

What are the trends in growth, water-use efficiency and mortality in European forests?

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Abstract

Background: European forests are increasingly affected by global change, yet evidence on long-term trends in tree growth, water-use efficiency (WUE), and mortality remains fragmented across regions, spatial scales, and methodological approaches. Different monitoring techniques, including tree rings, forest inventories, ecosystem flux measurements, remote sensing, and modelling, provide complementary but often non-overlapping insights, limiting the identification of consistent patterns at continental scale. This protocol describes a systematic literature review designed to synthesise existing evidence and address the following review question: What are the reported directions of long-term trends in growth, water-use efficiency, and mortality in European forests?

Methods: This protocol outlines a systematic literature review of peer-reviewed studies published between 1990 and 2024 that report long-term temporal trends of at least five years in growth, water-use efficiency, or mortality in European forest ecosystems. Eligible studies must examine European forests, report temporal trends, and employ empirical or modelling approaches, including tree rings, forest inventories, eddy covariance measurements, remote sensing, or process-based models. Reported trends will be classified as positive, negative, or neutral and analysed qualitatively across forest types, climatic zones, species, and methodological approaches. Rather than performing a quantitative meta-analysis, the review will apply a transparent narrative and qualitative synthesis to assess consistency across scales, identify biogeographic hotspots of evidence, and detect critical knowledge gaps. The findings will support researchers, forest managers, and policy makers by improving understanding of European forest responses to environmental change and informing future monitoring, modelling, and management strategies.

Keywords: tree rings, forest inventory, remote sensing, modelling, flux tower.

Background

European forests cover approximately 40% of the continent's land surface and play a vital role

in maintaining biodiversity, regulating the water cycle, sequestering carbon, and providing economic and cultural benefits (Pan et al., 2024). In this review, we refer to *European forests* using a geographic rather than a political framework, encompassing Northern, Western, Central, Southern, and Eastern Europe, including the Eastern part of Russia (Schuck et al., 2002; Kempeneers et al., 2011).

Forest functioning and resilience across Europe are increasingly challenged by multiple global change drivers, including climatic stressors such as rising temperatures, recurrent droughts, and extreme events, as well as atmospheric drivers such as increasing CO₂ concentrations and changes in nitrogen and sulphur deposition. A rapidly expanding body of literature has examined forest responses to these drivers, yet the resulting evidence remains fragmented across methodological approaches, spatial scales, and regions. Tree-ring analysis, forest inventories, eddy-covariance measurements, remote sensing, and models each capture different aspects of forest dynamics and operate at different temporal and spatial resolutions. As a result, findings are often difficult to reconcile, limiting the identification of robust, generalisable patterns at continental scale.

Recent continental-scale analyses of satellite-based remote sensing data have revealed widespread drought-associated forest canopy mortality across Europe, with approximately 500,000 ha affected between 1987 and 2016 (Senf et al., 2020). Additionally, global-scale assessments indicate that increasing aridity is constraining water-use efficiency (WUE), highlighting the vulnerability of forest carbon–water interactions under climate change (Wang et al., 2025). At the same time, isotopic tree-ring analyses reveal a moderate but consistent increase in WUE in European forests in response to rising CO₂, but with large regional variation (Frank et al., 2015). Consequently, a comprehensive synthesis integrating these different scientific approaches is still lacking, limiting our ability to identify general patterns, reconcile methodological discrepancies, and detect emerging regional or continental-scale trends.

This review is designed to fill that gap by systematically collecting, evaluating, and integrating published evidence from 1990 until 2024 to assess temporal and spatial trends in tree growth, WUE, and mortality in European forests. The specific time window was selected to ensure data coverage across different methodological approaches, with particular reference to ecosystem fluxes and remote sensing. By applying a transparent, pre-registered, and reproducible protocol, the review will strengthen the reliability of conclusions drawn from existing data and provide robust insights into how European forests are responding to ongoing environmental change. The outcomes will support researchers, forest managers, and policy makers by

informing evidence-based forest management and conservation strategies, contributing to climate mitigation and adaptation assessments, and identifying key knowledge gaps to guide future forest monitoring, experimental research, and modelling efforts.

