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SCIENCE-BASED INTEGRATED FOREST MANAGEMENT FOR CLIMATE MITIGATION

D2.1 Review paper on biodiversity and ecosystem functions of unmanaged versus managed forests

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1 Executive Summary

Forests are key players in the carbon cycle, having great potential to assist in mitigating climate change. How to best use these valuable assets, however, remains a question. Is it best to manage our forests either to adapt to the climate emergency or to optimize their mitigation potential, or should we leave forests unmanaged? This question is complex, as one should account for carbon stability (and disturbance regimes in forests, as such), harvested wood products, which too store carbon for long times, and the forest carbon pools and fluxes themselves. In this systematic review, we focus on the latter, investigating both carbon stocks and fluxes in managed and unmanaged forests across Europe.

Through a structured search string, we looked for articles that 1) explicitly compared managed and unmanaged forests, 'unmanaged' corresponding to 20 years of non-management, 2) were located in Europe, 3) contained field-measured data on carbon stocks or fluxes, either above-ground, below-ground, soil, dead wood or forest floor. A systematic review protocol was set up to outline the working methodology and increase transparency in literature screening and data processing. The search revealed close to 3,000 candidates suitable for inclusion in the review. After title, abstract, and full-text screening, 149 articles remained. From these articles, information on carbon measurements, management information, biotic and abiotic properties of the stands, and research quality was collected. In the end, 2204 records of carbon measurements were extracted. In addition, we collected reported evidence about trade-offs and synergies between different ecosystem services that these forests provide.

Research reports were well-distributed across Europe, with Germany being a front-runner in this research field. Data on above-ground, dead wood and soil carbon were abundant, whereas below-ground and forest floor carbon were less researched. Research generally accounted for differences in species composition and soil type but reported less consistently (or too general) on climate and topographic metrics. Surprisingly, the time since non-management was missing relatively frequently, though this metric is crucial when comparing managed and unmanaged forests in a comparative setting. To support future research in this field, we drafted a short guideline on the crucial variables to report.

Using general meta-analytic multivariate regression models, accounting for the biographical region and the article as random effects, we found that unmanaged forests have higher above-ground and dead wood carbon stocks. Below-ground carbon stocks trended towards a positive effect size, meaning that unmanaged stocks were higher, though the effect remained non-significant, possibly due to a lack of statistical power related to the number of observations. Soil and forest floor carbon stock differences remained insignificant, though limitations in the available data sources exist, making the INFORMA field campaign across the FMU regions an interesting addition to this puzzle. Flux data were relatively lacking across the board, especially for dead wood and below-ground carbon, and did not yield significant differences between managed and unmanaged forests.

Finally, we identified strong trade-offs between extractive practices and forest structure, carbon sequestration, and biodiversity, while we found strong synergies between forest structure, dead wood and biodiversity. Thus, management practices oriented towards good provision endanger ecosystem diversity and forest structure, with severe repercussions for

carbon sequestration and habitat provision. Hence, a management focused on wood extraction may risk key ecosystem services, essential for the proper functioning of the forest ecosystem.

In a follow-up on this Deliverable, we will detail the analysis with more advanced meta-analytical models accounting for repeated control conditions, allowing for more narrow investigations on time since non-management, forest types, management intensity and research quality effects.

2 Introduction and objectives

The European New Green Deal has forest carbon sequestration as a core element of its climate change mitigation policies (European Commission 2021). Much has been researched about the crucial role of forest systems for carbon sequestration in the EU (e.g. (Schulp, Nabuurs, and Verburg 2008; Ciais *et al.* 2008) yet uncertainties remain regarding the true forest carbon sink potential, and its ability to capture as much CO_2 as global estimates suggest (Roebroek *et al.* 2023). One of such key uncertainties is the long-term impacts of forest management on carbon sequestration (Ameray *et al.* 2021), especially regarding the benefits of carbon sequestration and storage of managed forests compared to unmanaged stands (Keith *et al.* 2014; Luyssaert *et al.* 2008). This is especially true for the effect of forest management on soil carbon storage. Such key carbon pool largely varies depending on both biotic factors (e.g., stand density, tree species), and abiotic factors (e.g., effects on under canopy micro-climate conditions, soil disturbances associated with management, climate extremes recurrence), which leads to large uncertainties regarding the ultimate effect of forest management on soil C stocks (Jandl *et al.* 2007; Bradford *et al.* 2016), and, by extension, on forest C balances when addressed at the whole ecosystem. Additionally, managing for C sequestration may negatively impact the provision of other key ecosystem services that forests provide to society, such as water regulation and water use, wood production and economic revenue, biodiversity shelter, social, cultural and spiritual benefits, in the form of trade-offs (e.g. Biber *et al.* 2020; Morán-Ordóñez *et al.* 2020)

Often, the information regarding the benefits of forest management and the temporal dynamics of its impact on ecosystem services provision is fragmentary. Evaluating the benefits of forest management on key ecosystem services provision requires an integration of the scattered evidence to see the whole picture. Such a picture is fundamental to develop the best management strategy that leverages the benefits of a C-oriented forest management strategy, and its trade-offs with other key ecosystem services provision (Muys and Messier 2023; Morán-Ordóñez *et al.* 2020).

Here, we aim to address the following questions: A) Which is the effect of forest management on in-stand carbon storage, when compared to unmanaged forests?, B) Are there differences in the impacts of forest management on carbon stocks in a bioclimatic gradient across Europe?, and C) Which are the synergies and trade-offs that a carbon-oriented management strategy presents with respect to other key ecosystem services?

Our driving hypotheses are, therefore: H1) Unmanaged forests will capture more carbon than managed stands, given their better-established stand structure and unaltered soils. H2) The impact of forest management on forest C sequestration will be larger in the moist climates in Europe, providing the low forest productivity of the driest regions. H3) There will appear trade-offs between managing for carbon storage and other key forest ecosystem services, such as water regulation, wood extraction, and soil carbon storage.

To answer these questions and test our hypotheses, we performed a systematic review of the scientific literature on the comparison of carbon stocks and fluxes between managed and unmanaged forests across the EU. Also, we further screened for the reports on trade-offs between different ecosystem services provision in managed stands.

3 Methodology

3.1 What is a systematic review?

Systematic reviews are literature studies, in which research articles are searched in a 'systematic' way. The 'system' is a framework, or working method, outlined before the start of the research. It typically comprises a clear methodology for searching articles, a defined rule-set for data extraction and data processing, and an outline of the research questions and hypotheses. This way, we ensure that the review is transparent and reproducible, minimizes potential biases, and remains within the original scope (avoiding 'drift').

Different tools are available to draft such 'systems', otherwise known as 'protocols'. Specific guidelines have been developed to maximize the quality of environmental/ecological systematic reviews, called the ROSES reporting guidelines (https://www.roses-reporting.com/). The ROSES guidelines feed into the PROCEED database – a database of systematic review protocols for environmental research.

3.2 The ROSES protocol for systematic reviews – PROCEED

For this systematic review, we drafted a systematic review protocol based on the ROSES guidelines (https://www.roses-reporting.com/systematic-review-protocols). The review protocol was submitted to and published in PROCEED, and is available at https://doi.org/10.57808/proceed.2024.20. PROCEED's registration process includes a review by the editorial board, including incorporation of revisions (https://www.proceedevidence.info/page/page?id=registration_process).

Summary – The Protocol

1) We research differences in **carbon pools** and **carbon sequestration** between comparable **managed** and **unmanaged forests** across **Europe**.

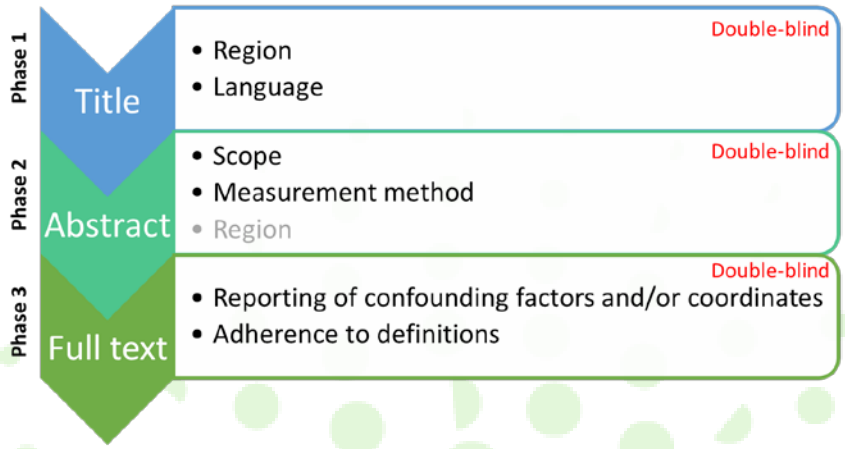
2) We include a qualitative **trade-off analysis**: what are the potential trade-offs and synergies when managing for carbon?

3) Through an iterative process, including a comprehensiveness analysis, we compiled a **structured search string** to find relevant research articles in **Web of Science**, **Scopus**, **Greenfile** and **Google Scholar**.

4) Articles were screened based on several **inclusion criteria**:
   Language: the article is written in English.
   Scope: comparable carbon field measurements in managed and unmanaged forests
   Comparability: managed and unmanaged forest stands are comparable
   Region: the forest areas measured within the article are situated in Europe.

Publication year: articles are published after 1990.

5) **Screening is done in a 3-step process**, including title screening, abstract screening, and full-text screening.



6) **Data extraction** is standardized through a data extraction **template**.

7) **Review quality** of external reviewers is assessed through a **calibration round** of three reference papers, and a **random quality check** of screening after all screening is finalized.

8) **Research quality** is assessed through a **critical appraisal**, allowing for **sensitivity analysis** on the final results.

3.3 Data post-processing

From the 149 final registers obtained from the analysed references, 37 of them had some definitions missing, namely the coordinates, the biographical region, the average annual temperatures (MAT), and/or the average annual precipitation (MAP). Here we describe the gap-filling procedure we used for each of these variables:

- Coordinates: No post-processing.
- MAT & MAP: For the stands where MAT and MAP were not provided, providing that the coordinates were available, we extracted MAT and MAP for the period 1970-2000 from the WorldClim database (Fick and Hijmans 2017). For the ones lacking both the coordinates and the MAT and MAP, we implemented no post-processing.
- Biographical region: Biographical region is a key element in our analysis, so we aimed to reduce the pool of missing values as far as we could. We proceeded as follows:
    - If the country was available, and the country only presented one biographical region, we assigned the biographical region according to the country. As an example, all the Finnish stands were assigned to the Boreal biographical region.

- If the country was not available, or the country presented more than one biographical region, and the MAT and MAP were provided, the biographical region was assigned by calculating a Linear Discriminant Analysis (LDA). We used as model inputs the registers in which biographical region, MAT, and MAP were available. We split the data into Training (80% of the registers), and Testing (20% of the registers). The sensitivity for the Testing dataset was 0.65. Then, we used the LDA to predict the biographical region for the missing registers meeting the data availability criteria.
- In case MAP and MAT data were not available, and the country presented more than one biographical region, we implemented no post-processing.

3.4 Analysis

3.4.1 Employing multivariate linear mixed-effects models for meta-analysis

Data were aggregated per unique combination of Article_ID, Site_ID and Metric_ID, resulting in a mean metric value for each comparison among managed and unmanaged forests. We calculated the weighted mean in case sample sizes were reported, and the regular mean in case of missing sample sizes. From these aggregated values, we then calculated the log response ratio (LnRR) for each comparison adjusted by Taylor expansion, which is advantageous in scenarios of large sampling variances and/or small to medium sample sizes (Lajeunesse 2011).

$$LnRR = \ln\left(\frac{\overline{X_1}}{\overline{X_2}}\right) + 0.5 * \left(\frac{{CV_1}^2}{n_1} - \frac{{CV_2}^2}{n_2}\right) \quad (1)$$

Where CV is the coefficient of variation for each aggregated record (managed/unmanaged per Site_ID). For records where standard deviations were missing, we employed the missing cases method of Nakagawa *et al.* (2023). Records with missing sample sizes were treated as being one measurement (i.e., having sample size n = 1).

