FORMAS
Ett forskningsråd för hållbar utveckling
A Research Council for Sustainable Development

What is the effect of harvest and associated management on soil carbon and greenhouse gas emissions in boreal and nemoral forests?

A systematic review protocol

Formas – Forskningsrådet för miljö, areella näringar och samhällsbyggande
Organisationsnummer:
202100-5232
Drottninggatan 89
Box 1206 111 82 Stockholm
Telefon:
08 775 40 00
registrator@formas.se
formas.se

What is the effect of harvest and associated management on soil carbon and greenhouse gas emissions in boreal and nemoral forests? A systematic review protocol

This systematic review protocol has been developed by Formas in collaboration with external subject experts.

Experts
Johan Stendahl, Swedish University of Agricultural Sciences
Erik Karltun, Swedish University of Agricultural Sciences
Karina Clemmensen, Swedish University of Agricultural Sciences
Michael Gundale, Swedish University of Agricultural Sciences
Monika Strömgren, Forestry Research Institute of Sweden

Formas
Magnus Land (project leader), senior analyst
Christel Hellberg, senior analyst
Matilda Svensson, information specialist

Please cite as
Land, M., K. Clemmensen, M. Gundale, C. Hellberg, E. Karltun, J. Stendahl and M. Strömgren (2025). What is the effect of harvest and associated management on soil carbon and greenhouse gas emissions in boreal and nemoral forests? A systematic review protocol. Report G2:2025. Stockholm, Formas. https://doi.org/10.65059/formas2025.001.

G2:2025
978-91-540-6243-0
2024–02768

Stockholm, 2025-11-21

Abstract

Background: The European Union (EU) and many other countries have ambitions to reach net zero emissions of greenhouse gases (GHGs). As net zero emissions may include GHG uptake by forests, the impact of forest management on the carbon sink-source balance is frequently debated. While the soil organic carbon constitutes a significant part of the total forest carbon stocks, changes in this pool are relatively slow and may be difficult to measure accurately. Consequently, it is debated whether soil carbon is lost in the short-term following management activities, and whether such losses are balanced by long-term gains in soil carbon. In boreal forests, commercial forest management is presently dominated by even-aged rotational silvicultural systems that are initiated via clear-cutting, while in nemoral forests, management systems are more variable and more frequently include uneven-aged forest stands. In the planned systematic review, we aim to compare soil carbon stocks and GHG emissions in forests with different silvicultural management. We will also evaluate the effect of specific harvest-associated management activities, including stump harvest, slash removal, mechanical site preparation, rutting prevention, compaction, and protective and maintenance ditching.

Methods: Literature will be searched using bibliographic databases provided by Web of Science, Scopus, CAB Abstracts, and ProQuest. Searches will also be conducted in bibliographies of relevant review articles and on web sites of relevant organizations. The comprehensiveness of the search will be tested through a list of relevant articles identified by the protocol development team before the searches. The search results will be screened in a two-stage process: first at title and abstract level, and second at full text level. The first stage will involve consistency tests between the reviewers. At the second stage, all retrieved articles will be screened independently by at least two reviewers. All studies included after full text screening will be critically appraised independently by two reviewers, using the Collaboration for Environmental Evidence Critical Appraisal Tool (CEECAT). Study characteristics and results will be compiled in narrative synthesis tables. If possible, study results will be further synthesized through meta-analysis. This systematic review supports Sweden's environmental quality objective of achieving reduced climate impact. Key stakeholders, including the Swedish Environmental Protection Agency and the Swedish Forest Agency, are expected to utilize the findings to inform policy and practice.

Table of content

1 Background 5
2 Objectives 6
3 Review questions 6
3.1 Definitions of the review question components (PICO/PECO) 7
3.2 Study selection criteria 7
4 Potential effect modifiers and reasons for heterogeneity 8
5 Stakeholder engagement and relevance for Swedish conditions 9
6 Methods 10
6.1 Literature search 10
6.2 Screening strategy 10
6.3 Data extraction 11
6.4 Study validity assessment / Critical appraisal 12
6.5 Synthesis methods 13
6.6 Conclusions and evidence grading 13
Acknowledgements 14
References 15
Appendix 1, Search strategy 17
Bibliographic databases and platforms 17
Search strings in bibliographic databases and platforms 17
Search strings in digital archives and search engines 22
Searches on specialist websites 24
Test references to assess comprehensiveness of the searches 25
Appendix 2, Data extraction forms 28

1 Background

Boreal and nemoral (temperate deciduous) forests are carbon (C) rich landscapes that have served as strong net C sinks, and they therefore play a pivotal role in the global C cycle [1]. Boreal forests alone cover approximately 17% of the terrestrial land surface area, and account for somewhere between 20 and 40% of terrestrial C stocks [2-5], with on average around 80% of the C in boreal forests found in soil [6]. Nemoral forests cover a more modest 10% of the terrestrial land area, and here soils account for 10 - 15% of the total C stocks. Soil C stocks in these systems can vary greatly among sites and regions, with major drivers of stock variation including topography, climate, parent materials, and forest composition [7, 8]. Given the large proportion of global terrestrial soil C in these biomes, it is crucial to understand how management activities affect the stability of these C stocks, as changed soil C balance may have implications for regional C balances, and even the global C cycle.

Boreal and nemoral forests are commonly subjected to both natural and anthropogenic disturbances, which have the potential to result in substantial soil C losses. The impacts of forestry activities on soil C stocks have been the focus of substantial societal debate, within the context of understanding whether forestry has a positive or negative effect on atmospheric CO_2 concentrations and climate change. Active forest management is presently the dominant influence in northern forests, with nearly all temperate forests, and more than half of the boreal region is under some form of management [6, 9]. In boreal forests, these are most often even-aged rotational silvicultural systems that are initiated via clear-cutting, and often followed by some form of site preparation and regeneration [9]. In nemoral forests, tree species mixtures and management systems are more variable, but both even- and uneven-aged approaches are frequently used, implementing many different regeneration strategies [10].

The net impact of forest management on the soil C sink-source balance is frequently debated, with specific debates focusing on whether soil C is lost in the short term following management activities (e.g. harvest or site preparation), and whether short term C losses are balanced by long term gains in soil C [11-13]. In response to this uncertainty, research focused on soil C stock changes and related C cycling processes (e.g. soil heterotrophic respiration) in relation to forestry activities has increased rapidly over recent decades. Studies are conducted in many different environmental contexts, and geographic regions, and can sometimes offer conflicting results, which can perpetuate debate. Systematic review and meta-analysis of published data is a useful pathway forward to aggregate available evidence and determine whether consensus can be reached from existing literature. Such analysis can also be used to identify where knowledge gaps remain, which in turn can identify the highest priority areas for new research. Therefore, the aim of this systematic review is to provide a state-of-knowledge summary of the impact of forestry practices on soil C stocks and related processes, and in doing so determine the degree of consensus, and knowledge gaps.

2 Objectives

The primary objective of the review is to quantify the effect of harvest and harvest associated management on soil organic C (SOC) stocks and greenhouse gas fluxes from soils in boreal and nemoral forests. Here, harvest management includes a range of practices and actions taken during and after final harvest until a new stand has been established. In rotation forestry, this usually involves tree felling, delimbing, forwarding logs and occasionally slash to a roadside landing, followed by mechanical site preparation, regeneration e.g. by planting or leaving seed trees, and possibly a precommercial thinning. The time span for these actions may vary from a few to 10 or 15 years after harvest, but the effects on the soil C stock and GHG fluxes may extend for substantially longer periods. As long-term effects may differ from short-term effects it is crucial to define the timeframe of the outcome measurements. For example, when looking at the effects of harvesting (compared to before or no harvest), an increased growth rate after harvest may in the long run compensate for short-term losses of soil C. Although some chronosequence studies may be able to show such long-term effects, we expect that most empirical studies have measured the effects on relatively short time scales. When considering long-term effects, it is also needed to account for climate change effects and natural disturbances such as wildfires, storm felling, diseases, and pest infestations. These factors are outside the scope of the review and may be better treated in modelling and risk assessment studies. The main objective of the planned systematic review is thus to estimate the magnitude and the time scale of the effects of harvest-related management practices, which is both debated and important for assessing the overall time-integrated effects.

In this review we focus on actions where contrasting management options have been practiced and can be compared. The management options that will be compared are further described in the section on review question components below.

In quantifying the effects of different harvest management options, the review will also aim at identifying factors that influence these effects (see section on potential effect modifiers/reasons for heterogeneity).

3 Review questions

The main question that the planned systematic review will attempt to answer is:

- What is the effect of harvest and associated management on soil carbon and greenhouse gas emissions in boreal and nemoral forests? A systematic review protocol

Secondary questions relate to the possible influence of effect modifiers, which include factors such as soil properties, site productivity, tree species identity, and climate. Our aim is to investigate whether these modifiers have any impact on the magnitude of the effects of the management options. Possible effect modifiers are treated in a separate section below.