Stakeholder engagement

The review objectives and protocol were developed within the EU-funded CLEANFOREST COST Action CA21138, a network that integrates researchers from different disciplines and fosters exchange between researchers and stakeholders. The review's concept and goals were defined following a panel discussion with stakeholders on the topic "Building a common vision on forest monitoring amid global change: challenges and opportunities", which was organized during the first CLEANFOREST annual meeting in 2023. In particular, a central aim of this review is to identify gaps in the monitoring of forest conditions at the European continental scale in the key metrics of growth, water-use efficiency, and mortality, highlighting areas where policy action is needed. Stakeholders will provide expert feedback on the search outcomes, assist in interpreting results, and support dissemination through European forest research and policy platforms. Their engagement ensures that the findings are relevant to forest management and conservation practices and policy priorities across Europe.

Objective of the review

This systematic review aims to address the current fragmentation of evidence by systematically collecting, evaluating, and synthesizing published studies from 1990 to 2024 that report temporal and spatial trends in tree growth, water-use efficiency (WUE), and mortality across European forests. The selected time window ensures coverage across a wide range of methodological approaches, with particular relevance to the expansion of ecosystem flux measurements and remote sensing observations. By applying a transparent, pre-registered, and reproducible protocol, the review will strengthen the reliability of conclusions drawn from existing data.

The primary review question is:

- i) What are the dominant directions (positive, negative, or neutral) of reported trends in tree growth, water-use efficiency, and mortality in European forests from 1990 to 2024?

To address this overarching question, the review will examine the following secondary questions:

- ii) To what extent do the reported trends in growth, water-use efficiency, and mortality agree across different spatial scales (tree, ecosystem, regional, continental) within and across methodological approaches?
- iii) Can we identify biogeographic hotspots, which are less represented in terms of studies and evidence on forest growth, water-use efficiency, and mortality under global change?
- iv) Where and for which forest types or drivers do significant knowledge gaps exist?
- v) Do the different approaches to measuring growth, water-use efficiency, and mortality yield similar trends and outcomes across studies?

The review questions are structured according to the PICO (Population, Intervention/Exposure, Comparator and Outcome) framework. The elements of these questions are:

- **Population:** comprises forest ecosystems across Europe, including boreal, temperate, and Mediterranean regions.
- **Intervention/Exposure:** consists of global change drivers influencing forest functioning, including climatic variability (e.g. warming, drought, and extreme events), increasing atmospheric CO₂ concentrations, and changes in nitrogen and sulphur deposition.
- **Comparator:** is based on temporal comparisons within studies using multi-year observations, allowing assessment of long-term trends over time.
- **Outcomes:** are the reported long-term directional trends (positive, neutral, or negative) in tree growth, water-use efficiency, and forest mortality.

The PICO elements are defined in more detail in the section on study eligibility criteria.

Methods

Searching for articles

Searches will be limited to peer-reviewed studies published between 1990 and 2024, written in English, and either conducted within Europe or reporting extractable European-scale results from global analyses.

Bibliographic databases

The primary source of scientific literature will be the Web of Science (WoS) Core Collection, which provides comprehensive coverage of peer-reviewed research across disciplines relevant to this review, including Forestry, Ecology, Environmental Sciences, Plant Sciences, Biodiversity Conservation, Meteorology and Atmospheric Sciences, Geosciences, Agronomy, Environmental Studies, and Remote Sensing.

The search strategy will be developed collaboratively by reviewer groups organised according to metric (growth, water-use efficiency, mortality) and methodological approach. Search terms will be refined through iterative testing to ensure that the resulting dataset is both representative of the evidence base and manageable for screening.