After preparation of the effect sizes, a multivariate linear mixed-effects model was employed using the *metafor* package in R (Viechtbauer 2010; R Core Team 2020). The basic model equation was:

$$LnRR \sim Bioregion + (1|Article/Site) \quad (2)$$

Data was split up for each main variable type – above-ground carbon, soil carbon, dead wood, below-ground carbon and forest floor (combining 'Organic layer' and 'Litter' in the original data extraction). Within this subset, the units of the measurements were checked and harmonized where possible. Incomparable units were removed from these analyses.

3.4.2 Trade-off analysis

A total of 478 interactions between ecosystem services were identified by the paper screening. We then grouped the evaluated ecosystem services in 11 different categories (*Biodiversity*, *Biomass Carbon Stock*, *Carbon sequestration*, *Dead wood*, *Forest Structure*, *Goods provision*, *Resilience*, *Soil Carbon Stock*, *Soil Fertility*, *Tree Regeneration,* and *Water Balance*), by defining a positive correlation – synergy, or a negative one – trade-off, among the two different ecosystem services only where the authors discussed such interaction in the text. From the originally reported 478 interactions, we kept a total of 326 negative or positive interactions (210 synergies and 116 trade-offs) between ecosystem services.

4 Results

4.1 The preliminary search string – a summary

A preliminary search string was constructed to search for relevant literature, comparing managed and unmanaged forests in Europe. The search string consisted of four components: 1) filtering out research in Europe, 2) research including 'unmanaged' and synonyms, 3) research including 'managed' and synonyms, and 4) research dealing with 'forests'. From this preliminary search string, a total of 4097 papers were extracted from Web of Science. These papers were subjected to keyword analysis, with the goal of identifying potential areas of opportunity for further investigation. From this analysis, it was clear that biodiversity was the most well-researched subject (Figure 1). However, an extensive meta-analysis on biodiversity in managed and unmanaged forests has already been performed by Paillet *et al.* (2010). **Carbon** was a very interesting subject to investigate; sufficient papers were available for a proper systematic review, reporting on these metrics would be relatively uniform, and it is a key subject within current forest policy. Both disturbance and structure were well-represented but had a large in-class variability. It was also expected that the structure would further feed into the carbon category. Keywords concerning water were fewer than 25.

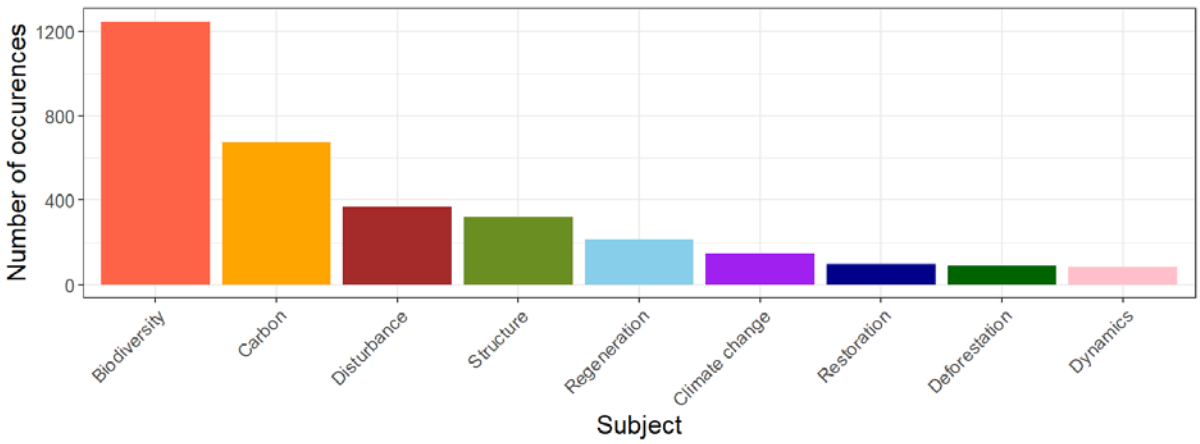


Figure 1. Key-word analysis of the preliminary search string.

Based on the keyword analysis of the preliminary search string, we decided to focus the remainder of the review on the carbon budget and to take other ecosystem functions into consideration as potential trade-offs or synergies. The preliminary search string was broadened to capture more relevant papers (but also increasing noise), and a specific compartment for carbon was added. This yielded a new preliminary search string for the actual systematic review.

4.2 Employing the search string – general search results

The preliminary search string was submitted to a comprehensiveness – we tested whether 20 benchmark articles could be found using the preliminary search string. 10 benchmark articles were selected by two reviewers independently, eliminating possible biases. Given that all resulting benchmark articles (19 unique articles) were available on Web of Science, the preliminary search string only extracted data from this database. Table 1 shows the inclusion rate of the benchmark articles against the preliminary search string, along with the main reasons for exclusion.

Table 1. Testing of the preliminary search string against 2x10 benchmark articles (19 unique articles), where % Inclusion is the percentage of benchmark articles found by the search string, and a description of the major reasons why benchmark articles were missed.

Reviewer	% Inclusion	Main problems
DNS	60	• Study area not mentioned in the title or abstract • No mention of managed forests in the abstract • Alternative terminology for unmanaged
JS	80	• Region not mentioned in title or abstract • Alternative terminology for managed

A detailed overview of the benchmark articles and the reason for exclusion is given in Appendix 1 and Appendix 2. Based on this comprehensiveness analysis, the preliminary search string was adapted to a final version, including all benchmark articles.

The final search string yielded a total of **2998** articles to be screened for the review. 2678 articles were found through Web of Science, with Scopus and Greenfile adding 299 and 21 articles, respectively. The latter two databases yielded 1492 overlapping articles with Web of Science.

4.3 Title screening

Title screening was based on Region (research must be conducted in Europe) and Language (only English articles are selected). Based on these criteria, 19.4% of the candidate papers were excluded (Figure 2). Most papers were excluded based on the Region.

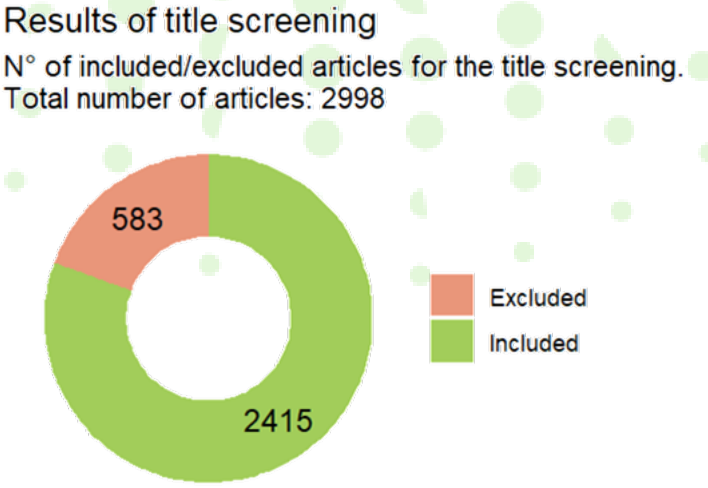


Figure 2. Screening results of the title screening.

4.4 Abstract screening

The abstract screening was based on Scope (papers must compare managed to unmanaged forests, and carbon pool measurements must be available). Measurement Method (field data, no simulation data, no remote sensing data) and Region. In total, 81.2% of remaining articles were excluded at this stage, leaving 453 articles for the full-text screening (Figure 3). Roughly 75% of articles were excluded due to them being outside of the scope of our review, while the remaining 25% were evenly split among Measurement Method and Region.

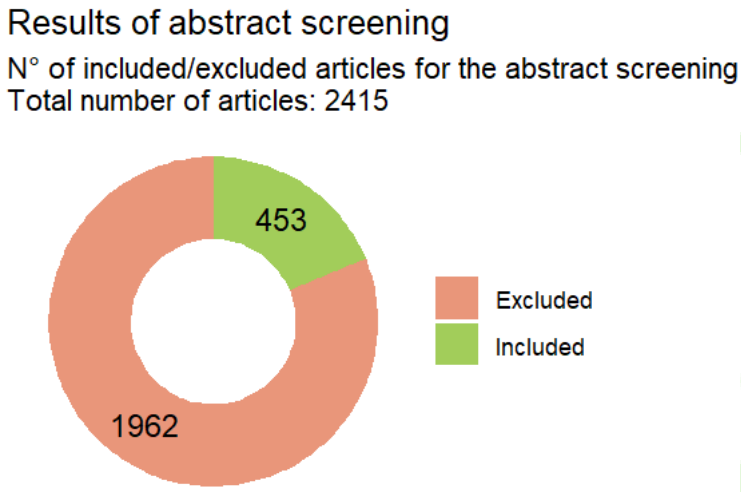


Figure 3. Screening results of the abstract screening.

4.5 Full-text screening

A team of twelve researchers from six universities and research institutes in five EU countries completed the full-text screening of the remaining 453 articles. To ensure consistency among the different researchers involved in screening, a calibration phase was set up. In this calibration phase, two leading researchers screened and extracted data from three benchmark articles (cfr. Section 4.2) in full text. This 'reference' extraction was discussed among the leading researchers, and discrepancies were resolved. In the next step, all 'external' screening researchers similarly screened the three benchmark articles, after which it was compared to the reference extraction, and issues/inconsistencies were resolved through a meeting with the lead researchers. The data extraction was also discussed in the WP2 meetings among different INFORMA partners involved in the review.

Inclusion of full text is mainly determined by data availability and adherence to definitions of (non-)management. Of the 453 papers that underwent full-text screening, 149 remained (Figure 4). Major reasons for exclusion were: 1) missing managed and/or unmanaged stands for comparison, 2) no carbon-related data available, 3) non-adherence to the unmanaged forest definition (> 20 years unmanaged), 4) research plots not located in Europe, and 5) modelling results without explicit field data observations. The resulting 149 papers underwent thorough data extraction, following the template outlined in the Systematic Review Protocol.

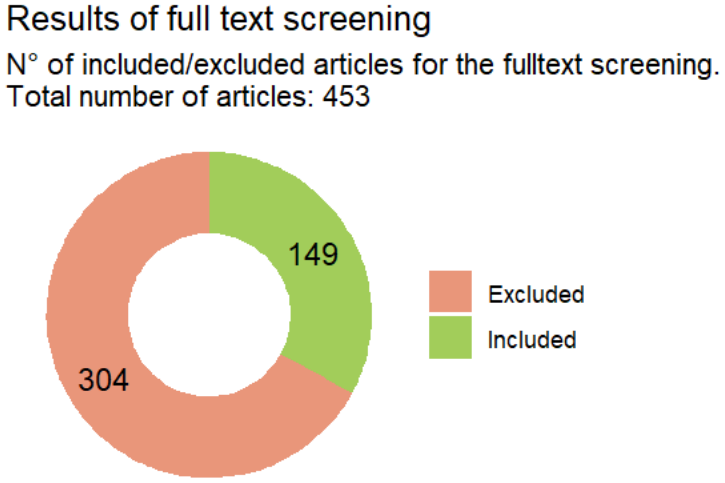


Figure 4. Screening results of the full text screening.