3.1 Definitions of the review question components (PICO/PECO)

To be included in the review the studies must meet the criteria outlined in Table 1. These criteria define the fundamental elements of the review question, i.e., eligible study population, intervention or exposure, comparator, and outcome. As we are interested in effects of both the harvest itself and a range of specific management activities associated with the harvest, there are multiple definitions of the intervention/exposure and comparator elements of the review question. We expect that most studies have been conducted on final harvest in rotation forestry systems, but we will also include studies on partial harvest, including commercial thinning. The latter category may include harvest practiced in continuous cover forestry (CCF) systems such as selection systems, group systems, and shelterwood systems according to the terminology suggested by Brunner et al. [14]. For some of the specific activities associated with harvest, i.e., rutting (unintentional linear ground damage induced by vehicles) and soil compaction, we are interested in the effects of both the exposure itself and of interventions to prevent or minimise the exposure. Interventions to prevent rutting include, e.g., driving equipment on frozen ground only and deploying protective mats, branches, or other materials. In Sweden like in many other countries, extensive ditching operations have been carried out historically to enhance productivity by lowering the ground water table. However, to be included in the planned systematic review, the ditching must be protective ditching or maintenance ditching carried out in direct connection to harvest.

3.2 Study selection criteria

In addition to the eligibility criteria defined by the review question components (PICO/PECO), the study selection criteria define eligible study design, study type, type of publication, and language:

- **Study design:** The studies should have a control-intervention (CI), before-after (BA), or a before-after control-intervention (BACI) design. Chrono-sequence studies, where time is substituted for space, may be eligible if the baseline is reasonably clear.
- **Study types:** Original empirical field studies. Modelling studies may be eligible if they provide empirical validation data that we can use. However, while modelling results may be discussed in the review they will not be included in any quantitative synthesis. Litterbag studies will not be eligible for the review, as their results do not directly relate to quantitative changes of the in-situ SOC stocks. Afforestation and deforestation studies will also be excluded as land use change is out of the scope of this review.
- **Publication type:** All publication types except master theses and preprints.
- **Language:** No language will be excluded during the screening stages. However, if translation recourses are limited, other languages than English, Swedish, Norwegian, and Danish may be excluded at later stages.

A list of articles excluded at full text screening, with a reason for excluding each article, will be provided in the systematic review.

Table 1. Eligibility criteria. Interventions and comparators should be read row by row.

Eligible Population	
Boreal and nemoral forest soils within the Cfb, Cfc, and the Df climate zones according to the Köppen classification [15]. Both mineral soils and peatland soils will be included, but they may be treated separately in the synthesis. All soil layers will be included but may be treated separately in the synthesis as well.	
Eligible Intervention/Exposure	**Eligible Comparator**
final harvest	before or no final harvest (including both managed and unmanaged forest)
Partial harvest (including commercial thinning and harvest in CCF systems)	before or no harvest (including both managed and unmanaged forest)
stump harvest	before or no stump harvest
mechanical site preparation (mounding, scarification, disc trenching/harrowing, ploughing)	before or no mechanical site preparation, mild manual site preparation
rutting	before or no rutting
rutting prevention (e.g., frozen ground, mats, branches, driving planning)	no rutting prevention
soil compaction	before or no compaction
soil compaction prevention	no compaction prevention
ditching (protective and maintenance)	before or no ditching
slash removal	no slash removal
Eligible outcomes	
Response variables reflecting changes or differences in forest soil organic carbon (SOC) stock, soil organic matter (SOM) stock, CO_2 flux as soil heterotrophic respiration, CH_4 flux, and N_2O flux. For mineral soil layers SOC and SOM concentrations will also be included. For acidic soils lacking carbonate minerals, total carbon (TC) will be an eligible response variable. Studies reporting transport of dissolved or total carbon in water (DOC and TOC) will not be eligible.	

4 Potential effect modifiers and reasons for heterogeneity

Parameters that may explain heterogeneity among study results are mainly related to soil properties, site productivity, regeneration strategy, climate, fertilization, and time. For greenhouse gas flux measurements, the time of year may also have an impact on the effect. Parameters that will be extracted and potentially analysed in the data synthesis are shown in Table 2. It should be noted however that values of some of the soil parameters, like pH and C/N ratio, may vary considerably across a soil profile and it may therefore be difficult to evaluate the influence of such parameters. In addition to effect modifiers mentioned above and in Table 2, the intensity of the studied intervention/exposure may also have an impact on the effect magnitude.

Table 2. Potential effect modifiers and variables to be extracted reflecting those effect modifiers.

Effect modifier	Parameters to be recorded
Soil properties	soil type, soil texture, C/N ratio, pH, moisture class
Site productivity	vegetation type (in ground layer and field layer), tree species
Regeneration strategy	choice of tree species and regeneration method (planting, direct seeding, or self-regeneration)
Climate	climate zone, mean annual temperature, temperature sum, growing season duration
Fertilization	type, amount, frequency, time since last fertilization
Time of year (GHG fluxes)	measurement date, season
Time	time since intervention

5 Stakeholder engagement and relevance for Swedish conditions

Reduced Climate Impact is one of 16 environmental quality objectives in the Swedish environmental objectives system, adopted by the Swedish parliament in 1999. As designated responsible agency for this environmental quality objective, The Swedish Environmental Protection Agency (EPA) is one of the main users of the planned systematic review. The Swedish Forest Agency, which is responsible for the environmental quality objective Sustainable Forests, is another key user and stakeholder. As important as the governmental agencies are the forest owners. In Sweden, approximately 49 % of the productive forest land is owned by roughly 310,000 private individuals, 25 % by private companies, and around 20 % by the state or state-owned companies [16]. The forest owners are broadly organized through LRF Skogsägarna, which is a trade organization for the forest owner associations Södra, Mellanskog, and Norra Skog. The planned systematic review may also be of interest to environmental non-governmental organizations (NGOs) like WWF and the Swedish Society for Nature Conservation (Naturskyddsföreningen).

In preparation for this systematic review protocol, we consulted representatives from the Swedish EPA, the Swedish Forest Agency, LRF Skogsägarna, Skogssällskapet (a public service foundation), Sveaskog (state-owned company), and the Swedish Society for Nature Conservation. They have also been offered to comment on a draft of this protocol.

6 Methods

6.1 Literature search

Searches for scientific literature will primarily be conducted using Web of Science Core Collection, Scopus, CAB Abstracts, and ProQuest. Searches for grey literature will be conducted using BASE (Bielefeld Academic Search Engine), SwePub, Finna, ProQuest Dissertations and Theses, and Google Scholar. These archives and search engines may also contain scientific literature. Search languages will be English in the scientific literature databases and platforms, and in English and Swedish in the searches for grey literature. Search strings (combinations of terms using Boolean characters) and further details for each source are shown in Appendix 1.

Additional searches will be made in bibliographies of relevant review articles identified in the screening process, and on specialist websites listed in Appendix 1. The comprehensiveness of the searches will be assessed by comparing the search results with a list of relevant records that was compiled before any searches were conducted (see Appendix 1). Contributions to this list of benchmark articles were provided by the authors of this protocol and stakeholders consulted at an early planning stage of the review. The search strategy will be adjusted until all articles in the benchmark list are captured. The number of relevant articles identified in the bibliographies of review articles that are not captured by our searches will be used as an indicator of the comprehensiveness of the searches. Searches will be updated if the systematic review is published later than 18 months after the original searches.

6.2 Screening strategy

The records found in the searches will be imported to EndNote, deduplicated, and further exported to Eppi Reviewer [17] for screening. The literature screening will be a two-stage process: at the first stage based on titles and abstracts and at the second stage based on full text. Initially at the first stage, a subset of 300 titles and abstracts will be screened by all reviewers. To test the level of agreement among reviewers, Cohen's Kappa values will be calculated. Disagreements will be resolved and if necessary, the eligibility criteria will be clarified. This procedure will be repeated until we are confident that the eligibility criteria are interpreted the same way by all reviewers and that the screening process is repeatable. After that the remaining records at stage one will be split between two reviewers. At stage two, all retrieved full text articles will be double screened by two reviewers and disagreements will initially be discussed and resolved by the two reviewers. If needed, all reviewers will be involved to resolve doubtful cases.

During the screening process the records will be coded with one of the codes in Table 3. Even though several reasons for excluding an item may apply, each item will be coded with only one reason to exclude. However, relevant review articles will be coded with both "Relevant review" and "EXCLUDE" (stage 1) or "EXCLUDE on Study type" (stage 2). The reference lists in these reviews will be used to search for additional relevant studies not captured by our searches. To avoid potential conflicts of interest, members of the review team will not participate in decisions regarding the inclusion or exclusion of studies in which they were authors. The results of the screening process will be shown in a ROSES flow diagram [18].