Each reviewer group will identify six to eight core keywords relevant to the review question (e.g. growth, mortality, water-use efficiency, $\delta^{13}\text{C}$, forest, Europe). These terms will be combined using simple Boolean operators, as preliminary testing indicated that parsimonious search strings retrieved relevant studies more efficiently than highly complex formulations. The final Boolean search string, implemented using WoS syntax, is presented in Table 1.

All records retrieved from the WoS search will be exported, merged, and deduplicated prior to screening.

Table 1. Final search string of the review.

Comparator	Compartment	Search string
	Organism	Forest OR tree (all fields)
AND	Metric	water use efficiency OR growth OR mortality (all fields)
AND	Method	Dendrometer* OR tree ring OR inventory OR satellite OR “remote sensing” OR “flux tower” OR model* (all fields)
AND	Language	English

No additional web-based search engines will be used in this review. All bibliographic searches will be conducted exclusively in the WoS database, which provides comprehensive and high-quality coverage of peer-reviewed literature in environmental sciences, forestry, and ecology. WoS ensures advanced search capabilities (e.g., Boolean logic, topic, and author keyword searches) and facilitates the export and management of references for

transparent screening and data extraction.

Article screening and study eligibility criteria

Screening strategy

Screening will be conducted in two stages using Rayyan (Ouzzani et al., 2016), an open-access online tool that facilitates independent decisions by reviewers and efficient conflict resolution. In the first stage, titles and abstracts will be screened to exclude clearly irrelevant studies. In the second stage, full-text screening will confirm eligibility based on the inclusion criteria (Figure 1).

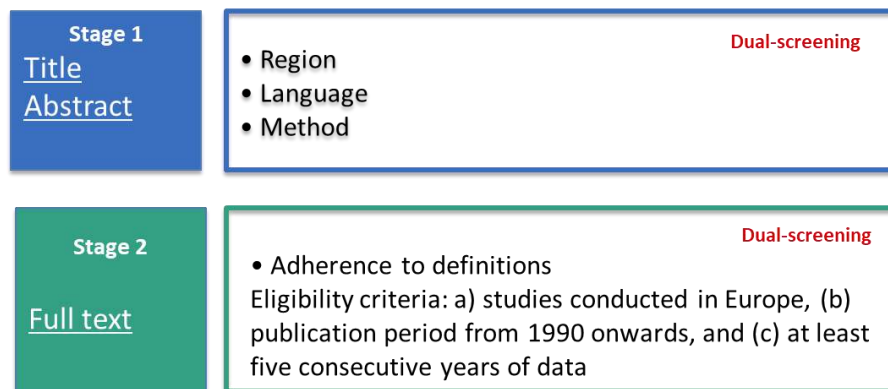


Figure 1. The article screening phases include the criteria that are being checked in each phase. Dual screening refers to the fact that each article is evaluated by two reviewers independently.

A subset of records will be screened independently by at least two reviewers, with discrepancies resolved by consensus or by consultation with a third reviewer. The process will be coordinated through the Working Group 2 ([WG2 core team](#)) — *Interactions between global change drivers and forest ecosystems health and functioning* — of the CLEANFOREST network to ensure consistency across review groups. Screening decisions and reasons for exclusion at the full-text stage will be documented in a standardized spreadsheet. This structured approach ensures transparency and reproducibility of the study selection process.

Eligibility criteria

Eligibility criteria: The studies will be screened with regard to the population, exposure, comparator, outcome, and study design.

Eligible Population: Forest ecosystems across the European continent, including boreal, temperate, and Mediterranean regions. Studies may focus on forest stands with dominant tree species (e.g., *Picea abies*, *Pinus sylvestris*, *Fagus sylvatica*, *Quercus spp.*) or mixed stands.

Eligible Intervention/Exposure: Global change drivers such as climate variability (warming, drought, heatwaves, precipitation extremes), increase in atmospheric CO₂, and altered nitrogen or sulphur deposition that influence forest carbon and water dynamics.

