Carbon sequestration = 169.69 kt CO_2eq/ yrCarbon storage (lifetime) = 4261.57 $ktCO_2eq$/ yrMonetary value = almost 32 million USD per year.LCA-	Air pollutant related adverse health effects	Removal potential (t/yr) of air pollutants (CO, NO_2, O_3, SO_2, PM_{10}, $PM_{2.5}$) **Results:** 5,209 t/yr = 51 % increased removal compared to current state. Corresponds to a monetary value of 4,098,118 USD, which is calculated based on adverse health effects	Hydrological benefits	Negative impacts of tree production and planting (e.g. energy consumption) would be compensated after approximately 200 days, using ReCiPe midpoint

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Table 2 (*continued*)

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					(planting 2.34 million trees).	analysis:carbon sink = 1.7 x 100 million kg CO_2 eq (compared to present 1.12 x 100 million kg CO_2 eq		related to changes in pollutants concentration.		impact assessments of 2.34 million trees planted. ReCiPe midpoint impacts avoided are: Global warming, ozone formation/ human health, $PM_{2.5}$ formation, NOx formation, acidification, water consumption.The results suggest opportunities to improve people's QoL, reduce environmental damage, and bring economic development.
5. Paletto et al. (2017)	Experimental study. Random allocation of selective and traditional thinning in three forest parcels.	To analyse the difference in economic value related to different ES depending on management practices	Italy, Tuscany (central Italy)	Peri-urban, close to Florence. Mainly black pine forest with high level of multifunctionality. Reforestation area. 2,700 trees/ha. Total surface 1,035 ha	Two experimental management regimes:1. Selective thinning = 30–40 % of basal area (proposed treatment for improving tourist attractiveness and climate mitigation.)2. Traditional thinning = 15–20 % of basal area. (The common treatment in the area, BU.)3. Control (status quo)	1. Selective thinning: 3,980 tCO_2 eq/ha/yr2. Traditional thinning: 3,184 tCO_2eq/ha/yr3. Status quo: 2,939 t CO_2eq/ha/yr	Recreation	Questionnaire of recreational value**Results:** Preference for selective thinning. Unmanaged forest was negatively evaluated. Total social surplus in terms ofrecreational benefitsequal to− 179.2 €/ha/yr (status quo),− 193.2 €/ha/yr (traditional thinning)− 231.9 €/ha/yr (selectivethinning).	Wood production	The selective thinning management has the greatest positive effect on both carbon sequestration and recreation. Recreation was the most important for economic value in both management strategies.
6. Paletto et al. (2021)	Same design as Paletto et al. 2017, but adds a MCDA to identify optimal forest restoration scenario for	To analyse the impact of two different forest restoration practiceson three ESs (wood production, climate change mitigation, and recreation)	Italy, Tuscany (central Italy)	Same as above	Same as above	The C-sequestration increases comparedwith the BU scenario: Selective thinning: equal to 7.5 tCO_2/ha/yr + 36.9 tCO_2/ha/yr	Recreation	Same as above	Wood production	Selective thinning best for recreational opportunities and also, on a relative scale, for carbon sequestration.

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Author (Year)	Design and methodology	Study aim	Country (and area if indicated)	Urban/rural/ geographical/ climate context/ type/distance to population/size	"Intervention". Forest related factors, e.g. management strategy, LULC change, species	Carbon sink capacity – absolute or relative	Exposure pathway or health outcome	Outcome metric (see Table S3 for details) and result	Other co-benefits or ES	Conclusion/ summary of results
	increased ES supply.					in soilTraditional thinning:20.1 tCO2/ha/yr + 33.3 tCO_2/ha/yr				
7. Pukkala (2022)	Modelling (tool development) and case study	To develop an index (externality score) for different forest types to assess "externalities", i.e., nontimber products (incl. carbon sequestration and recreation) and to test it in two case studies.	Finland	2 case studies:1. Northern boreal zone. Mostly pine. 440 ha2. Southern boreal zone. Scots pine, Norway spruce, and silver birch. 426 ha.	Four different management plans:- RFM with thinning from below and without green-tree retention (clear cutting)- RFM retention with thinning from below and green-tree retention in clear-felling- CCF without green-tree retention- CCF retention with green-tree retention	Model-based relative differences:1. RFM: low capacity2. RFM retention: medium–low capacity3. CCF: medium–high4. CCF retention: high	o Scenic beauty/ recreationo Lingonberry yieldo Bilberry yieldo Mushroom yield	Scenic beauty/recreation indexYield estimates from previously developed models**Results:** Lingonberry yield increase with clear cuttingOtherwise, results are not presented per separate index, but put together in the score (see summary of results)	No	CCF predicted higher externality scores, i.e., better for both carbon sink and recreation (and biodiversity and albedo). Green-tree retention improved the values even a bit more.Sparse tree stand composed of tall trees, preferably birches and pines, gave the highest scoreClear cutting maximised economic profitability but decreased recreational co-benefits with 50 %
8. Pukkala (2018)	Prediction models	To analyse consequences of favouring broadleaved species in management on e. g. carbon sequestration and recreational values	Finland, southern part	2 sites:1 = 210 ha, 49 % spruce2 = 502 ha, 30 % spruce	Compares 3 different modelled forest management strategies: (1) conifer-oriented management; (2) mixed-stand-oriented management; and, (3) broadleaf-oriented management.	Conifer oriented led to highest carbon seq. in the longer term, mixed stand medium, broadleaf lowest (though very small differences)	Scenic beauty/ recreation.	Scenic beauty index and yield models**Results:**Not presented quantitatively. Scenic beauty/recreation index best for broad-leaf-oriented management and worst for conifer-oriented (substantial differences)	Biodiversity, resistance, resilience (to disturbances and pests)	Conifer-oriented management led to highest carbon sequestration. Scenic beauty/ recreation index best for broad-leaf-oriented management and worst for conifer-oriented.
9. Pukkala (2016)	Modelling. DEA model	To compare different management strategies in terms of various ES, including overall efficiency analysis	Finland, three case studies in South, Central, and Northern Finland	Size ranged from 200 ha to 450 ha.The southernmost forest had almost equal volumes ofScots pine, Norway spruce and broadleaved specieswhile spruce	Compares 3 management strategies:even-aged rotation RFM, e.g. clear cutting,CCF) and AAF. (mixture of CCF and RFM also	RFM highest carbon sink capacity, CCF moderate, and AAF lowest (but very small differences)	Scenic beauty/ recreation	Scenic beauty index**Results**RFM lowest, AAF moderate, CCF highest	Wood production, suitabilityof the forest to Siberian jay.	CCF provided most ES in general. Multi-objective management provided more ES than single-objective