Table 3. Coding options at stage 1 (title and abstract) and stage 2 (full text).

Codes for title and abstract screening	Codes for full text screening
INCLUDE	INCLUDE
EXCLUDE	EXCLUDE on Population
Relevant review	EXCLUDE on Intervention
	EXCLUDE on Comparator
	EXCLUDE on Outcome
	EXCLUDE on Study type
	EXCLUDE on Climate zone
	EXCLUDE on Language
	Relevant review

6.3 Data extraction

Data (results) and meta-data will be extracted from included studies by mainly one reviewer, using predesigned Excel spreadsheets (see Appendix 2). To test the repeatability of the process, and to assess the risk of mistakes in the data and meta-data extraction, a second reviewer will independently extract data and meta-data from a subset of included articles (approximately 10%). Disagreements will be resolved through discussions. If any ambiguities remain, data and meta-data will be extracted independently by a second reviewer from an additional set of articles. After that, any doubts during data extraction performed by a single reviewer will be discussed and cleared among all reviewers. All extracted metadata and data used in meta-analysis will be available in an Appendix (see also section on data synthesis and presentation).

The extracted data and meta-data will be recorded as reported and if necessary standardised in the synthesis stage. If repeated measurements have been carried out, data for all reported time points will be recorded. Depending on temporal representation of the data, each datapoint will be classified according to data type:

- **Momentary:** Short-term (<1 day) measurement on a specific occasion. Most relevant for gas flux measurements.
- **Annual average:** Annual average of several short-term or continuous measurements for one year or a multiple of whole years. Most relevant for gas flux measurements.
- **Period average:** Average of several short-term or continuous measurements during a period other than a multiple of whole years (e.g., 8 or 20 months). Most relevant for gas flux measurements.
- **Time-integrated:** Measurements representing a cumulative effect since time of intervention or exposure. Most relevant for soil samples but may also apply to amount of emitted gas.

In cases where outcome data were reported in graphic figures, we will use WebPlotDigitizer [19] to extract data. Should there be missing data or unclear information in some article we will consider reaching out to the corresponding author and request additional information. It is however unlikely that we will have

the resources to do that for a large number of articles. For some parameters that may be rarely reported, we will attempt to retrieve data from global databases. For example, climate zone will be retrieved from World Map of the Köppen-Geiger climate classification [15]. Metadata will be recorded in a separate column for each comparison. A comparison is here defined as a contrast between a specific intervention treatment and a specific control treatment in a specific study, whereas a study is defined as an investigation at a specific location during a specific time interval. A study may thus report results from several comparisons, for which several outcomes may have been measured at more than one soil depth or in more than one soil layer.

6.4 Study validity assessment / Critical appraisal

Critical appraisal of relevant studies will include an assessment of internal and external validity.

Internal validity

Internal validity of a study may be reduced by systematic errors, or bias, caused by inappropriate research methods resulting in inaccurate results. The risk of bias in each study will be assessed using the CEE Critical appraisal tool, version 0.3 [20]. After an initial round of trial assessments of approximately 5 studies we will evaluate the tool and if appropriate modify it to adapt the criteria to the type of studies included in the planned review. As guidance, we will use the principles and framework for assessing internal validity suggested by Frampton et al. [21].

External validity

Applicability is one important aspect of external study validity, i.e., the degree to which the studies are appropriate or applicable for answering the review question in a particular context. This is primarily assessed during study eligibility screening. Another aspect of external validity that needs to be considered when evaluating the strength of evidence is the transferability of study results from small-scale experimental studies to full-scale forest harvesting practices. Studies will not be excluded based on the scale of the study, but we will record the type and scale of included studies to be able to perform subgroup analyses and assess the overall transferability of the evidence base.

Coding for study validity assessment

Critical appraisal and coding for internal study validity will start with an exercise where all reviewers assess the studies reported in the same five articles, followed by discussions and reconciliation of disagreements. Having aligned our interpretation of the criteria, the critical appraisal and coding for internal study validity will from that point be carried out by five reviewers, and each study will be critically appraised independently by two reviewers. The pairs of reviewers will rotate so that all reviewers will assess a subset of articles in pair with each of the other four reviewers. This means that the included articles will be subdivided in ten batches and that the five reviewers will assess four batches each. After each round of assessments, the disagreements within pairs will be recorded and reconciled through discussions among all reviewers. In this way the interpretation and application of the criteria will become increasingly aligned among the reviewers, enabling reconsideration of earlier assessments if appropriate. The reviewers will not be allowed to assess the validity of their own work. If quantitative synthesis is feasible, a sensitivity analysis will be performed, comparing results with and without excluding studies with low internal validity. Internal validity (overall risk of bias) may also be used as a categorical variable in meta-regressions.

6.5 Synthesis methods

Included studies will be summarized in a metadata table based on the metadata extraction form shown in Appendix 2. The purpose of the metadata table is to provide a quick overview of the key characteristics of each included study, including risk of bias assessments. The metadata table will in turn be summarized through presentation of descriptive statistics regarding some of the key characteristics, for example location of the studies, intervention treatments, control treatments, measured outcomes, time and duration of the studies, as well as parameters related to potential effect modifiers (see previous section). The meta-data table will also be transposed and merged with the data table and calculated effect sizes, providing a complete dataset for all analyses undertaken in the systematic review.

Quantitative synthesis through meta-analysis will be performed when at least five comparisons involving the same intervention treatment and control treatment are available, using the metafor package in R [22]. Raw mean difference (D) will be used as effect size. Alternatively, we may consider using log response ratio as effect size if D is not feasible.

Some studies may investigate multiple intervention treatments (e.g., multiple site preparation techniques) or multiple intensities of one intervention treatment (e.g., planting density or site preparation depth), and one shared control treatment. Comparisons between the different intervention treatments or treatment intensities and the shared control treatment are not independent. Also, repeated measurements at multiple timepoints in the same study are not independent. To account for the non-independence of sampling variances, we will construct a variance covariance matrix using the vcalc function in the metafor package [22, 23]. Moreover, effect sizes from studies conducted at the same site (and soil) may not be independent even if there is a separate control group for each intervention group. To account for non-independence among such effect sizes we will use a multilevel random-effects model nested around study location. In cases where studies report results from multiple timepoints we will use data from specific timepoints in separate meta-analyses to examine the effects at a specific time after the intervention. However, we will also explore the feasibility of using variance-covariance matrix structures allowing meta-analysis of effect sizes reported at multiple time-points to examine effects over the entire study period (see, e.g., [24, 25]). Separate meta-analyses will be performed for each outcome measure. In each meta-analysis, we will thus use only one response variable per comparison. However, SOM may be converted to SOC using a multiplication factor of 0.58, and CH_4 flux and N_2O flux may be converted to CO_2-equivavalent fluxes using multiplication factors of 25 for CH_4 and 298 for N_2O.

In case of significant heterogeneity among study results, we will attempt to identify potential effect modifiers, including time after intervention/exposure, through subgroup analyses and meta-regressions. The meta-analyses based on intercept-only models will be illustrated in forest plots, whereas meta-regressions based on a single continuous effect modifier will be illustrated in regression plots. To assess the risk of publication bias, funnel plots and Egger's regression tests will be employed when at least 10 comparisons are available.

6.6 Conclusions and evidence grading

Conclusions will be based on results from the meta-analyses and narrative syntheses. These conclusions will be evidence-graded, i.e. we will describe how much confidence we have in the conclusions based on the size of the dataset underpinning the conclusion, if the studies have been conducted by different research groups and in various locations, the robustness of the result, the risk of bias of the studies,

transferability to the Swedish context and consistency between studies. The method of grading is inspired by the GRADE: framework. The conclusions will be categorized into the following four levels, and the reasons for the decisions for each grading will be stated in a table or text:

- **When we state we are very certain**, it means we assess the evidence as robust and that future research is unlikely to affect the result.
- **When we say we are fairly certain**, it means we have identified some shortcomings in the evidence, but these are not considered to weaken the conclusion.
- **When we say we are less certain**, it is because we have identified shortcomings in the evidence that may weaken the conclusion, and the aggregated results may therefore be misleading.
- **When we use the word uncertain in a conclusion**, it means we have identified serious shortcomings.

Also, the stronger the evidence, the less likely it is that reported results will be affected by new research findings in the foreseeable future.

Acknowledgements

We would like to express our sincere gratitude to Neal Haddaway, Cecilia Akselsson, and an anonymous reviewer for valuable comments on an earlier draft, contributing to a significant improvement of the manuscript. We would also like to thank the stakeholders mentioned in the background section for taking time and sharing their insightful perspectives.