Eligible Comparator: Temporal comparisons within individual studies based on multi-year observations. Only studies covering a minimum of five consecutive years are considered suitable for assessing long-term trends. Comparisons will be conducted across methodological approaches (tree-ring analysis, forest inventories, eddy-covariance flux measurements, remote sensing, and process-based models), as well as across forest types, dominant species, and bioclimatic regions. The climatic zones of each study site will be classified using the Köppen–Geiger climate classification system, following Beck et al. (2018).

Eligible Outcomes: Quantitative or categorical long-term trends in tree growth, water-use efficiency (WUE), and mortality observed from 1990 until 2024. Outcomes must describe a clear directional change over time (increasing, decreasing, or stable), derived from statistical analyses (e.g. regression or time-series models) or from sufficiently explicit multi-year observational evidence that allows unambiguous trend classification.

Eligible types of study design: Studies must report data covering at least five years to allow meaningful trend detection. Instances where directional changes in trends occurred that persisted for longer than 5 years are considered separately. This temporal window (1990–2024) was selected because it corresponds to the installation and widespread adoption of eddy covariance and remote sensing measurements, enabling consistent comparison with contemporary climate drivers. In addition, the late 1990s mark the onset of systematic monitoring of atmospheric nitrogen and sulphur deposition across European forest sites within the ICP Forests network, which provides harmonized data on atmospheric inputs and their effects on forests (Vesterdal et al., 2025).

This structure enables the synthesis of forest responses to environmental change across spatial

scales and time periods, and the identification of consistent or divergent patterns among approaches and regions. Studies will be included if they examine European forest ecosystems and assess the influence of at least one global-change driver (e.g., climate variability, CO₂, N or S deposition). To ensure meaningful temporal comparisons, only studies reporting trends based on ≥ 5 years of observations and falling within the 1990–2024 window will be considered.

Consistency checking

To ensure screening consistency, 20% of titles and abstracts and 100% of full-texts will be cross-checked by at least by two independent reviewers. Any discrepancies will be discussed in calibration meetings to refine the interpretation of the eligibility criteria. Updated guidelines will then be circulated to all groups. Screening consistency will be re-assessed mid-way through the process to confirm stable levels of agreement. All inclusion and exclusion decisions will be documented in Rayyan to maintain a transparent record of reviewer assignments and justifications. Disagreements between the two independent reviewers will be examined on a case-by-case basis, with consensus achieved through discussion or, if necessary, consultation with a third reviewer.

To ensure repeatability, approximately 15% of extracted entries will be independently verified by a second reviewer. Possible discrepancies will be discussed and corrected in consensus meetings, and to maintain harmonization across review groups. In addition, post-extraction quality control will include visualization-based checks of geographic coordinates, whereby extracted locations will be mapped and compared against reported study location names. This step allows the identification of inconsistencies that may not be evident during initial extraction, including imprecise or erroneous coordinates reported in the original studies. Such iterative quality-control procedures are a standard part of data curation and contribute to improving the overall reliability of the compiled dataset.

Reporting screening outcomes

Screening outcomes will be reported using a PRISMA flow diagram adapted to the review context. The diagram will show the number of records retrieved, duplicates removed, studies screened, full-texts assessed, and final studies included.

A supplementary table will list all excluded full-text articles with specific reasons for exclusion

(e.g., outside Europe, no temporal trend reported, not peer-reviewed). The list of eligible studies will be provided in an appendix with basic metadata (authors, year, country, data source, and key metric). This transparent reporting will ensure full traceability of the study selection process.

Study validity assessment

Each included study will undergo a qualitative appraisal to assess internal and external validity.

Internal validity

The assessment will examine whether the study: (i) provides a clear and explicit indication of a trend in forest growth, water-use efficiency, or mortality; (ii) includes data within the predefined temporal window (1990–2024); (iii) covers a minimum time span of five years; and (iv) reports methods and data sources with sufficient detail to allow assessment of positive, neutral, or negative trends.