4.6 Data cleaning

Some categories within the data extraction are well-established (e.g., forest type, being either Single Species Broadleaved, Single Species Coniferous, Broadleaved Mixed, Coniferous Mixed or Multimix), other categories are more 'open'. In these cases, some reclassification was needed to harmonize the dataset. Harmonization included:

a) Checking writing styles of measurement units (e.g., m^3 ha^{-1} compared to m^3/ha);
b) Reclassifying Time_Unm (time since no management) into '20-50', '50-100', '100-300' and '>300' years. Records classified as 'Old' in articles (i.e., primary and 'old-growth' forests) are automatically assigned the '>300' class;
c) Species nomenclature is harmonized (e.g., *Fagus sylvatica L.* compared to *Fagus sylvatica*), and subspecies are systematically removed;
d) Soil types are harmonized (e.g., 'podzol' compared to 'podsols'), and sub-qualifiers within soil classification are removed (e.g., 'Dystric cambisol' becomes 'Cambisol'). Soil information unrelated to WRB classification is retained, but in WRB assessment is classified as 'Others'.
e) Missing values for MAT, MAP and Biographical region were extracted using the coordinates of the sites, if available, according to Section 3.3.

4.7 Data orientation

A total of 267 comparisons between managed and unmanaged forests, coming from the 149 included research articles, are located in 27 countries. The research sites are scattered across Europe, covering the major biogeographical regions including the Alpine, Atlantic, Boreal, Continental and Mediterranean regions (Figure 5; Figure 6). The systematic review is especially well-represented in the Boreal region as compared to the IFMP, with much research having been performed in both Sweden and Finland (Figure 7). Romania is notably underrepresented by the systematic review, even though the country harbors a crucial part of

Europe's old-growth forests (Sabatini *et al.* 2018). Germany, on the other hand, is the leading country for management-related research (Figure 7).

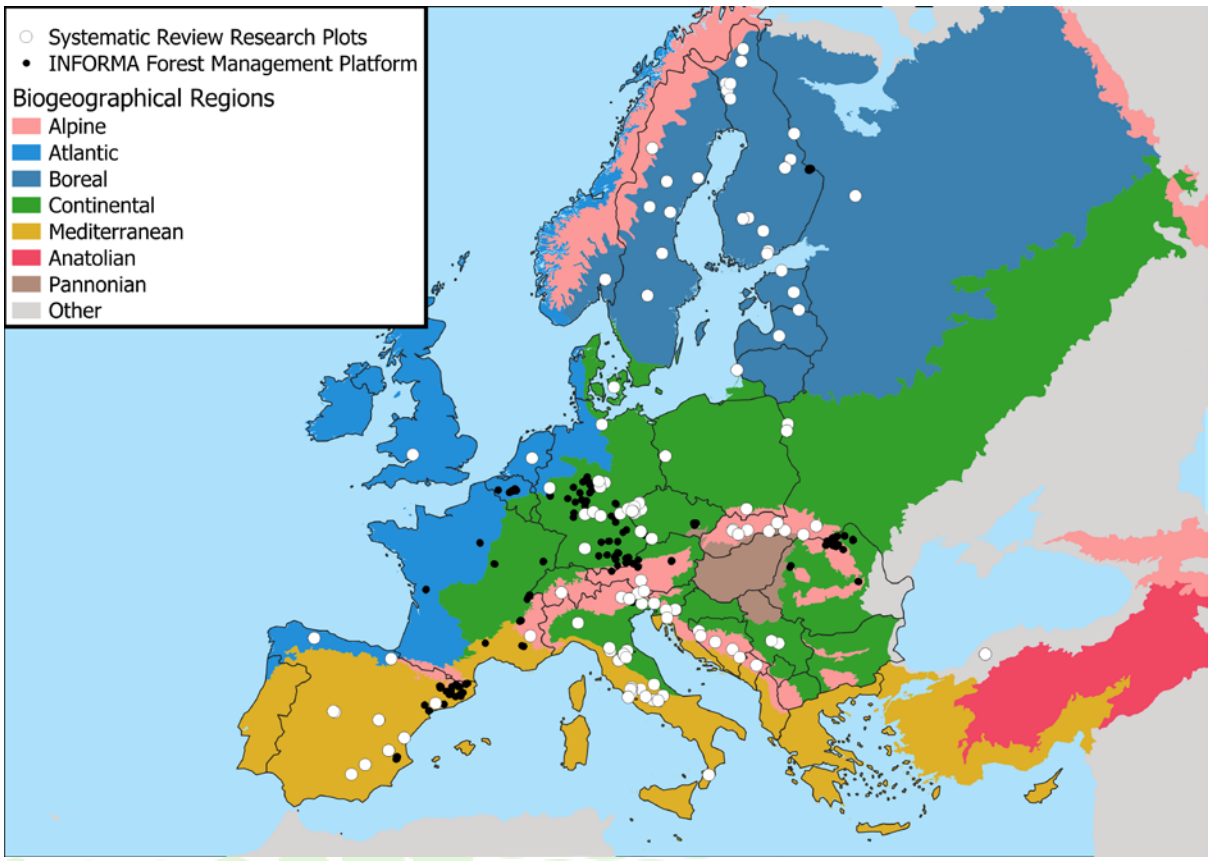


Figure 5. Location of the systematic review research plots, covering the major biogeographical regions of Europe. The INFORMA Forest Management Platform is plotted alongside the systematic review research plots, showing the complementarity.

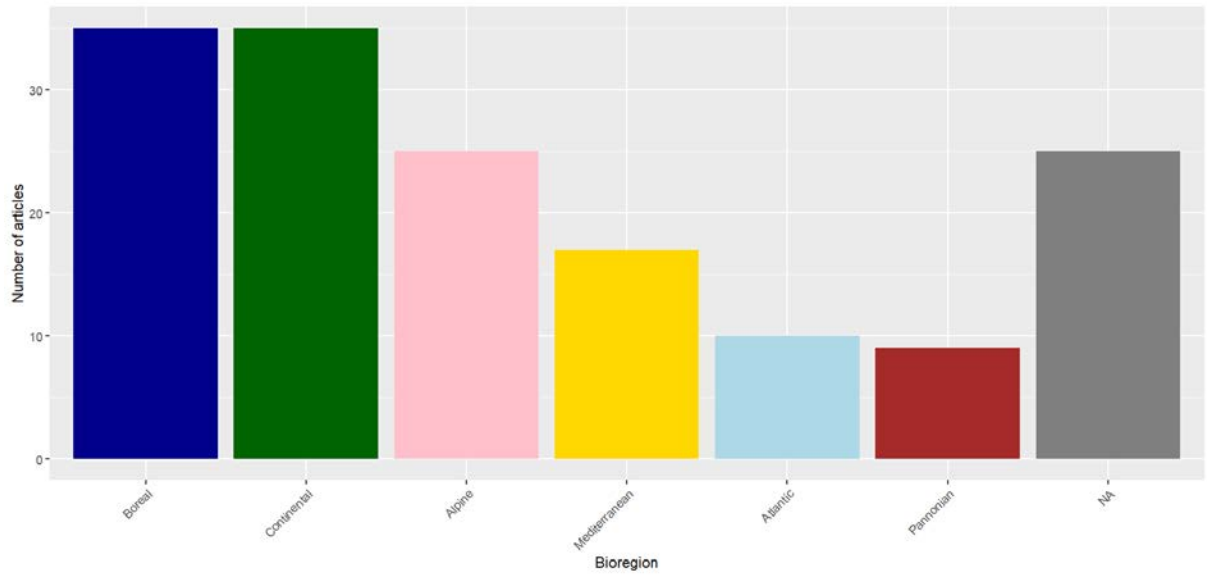


Figure 6. Distribution of included articles among biogeograpgical regions. Biogeographical regions were either reported as such, extracted based on the country in which the research took place, or derived from the reported or extracted mean annual temperature and mean annual precipitation (Section 3.3).

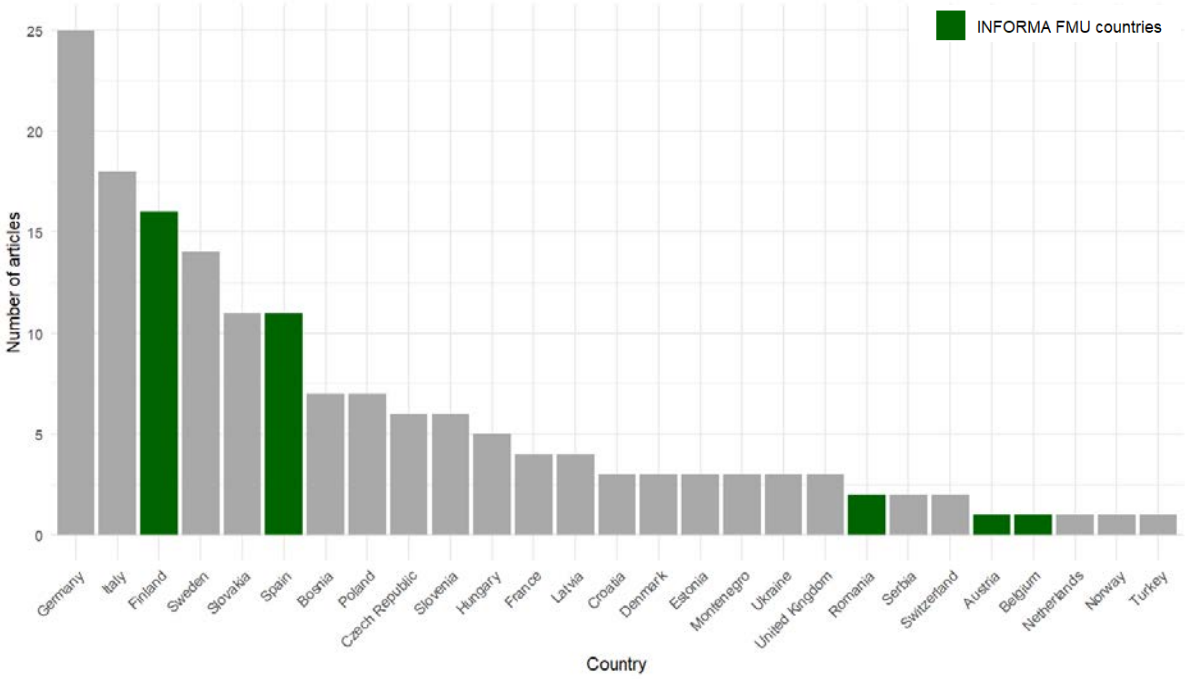


Figure 7. Distribution of included articles among countries. INFORMA FMU countries are highlighted in dark green.

Dead wood is the most measured variable among data records, closely followed by above-ground carbon and soil carbon (Figure 8). Below-ground carbon, litter and the organic layer are frequent. Of the records, the vast majority (90%) deal with **stocks**. This is expected; flux data is generally harder and more complex to measure correctly, can be more costly, or, in case fluxes are derived from differences in stocks over time, take a long time to gather. Especially for the comparison of managed and unmanaged forests, carbon flux experiments seem to be rare.

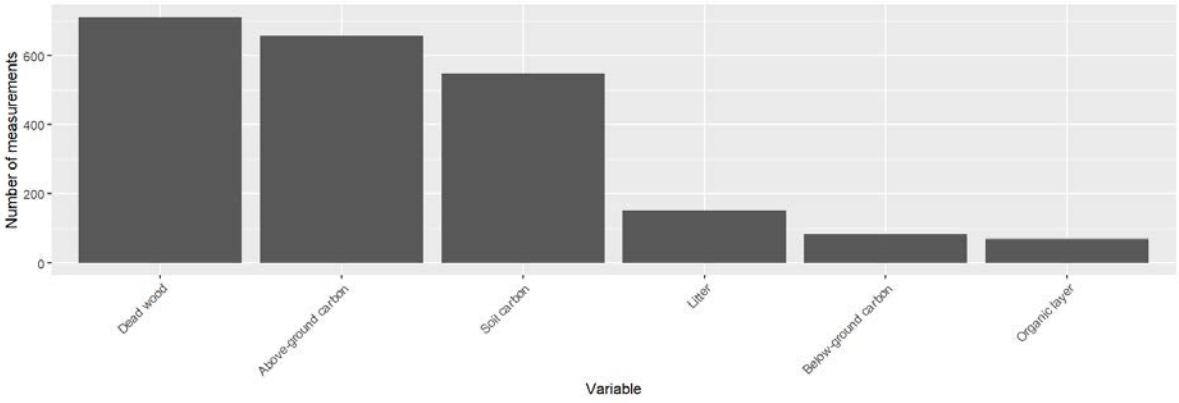


Figure 8. Number of measurement records for each variable type considered in the systematic review.