References

1. Watts JD, Farina M, Kimball JS, Schiferl LD, Liu ZH, Arndt KA, Zona D, Ballantyne A, Euskirchen ES, Parmentier FJW *et al*: **Carbon uptake in Eurasian boreal forests dominates the high-latitude net ecosystem carbon budget**. *Global Change Biology* 2023, **29**(7):1870-1889. https://doi.org/10.1111/gcb.16553
2. Tarnocai C, Canadell JG, Schuur EAG, Kuhry P, Mazhitova G, Zimov S: **Soil organic carbon pools in the northern circumpolar permafrost region**. *Global Biogeochemical Cycles* 2009, **23**. https://doi.org/10.1029/2008GB003327
3. Lorenz K, Lal R: **Introduction**. In: *Carbon Sequestration in Forest Ecosystems.* Dordrecht: Springer Netherlands; 2010: 1-21. https://doi.org/10.1007/978-90-481-3266-9_1
4. Bradshaw CJA, Warkentin IG: **Global estimates of boreal forest carbon stocks and flux**. *Global and Planetary Change* 2015, **128**:24-30. https://doi.org/10.1016/j.gloplacha.2015.02.004
5. Anderson JM: **The effects of climate change on decomposition processes in grassland and coniferous forests**. *Ecological Applications* 1991, **1**(3):326-347. https://doi.org/10.2307/1941761
6. Pan YD, Birdsey RA, Fang JY, Houghton R, Kauppi PE, Kurz WA, Phillips OL, Shvidenko A, Lewis SL, Canadell JG *et al*: **A Large and Persistent Carbon Sink in the World's Forests**. *Science* 2011, **333**(6045):988-993. https://doi.org/10.1126/science.1201609
7. Jandl R, Lindner M, Vesterdal L, Bauwens B, Baritz R, Hagedorn F, Johnson DW, Minkkinen K, Byrne KA: **How strongly can forest management influence soil carbon sequestration?** *Geoderma* 2007, **137**(3-4):253-268. https://doi.org/10.1016/j.geoderma.2006.09.003
8. Sothe C, Gonsamo A, Arabian J, Kurz WA, Finkelstein SA, Snider J: **Large Soil Carbon Storage in Terrestrial Ecosystems of Canada**. *Global Biogeochemical Cycles* 2022, **36**(2). https://doi.org/10.1029/2021GB007213
9. Gauthier S, Bernier P, Kuuluvainen T, Shvidenko AZ, Schepaschenko DG: **Boreal forest health and global change**. *Science* 2015, **349**(6250):819-822. https://doi.org/10.1126/science.aaa9092
10. Ameray A, Bergeron Y, Valeria O, Montoro Girona M, Cavard X: **Forest Carbon Management: a Review of Silvicultural Practices and Management Strategies Across Boreal, Temperate and Tropical Forests**. *Current Forestry Reports* 2021, **7**(4):245-266. https://doi.org/10.1007/s40725-021-00151-w
11. Bellassen V, Luyssaert S: **Managing forests in uncertain times**. *Nature* 2014, **506**(7487):153-155. https://doi.org/10.1038/506153a
12. Peichl M, Martínez-García E, Fransson JES, Wallerman J, Laudon H, Lundmark T, Nilsson MB: **On the uncertainty in estimates of the carbon balance recovery time after forest clear-cutting**. *Global Change Biology* 2023, **29**(15):E1-E3. https://doi.org/10.1111/gcb.16772
13. Lindroth A: **Clarifying the carbon balance recovery time after clear-cutting**. *Global Change Biology* 2023, **29**(15):4178-4179. https://doi.org/10.1111/gcb.16771

14. Brunner A, Valkonen S, Goude M, Hanssen KH, Erefur C: **Definitions and Terminology: What Is Continuous Cover Forestry in Fennoscandia?** In: *Continuous Cover Forestry in Boreal Nordic Countries.* Edited by Rautio P, Routa J, Huuskonen S, Holmström E, Cedergren J, Kuehne C. Cham: Springer Nature Switzerland; 2025: 11-43. https://doi.org/10.1007/978-3-031-70484-0_2

15. Kottek M, Grieser J, Beck C, Rudolf B, Rubel F: **World map of the Koppen-Geiger climate classification updated**. *Meteorol Z* 2006, **15**(3):259-263. https://doi.org/10.1127/0941-2948/2006/0130

16. **Fastigheter och ägare** [https://www.skogsstyrelsen.se/statistik/fastighets--och-agarstruktur/]

17. **EPPI Reviewer** [https://eppi.ioe.ac.uk/cms/Default.aspx?alias=eppi.ioe.ac.uk/cms/er4]

18. Haddaway NR, Macura B, Whaley P, Pullin AS: **ROSES Flow diagram for Systematic Reviews. Version 1.0**. https://www.roses-reporting.com/flow-diagram; 2017.

19. **Webplotdigitizer: Version 4.6** [https://automeris.io/WebPlotDigitizer/]

20. Konno K, Livoreil B, Pullin AS: **Collaboration for Environmental Evidence Critical Appraisal Tool Version 0.3 (Prototype)**; 2021.

21. Frampton G, Whaley P, Bennett M, Bilotta G, Dorne J-LCM, Eales J, James K, Kohl C, Land M, Livoreil B *et al*: **Principles and framework for assessing the risk of bias for studies included in comparative quantitative environmental systematic reviews**. *Environmental Evidence* 2022, **11**(1):12. https://doi.org/10.1186/s13750-022-00264-0

22. Viechtbauer W: **Conducting Meta-Analyses in R with the metafor Package**. *Journal of Statistical Software* 2010, **36**(3):1 - 48. https://doi.org/10.18637/jss.v036.i03

23. Nakagawa S, Yang Y, Macartney EL, Spake R, Lagisz M: **Quantitative evidence synthesis: a practical guide on meta-analysis, meta-regression, and publication bias tests for environmental sciences**. *Environmental Evidence* 2023, **12**(1):8. https://doi.org/10.1186/s13750-023-00301-6

24. Ishak KJ, Platt RW, Joseph L, Hanley JA, Caro JJ: **Meta-analysis of longitudinal studies**. *Clinical Trials* 2007, **4**(5):525-539. https://doi.org/10.1177/1740774507083567

25. Trikalinos TA, Olkin I: **Meta-analysis of effect sizes reported at multiple time points: A multivariate approach**. *Clinical Trials* 2012, **9**(5):610-620. https://doi.org/10.1177/1740774512453218

Appendix 1, Search strategy

Bibliographic databases and platforms

Table S1:4. Bibliographic databases and platforms that will be used in searches for literature.

Database/platform	Publisher and URL	Fields to search
Web of Science[1)]	Clarivate Analytics, https://clarivate.com/products/web-of-science/	title, abstract, author keywords
Scopus	Elsevier, https://www.scopus.com/	title, abstract, author keywords
CAB Abstracts[2)]	Wolters Kluwer, https://www.ovid.com/ovid/home/index.html	title, abstract
ProQuest[3)]	Clarivate, https://www.proquest.com/	title, abstract, identifiers

[1)] Web of Science™ Core Collection, including Science Citation Index Expanded (SCI-EXPANDED), Social Sciences Citation Index (SSCI), Arts & Humanities Citation Index (A&HCI), Conference Proceedings Citation Index- Science (CPCI-S), Conference Proceedings Citation Index- Social Science & Humanities (CPCI-SSH) and Emerging Sources Citation Index (ESCI).

[2)] Segments covering 1973-2025 week 36.

[3)] Agriculture Science Collection including AGRICOLA (1970-current) and Agriculture Science Database (1998-current).

Search strings in bibliographic databases and platforms

For each bibliographic database we have combined three search strings. The search strings are equal regarding terms relating to population and intervention but differ regarding terms relating to outcome.

Table S1:2. Search strings for Web of Science Core Collection.