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Author (Year)	Design and methodology	Study aim	Country (and area if indicated)	Urban/rural/ geographical/ climate context/ type/distance to population/size	"Intervention". Forest related factors, e.g. management strategy, LULC change, species	Carbon sink capacity – absolute or relative	Exposure pathway or health outcome	Outcome metric (see Table S3 for details) and result	Other co-benefits or ES	Conclusion/ summary of results
				was dominating in Central Finland andpine in the north.	called free-style management)					management that only maximised economic profitability.
10. Schaubroeck et al. (2016)	Case study. Environmental Impact Assessment and Modelling. Monetisation approach	To assess ES provision from forests following different climate change and management scenarios as well as an assessment of forest ecosystem as such.	Belgium, "De Inslag" Forest in Brasschaat	Close to residential area. Forest and nature reserve. Scots pine.	Tests different thinning regimes (all based on management after initial clear-cut): LOW = no thinning,MID = 50 %HIGH = 100 %(and under different climate change scenarios)	Values ofCO_2 sequestration = 168 − 371€/ha/ yr with different values for different climate change scenarios. LOW performs best, then MID, and least well HIGH (although the forest ecosystem as such is altogether positive)	Avoided air pollution related damage to human health (healthy life years lost.)	Prevention of DALY. Air pollution removal by foliage uptake is modelled. Estimated DALY: 2.6E-04/kg PM**Results**Monetary value based on avoided damage cost. $PM_{2.5}$ removal: 622-1172€/ha/ yr with different values for different climate change scenariosPrevention of DALY in all scenarios (highest prevention in the LOW scenario), varying from avoiding0.014–0.029 DALY/ha/yr, equal to avoiding 5.0 – 10.6 DALYs/ha/yr depending on climate change scenario	Water purification, wood production, NOx emissions, NH_3 uptake and nitrogen removal.	Substantial values related to both CO_2 sequestration and prevention of DALYs.All services included, the LOW scenario is estimated to have a 1.25–1.30 times higher total monetary value and the HIGH scenario a 1.71–1.92 times lower value of ES. I.e. LOW would be the optimal management choice.Clear positive effect on human health through reduced damaged wasestimated in all cases.Over a complete management cycle, this represents a prevention of 1.1–2.3DALY/ha, depending on thinning intensity and climate change scenario (most prevention from the LOW scenario).
11. Thrippleton et al. (2023)	Case study. Modelling and MCDA	To evaluate effect of different harvest intensities on disturbance risk and assess trade-offs with BES, under a set of climate change scenarios.	Switzerland, Davos	Close to urban area. High-elevation/ mountain forest. Alpine climate. Spruce dominated but also European larch, Swiss stone, and some	Three management strategies:1. Current (MED). Harvest interval of 30 years and harvest intensity of 35 % basal	Relative measures.INC – reduced carbon sink	Recreation	Indicator based on stand attributes linked to recreation[75]**Results**INC – increased recreation	Timber, biodiversity, disturbance protection	The INC strategy improved the recreation value, but resulted in trade-off with carbon sequestration. The highest

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Table 2 (*continued*)