The main species found in our review correspond well to the expected dominant tree species in a European context. *Fagus sylvatica*, *Picea abies*, *Pinus sylvestris* and *Abies alba* make up the bulk of the measurements, corresponding to the major European tree species (Köhl, Linser, and Prins 2020). Several of the next species, such as *Quercus sp.*, *Pinus halepensis* and *Betula sp.* are relatively common, but are usually either restricted in distribution range (e.g. several Mediterranean species), or only appear in specific (less-frequent) circumstances

(e.g., pioneer species). Other tree species are sporadically present, but are generally species that are mixed with one of the major tree species, and in doing so, less frequently make up 20% of the stand or plot.

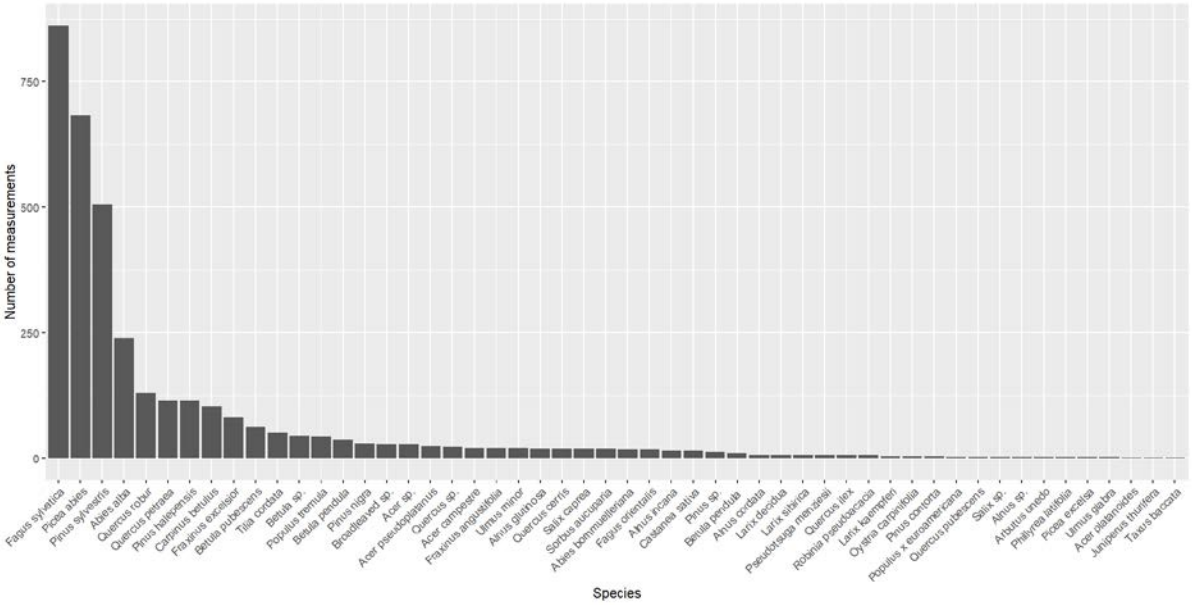


Figure 9. Number of measurement records per main tree species. Tree species are counted from a 20% presence cut-off.

When assessing unmanaged forests, the time since cessation of management is an important factor to consider. Natural processes take time to recover, and natural structures take time to develop (Kadavý, Kneifl, and Uherková 2025). Most European unmanaged forests are relatively young (20-150 years) and have not had sufficient time to develop their full natural potential (Krueger, Schulz, and Borken 2017). These young reserves are complemented by a very small, but important portion of forests, which have been unmanaged for centuries, or have even never been managed at all (Sabatini *et al.* 2018). This distribution of time since no-management corresponds to what we found in the review (Figure 10). There is a major focus on either very young reserves (20-100 years) or the primary forests (>300 years), which are frequently labeled as the 'references'. The transition between these two states seems to be largely absent, which can be attributed either to a lack of detailed information regarding the time of no management or the sheer absence of these transitional forests within the European context.

Remarkable is the number of measurements in which the time since no management is not reported. This category does not include forests that were labelled as 'old-growth' or 'primary', and purely consists of records where no information regarding the time of no management was present. For managed forests, a similar trend can be observed, in which management information is rarely reported, even at the lowest level of detail (Figure 11). Managed forests are frequently labeled as just 'being managed', though information such as harvest type and intensity, thinning intensity and rotation length have a large influence on chemical, physical and general ecological processes in the forest (Kadavý, Kneifl, and Uherková 2025).

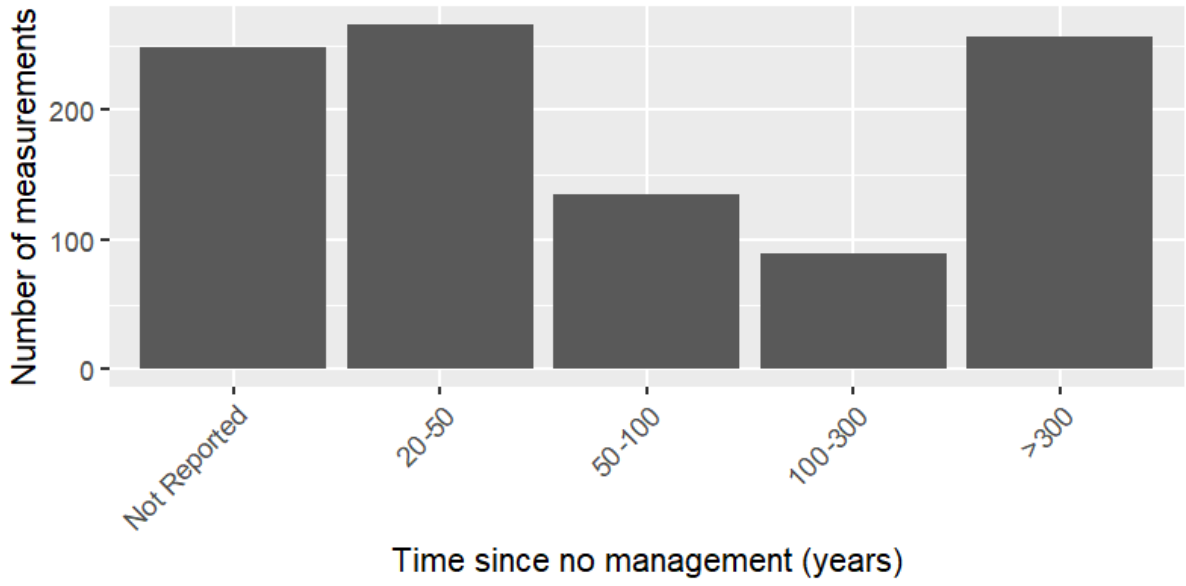


Figure 10. Number of measurements for the different categories of time since no management. Forest unmanaged for more than 300 years usually refers to the primary forests.

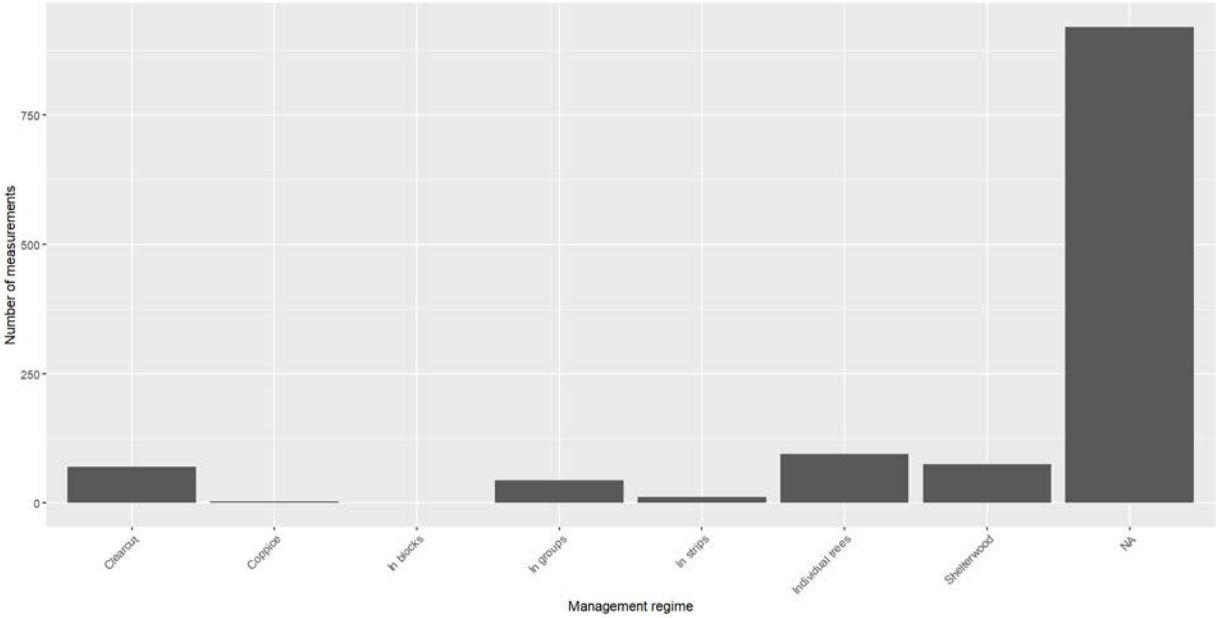


Figure 11. Number of measurements for each management regime category, related to the type of final harvest.

4.7.1 Above-ground carbon

Stocks

Figure 12 shows the modeling results for above-ground carbon stocks. A statistically significant effect ($p < 0.0001$) is observed for the overall model, indicating that unmanaged forests have a higher carbon stock than managed forests in Europe. An effect size of 0.21 corresponds to a difference of 23.4% in carbon stocks. Among biographical regions, this effect seems to be most pronounced in forests located in the Atlantic and Boreal biogeographical regions, though the Atlantic case has a high level of uncertainty, partially due to the low number of records contributing to it. The effect seems least prominent in Mediterranean and Pannonian cases, though they still follow the general trend of unmanaged forests having a higher above-ground carbon stock.