For this review, a *trend* is defined as any directional change (increase, decrease, or stability) quantified or described over time using statistical analyses (e.g., linear or nonlinear regression, time-series models) or through clearly interpretable long-term observational evidence. Studies that present only single-year measurements or lack temporal replication will not be considered valid for trend assessment.

Internal validity will also be considered in relation to the clarity of the linkage between data, methods, and reported outcomes. Studies with ambiguous trend definitions, unclear temporal coverage, or insufficient description of analytical procedures will be excluded or classified as “trend unknown” and omitted from the synthesis. Where multiple metrics, species, or sites are reported within a single study, each case will be treated independently, provided that trend attribution is clearly defined.

External validity

The assessment of external validity will focus on the extent to which the evidence synthesised in this review can be interpreted and compared across different European forest ecosystems, forest types, species, climatic zones, and methodological approaches. External validity will be

addressed by considering the geographic and ecological coverage of the included studies, which will span boreal, temperate, and Mediterranean forests across Europe, within the predefined geographic and temporal scope of the review.

By synthesising trends derived from complementary methods: dendrometer monitoring, tree-ring analyses, forest inventories, eddy-covariance measurements, remote sensing, and models, the review will enable systematic comparison of reported trend directions (positive, neutral, negative) across spatial scales and methodological frameworks. In addition, classifying study sites according to European forest types and Köppen–Geiger climate zones (Peel et al., 2007) will support structured and transparent interpretation of trends along major ecological and bioclimatic gradients.

Potential effect modifiers/reasons for heterogeneity

Potential effect modifiers expected to influence variability in trends include:

- *Forest type* (boreal, temperate, Mediterranean)
- *Species/genus*
- *Conifer vs. Broadleaf*
- *Climatic zone* (Köppen-Geiger zones)
- *Coordinates*
- *Methodological approach* (dendrometers, tree-rings, national forest inventories, eddy fluxes, remote sensing, modeling)
- *Temporal coverage* (length of study period)
- *Data resolution* (annual vs. multi-annual)

This list was compiled based on prior literature and expert consultation and WG2 discussions within the CLEANFOREST project. During synthesis, these modifiers will be explored qualitatively through partition tree analysis to identify combinations most associated with consistent trend directions.

Data extraction

Meta-data extraction and coding strategy

Metadata coding will follow predefined categorical schemes for key descriptors. Forest type will be coded according to the EEA classification updated by Barbati et al. (2014), Bioregion

will also be categorized following the EEA classification (Cervillini et al., 2020) while climate conditions will be assigned using the updated Köppen–Geiger climate classes (Beck et al., 2018). Additional categorical variables will include method type and trend direction. Continuous variables such as latitude, longitude, elevation, and study duration will be entered as numeric fields (Table 2), ensuring consistent and replicable extraction across reviewers.

Coding will be performed in R to facilitate subsequent synthesis (R Core Team 2023). Each reported tree species per case (study × metric) will represent one record in the database. A random sample (~10%) of extracted records will be cross-checked by another reviewer for consistency.

Data synthesis and presentation

The review will not involve quantitative data extraction. With ‘Data’ we refer to the information reported in the papers regarding the trend of a given parameter and all ancillary data. Specifically, data will be extracted using a standardized spreadsheet template designed to capture qualitative information (Table 2). Each study will be coded for publication details (authors, year, country), methodological approach (tree-rings, inventory, eddy-fluxes, remote sensing, modeling), forest type, dominant species/genus, climatic zone, temporal coverage, and reported trend direction (positive, neutral, negative). Where a study has measured relevant data but not presented a trend analysis, the trend direction will be marked as “unknown” and the study excluded from analysis.

Data extraction will be conducted independently by at least two review team members for each study group, followed by verification by a designated coordinator. In cases of missing data, extractors members will record “NA” and capture all available contextual information to ensure dataset completeness. This process ensures reproducibility and structured and transparent data management.

Based on the geographic coordinates reported in each study, we will process all spatial data in R using the *sf* package (Pebesma, 2018). Elevation values for each observation will be subsequently extracted from global topographic data using the *rnaturalearth* package (South, 2023).