Author (Year)	Design and methodology	Study aim	Country (and area if indicated)	Urban/rural/ geographical/ climate context/ type/distance to population/size	"Intervention". Forest related factors, e.g. management strategy, LULC change, species	Carbon sink capacity – absolute or relative	Exposure pathway or health outcome	Outcome metric (see Table S3 for details) and result	Other co-benefits or ES	Conclusion/ summary of results
				broadleaves. Average standing volume = 225 m^3/ ha. Average DBH = 25 cm.	removal2. Decreased (DEC) 0.25 % basal removal. Same harvest interval3. Increased (INC) 0.45 % basal removal. Same harvest interval					overall utility occurred for the INC strategy followed by MED and DEC
12. Thrippleton et al. (2021)	Case studies. Tool development and MCDA	(1) identify and quantify synergiesand trade-offs between BES for different management strategies;(2) identify the management strategy that bestprovides multiple BES; (3) analyse shifts in BES provisioningunder climate change; and (4) analyse four alternative BESdemand preferences	Switzerland, Northern part	Case study 1: Lowland plateau, mainly for timber production.Case study 2: Lowland plateau, mainly for recreation, close to urban areaCase study 3: High elevation, focus on biodiversity and protection against hazards	Four management strategies were compared:1. No management (baseline)2. Business as usual (MED)3. High intensity (aiming for increased timber use) (HIGH)4. Low intensity (more biodiversity focused) (LOW	Relative measures from models to compare with other services, see conclusionLOW – increased carbon sink	Recreation	Same as above**Results**MED – increased recreation	Biodiversity, timber, disturbance protection	Increased carbon sequestration by reduced intensity. Synergies between carbon sink and biodiversity, and between biodiversity, recreation and protection, and on the other side trade-offs of timber production with carbon sequestration, biodiversityand protection function. Synergy between biodiversity and recreation varied between the CSs, which is explained by different tree species settings. Context-dependent performance of the strategies, i.e., geographic location, altitude, etc., must be considered when planning for synergies. In general, an intermediate intensity (BU)

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Author (Year)	Design and methodology	Study aim	Country (and area if indicated)	Urban/rural/geographical/climate context/type/distance to population/size	"Intervention". Forest related factors, e.g. management strategy, LULC change, species	Carbon sink capacity – absolute or relative	Exposure pathway or health outcome	Outcome metric (see Table S3 for details) and result	Other co-benefits or ES	Conclusion/summary of results
										seemed optimal for recreation. Small effects of climate change scenarios on the services

REVIEW

Author/Title/Journal/Year (to be separated for journal table formatting)	Design and methodology	Review aim	Databases	Proportion included papers	Forest-based mitigation strategy	Health indicators	Other co-benefits included	Conclusion/summary of results
13. Pérez-Silos et al. (2021)	Semi-quantitative systematic review	Assessing the general efficiency of pastlarge-scale afforestation programs in Spain on the provision ofES and other socioecologicalattributes.	Scopus and Dialnet	75/1441	Afforestation. Carbon sequestration assessed in 6 studies.	Based on ES-framework, including cultural services: Interactions with forests that promote health (assessed in 7 studies)	Water, timber, wild plants provision; erosion protection, hydrological regulation, landscape connectivity, life cycle - habitat protection, soil properties, fire protection, social structure, economic structure, biodiversity	Afforestation promoted both carbon sequestration and cultural services, but there was often a trade-off with timber provision, which was commonly the driving force to determine management strategies. Regulating ES have also been less promoted because of the production goal, which has also resulted in biodiversity loss.

* Acronyms: LMI = Low Management Intensity; MMI = Medium management intensity; HMI = High management intensity; RAFL = Recreation Aesthetic Forest Landscape; LCA = Life Cycle Assessment; LULC = Land Use Land Cover; QoL = Quality of Life; MCDA = Multi criteria decision analysis; BU = business as usual; RFM = Rotation forest management; CCF = Continuous cover forestry; AAF = any-aged forestry; DEA = Data envelopment analysis; EIA = Environmental impact assessment; DALY = disability adjusted life years; PM = particulate matter; MCDA = Multi-criteria Decision Analysis; BES = Biodiversity and ES; DBH = Diameter at breast height.

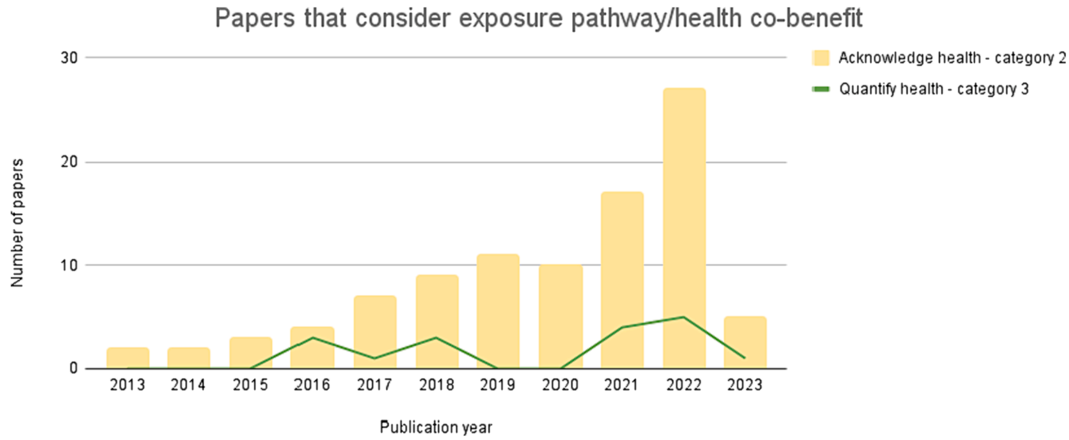

Fig. 3. Temporal trend of number of publications on forest-based carbon sinks that acknowledge and/or quantify human co-benefits over the past decade.