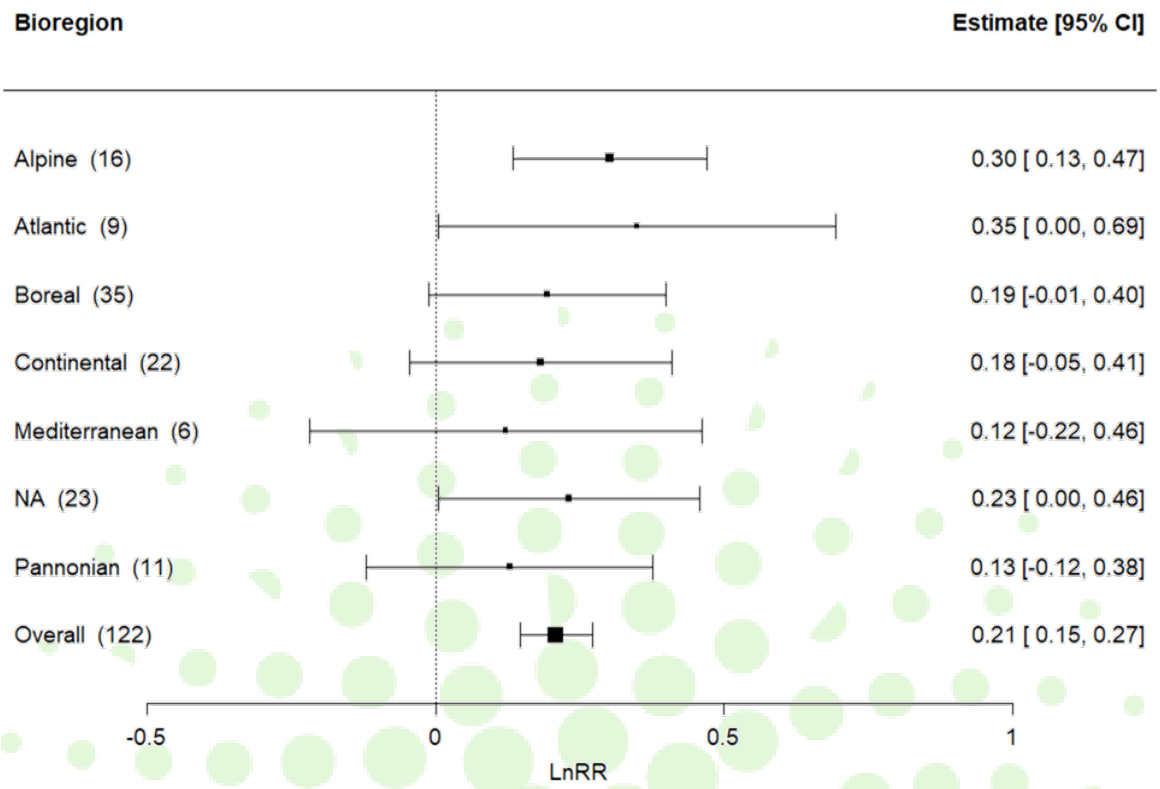


Figure 12. Modeling results of the different biogeographical region effects, and the overall effect size, for above-ground carbon. Positive values indicate higher above-ground carbon in unmanaged forests.

Fluxes

Carbon sequestration in above-ground biomass did not seem to significantly differ between managed and unmanaged forests (Figure 13; p-value = 0.9424). Differences among biographical regions are apparent and statistically significant, but often result from observations in single or a few studies.

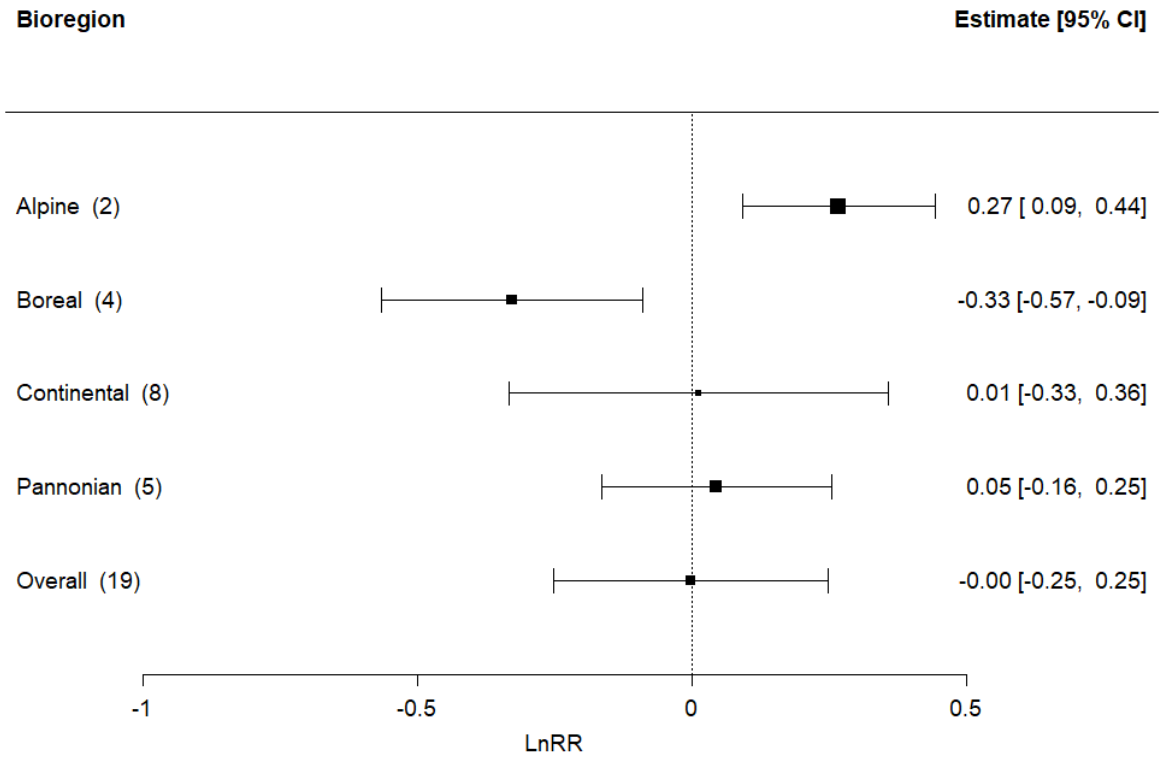


Figure 13. Modeling results of the different biogeographical region effects, and the overall effect size for above-ground carbon fluxes. Positive values correspond to a higher above-ground carbon flux in unmanaged forests.

4.7.2 Below-ground carbon

Stocks

No overall statistically significant effect was found for differences of below-ground carbon stocks between managed and unmanaged forests (p-value = 0.1206; Figure 14), though the effect sizes rather trend positively. However, many records (14/19) had missing standard deviations, whereas the variance of the remaining records was relatively large, leading to overall quite large confidence intervals. The actual records may be more precise, which would make the resulting effect size more precise and thus potentially statistically significant.

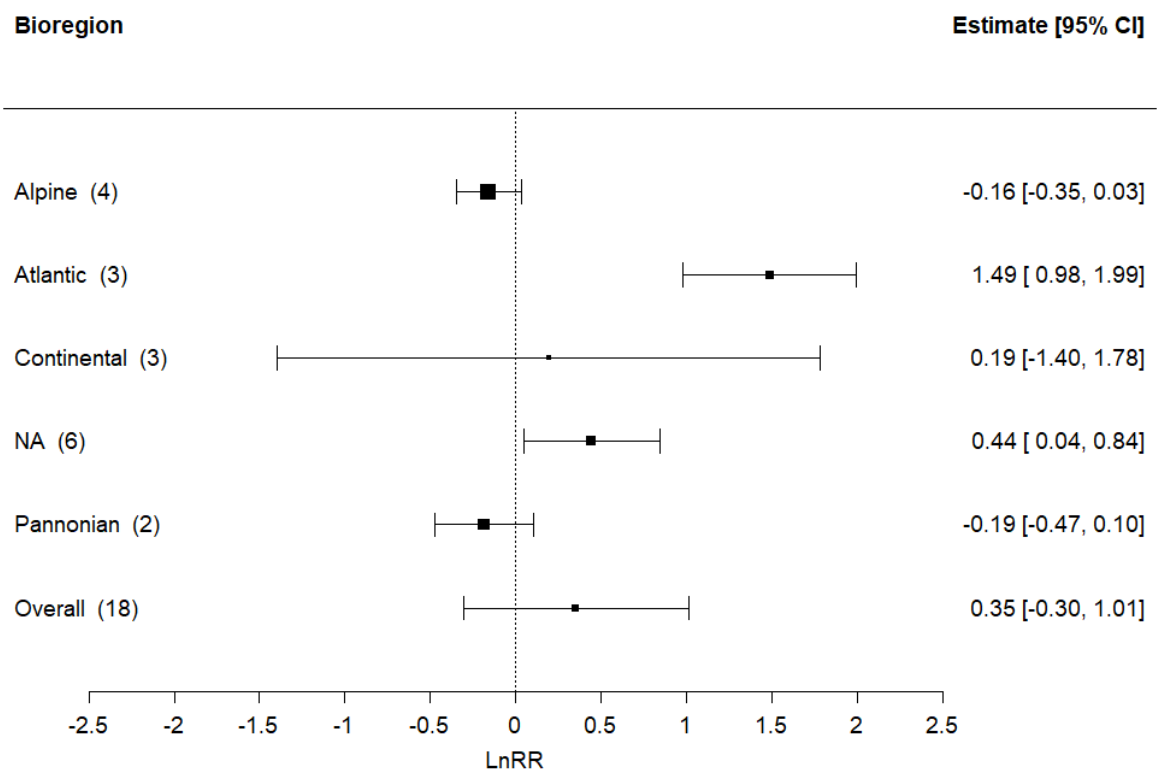


Figure 14. Modeling results of the different biogeographical region effects, and the overall effect size, for below-ground carbon. Positive values indicate higher below-ground carbon in unmanaged forests.

Fluxes

There were no records related to below-ground carbon fluxes.

4.7.3 Soil Carbon

Stocks

Soil carbon stocks between managed and unmanaged forests were not statistically different, with a p-value of 0.6028. All biographical region's effect sizes were close to neutral. The boreal biographical region has a good representation of soil carbon assessment between managed and unmanaged forests, though this is primarily (92/103 records) through the assessment of Simola (2018), assessing soil carbon in tilled and non-tilled forest areas across Finland.

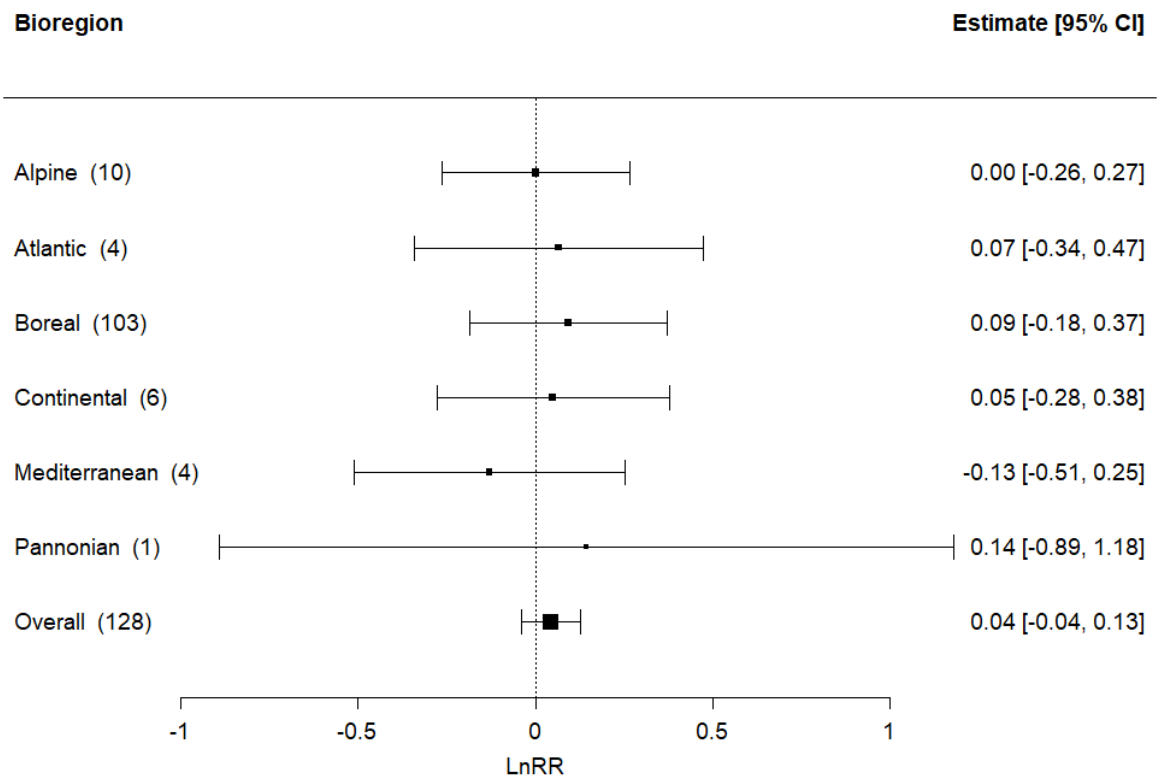


Figure 15. Modeling results of the different biogeographical region effects, and the overall effect size, for soil carbon. Positive values indicate higher soil carbon in unmanaged forests.