Table 2. Variable extraction per study for the literature review.

Variable	Description and Definition
ID	A unique identifier will be assigned to each case in the database.
DOI	DOI of the article.
Title	Title of the article
Authors	Authors of the article
Reviewed by	Reviewer(s) of the article
Country	Country/Countries in which the research takes place
Include	This variable will indicate whether the study will be retained for quantitative analysis (<i>yes/no/maybe</i>) after screening.
Subgroup	Growth, WUE, mortality
Method	Method used to assess the trend (e.g., tree-ring analysis, forest inventory, eddy-covariance fluxes, remote sensing, model simulation, or dendrometer monitoring).
Climate zone	The Köppen–Geiger climatic classification of the study site will be recorded, following Beck et al. (2018).
Start time	Year of the beginning of the study
Start time	Year of the end of the study
Time	The duration of the observation period used for trend estimation (in years) will be documented. Only studies covering ≥ 5 years and starting from 1990 until 2024 will be included
Forest type	Forest type will be classified according to the European Forest Classification by Barbati et al. (2014) (e.g., boreal coniferous, temperate broadleaf, mixed forest).

Trend	The direction of the reported trend will be categorized as <i>positive</i> , <i>negative</i> , <i>neutral</i> .
Latitude (lat)	Geographic coordinate of the study site (decimal degrees).
Longitude (lon)	Geographic coordinate of the study site (decimal degrees).
Tree species	The scientific name of the tree species analyzed will be entered. When multiple species are reported, each species will be entered as a separate case.
Elevation	Elevation of the study site above sea level (m).
Leaf Trait	Leaf trait category of the dominant species: <i>broadleaf deciduous</i> or <i>evergreen conifer</i>
Species / Genus	Tree species / genus observed during the study
Bioregion	Bioregion of the study location according the European Environment Agency classification (Cervellini et al., 2020)

We will conduct a narrative and qualitative synthesis of studies reporting trends in tree growth, WUE and mortality across Europe from 1990 until 2024. The review will systematically compile all cases where trends will be statistically tested and classified as positive, neutral, or negative. Qualitative information on the direction of change will be extracted, along with the associated descriptive variables (i.e., forest type, latitude, climatic zone, genus, and study method).

These categorical data will be analysed using partition tree models to identify the main combinations of descriptive variables associated with each trend direction (Zeileis et al., 2008). The synthesis will therefore combine a narrative description of the evidence base with a qualitative exploration of hierarchical relationships between drivers of change.

The narrative component will contextualise the partition-tree results in ecological and biogeographical terms, while the qualitative synthesis will focus on the interpretation of cases where one trend type (positive, neutral, or negative) clearly dominates within a node of the

model (six dominant cases in total).

Narrative synthesis methods

We will conduct a narrative synthesis to describe and interpret the spatial and ecological patterns identified by the partition tree analyses (qualitative analysis). The synthesis will integrate the statistical output of the partition tree models with a geographical visualization of the dominant trends in tree growth, WUE and mortality.

For each response variable, the terminal nodes of the partition trees will classify each case according to their dominant trend (positive, neutral, or negative), and these categories will then be mapped across Europe. Mapping will be performed in R by linking each case to its geographical coordinates and visualizing the resulting classifications using color-coded symbols representing trend direction.

Descriptive statistics will summarize the proportion of positive, neutral, and negative trends within each terminal node, and these results will be presented in bar plots and tables to complement the spatial patterns. The narrative interpretation will focus on explaining how combinations of descriptive variables (forest type, genus/species, latitude, Köppen climatic zone, and study method) will be associated with the spatial distribution of trend dominance.

This approach will allow for a visual and contextual synthesis of heterogeneous evidence, highlighting consistent geographical clusters and potential environmental gradients underlying observed temporal changes in European forests. Descriptive maps of the observed trends will be produced in R using the *ggplot2* package (Wickman, 2016).