String ID	Terms
String 1	(TI=(forest* OR hardwood OR wood OR conifer* OR deciduous OR pinus OR picea OR larix OR betula OR acer OR fagus OR sorbus OR salix) OR AB=(forest* OR hardwood OR wood OR conifer* OR deciduous OR pinus OR picea OR larix OR betula OR acer OR fagus OR sorbus OR salix) OR AK=(forest* OR hardwood OR wood OR conifer* OR deciduous OR pinus OR picea OR larix OR betula OR acer OR fagus OR sorbus OR salix)) **AND** (TI=(soil OR "forest floor" OR solum) OR AB=(soil OR "forest floor" OR solum) OR AK=(soil OR "forest floor" OR solum)) **AND** (TI=(harvest* OR logging OR uneven-aged OR "continuous cover" OR felling OR clear-cut* OR clearcut* OR thinning OR "site preparation" OR mound* OR scarification OR harrow* OR plough* OR plow* OR stump OR slash OR brash OR trench OR drain OR ditch OR compaction OR rutting OR "ground damage" OR "stand age" OR chronosequence OR chronosequences) OR AB=(harvest* OR logging OR uneven-aged OR "continuous cover" OR felling OR clear-cut* OR clearcut* OR thinning OR "site preparation" OR mound* OR scarification OR harrow* OR plough* OR plow* OR stump OR slash OR brash OR trench OR drain OR ditch OR compaction OR rutting OR "ground damage" OR "stand age" OR chronosequence OR chronosequences) OR AK=(harvest* OR logging OR uneven-aged OR "continuous cover" OR felling OR clear-cut* OR clearcut* OR thinning OR "site preparation" OR mound* OR scarification OR harrow* OR plough* OR plow* OR stump OR slash OR brash OR trench OR drain OR ditch OR compaction OR rutting OR "ground damage" OR "stand age" OR chronosequence OR chronosequences)) **AND** (TI=("carbon balance" OR "carbon pool" OR "carbon sink" OR "carbon source" OR "carbon stock*" OR "carbon concentration*" OR "heterotrophic

	respiration" OR "soil C" OR "soil carbon" OR "soil organic carbon" OR "soil organic matter" OR "soil respiration") OR AB=("carbon balance" OR "carbon pool" OR "carbon sink" OR "carbon source" OR "carbon stock*" OR "carbon concentration*" OR "heterotrophic respiration" OR "soil C" OR "soil carbon" OR "soil organic carbon" OR "soil organic matter" OR "soil respiration") OR AK=("carbon balance" OR "carbon pool" OR "carbon sink" OR "carbon source" OR "carbon stock*" OR "carbon concentration*" OR "heterotrophic respiration" OR "soil C" OR "soil carbon" OR "soil organic carbon" OR "soil organic matter" OR "soil respiration"))
String 2	(TI=(forest* OR hardwood OR wood OR conifer* OR deciduous OR pinus OR picea OR larix OR betula OR acer OR fagus OR sorbus OR salix) OR AB=(forest* OR hardwood OR wood OR conifer* OR deciduous OR pinus OR picea OR larix OR betula OR acer OR fagus OR sorbus OR salix) OR AK=(forest* OR hardwood OR wood OR conifer* OR deciduous OR pinus OR picea OR larix OR betula OR acer OR fagus OR sorbus OR salix)) **AND** (TI=(soil OR "forest floor" OR solum) OR AB=(soil OR "forest floor" OR solum) OR AK=(soil OR "forest floor" OR solum)) **AND** (TI=(harvest* OR logging OR uneven-aged OR "continuous cover" OR felling OR clear-cut* OR clearcut* OR thinning OR "site preparation" OR mound* OR scarification OR harrow* OR plough* OR plow* OR stump OR slash OR brash OR trench OR drain OR ditch OR compaction OR rutting OR "ground damage" OR "stand age" OR chronosequence OR chronosequences) OR AB=(harvest* OR logging OR uneven-aged OR "continuous cover" OR felling OR clear-cut* OR clearcut* OR thinning OR "site preparation" OR mound* OR scarification OR harrow* OR plough* OR plow* OR stump OR slash OR brash OR trench OR drain OR ditch OR compaction OR rutting OR "ground damage" OR "stand age" OR chronosequence OR chronosequences) OR AK=(harvest* OR logging OR uneven-aged OR "continuous cover" OR felling OR clear-cut* OR clearcut* OR thinning OR "site preparation" OR mound* OR scarification OR harrow* OR plough* OR plow* OR stump OR slash OR brash OR trench OR drain OR ditch OR compaction OR rutting OR "ground damage" OR "stand age" OR chronosequence OR chronosequences)) **AND** (TI=("carbon dioxide" OR methane OR "nitrous oxide" OR CO2 OR CH4 OR N2O OR "greenhouse gas*") OR AB=("carbon dioxide" OR methane OR "nitrous oxide" OR CO2 OR CH4 OR N2O OR "greenhouse gas*") OR AK=("carbon dioxide" OR methane OR "nitrous oxide" OR CO2 OR CH4 OR N2O OR "greenhouse gas*")) **AND** (TI=(flux OR efflux OR emission OR exchange OR oxidation OR emitted OR release OR capture OR storage) OR AB=(flux OR efflux OR emission OR exchange OR oxidation OR emitted OR release OR capture OR storage) OR AK=(flux OR efflux OR emission OR exchange OR oxidation OR emitted OR release OR capture OR storage))
String 3	(TI=(forest* OR hardwood OR wood OR conifer* OR deciduous OR pinus OR picea OR larix OR betula OR acer OR fagus OR sorbus OR salix) OR AB=(forest* OR hardwood OR wood OR conifer* OR deciduous OR pinus OR picea OR larix OR betula OR acer OR fagus OR sorbus OR salix) OR AK=(forest* OR hardwood OR wood OR conifer* OR deciduous OR pinus OR picea OR larix OR betula OR acer OR fagus OR sorbus OR salix)) **AND** (TI=(soil OR "forest floor" OR solum) OR AB=(soil OR "forest floor" OR solum) OR AK=(soil OR "forest floor" OR solum)) **AND** (TI=(harvest* OR logging OR uneven-aged OR "continuous cover" OR felling OR clear-cut* OR clearcut* OR thinning OR "site preparation" OR mound* OR scarification OR harrow* OR plough* OR plow* OR stump OR slash OR brash OR trench OR drain OR ditch OR compaction OR rutting OR "ground damage" OR "stand age" OR chronosequence OR chronosequences) OR AB=(harvest* OR logging OR uneven-aged OR "continuous cover" OR felling OR clear-cut* OR clearcut* OR thinning OR "site preparation" OR mound* OR scarification OR harrow* OR plough* OR plow* OR stump OR slash OR brash OR trench OR drain OR ditch OR compaction OR rutting OR "ground damage" OR "stand age" OR chronosequence OR chronosequences) OR AK=(harvest* OR logging OR uneven-aged OR "continuous cover" OR felling OR clear-cut* OR clearcut* OR thinning OR "site preparation" OR mound* OR scarification OR harrow* OR plough* OR plow* OR stump OR slash OR brash OR trench OR drain OR ditch OR compaction OR rutting OR "ground damage" OR "stand age" OR chronosequence OR chronosequences)) **AND** (TI=("total carbon" OR "total C" OR biomass OR "forest floor carbon" OR "organic matter" OR "organic mass" OR "organic carbon") OR AB=("total carbon" OR "total C" OR biomass OR "forest floor carbon" OR "organic matter" OR "organic mass" OR "organic carbon") OR AK=("total carbon" OR "total C" OR biomass OR "forest floor carbon" OR "organic matter" OR "organic mass" OR "organic carbon")) **AND** (TI=(stock OR mass OR content OR concentration OR store OR accumulat* OR gain OR loss OR mobilisation) OR AB=(stock OR mass OR content OR concentration OR store OR accumulat* OR gain OR loss OR mobilisation) OR AK=(stock OR mass OR content OR concentration OR store OR accumulat* OR gain OR loss OR mobilisation))
Search string	**1 OR 2 OR 3**

Table S1:3. Search strings for Scopus.