Fluxes

Only five records (in two articles) reported on fluxes of soil carbon; one article assessed the carbon sequestration in the soil over 30 years, and found that the unmanaged forest had sequestered more carbon in the soil than their managed counterparts (1.8 t C/ha/year vs 1.7 and 1.5 t C/ha/year, respectively) (D'Acqui *et al.* 2017). The other article, containing four separate comparisons of management and non-management (two comparison sites, measurements in 2017 and 2018), assessed basal respiration. They found that respiration rates between managed and unmanaged parts of the sites did not differ significantly (Lull *et al.* 2024).

4.7.4 Dead wood

Stocks

Unmanaged European forests on average have three times more dead wood compared to managed forests ($p < 0.0001$). The effect is most pronounced in Alpine and Pannonian forests, whereas the difference is smallest in Atlantic forests (Figure 16). It is noteworthy that for Atlantic forests, some observations between managed and unmanaged forests were relatively similar. These cases corresponded to comparisons of forest reserves, of which at least one had been unmanaged for less than 20 years (and was thus considered to be managed for this

review). Though these very young reserves still lack features typical of longer-term unmanaged forests, large amounts of dead wood can be created within a relatively short time frame (Bauhus, Puettmann, and Messier 2009).

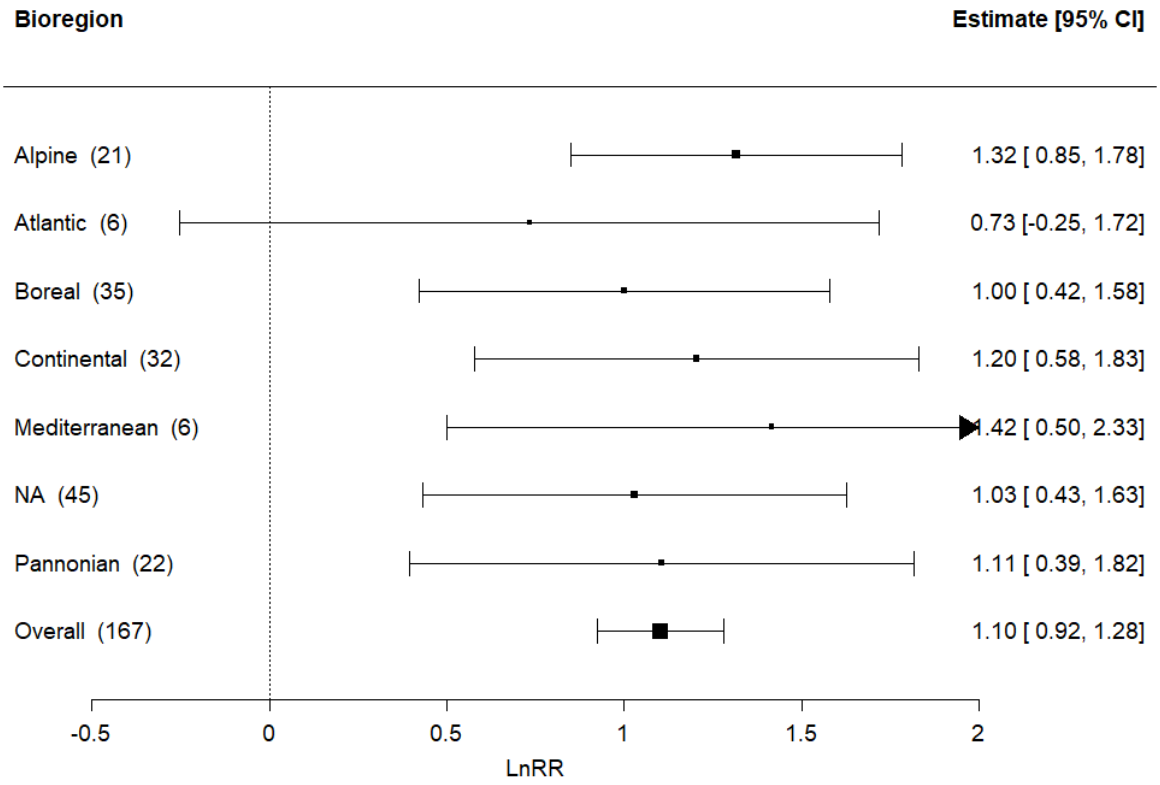


Figure 16. Modeling results of the different biogeographical region effects and the overall effect size for dead wood. Positive values correspond to more dead wood in unmanaged forests.

Fluxes

There were no records related to dead wood carbon fluxes.

4.7.5 Forest floor

Stocks

Total soil Carbon stocks were not statistically different (p-value = 0.6599) between managed and unmanaged forests. The bulk of the comparisons were made in the Boreal biographical region, though this was related to one study containing remeasurements of the same areas.

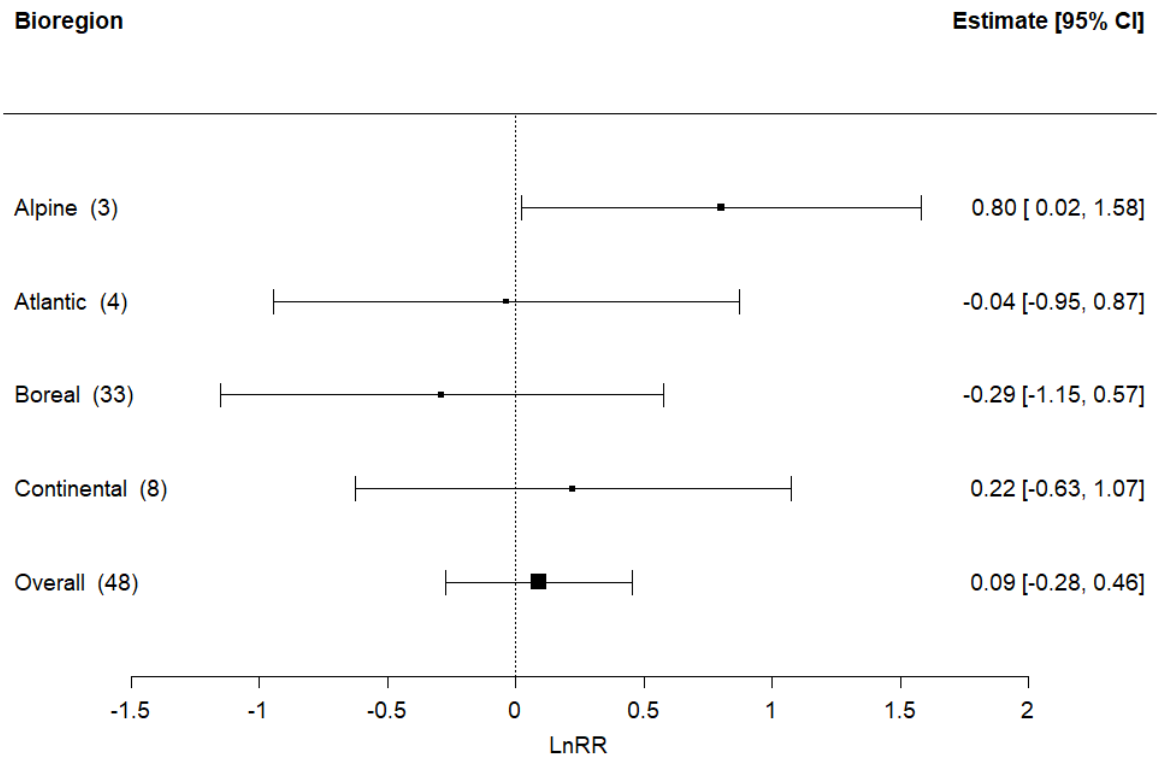


Figure 17. Modeling results of the different biogeographical region effects and the overall effect size for the forest floor. Positive values correspond to more carbon in the forest floor in unmanaged forests.

Fluxes

Forest floor fluxes did not differ significantly between managed and unmanaged forests (Figure 18), as the number of comparisons is low and no general trends in the data can be found.

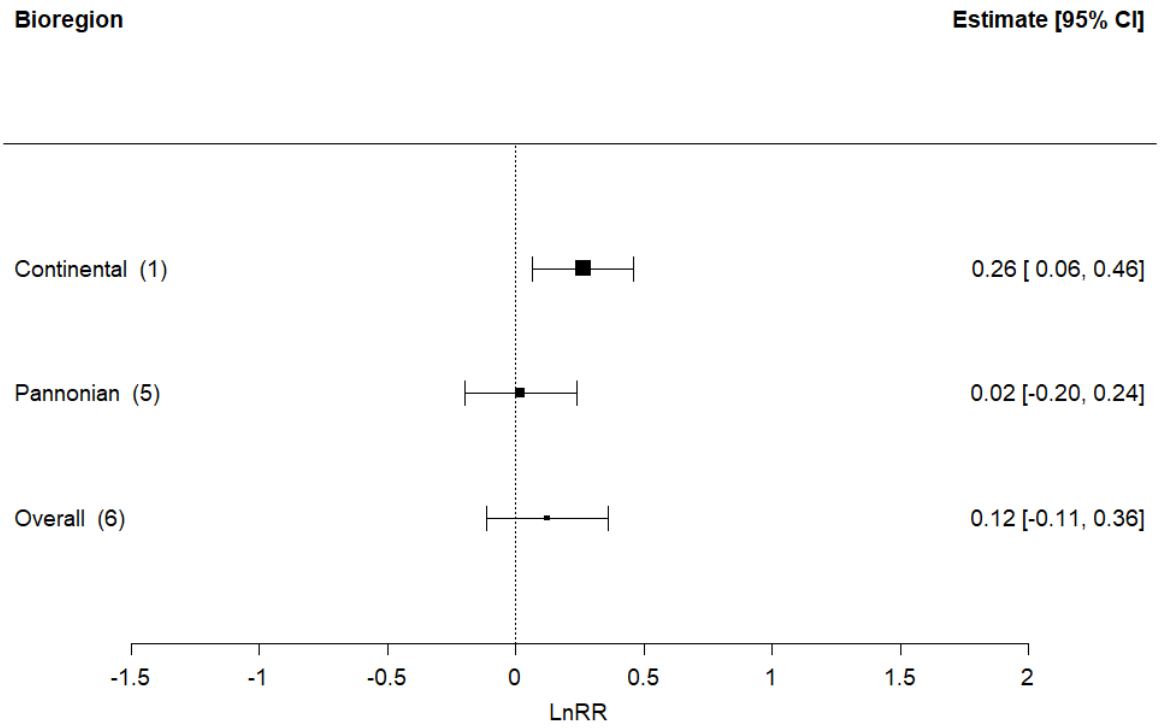
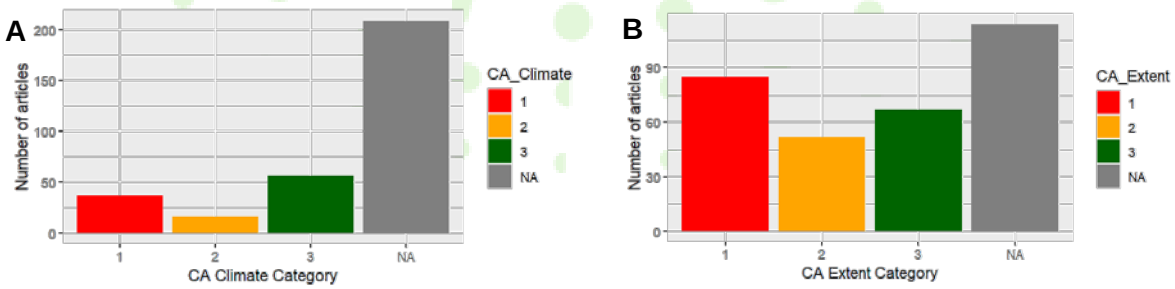


Figure 18. Modeling results of the different biogeographical region effects and the overall effect size for forest floor fluxes. Positive values correspond to higher fluxes in unmanaged forests.