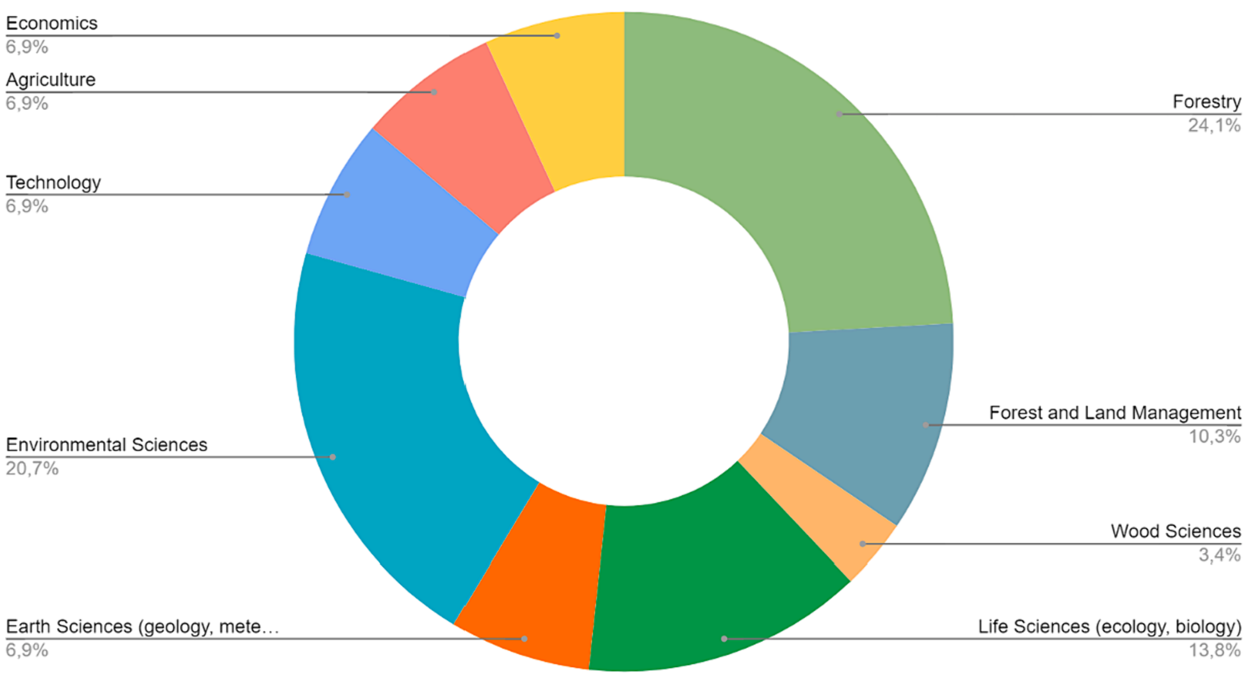

Fig. 4. Author affiliations per scientific discipline.

valuation and environmental impact assessment methods, including assessment of air pollution removal. They assumed 2.6E-04 Disability Adjusted Life Years (DALY)/kg PM, which, with an optimal thinning regime (in this case, 30 % thinning after 14 years following clear-cut and then no subsequent thinning), equalled a *prevention* of 1.1–2.3 DALY/ha over a complete management cycle. The study also concluded that the economic revenue from the forest if used for production would be 2.5 – 8.6 times lower compared to the value of the other ES (including human health and carbon sink). Similarly, Pukkala et al. (2018) concluded that the currently practised conifer-oriented Finnish forest management, with mainly production goals, results in uncertain economic gains at a high cost in biological diversity and amenity values, such as recreation and carbon sequestration.

In general, the studies concluded that continuous cover management provides more benefits, both in terms of exposure pathways and health co-benefits, compared to clear-cutting approaches, especially with short rotations. A mixed species approach and dominance of broadleaf-, compared to coniferous-oriented, management increased values of recreation and aesthetics with assumed positive impacts on human health (Tveit et al., 2006; Lundholm et al., 2020). Regarding harvest intensity, selective and relatively intense thinning regimes resulting in comparatively sparse tree stands and open forest landscapes provided the most human co-benefits (apart from honey production that was negatively impacted by high thinning regimes) compared to low thinning regimes, according to our review. However, as previously described, the impact of thinning intensity on carbon sink is not straightforward and therefore the synergies with human co-benefits must be interpreted cautiously. Reforestation and tree planting had positive impacts on exposure pathways and health overall. The review by Perez-Silos et al. (2021) (Pérez-Silos et al., 2021) suggested that afforestation programmes in Spain promoted both carbon sequestration and cultural services, but the main outcome from the afforestation activities was timber production.