Qualitative synthesis methods

We will synthesise qualitative data using a partition tree approach implemented through the *ctree* function of the party package in R (Hothorn et al., 2015). This method allows to identify hierarchical and non-linear relationships among categorical predictors and the qualitative response variable representing the direction of the trend (positive, neutral, or negative).

The partition tree approach will recursively split the dataset based on statistically significant predictors, thereby revealing the most relevant combinations of factors explaining variation in observed trends across studies. Each terminal node will represent a subgroup of cases sharing similar characteristics, and the proportion of positive, neutral, and negative trends within each

node will be used to interpret dominant patterns.

The analysis will focus on interpreting nodes where one trend type clearly dominates, providing a transparent and interpretable qualitative synthesis of patterns across studies. The resulting tree structure will serve as a framework for qualitative interpretation, linking methodological and ecological drivers with observed outcomes.

This approach will allow the review to synthesise complex and heterogeneous qualitative data while maintaining reproducibility and interpretability.

Other synthesis methods

Although no quantitative meta-analysis will be performed, the review will employ mixed-method visualization to enhance interpretation. Results from the qualitative partition tree analysis will be combined with spatial mapping and summary plots.

Geographic data will be plotted using R packages (e.g., *ggplot2*, *sf*) to visualize the distribution of dominant trends and their association with climatic gradients or forest types. Integrating qualitative patterns with spatial summaries will facilitate cross-scale interpretation and highlight areas with convergent or divergent evidence.

Assessment of risk of publication bias

A formal statistical assessment of publication bias will not be performed because no data extraction and meta-analysis will be undertaken. Instead, we will qualitatively evaluate the likelihood of bias based on the breadth of the search strategy and the distribution of study outcomes (i.e., number of studies indicating negative, neutral, and positive trends) across geographic regions and bioclimatic zones of Europe. We will only focus on peer-reviewed articles published in English and indexed in the WoS database. Although this choice might reduce the breadth of the search strategy, it will ensure a full reproducibility of the review and avoid the risk of including grey literature and systematically excluding unpublished studies in languages other than English. This potential bias should be taken into account when interpreting the overall weight of the evidence.

Knowledge gap identification strategy

We will tabulate the existing number of studies per European geographic regions, forest type,

climatic zone, and tree species/genus, detailing negative, neutral, or positive trends in tree growth, WUE, and mortality according to the study methods (dendrometers, tree rings, forest inventories, eddy-fluxes, remote sensing, modelling). From these tables, regional and species-specific knowledge gaps will be identified based on the number of studies per descriptor. These data will provide context for the quantitative results, helping to identify shortcomings in both the existing literature and this review, especially the possible lack of regional representation in tree growth, WUE, and tree mortality research across the European continent.

Demonstrating procedural independence

We aim to ensure that authors are not assigned to review their own studies, although we cannot guarantee that this will be avoided completely, as papers to review will be randomly assigned.

Declarations

Ethics approval and consent to participate

Not applicable. This study is a protocol for a systematic literature review and does not involve human participants, animals, or the collection of primary data.

Consent for publication

Not applicable.

Availability of data and materials

No datasets were generated or analysed for this protocol article. This manuscript describes the methodology for a systematic literature review. All data supporting the conclusions of the final review will be derived from published, peer-reviewed sources identified through the search strategy described herein. Upon completion of the review, the extracted metadata and trend classifications (including study characteristics, geographic information, methods, and qualitative trend direction) will be made publicly available in a machine-readable format via an open-access data repository (e.g. Zenodo or a comparable community-endorsed repository). The repository link and persistent identifier (DOI) will be provided in the final review manuscript. Search strings, screening decisions, and exclusion reasons will be reported in the article and/or supplementary materials to ensure transparency and reproducibility.

Competing interests

The authors declare that they have no competing interests.

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Author's contributions

PFP led the protocol design, writing, and coordination; ML and DC assisted with the protocol design and writing; DC and CL led the design, writing and coordination of the initial protocol. All collaborators supported the writing process, commented on and approved both the initial and final versions of the protocol.