4.7.6 Critical appraisal

The critical appraisal is a tool used to assess the research quality of the extracted papers. We evaluated the critical appraisal based on climate, extent, time of measurement, elevation, aspect, slope, soil type, species composition and adherence to 'non-management' definitions. A score of 1 indicates poor quality, and a score of 3 indicates good quality. The classification thresholds are described in the systematic review protocol (Simons *et al.* 2024). A critical appraisal indicator is only evaluated when data for both managed and unmanaged forests are available. If not, the indicator was set as '*NA*', which is being treated as having the lowest quality value. Quality scores for all indicators are shown in Figure 12.



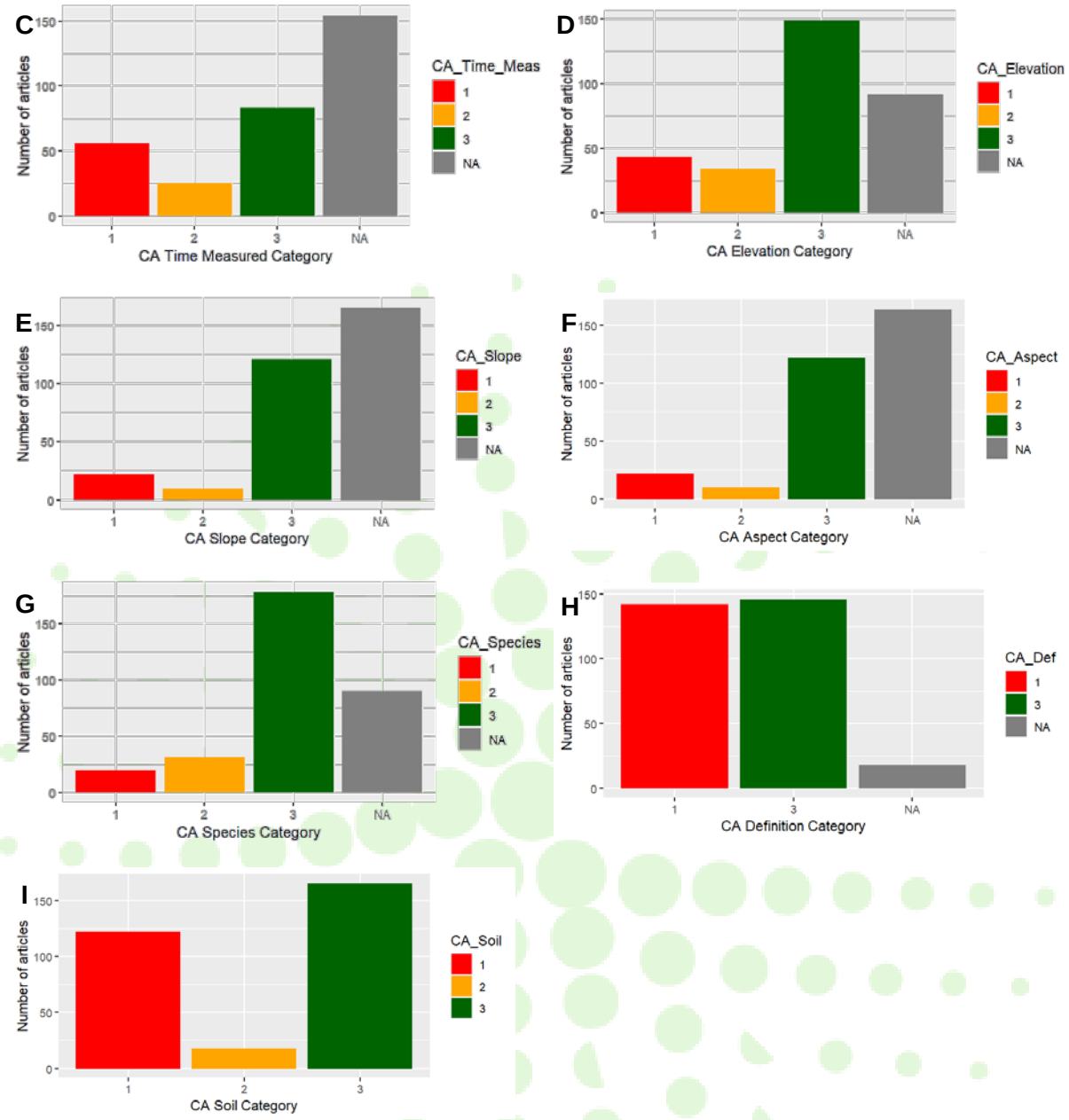


Figure 19. Critical appraisal assessment for the included papers. Critical appraisal was assessed for A) Climate, B) Extent, C) Measurement Time, D) Elevation, E) Slope, F) Aspect, G) Species Composition, H) Definition of Unmanaged Forests, I) Soil Type. A CA score of 3 indicates good quality, 1 indicates poor quality. Non-reported metrics were reported as missing ('NA'). For CA_Def, categories 2 and 3 are merged since no clear distinction could be made. For CA_Soil, a missing value equals a score of 1 as per definition.

Best-performing quality indicators were Species and Soil (Figure 12 G and I). Species composition and soil type seem to be widely recognized as important modifier effects when comparing managed and unmanaged forests (or forests in general). However, the number of missing values remains significant. This is mainly due to the lack of detailed information for species composition, usually related to the reporting of basal area or stem number percentages per species. For soil types, missing values correspond to a score of 1 (as per definition, see the Systematic Review Protocol).

Topographic modifier effects (elevation, slope and aspect) were usually either reported (and accounted for) well, or not reported at all (Figure 12 D, E and F). This is expected: regions

with low elevational ranges, and consequently flat slopes, justifiably do not consider topographic indicators as important modifier effects to report. Regions with large elevational ranges are used to incorporate elevation, slope and aspect in their analyses, minimizing differences among them, and reporting them in sufficient detail.
Climate, on the other hand, is frequently reported insufficiently. This lack of reporting is probably caused by 1) the relationship of temperature and precipitation with elevation, 2) the 'nearness' of the sites under investigation, in which climate is considered constant, or 3) the general reporting of climate for the region, but not differentiating climate for the managed and unmanaged sites, or different forest sites under investigation.

4.8 Interactions between pairs of ecosystem services

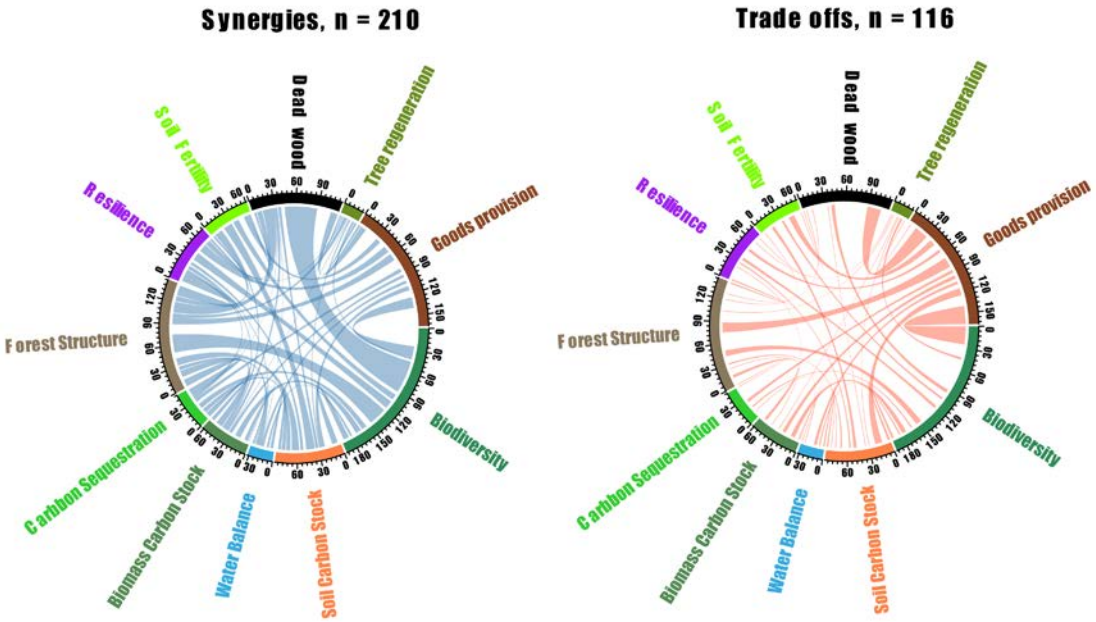


Figure 20. Correlation analysis for the 326 reports on synergy (n = 210) or trade-off (n = 116) between pairs of ecosystem services. The numbers indicate the number of registers referring to a given ecosystem service, and the links in blue (red) indicate reported synergy (trade-off) among two pairs of ecosystem services in the same paper.

A total of 326 reports on pairs of synergy and trade-off between ecosystem services, from 146 different papers, were analyzed. Of these, 210 pairs consisted of synergies and 116 consisted of trade-offs. The strongest synergies found were between dead wood and biodiversity (45 registers), biodiversity and forest structure (25 registers), dead wood and forest structure (15 registers), biodiversity and goods provision (15 registers), and resilience and forest structure (14 registers). These pairs of synergies highlight the importance of the old-grown forest's well-developed structure to sustain biodiversity at different levels (e.g., canopy, litter, soil), and enhance forest resilience. On the other hand, most of the tradeoffs found (n) reflected the impact of management itself, with a goods provision forest management negatively impacting biodiversity, forest structure, dead wood pools and soil quality (both in terms of soil carbon stocks and soil fertility). This highlights that managing forests for wood extraction generally worsens the forest services related to a structurally diversified and old-grown stand.

5 Discussion

5.1 Carbon pools in managed and unmanaged European forests

Retaining carbon stocks and increasing carbon sequestration are two forest management goals that are becoming increasingly important in the face of climate change. Forest management influences the carbon balance by altering the structure and energy fluxes of the forest (Noormets 2015). In this review, we found that unmanaged forests had a higher above-ground carbon stock compared to managed forests (Figure 12). At mature stages, unmanaged forests regularly have a lower stand density than their managed counterparts (e.g. Baran et al. 2020), but this discrepancy is offset by a higher number of large-diameter trees. This explains the frequent observation that above-ground carbon stocks increase with time since non-management, as the diameter of the largest trees is allowed to develop further (Albrich et al. 2021; Luyssaert et al. 2008). Stand density itself, however, can also increase in the first years after abandonment, contributing further to a heightened above-ground carbon stock in unmanaged forests (Meyer, Nagel, and Feldmann 2021). The incremental gain of time since no-management on above-ground carbon stock is expected to decrease as unmanaged forests become unmanaged for longer (Albrich et al. 2021), as living trees become older and reach their maximum living age, which ultimately through mortality creates gaps and starts regeneration, resetting the successional stage. This effect of stand age and time since non-management will be investigated in further analyses.