String ID	Terms
String 1	(TITLE(forest* OR hardwood OR wood OR conifer* OR deciduous OR pinus OR picea OR larix OR betula OR acer OR fagus OR sorbus OR salix) OR ABS(forest* OR hardwood OR wood OR conifer* OR deciduous OR pinus OR picea OR larix OR betula OR acer OR fagus OR sorbus OR salix) OR AUTHKEY(forest* OR hardwood OR wood OR conifer* OR deciduous OR pinus OR picea OR larix OR betula OR acer OR fagus OR sorbus OR salix)) **AND** (TITLE(soil OR "forest floor" OR solum) OR ABS(soil OR "forest floor" OR solum) OR AUTHKEY(soil OR "forest floor" OR solum)) **AND** (TITLE(harvest* OR logging OR uneven-aged OR "continuous cover" OR felling OR clear-cut* OR clearcut* OR thinning OR "site preparation" OR mound* OR scarification OR harrow* OR plough* OR plow* OR stump OR slash OR brash OR trench OR drain OR ditch OR compaction OR rutting OR "ground damage" OR "stand age" OR chronosequence OR chronosequences) OR ABS(harvest* OR logging OR uneven-aged OR "continuous cover" OR felling OR clear-cut* OR clearcut* OR thinning OR "site preparation" OR mound* OR scarification OR harrow* OR plough* OR plow* OR stump OR slash OR brash OR trench OR drain OR ditch OR compaction OR rutting OR "ground damage" OR "stand age" OR chronosequence OR chronosequences) OR AUTHKEY(harvest* OR logging OR uneven-aged OR "continuous cover" OR felling OR clear-cut* OR clearcut* OR thinning OR "site preparation" OR mound* OR scarification OR harrow* OR plough* OR plow* OR stump OR slash OR brash OR trench OR drain OR ditch OR compaction OR rutting OR "ground damage" OR "stand age" OR chronosequence OR chronosequences)) **AND** (TITLE("carbon balance" OR "carbon pool" OR "carbon sink" OR "carbon source" OR "carbon stock*" OR "carbon concentration*" OR "c balance" OR "c pool" OR "c sink" OR "c source" OR "c stock*" OR "c concentration*" OR "heterotrophic respiration" OR "soil C" OR "soil carbon" OR "soil organic carbon" OR "soil organic matter" OR "soil respiration") OR ABS("carbon balance" OR "carbon pool" OR "carbon sink" OR "carbon source" OR "carbon stock*" OR "carbon concentration*" OR "c balance" OR "c pool" OR "c sink" OR "c source" OR "c stock*" OR "c concentration*" OR "heterotrophic respiration" OR "soil C" OR "soil carbon" OR "soil organic carbon" OR "soil organic matter" OR "soil respiration") OR AUTHKEY("carbon balance" OR "carbon pool" OR "carbon sink" OR "carbon source" OR "carbon stock*" OR "carbon concentration*" OR "c balance" OR "c pool" OR "c sink" OR "c source" OR "c stock*" OR "c concentration*" OR "heterotrophic respiration" OR "soil C" OR "soil carbon" OR "soil organic carbon" OR "soil organic matter" OR "soil respiration"))
String 2	(TITLE(forest* OR hardwood OR wood OR conifer* OR deciduous OR pinus OR picea OR larix OR betula OR acer OR fagus OR sorbus OR salix) OR ABS(forest* OR hardwood OR wood OR conifer* OR deciduous OR pinus OR picea OR larix OR betula OR acer OR fagus OR sorbus OR salix) OR AUTHKEY(forest* OR hardwood OR wood OR conifer* OR deciduous OR pinus OR picea OR larix OR betula OR acer OR fagus OR sorbus OR salix)) **AND** (TITLE(soil OR "forest floor" OR solum) OR ABS(soil OR "forest floor" OR solum) OR AUTHKEY(soil OR "forest floor" OR solum)) **AND** (TITLE(harvest* OR logging OR uneven-aged OR "continuous cover" OR felling OR clear-cut* OR clearcut* OR thinning OR "site preparation" OR mound* OR scarification OR harrow* OR plough* OR plow* OR stump OR slash OR brash OR trench OR drain OR ditch OR compaction OR rutting OR "ground damage" OR "stand age" OR chronosequence OR chronosequences) OR ABS(harvest* OR logging OR uneven-aged OR "continuous cover" OR felling OR clear-cut* OR clearcut* OR thinning OR "site preparation" OR mound* OR scarification OR harrow* OR plough* OR plow* OR stump OR slash OR brash OR trench OR drain OR ditch OR compaction OR rutting OR "ground damage" OR "stand age" OR chronosequence OR chronosequences) OR AUTHKEY(harvest* OR logging OR uneven-aged OR "continuous cover" OR felling OR clear-cut* OR clearcut* OR thinning OR "site preparation" OR mound* OR scarification OR harrow* OR plough* OR plow* OR stump OR slash OR brash OR trench OR drain OR ditch OR compaction OR rutting OR "ground damage" OR "stand age" OR chronosequence OR chronosequences)) **AND** (TITLE("carbon dioxide" OR methane OR "nitrous oxide" OR CO2 OR CH4 OR N2O OR "greenhouse gas*") OR ABS("carbon dioxide" OR methane OR "nitrous oxide" OR CO2 OR CH4 OR N2O OR "greenhouse gas*") OR AUTHKEY("carbon dioxide" OR methane OR "nitrous oxide" OR CO2 OR CH4 OR N2O OR "greenhouse gas*")) **AND** (TITLE(flux OR efflux OR emission OR exchange OR oxidation OR emitted OR release OR capture OR storage) OR ABS(flux OR efflux OR emission OR exchange OR oxidation OR emitted OR release OR capture OR storage) OR AUTHKEY(flux OR efflux OR emission OR exchange OR oxidation OR emitted OR release OR capture OR storage))

String 3	(TITLE(forest* OR hardwood OR wood OR conifer* OR deciduous OR pinus OR picea OR larix OR betula OR acer OR fagus OR sorbus OR salix) OR ABS(forest* OR hardwood OR wood OR conifer* OR deciduous OR pinus OR picea OR larix OR betula OR acer OR fagus OR sorbus OR salix) OR AUTHKEY(forest* OR hardwood OR wood OR conifer* OR deciduous OR pinus OR picea OR larix OR betula OR acer OR fagus OR sorbus OR salix)) **AND** (TITLE(soil OR "forest floor" OR solum) OR ABS(soil OR "forest floor" OR solum) OR AUTHKEY(soil OR "forest floor" OR solum)) **AND** (TITLE(harvest* OR logging OR uneven-aged OR "continuous cover" OR felling OR clear-cut* OR clearcut* OR thinning OR "site preparation" OR mound* OR scarification OR harrow* OR plough* OR plow* OR stump OR slash OR brash OR trench OR drain OR ditch OR compaction OR rutting OR "ground damage" OR "stand age" OR chronosequence OR chronosequences) OR ABS(harvest* OR logging OR uneven-aged OR "continuous cover" OR felling OR clear-cut* OR clearcut* OR thinning OR "site preparation" OR mound* OR scarification OR harrow* OR plough* OR plow* OR stump OR slash OR brash OR trench OR drain OR ditch OR compaction OR rutting OR "ground damage" OR "stand age" OR chronosequence OR chronosequences) OR AUTHKEY(harvest* OR logging OR uneven-aged OR "continuous cover" OR felling OR clear-cut* OR clearcut* OR thinning OR "site preparation" OR mound* OR scarification OR harrow* OR plough* OR plow* OR stump OR slash OR brash OR trench OR drain OR ditch OR compaction OR rutting OR "ground damage" OR "stand age" OR chronosequence OR chronosequences)) **AND** (TITLE("total carbon" OR "total C" OR biomass OR "forest floor carbon" OR "organic matter" OR "organic mass" OR "organic carbon") OR ABS("total carbon" OR "total C" OR biomass OR "forest floor carbon" OR "organic matter" OR "organic mass" OR "organic carbon") OR AUTHKEY("total carbon" OR "total C" OR biomass OR "forest floor carbon" OR "organic matter" OR "organic mass" OR "organic carbon")) **AND** (TITLE(stock OR mass OR content OR concentration OR store OR accumulat* OR gain OR loss OR mobilisation OR pool) OR ABS(stock OR mass OR content OR concentration OR store OR accumulat* OR gain OR loss OR mobilisation OR pool) OR AUTHKEY(stock OR mass OR content OR concentration OR store OR accumulat* OR gain OR loss OR mobilisation OR pool))
Search string	**1 OR 2 OR 3**

Table S1:4. Search strings for CAB Abstracts.

String ID	Terms
String 1	((forest* OR hardwood OR wood OR conifer* OR deciduous OR pinus OR picea OR larix OR betula OR acer OR fagus OR sorbus OR salix) **AND** (soil OR forest floor OR solum) **AND** (harvest* OR logging OR uneven-aged OR continuous cover OR felling OR clear-cut* OR clearcut* OR thinning OR site preparation OR mound* OR scarification OR harrow* OR plough* OR plow* OR stump OR slash OR brash OR trench OR drain OR ditch OR compaction OR rutting OR ground damage OR stand age OR chronosequence OR chronosequences) **AND** (carbon balance OR carbon pool OR carbon sink OR carbon source OR carbon stock* OR carbon concentration* OR heterotrophic respiration OR soil C OR soil carbon OR soil organic carbon OR soil organic matter OR soil respiration)).ab,ti
String 2	((forest* OR hardwood OR wood OR conifer* OR deciduous OR pinus OR picea OR larix OR betula OR acer OR fagus OR sorbus OR salix) **AND** (soil OR forest floor OR solum) **AND** (harvest* OR logging OR uneven-aged OR continuous cover OR felling OR clear-cut* OR clearcut* OR thinning OR site preparation OR mound* OR scarification OR harrow* OR plough* OR plow* OR stump OR slash OR brash OR trench OR drain OR ditch OR compaction OR rutting OR ground damage OR stand age OR chronosequence OR chronosequences) **AND** (carbon dioxide OR methane OR nitrous oxide OR CO2 OR CH4 OR N2O OR greenhouse gas*) **AND** (flux* OR efflux OR emission? OR exchange OR oxidation OR emitted OR release? OR capture OR storage)).ab,ti
String 3	((forest* OR hardwood OR wood OR conifer* OR deciduous OR pinus OR picea OR larix OR betula OR acer OR fagus OR sorbus OR salix) **AND** (soil OR forest floor OR solum) **AND** (harvest* OR logging OR uneven-aged OR continuous cover OR felling OR clear-cut* OR clearcut* OR thinning OR site preparation OR mound* OR scarification OR harrow* OR plough* OR plow* OR stump OR slash OR brash OR trench OR drain OR ditch OR compaction OR rutting OR ground damage OR stand age OR

	chronosequence OR chronosequences) **AND** (total carbon OR total C OR biomass OR forest floor carbon OR organic matter OR organic mass OR organic carbon) **AND** (stock? OR mass OR content OR concentration? OR store? OR accumulat* OR gain? OR loss*2 OR mobilisation)).ab,ti
Search string	**1 OR 2 OR 3**

Table S1:5. Search strings for ProQuest.