By reviewing papers in Category 2, we identified a number of characteristics that could potentially be used as indicators for high potential of carbon sink capacity together with human co-benefits. Such characteristics included: age, size, and altitude of forest stand (Kim et al., 2022; Pugh et al., 2019; Gilhen-Baker et al., 2022); age, height, and diameter at breast height (DBH) of tree (Gilhen-Baker et al., 2022; Donovan et al., 2022); tree canopy, species, and diversity (Tang et al., 2022; Steenberg et al., 2023; Buotte et al., 2020); protection regime (e.g., nature reserve,

Fig. 5. Word cloud of keywords used in the included articles.

biosphere, or recreational area) (Berglihn and Gómez-Baggethun, 2021; Oliveira, 2022); and general biodiversity (Buotte et al., 2020). Many of these environmental parameters have been used in the development of scales and tools to assess the scenic beauty and recreational value of a forest, sometimes then further linked to health benefits. For example, the Recreation Aesthetics Forest Landscape (RAFL) tool developed by Tveit et al. (2006) (Tveit et al., 2006) includes parameters such as level of naturalness, openness, tree sizes, mean stand age, and share broadleaves. Pukkala et al. (2018) (Pukkala, 2018) developed a recreation index considering dominant height, age, mean diameter, pine vs spruce vs birch volume, and stems/ha. In addition, some studies indicated variables such as distance to population and greenness per capita, characteristics that would most likely have an impact on both exposure pathways and health co-benefits (Annerstedt van den Bosch et al., 2016). Greenness per capita would most typically refer to an earth observation-based metric, such as Normalised Difference Vegetation Index (NDVI), which measures healthy vegetation and not necessarily forest though.

Synergies between carbon sink capacity and exposure pathways or health co-benefits for various mitigation activities could be identified, meaning that some activities and factors act positively on both carbon sink capacity and human co-benefits, while others present trade-offs (Table 3). Continuous cover, afforestation and tree cover increase, species diversity, and mixed forest stands seemed to result in "win-win" effects on both carbon sink and exposure pathways and health co-benefits. On the other hand, there seemed to be a trade-off for coniferous vs broadleaf trees, where the former might have a stronger impact on carbon sink potential, while the latter may be more important for exposure pathway co-benefits. In a modelling study, high thinning (30 % every fifth year), resulting in an open forest landscape, was important for recreation value but negatively influenced carbon sink capacity, although again – the relative carbon sink impact of thinning is determined by various factors, including wood use after harvest. Clear cutting, which tends to be negatively associated with exposure pathways and health co-benefits, was associated with a positive impact on carbon sink potential in one study (Pukkala 2016), but the reverse in another

Table 3
Synergies and trade-offs between carbon sink capacity and human co-benefits for various forest- based mitigation strategies, activities, and characteristics. Synergies are indicated by + and trade-offs by -.

Forest related factor	Carbon sink	Exposure pathway ("provisioning")	Exposure pathway ("regulating")	Exposure pathway ("cultural")	Health co-benefits (DALYs)
Rotation/thinning					
Clear cutting	-[68], +[66]			-[68], -[72] *	
Clear-cutting with tree-retention	+[68]			+[68]	
Continuous cover (as general principle compared to rotation management)	+[68], +[69]			+[68], +[69]	
High thinning	-[67]			+[71]	
Low thinning	+[67], +7[1]	+[73]	+[67]	+/-[71]	+[67]
Other					
Afforestation	+[63]			+[63]	
Species diversity	+[68]			+[68]	
Coniferous	+[66]			-[66]	
Broad-leaf	-[66]			+[66]	
Mixed	+[66]			+[66]	
Selective, recreational management (based on policy goals aiming for recreation instead of production)	+[65] +[74,75]			+[65], +[74,75]	
Urban location					
Tree cover increase	+[72]				+[72]

* For these two studies (Pukkala, 2022; Oliveira, 2022), we categorised berry picking as a cultural service rather than a provisioning service.

(Pukkala 2022).

One study, Baskent & Kaspar (2022) (Başkent and Kašpar, 2022), tested and compared different combinations of management strategies. While the study demonstrated significant differences in carbon sink potential depending on management combination, the variation in impact on exposure pathways (aesthetic value/recreation) was negligible, with only a slightly lower index for the high management intensity option.

3.4. Regional context

For the studies in Category 2, we mapped the results across Europe and indicated where health outcomes were also quantified (i.e., Category 3) (Fig. 6). The majority of the research that has acknowledged human co-benefits has been conducted in Mediterranean forests, woodlands, and scrubs in Southern Europe (approximately 40 publications, six of which also quantified the benefits to humans). A number of studies were performed in Northern Europe (almost 30 studies, four of which quantified human benefits), with a relatively equal mix between boreal (in Finland, Sweden, Norway) and temperate forests (in Latvia, UK, and Ireland). In Western Europe (temperate zone), human co-benefits were recognised in 12 studies and three of those applied quantification. Finally, six studies from Eastern Europe (temperate zone) acknowledged co-benefits, but no quantification was applied.

There was an equal mix of studies conducted in remote rural vs in *peri*-urban and urban areas.