In addition, we confirmed that unmanaged European forests have a higher dead wood stock compared to managed forests (Figure 16). The large confidence interval in several biographical regions can mainly be attributed to a lower sample size, and due to variability among management regimes, with some records comparing older unmanaged forests with more recent unmanaged forests (< 20 years, and thus for this review seen as managed) or close-to-nature management regimes (in which dead wood is usually retained to a larger extent), and others comparing unmanaged forests to high-intensity forest management regimes, such as clearcuts, in which dead wood is typically removed or just barely created in the first place (e.g. Ziaco et al. 2012). However, here we must consider that the accumulation of dead biomass can also influence the resilience of forest ecosystems to natural disturbances, for example, pests such as boring insects in coniferous forests or a greater risk of ignition and spread of forest fires, especially in the Mediterranean region.

Below-ground carbon in unmanaged forests has higher stocks compared to managed forests, though non-significant in our analysis. Few studies investigate below-ground carbon stocks (e.g., root biomass), especially while comparing managed and unmanaged forests (Figure 14). Forest fine-root biomass, Claus and George (2005) concluded that a maximum biomass was reached at an adult stage of the forest, but saw a decrease at the mature stage, after which a steady-state occurred, which is usually seen as the conventional theory. However, Jagodzinski et al. (2016) found that fine root biomass increased linearly across tree age classes. Bolte et al. (2004) found that coarse root biomass increased as tree dimensions increased, which would align with our trend that unmanaged forests have a higher root biomass. As such, investing resources into further clarifying differences in below-ground carbon stocks between managed and unmanaged forests, e.g., through the use of

observational, comparative studies, is worthwhile to better quantify total carbon stock dynamics.

Soil carbon and forest floor carbon stocks did not seem to differ between managed and unmanaged forests. For soil carbon, it should be noted that the vast majority of the records related to a study in Finland (Simola 2018) where a specific tillage/non-tillage setup was tested. Though this setup is valid, it may not be representative for a larger share of forest management regimes across Europe. The soil carbon setup thus would greatly benefit from the additional measurements in the INFORMA field campaign of WP1/WP5, in which we measured soil carbon for a multitude of patches in the INFORMA Forest Management Platform. Together, we can use the data from this systematic review which should give us a good understanding of soil carbon dynamics between managed and unmanaged forests across the different biogeographical regions of Europe.

Forest floor differences did not follow a single trend, with both biogeographical regions showing positive and negative effect sizes. Firstly, similar to the below-ground carbon analysis, observations were relatively limited, lowering the statistical power of the dataset. However, this variation can also be attributed to the complexity of the matter: the forest floor is influenced by a multitude of factors, among which, climate, litter quality and canopy gaps (Penne et al. 2010; Schulp et al. 2008; Purahong et al. 2014). Litter quality is directly related to tree species (Schulp et al. 2008); this can be vastly different in managed and unmanaged forests, and can be beneficial for either side depending on the chosen/natural species. In this review, however, most of the studies operated on similar forest types having a comparable species composition (Figure 19.G). We thus expect this factor to play a minor role in this review and could potentially be something to account for in further research.

Fluxes were harder to harmonize, and also more limited regarding their number of records. Only above-ground carbon fluxes, i.e., net primary productivity (NPP), had a number of records that was sufficient for synthesis. It was expected that carbon sequestration would be higher in managed forests, as individual trees usually get more space and resources to grow, and are typically younger (Noormets 2015). However, among the available records, no evidence was found for an increased sequestration in managed forests (Figure 13). Similar to the forest floor analysis, it is noteworthy that species composition also plays a major role here; species were typically very similar among managed and unmanaged forests in this review, which does not always reflect the choice forest owners make: when an owner decides to manage her/his forest, the choice of species for maximizing productivity is a key decision to make, and is not by default similar to the species that would be chosen for forestry targeting conservation and/or non-management (Dieler et al. 2017). Regardless, whether species composition is similar or not, both need additional observations in a comparative design such as the one present in the INFORMA Forest Management Platform.

More striking was the lack of studies looking into soil carbon fluxes' differences among managed and unmanaged forests. Likely, this relates to the fact that soil carbon fluxes are harder and more expensive to measure. In addition, soil carbon fluxes can be spatially extremely heterogeneous, making it harder to get an accurate estimate of average flux rates at the "patch"-size (Shahbaz et al. 2022). Flux towers are great tools to resolve these problems, though current flux towers are not set up to measure differences between forest reserves and nearby managed forest areas.

Lastly, no records were found for dead wood fluxes. Fluxes in dead wood mainly relate to mortality of trees, intentionally created dead wood by leaving residue in the forest after management, or the decomposition rate of dead wood (i.e., negative flux), generating an habitat which positively impacts biodiversity, as identified by the trade-off analysis. Within our review, decomposition and mortality were not search terms as such, which may have made our approach less suitable to find the relevant literature among these fluxes. However, dead wood fluxes can also simply be quantified as a difference in dead wood over time, e.g., through remeasurement of research plots, which was also not the case within the studies we extracted. Regardless, dead wood fluxes are less relevant to the management context: dead wood can be created extremely quickly, and similarly removed in an instant. The stocks, as well as the properties of the dead wood (species, decomposition stage, dead wood size…), are of higher importance for both the accounting of carbon stocks and the conservation of biodiversity (Parajuli and Markwith 2023).

5.2 Compromises and synergies in ecosystem services provision

The relevance of old-grown, unmanaged forests to promote biodiversity is well known (e.g. Spies 2004; Dieler et al. 2017), providing that such forests increase structural diversity and, therefore, habitat heterogeneity (Hekkala et al. 2023). The reported synergies between biodiversity, forest structure and dead wood align with this fact. Increasing structural diversity and dead wood pool provide the habitats necessary for several organisms, such as saproxylic fungi (Küffer et al. 2008), cavity-nesting birds (Sandström et al. 2019), or xylophagous insects (Parisi et al. 2023), among others, to thrive. On the other hand, management for goods extraction tends to homogenize forest structure, reducing structural complexity and therefore negatively impacting biodiversity. A similar trade-off pattern is observed between extractive management and soil and standing biomass stocks. Removing part of the biomass for timber extraction reduces standing carbon stock, while also limiting the fluxes of organic matter to the soil (Mäkipää et al. 2023). Therefore, any intervention aiming to maximize forest carbon stocking capacity should include in their balances the trade-off between management intensity VS forest carbon storage. Providing that wood products also store carbon, specific wood products life-cycle analysis are necessary to shed more light regarding the overall effects of forest management on carbon sequestration in the wood (Evans et al., 2022). Additionally, the potential for fuel substitution of low-quality wood products (Myllyviita et al., 2021), such as firewood, should be further integrated into the analysis.

5.3 What is next? Building on the systematic review analysis

As the systematic review yielded a number of suitable studies (149 studies, with 2,204 records) for a diverse set of indicators, processing both the data and the statistics should be done with a great eye for detail. As such, we would like to extend the analysis from the first analysis shown here. Firstly, post-processing of measurement records that have diverging measurement units, and more complex research designs (e.g., re-measurements, temporal shifts…) will be done in more detail. Linked to the latter, statistical methods will be adapted to a divergent data structure, in which records are not aggregated per Site_ID, but are individually

compared for each managed/unmanaged combination. This creates a dependence of the effect sizes, as the control metric (i.e., the unmanaged forest) can be identical for multiple effect sizes (managed/unmanaged comparisons). The elaborated statistical model will account for this dependency. Consequently, this deeper analysis will allow us to investigate the effect of time since non-management, forest type and others reported impacting factors (Lajeunesse 2011). Secondly, the critical appraisal will be used more intensively to investigate the effects of missing or lower-quality data on the final research findings. Regarding the trade-off assessment, we plan to expand the analysis per biographical region, as we expect that the general trends here observed will be tinted when addressed at the biographical region level. Lastly, as mentioned in the Systematic Review Protocol, several records will be added after a final screening on Google Scholar, which increases the presence of gray literature in the review (Simons *et al*. 2024).

5.4 Reporting on comparative analysis in forestry research

Throughout the review, it became clear that there was a large variability in the reporting quality among articles. The data extraction template set up in the systematic review protocol served as an ideal scenario, though crucial data was frequently missing, either related to the core management variables (Figure 10 and Figure 11) or to potential modifier effects such as topography, climate and soil conditions (Figure 12). The reporting of these variables allows other scientists to better understand and contextualize the results of the comparative analysis and facilitates large-scale meta-analyses to explore more in-depth research questions while accounting for potential effect modifiers.

In Table 2 we present a list of important variables to report on in comparative analysis. Besides variables that are specific to either unmanaged or managed forests, the reporting should happen for both the managed and the unmanaged forests. Most emphasis should be put on the coordinates – with available coordinates; other variables can potentially be extracted from European-wide or national databases. Data can be either reported as an ensemble of plots, in which variables relate to mean values, or at the plot level, in which variables are specific to each plot. In the case of reporting as an ensemble (i.e., replication plots), reporting the number of plots and standard errors are fundamental for data integration exercises such as ours.

Table 2. Reporting guideline for comparative analyses in forestry – variable types are either general, modifier effects (environmental), related to management or describing forest structure.

Variable type	Variable	Unit
General	Coordinates	Decimal degrees, or DMS
	Measurement year(s)	Year
	Number of plots	/
Modifier effect - climate	Mean Annual Temperature (MAT)	°C
	Mean Annual Precipitation (MAP)	Mm
Modifier effect - topography	Elevation	M
	Slope	°
	Aspect	Northing and easting
Modifier effect - soil	Soil type	WRB classification
	Soil depth	M
Management information	Time since no management Time since last harvest	Years
	Harvest type	Individual trees, in groups, clearcut, shelterwood, etc.
	Harvest intensity	% of basal area, or % of volume
	Thinning intensity	% of basal area, or % of volume
	Thinning frequency	Years
	Rotation length	Years
	Management history	Changes in management information for past management
Forest structure information	Species composition	% of basal area per species
	Stand age	Years
	Age distribution	Even-aged/Uneven-aged

6 References

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7 Appendix

Appendix 1. Benchmark articles suggested by reviewer 1, alongside their response to different subsegments of the preliminary search string.

Paper	Found through search string?	Present in WoS?	Retained on region	Retained on unmanaged	Retained on managed	Retained on forest	Retained on carbon
Herbst *et al.* (2015)	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Merino *et al.* (2007)	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Schulp *et al.* (2008)	**No**	Yes	Yes	Yes	**No**	Yes	Yes
Mund and Schulze (2006)	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Krueger *et al.* (2017)	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Nagel *et al.* (2023)	**No**	Yes	**No**	Yes	**No**	Yes	Yes
Leuschner *et al.* (2022)	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Schulze *et al.* (2020)	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Dieler *et al.* (2017)	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Nord-Larsen *et al.* (2019)	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Appendix 2. Benchmark articles suggested by reviewer 2, alongside their response to different subsegments of the preliminary search string.

Paper	Found through	Present in WoS?	Retained on region	Retained on unmanaged	Retained on managed	Retained on forest	Retained on carbon

	search string?						
Uri *et al.*, (2022) STOTEN	**No**	Yes	**No**	**No**	Yes	Yes	Yes
Krug *et al.*, (2012)	**No**	Yes	**No**	Yes	Yes	Yes	Yes
Herbst *et al.*, (2015)	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Allen *et al.*, (2016)	**No**	Yes	Yes	Yes	**No**	Yes	Yes
Helin *et al.*, (2016)	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Seidl *et al.*, (2008)	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Neumann *et al.*, (2021)	Yes	Yes	Yes	Yes	Yes	Yes	No
Lindner *et al.*, (2010)	Yes	Yes	Yes	Yes	Yes	Yes	No
Dalmonech *et al.*, (2022)	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Scheelhaas *et al.*, (2018)	**No**	Yea	Yes	**No**	Yes	Yes	**No**