String ID	Terms
String 1	TITLE,ABSTRACT,IF(forest* OR hardwood OR wood OR conifer* OR deciduous OR pinus OR picea OR larix OR betula OR acer OR fagus OR sorbus OR salix) **AND** TITLE,ABSTRACT,IF(soil OR "forest floor" OR solum) **AND** TITLE,ABSTRACT,IF(harvest* OR logging OR uneven-aged OR "continuous cover" OR felling OR clear-cut* OR clearcut* OR thinning OR "site preparation" OR mound* OR scarification OR harrow* OR plough* OR plow* OR stump OR slash OR brash OR trench OR drain OR ditch OR compaction OR rutting OR "ground damage" OR "stand age" OR chronosequence OR chronosequences) **AND** TITLE,ABSTRACT,IF("carbon balance" OR "carbon pool" OR "carbon sink" OR "carbon source" OR "carbon stock*" OR "carbon concentration*" OR "c balance" OR "c pool" OR "c sink" OR "c source" OR "c stock*" OR "c concentration*" OR "heterotrophic respiration" OR "soil C" OR "soil carbon" OR "soil organic carbon" OR "soil organic matter" OR "soil respiration")
String 2	TITLE,ABSTRACT,IF(forest* OR hardwood OR wood OR conifer* OR deciduous OR pinus OR picea OR larix OR betula OR acer OR fagus OR sorbus OR salix) **AND** TITLE,ABSTRACT,IF(soil OR "forest floor" OR solum) **AND** TITLE,ABSTRACT,IF(harvest* OR logging OR uneven-aged OR "continuous cover" OR felling OR clear-cut* OR clearcut* OR thinning OR "site preparation" OR mound* OR scarification OR harrow* OR plough* OR plow* OR stump OR slash OR brash OR trench OR drain OR ditch OR compaction OR rutting OR "ground damage" OR "stand age" OR chronosequence OR chronosequences) **AND** TITLE,ABSTRACT,IF("carbon dioxide" OR methane OR "nitrous oxide" OR CO2 OR CH4 OR N2O OR "greenhouse gas*") **AND** TITLE,ABSTRACT,IF(flux* OR efflux OR emission? OR exchange OR oxidation OR emitted OR release? OR capture OR storage)
String 3	TITLE,ABSTRACT,IF(forest* OR hardwood OR wood OR conifer* OR deciduous OR pinus OR picea OR larix OR betula OR acer OR fagus OR sorbus OR salix) **AND** TITLE,ABSTRACT,IF(soil OR "forest floor" OR solum) **AND** TITLE,ABSTRACT,IF(harvest* OR logging OR uneven-aged OR "continuous cover" OR felling OR clear-cut* OR clearcut* OR thinning OR "site preparation" OR mound* OR scarification OR harrow* OR plough* OR plow* OR stump OR slash OR brash OR trench OR drain OR ditch OR compaction OR rutting OR "ground damage" OR "stand age" OR chronosequence OR chronosequences) **AND** TITLE,ABSTRACT,IF("total carbon" OR "total C" OR biomass OR "forest floor carbon" OR "organic matter" OR "organic mass" OR "organic carbon") **AND** TITLE,ABSTRACT,IF(stock? OR mass OR content OR concentration? OR store OR accumulat* OR gain? OR loss OR mobilisation OR pool)
Search string	**1 OR 2 OR 3**

Search strings in digital archives and search engines

Table S1:6. Preliminary searches in BASE (Bielefeld Academic Search Engine, https://www.base-search.net/). Document types searched for will include doctoral and postdoctoral thesis, master's thesis, report, review, dataset, and unknown. Searches will be limited to content providers from Europe and North America. The search strings resulted in 467 unique records.

Searched field	Search string	Date	Records
All fields	(forest*) **AND** (soil "forest floor") **AND** (harvest* logging uneven-age* felling clear-cut* "site preparation" stump slash "logging residue*" ditch* fertiliz* "stand age" chronosequence) **AND** ("carbon source" "soil C" "soil carbon" "soil organic carbon" "soil organic matter" "soil respiration")	250613	341
All fields	(forest*) **AND** (soil "forest floor") **AND** (harvest* logging uneven-age* felling clear-cut* "site preparation" stump slash "logging residue*" ditch* fertiliz* "stand age" chronosequence) **AND** ("carbon dioxide" methane "nitrous oxide" CO2 CH4 N2O "greenhouse gas*") **AND** (flux efflux emission exchange)	250613	206
All fields	(forest*) **AND** (soil "forest floor") **AND** (harvest* logging uneven-age* felling clear-cut* "site preparation" stump slash "logging residue*" ditch* fertiliz* "stand age" chronosequence) **AND** ("total carbon" "forest floor carbon" "organic matter" "organic carbon") **AND** (stock mass content concentration)	250613	184

Table S1:7. Preliminary searches in Finna (https://finna.fi/?lng=en-gb).

Language	Searched field	Search string	Date	Records
English	all fields	(forest*) **AND** (soil OR "forest floor") **AND** (harvest* OR logging OR clear-cut* OR "continuous cover" OR "site preparation" OR stump OR slash) **AND** ("greenhouse gas" OR "greenhouse gases" OR "carbon dioxide" OR CO2 OR "nitrous oxide" OR N2O OR methane OR CH4 OR "organic carbon")	250509	84
Swedish	all fields	(skog) **AND** (mark OR skogsmark) **AND** (avverkning OR skörd OR kalhygge* OR trakthygge* OR hyggesfri* OR kontinuitet* OR markberedning OR stubbskörd OR grot) **AND** (växthusgas* OR koldioxid OR CO2 OR lustgas OR N2O OR metan OR CH4 OR "organiskt kol" OR markkol)	250509	2

Table S1:8. Preliminary searches in Swepub (https://swepub.kb.se/).

Language	Searched field	Search string	Date	Records
English	entire document	(forest*) **AND** (soil OR "forest floor") **AND** (harvest* OR logging OR clear-cut* OR "continuous cover" OR "site preparation" OR stump OR slash) **AND** ("greenhouse gas" OR "greenhouse gases" OR "carbon dioxide" OR CO2 OR "nitrous oxide" OR N2O OR methane OR CH4 OR “organic carbon”)	250509	167
Swedish	entire document	(skog) **AND** (mark OR skogsmark) **AND** (avverkning OR skörd OR kalhygge* OR trakthygge* OR hyggesfri* OR kontinuitet* OR markberedning OR stubbskörd OR grot) **AND** (växthusgas* OR koldioxid OR CO2 OR lustgas OR N2O OR metan OR CH4 OR “organiskt kol” OR markkol)	250509	9

Table S1:9. Preliminary searches in ProQuest Dissertations and Theses (https://www.proquest.com/).

Language	Searched field	Search string	Date	Records
English	Abstract	Same search string as in Table S1:5	250612	9

Table S1:10. Search strings for Google Scholar. The first 100 records from each search string will be merged, deduplicated and screened.

No.	Search string
1	Forest **AND** soil **AND** (clear-cut OR "continuous cover" OR "site preparation" OR stump OR slash) **AND** CO2 **AND** flux
2	Forest **AND** soil **AND** (clear-cut OR "continuous cover" OR "site preparation" OR stump OR slash) **AND** “soil organic carbon”
3	Forest **AND** soil **AND** (clear-cut OR "continuous cover" OR "site preparation" OR stump OR slash) **AND** “soil organic matter”
4	Forest **AND** soil **AND** (clear-cut OR "continuous cover" OR "site preparation" OR stump OR slash) **AND** CH4 **AND** flux
5	Forest **AND** soil **AND** (clear-cut OR "continuous cover" OR "site preparation" OR stump OR slash) **AND** N2O **AND** flux

Searches on specialist websites

Table S1:11. Specialist websites that will be searched.