4. Discussion

The findings of this review show that among the 349 studies that analysed forest-based climate change mitigation strategies over the last decade in Europe, only 97 studies acknowledged the potential link to human health impacts and only 13 studies measured and quantified exposure pathways or health outcomes. The scientific disciplines represented in the literature were heavily dominated by forest and environmental sciences and lacked the involvement of health researchers. We identified "ecosystem services" as a key term in the literature, which aligns with our initial framework of considering exposure pathways to health within the context of provisioning, regulating, and cultural ES. This was also mirrored by the types of co-benefits that were measured, with the majority referring to exposure pathways, mostly cultural ES (recreational and aesthetic experiences), but also provisioning (collecting edible plants or hunting). Two studies analysed regulating ES (air pollution reduction from urban forests) and also included assessments of direct health impacts, in terms of economic savings related to lower costs for air pollution related illness and DALYs, respectively. The study

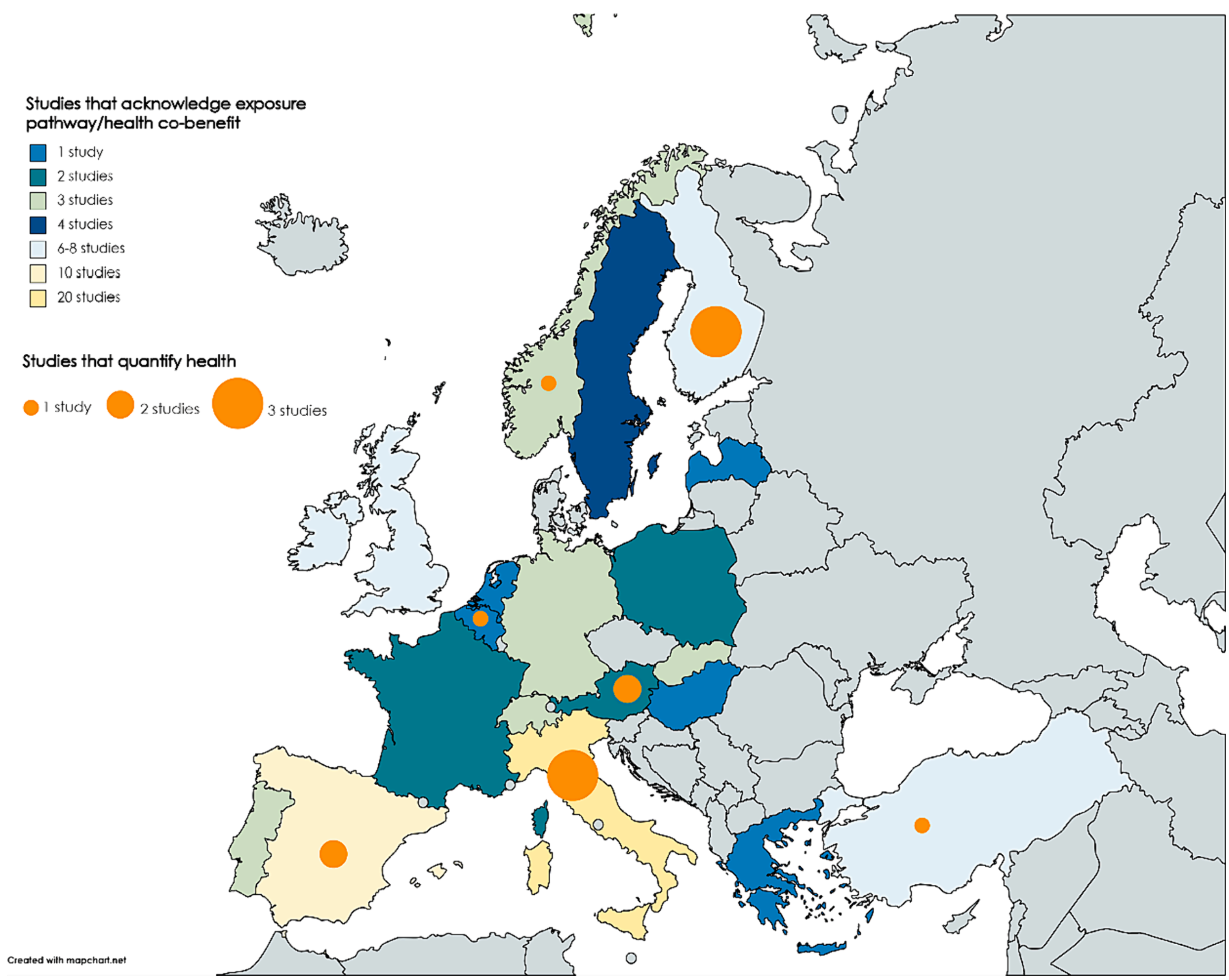

Fig. 6. Map of European countries where forest-based carbon sink strategies have been studied and where exposure pathways or human health co-benefits have been acknowledged (colour indication) and, in some cases, quantified (orange dots). None of the 16 studies that had a pan-European perspective quantified exposure pathways or health co-benefits and are not represented in the figure. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

that assessed DALYs (Schaubroeck, 2016) stood out as an example covering the full chain going from forest management strategies to health co-benefits, using an environmental impact assessment approach to assess health co-benefits from the forest's air pollution removal capacity and provided a quantitative estimate of up to 10.6 DALYs prevented per year/ha with optimal management principles. The authors were, however, exclusively from disciplines related to environment and technology and more integration of health sciences and related methodologies (e.g. health impact assessment) are needed to advance understanding and more adequately account for the role of LULUCF in delivering health co-benefits of climate change mitigation. Due to the small number of studies, it was difficult to identify synergies and trade-offs for specific mitigation activities, although the findings suggest that certain approaches and characteristics, may provide opportunities for win-win situations. These approaches included continuous cover and selective recreational management principles, afforestation, species diversity, mixed forests, and increased tree cover in cities.