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References

Barbati A, Marchetti M, Chirici G, Corona P. European forest types and forest Europe SFM indicators: tools for monitoring progress on forest biodiversity conservation. *Forest Ecol Manag.* 2014;321:145–157.

Beck HE, Zimmermann NE, McVicar TR, Vergopolan N, Berg A, Wood EF. Present and future Köppen–Geiger climate classification maps at 1-km resolution. *Sci Data.* 2018;5:180214. doi:10.1038/sdata.2018.214.

Cervellini, M., Zannini, P., Di Musciano, M., Fattorini, S., Jiménez-Alfaro, B., Rocchini, D., ... & Chiarucci, A. (2020). A grid-based map for the Biogeographical Regions of Europe. *Biodiversity Data Journal*, 8, e53720.

Cronin P, Ryan F, Coughlan M. Undertaking a literature review: a step-by-step approach. *Br J Nurs*. 2008;17(1):38–43.

Frank DC, Poulter B, Saurer M, Esper J, et al. Water-use efficiency and transpiration across European forests during the Anthropocene. *Nat Clim Change*. 2015;5(6):579–583.

Garnier S. *viridis*: default color maps from matplotlib. R package version 0.6.2. 2021.

Haddaway NR, Brown C, Eales J, et al. The multifunctional roles of vegetated strips around and within agricultural fields. *Environ Evid*. 2018;7:14.

Hothorn T, Hornik K, Zeileis A. *ctree*: conditional inference trees. *Compr R Arch Netw*. 2015.

Kempeneers P, Sedano F, Seebach L, Strobl P, San-Miguel-Ayanz J. Data fusion of different spatial resolution remote sensing images applied to forest type mapping. *IEEE Trans Geosci Remote Sens*. 2011;49(12):4977–4986.

Ouzzani M, Hammady H, Fedorowicz Z, Elmagarmid A. Rayyan—a web and mobile app for systematic reviews. *Syst Rev*. 2016;5(1):210.

Owen R. *The essential guide to effect sizes: statistical power, meta-analysis, and the interpretation of research results*. Cambridge: Cambridge University Press; 2010.

Pan Y, Birdsey RA, Phillips OL, Houghton RA, Fang J, Kauppi PE, et al. The enduring world forest carbon sink. *Nature*. 2024;631(8021):563–569.

Pebesma E. Simple features for R: standardized support for spatial vector data. *R J*. 2018;10(1):439–446.

R Core Team. *R: a language and environment for statistical computing*. Vienna: R Foundation for Statistical Computing; 2023.

Senf C, Buras A, Zang CS, et al. Excess forest mortality is consistently linked to drought across Europe. *Nat Commun*. 2020;11:6200.

South A. *rnaturalearth*: world map data from Natural Earth. R package version 0.1.0. 2023.

Schuck A, Van Brusselen J, Päivinen R, Häme T, Kennedy P, Folving S. Compilation of a calibrated European forest map derived from NOAA-AVHRR data. *EFI Internal Report 13*.

European Forest Institute; 2002.

Vesterdal L, Schaub M, Schwärzel K, Ferretti M, Cools N, De Vos B, et al. Forest condition and environmental drivers in Europe – recent evidence from selected studies. In: Michel A, Hagenmüller K, Kirchner T, Prescher AK, Schwärzel K, editors. *Forest condition in Europe: the 2025 assessment*. ICP Forests technical report under the UNECE convention on long-range transboundary air pollution. Thünen Institute of Forest Ecosystems; 2025. p. 12–18.

Wang M, Peng S, Lu Z, Xu X, Felton A, Chen A. Increasing constraint of aridity on tree intrinsic water use efficiency. *Nat Commun.* 2025;16(1).

Wickham H. *ggplot2: elegant graphics for data analysis*. New York: Springer; 2016.

Zeileis A, Hothorn T, Hornik K. Model-based recursive partitioning. *J Comput Graph Stat.* 2008;17(2):492–514.