4.1. A call for interdisciplinarity and research recommendations

Building on the concept of ES may be a strategic starting point for bridging forestry and health disciplines within the context of climate change mitigation and initiate a common scientific language. While research on ES has typically been conducted in environmental sciences, over the last decade, it has slowly gained attention within environmental health research (Crouse et al., 2017; van den Bosch, 2017), not the least to communicate human health's dependence on healthy ecosystems and biodiversity (van den Bosch Cave et al., 2016). There is a need for the interdisciplinary research community working at the interface of ES and health to develop metrics and methods to quantify associations between forest management strategies and characteristics (e.g., tree species, canopy area, age of forest, and biodiversity), mitigation potential, exposure pathways, and attributable health benefits using a framework, such as that in Fig. 1 with further developments. Such metrics and indicators are needed to monitor progress towards health-centred climate change mitigation and further identify synergies and trade-offs for specific activities and strategies.

A promising approach to advance understanding in this area is to combine health impact and life-cycle assessment to evaluate policy or other "what if" scenarios in an integrated way. One major challenge is the lack of spatially explicit information in most life cycle assessment tools, which makes linkage with specific populations considered in the health impact assessment difficult (Villanueva et al., 2021). Identifying which population subgroups are exposed to forests outside cities is another challenge for health impact assessment in this area. Different approaches would be needed to identify the proportion of the population likely to visit such forests and benefit from cultural ES versus provisioning and regulating ES, which occur on larger spatial scales, such as a watershed for water purification or airshed for air pollution reductions.

Schaubroeck et al. (2016) (Schaubroeck, 2016) and Oliveria et al. (2022) (Oliveira, 2022) used economic indicators to quantify the impact of forest management strategies on both carbon sink and health co-benefits. Methods for economic valuation are an important area for future development, as the potential health co-benefits of forest management are currently not adequately considered in cost-benefit calculations used to prioritise climate change mitigation strategies. A number of indicators of climate change-related costs already exist, such as the costs of heat-related mortality (Adélaïde et al., 2022), climate-related extreme events (EEA, 2023), and premature mortality due to air pollution (Nair et al., 2021). These methods could be adapted to quantifications of forest-based mitigation activities and combined with expected savings related to health care expenditures to improve the understanding of economic benefits over time as a further argument for investments in climate-smart forest management practices (Nejade et al., 2022). These methods are also needed to better assess and remedy imbalances in the full social and environmental costs and benefits of mitigation. For example, individual forest-owners often have a short-term benefit of higher economic revenues from a production forest using intensive management principles, including clear-cutting, which can be at odds with broader sustainability goals.

Another potential for interdisciplinary research includes the study of trees to filter air pollution, related with epidemiological studies. However, the existing models (i.e., i-Tree) are based on rough estimations, without including plant species, leaf morphology, canopy area, characteristics of air pollutants, or local meteorological conditions. These general estimations based on allometric models are prone to generating methodological pitfalls and a recent study, using data from a large number of monitoring stations in both Europe and the United States, concluded that the air pollution filtration potential of urban trees is marginal (Bowditch et al., 2020).

Our review suggested that urban and *peri*-urban forests may play an important role as carbon sinks for mitigation purposes (Pukkala, 2018; Oliveira, 2022; Paletto, 2021; Paletto et al., 2017), but more studies are needed to understand the relative magnitude of this potential and how it could be optimised by adequate species selection, configuration, and appropriate accessibility for everyone. The human co-benefits of such actions are unknown, which calls for further research. Given the high urbanisation level in Europe, investments in urban forests may be a particularly efficient policy approach for obtaining co-benefits from forest-based climate mitigation. This is especially important since urban citizens often live far from natural areas and lack daily contact with local nature and biodiversity, which impacts individual wellbeing directly (Venter et al., 2024). However, the relative importance of urban vs non-urban forests is insufficiently understood, and analyses of any trade-offs between mitigation potential and health impact must be conducted.

Through our review of papers in Category 2, we identified a number of factors that could potentially be used in future attempts to bring together indicators for climate-smart forestry and human co-benefits, including, for instance, characteristics such as age and size of trees and forests, species composition, biodiversity, and protection regime. Factors such as distance to forests, proximity to large populations, and the impact of different management techniques on the frequency of visits, use, and enjoyment for various population groups should also be systematically studied through, for example, longitudinal studies and new evaluation methods (Lamb et al., 2019) and also assessed for the potential use as "planetary health metrics" (Haines et al., 2018). In addition, qualitative research to better understand people's preferences and perceptions of different forest environments should be conducted. Finally, long term studies based on permanent plots and addressing issues of replicability are critical (Filassola and Cahill, 2021).

As the field moves forward, attention should be given to moderating and contextual factors, such as people's perceptions of forests and ecosystem services, socioeconomic situation, climate zone, and geographical region. Too few studies included comparisons between different contexts, and individual-level factors, such as age and gender, were not considered. Furthermore, a better understanding of how climate change and biodiversity loss (with cascading effects on species diversity and trophic webs) and environmental degradation will impact forest management and the carbon sink potential is needed in combination with models of how this may influence exposure pathways and health co-benefits. To obtain this understanding, long-term monitoring and scenario modelling must be conducted, incorporating data on relevant environmental variables (e.g., management principles, biodiversity, age, dry deposition, and GHG emissions) and pathway and health variables (e.g., use of forests, quality of life, noncommunicable diseases, and mortality).

4.2. Trade-offs

Trade-offs related to the use of European forests for climate change mitigation are unavoidable (Luyssaert et al., 2018). An apparent risk with forests is fires, which cause threats to human health across the globe (EFFIS, 2023). The frequency and severity of wildfires have increased exponentially over the last decade, resulting in an increased risk of respiratory morbidity and mortality (Liu et al., 2015). The majority of wildfires are anthropogenic (Abatzoglou and Williams, 2016) due to land use changes that result in higher vulnerability to droughts and fires (Hobbhahn et al., 2019). Thus, reforestation and afforestation do not necessarily result in an increased risk of forest fires but can still serve as NbS if behavioural modifications, policies, and forest management are adequately adapted (Alcasena et al., 2019; Oliveira et al., 2021). For example, management principles based on diversifying tree species and moderate thinning contribute to preventing the risk of forest fires (European Commission, Joint Research Centre, Marin Ferrer M, Poljanšek K, Clark I, De Groeve T. Science for disaster risk management, 2017), which, according to this review, can be aligned with positive outcomes for carbon sink capacity and human co-benefits. Another trade-off relates to water availability. Due to growing water scarcity, competing demands can occur between resources for reforestation and human needs (Trabucco et al., 2008; Moss et al., 2019). Future research should use multideterminant models, vegetation-climate feedbacks, and LCAs (D'Amato et al., 2020; Quevedo-Cascante et al., 2023; Chen et al., 2022) to identify optimal win-win situations. This review indicated that deciduous forests were preferred for recreational activities and that these types of forests are also superior to coniferous forests for temperature reduction (Luyssaert et al., 2018); however, coniferous forests tend to have higher carbon sink potential because of their faster growth rate. Additionally, different species have varying resilience to climate change itself. Using and managing urban forests for climate change mitigation may also induce some challenges and potential trade-offs. For example, adequate species selection for urban trees is critical to avoid trade-offs and risks related to emission of biogenic volatile organic compounds and allergenic pollen. In addition, environmental inequalities and the phenomenon of green gentrification (Dooling, 2009), i.e. that disadvantaged populations are displaced when neighbourhoods are getting greener due to higher property costs, must be prevented through appropriate policy measures and equal access to healthy environments must always be prioritised in urban planning. Displacement of indigenous populations must also be avoided and, for example, afforestation actions should be evaluated for their long-term impact on climate mitigation and human co-benefits to avoid phenomena such as greenwashing (Buse et al., 2022).

4.3. Limitations of the review

Our review captured only the last decade of research to focus on recent methods and to identify where research is currently ongoing. We only searched publications in English, which may have failed to identify some records written in other languages. This should be addressed in future reviews. We did not identify much literature on the carbon sink potential from forests related to the use of wood products and the substitution of energy-intensive materials in our review. It is possible that our search terms failed to capture this research or that the exposure pathways and health co-benefits of this capacity are less obvious. Nevertheless, this should be further explored in future studies. The search strategy was inspired by an expert review on forest-based climate change mitigation and adaptation in Europe(Verkerk Delacote et al., 2022) and was further developed in collaboration with a librarian, but we acknowledge that the search syntax could be further elaborated and platforms for grey literature should also be assessed in future reviews. The attempt to identify synergies and trade-offs of various strategies and human co-benefits is crude (Table 3). We did not separate by different activities, such as management or afforestation, and the absolute impact was not considered. Our primary aim was to provide a preliminary suggestion for how these analyses may be considered in future research on interactions and combined approaches. Finally, for feasibility reasons, we restricted our search to European affiliations, under the assumption that very few studies, if any, would be missed by this approach. Nevertheless, a review including non-European affiliations and study areas is warranted and, in general, a review of this research nexus on a global scale is recommended, although the area is highly context dependent and as such, relevance for policy and practice may vary.

4.4. Conclusion

The planet and its inhabitants are increasingly experiencing the consequences of anthropogenic impacts on the climate. Joined-up approaches are needed to urgently address the multitude of threats to both ecosystems and human beings and identify optimal mitigation strategies to prevent further degradation while simultaneously realising human health co-benefits. This review demonstrates that there is currently a lack of evidence that considers both forest-based climate change mitigation and exposure pathways and human health co-benefits. By developing a conceptual model to guide an integrated perspective, by identifying factors that are critical for both human co-benefits and mitigation capacity, and by finding research gaps and promising methods, this scoping review may potentiate a new line of interdisciplinary research to more fully account for the full range of potential health co-benefits of climate change mitigation.

CRediT authorship contribution statement

Matilda van den Bosch: Writing – original draft, Methodology, Formal analysis, Conceptualization. **María Lucía Bartolomeu:** Writing – review & editing, Visualization, Formal analysis. **Sarah Williams:** Writing – review & editing, Visualization, Formal analysis. **Corina Basnou:** Writing – review & editing. **Ian Hamilton:** Writing – review & editing. **Mark Nieuwenhuijsen:** Writing – review & editing. **Joan Pino:** Writing – review & editing. **Cathryn Tonne:** Writing – review & editing, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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Appendix A. Supplementary data

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