Organisation	URL
Skogforsk	www.skogforsk.se
Skogsstyrelsen	www.skogsstyrelsen.se
Naturvårdsverket	www.naturvardsverket.se
LUKE	www.luke.fi
NIBIO - Norwegian Institute of Bioeconomy Research	https://www.nibio.no
Silava (Latvian State Forest Research Institute)	https://www.silava.lv
Slovenian Forestry Institute	https://www.gozdis.si
European Environment Agency	https://www.eea.europa.eu/en
U.S. Environmental Protection Agency	https://www.epa.gov/
Natural resources Canada	https://natural-resources.canada.ca/forests-forestry
BFW - Austrian Research Centre for Forests	https://www.bfw.gv.at
Thünen Institute of Forest Ecosystems	https://www.thuenen.de/en
INRAE - National Research Institute for Agriculture, Food and Environment	https://www.inrae.fr
USDA Forest Service - Research and Development	https://www.fs.usda.gov/research
Canadian Forest Service	https://www.nrcan.gc.ca/forests
FPInnovations	https://www.fpinnovations.ca
Service Public de Wallonie – Département de la Nature et des Forêts	https://www.wallonie.be/fr/nature-et-forets
Executive Forest Agency	http://www.iag.bg
Naturstyrelsen	https://naturstyrelsen.dk
Estonian Environment Agency	https://www.envir.ee
Jord- och skogsbruksministeriet	https://mmm.fi
Office National des Forêts (ONF)	https://www.onf.fr
Department of Agriculture, Food and the Marine – Forestry Division	https://www.gov.ie/en/organisation/department-of-agriculture-food-and-the-marine/
Hrvatske šume d.o.o.	https://www.hrsume.hr
State Forest Service	https://www.vmd.gov.lv
State Forest Enterprise	https://www.valstybinemiskuuredija.lt
Administration de la nature et des forêts	https://anf.gouvernement.lu
Staatsbosbeheer	https://www.staatsbosbeheer.nl
Lasy Państwowe (State Forests)	https://www.lasy.gov.pl
Ministry of Environment, Waters and Forests	http://www.mmediu.ro
National Forest Centre	https://www.nlcsk.sk
Forest Management Institute	https://www.uhul.cz
Federal Ministry of Food and Agriculture (BMEL)	https://www.bmel.de
National Food Chain Safety Office – Forestry Directorate	https://portal.nebih.gov.hu
Bundesministerium für Land- und Forstwirtschaft, Regionen und Wasserwirtschaft	https://www.bml.gv.at
Forestry Commission	https://www.gov.uk/government/organisations/forestry-commission

Test references to assess comprehensiveness of the searches

Botroh, A.M. et al., 2023. Nine-years effect of harvesting and mechanical site preparation on bryophyte decomposition and carbon stocks in a boreal forested peatland. Forest Ecology and Management, 540: 11.

Bradford, M.A., Ineson, P., Wookey, P.A., Lappin-Scott, H.M., 2000. Soil CH4 oxidation:: response to forest clearcutting and thinning. Soil Biology & Biochemistry, 32(7): 1035-1038.

Covington, W.W., 1981. Changes in forest floor organic-matter and nutrient content following clear cutting in northern hardwoods. Ecology, 62(1): 41-48.

Epron, D. et al., 2016. Effects of compaction by heavy machine traffic on soil fluxes of methane and carbon dioxide in a temperate broadleaved forest. Forest Ecology and Management, 382: 1-9.

Falsone, G., Celi, L., Caimi, A., Simonov, G., Bonifacio, E., 2012. The effect of clear cutting on podzolisation and soil carbon dynamics in boreal forests (Middle Taiga zone, Russia). Geoderma, 177: 27-38.

Federer, C.A., 1984. Organic-matter and nitrogen-content of the forest floor in even-aged northern hardwoods. Canadian Journal of Forest Research, 14(6): 763-767.

Grünzweig, J.M., Valentine, D.W., Chapin, F.S., 2015. Successional Changes in Carbon Stocks After Logging and Deforestation for Agriculture in Interior Alaska: Implications for Boreal Climate Feedbacks. Ecosystems, 18(1): 132-145.

Gundale, M.J. et al., 2024. The biological controls of soil carbon accumulation following wildfire and harvest in boreal forests: A review. Global Change Biology, 30(5): 20.

Hagemann, U., Moroni, M.T., Shaw, C.H., Kurz, W., Makeschin, F., 2010. Comparing measured and modelled forest carbon stocks in high-boreal forests of harvest and natural-disturbance origin in Labrador, Canada. Ecological Modelling, 221(5): 825-839.

Howard, E.A., Gower, S.T., Foley, J.A., Kucharik, C.J., 2004. Effects of logging on carbon dynamics of a jack pine forest in Saskatchewan, Canada. Global Change Biology, 10(8): 1267-1284.

Johnson, C.E., 1995. Soil-nitrogen status 8 years after whole-tree clear-cutting. Canadian Journal of Forest Research, 25(8): 1346-1355.

Johnson, C.E., Johnson, A.H., Huntington, T.G., Siccama, T.G., 1991. Whole-tree clear-cutting effects on soil horizons and organic-matter pools. Soil Science Society of America Journal, 55(2): 497-502.

Jörgensen, K., Granath, G., Lindahl, B.D., Strengbom, J., 2021. Forest management to increase carbon sequestration in boreal Pinus sylvestris forests. Plant and Soil, 466(1-2): 165-178.

Kataja-aho, S., Smolander, A., Fritze, H., Norrgård, S., Haimi, J., 2012. Responses of Soil Carbon and Nitrogen Transformations to Stump Removal. Silva Fennica, 46(2): 169-179.

Krause, H., 1998. Forest floor mass and nutrients in two chronosequences of plantations: Jack pine vs. black spruce. Canadian Journal of Soil Science, 78(1): 77-83.

Kyaschenko, J., Clemmensen, K.E., Hagenbo, A., Karltun, E., Lindahl, B.D., 2017. Shift in fungal communities and associated enzyme activities along an age gradient of managed Pinus sylvestris stands. Isme Journal, 11(4): 863-874.

Mallik, A.U., Hu, D., 1997. Soil respiration following site preparation treatments in boreal mixedwood forest. Forest Ecology and Management, 97(3): 265-275.

Martin, J.L., Gower, S.T., Plaut, J., Holmes, B., 2005. Carbon pools in a boreal mixedwood logging chronosequence. Global Change Biology, 11(11): 1883-1894.

Martinez-Garcia, E. et al., 2022. Overstory dynamics regulate the spatial variability in forest-floor CO2 fluxes across a managed boreal forest landscape. Agricultural and Forest Meteorology, 318: 14.

Mjöfors, K., Strömgren, M., Nohrstedt, H., Johansson, M.B., Gärdenäs, A.I., 2017. Indications that site preparation increases forest ecosystem carbon stocks in the long term. Scandinavian Journal of Forest Research, 32(8): 717-725.

Mojeremane, W., Rees, R.M., Mencuccini, M., 2012. The effects of site preparation practices on carbon dioxide, methane and nitrous oxide fluxes from a peaty gley soil. Forestry, 85(1): 1-15.

Molchanov, A.G., Kurbatova, Y.A., Olchev, A.V., 2017. Effect of Clear-Cutting on Soil CO2 Emission. Biology Bulletin, 44(2): 218-223.

Moroni, M.T., Shaw, C.H., Otahal, P., 2010. Forest carbon stocks in Newfoundland boreal forests of harvest and natural disturbance origin I: field study. Canadian Journal of Forest Research, 40(11): 2135-2145.

Mäkinen, H., Smolander, A., 2025. Effects of logging residue on the growth and properties of the humus layer in Scots pine and Norway spruce stands. Forest Ecology and Management, 580: 7.

Nilsen, P., Strand, L.T., 2013. Carbon stores and fluxes in even- and uneven-aged Norway spruce stands. Silva Fennica, 47(4): 15.

Nordborg, F., Nilsson, U., Gemmel, P., Örlander, G., 2006. Carbon and nitrogen stocks in soil, trees and field vegetation in conifer plantations 10 years after deep soil cultivation and patch scarification. Scandinavian Journal of Forest Research, 21(5): 356-363.

Orlander, G., Egnell, G., Albrektson, A., 1996. Long-term effects of site preparation on growth in Scots pine. Forest Ecology and Management, 86(1-3): 27-37.

Pearson, M., Saarinen, M., Minkkinen, K., Silvan, N., Laine, J., 2012. Short-term impacts of soil preparation on greenhouse gas fluxes: A case study in nutrient-poor, clearcut peatland forest. Forest Ecology and Management, 283: 10-26.

Peichl, M. et al., 2022. Landscape-variability of the carbon balance across managed boreal forests. Global Change Biology: 14.

Peltoniemi, M., Mäkipää, R., Liski, J., Tamminen, P., 2004. Changes in soil carbon with stand age -: an evaluation of a modelling method with empirical data. Global Change Biology, 10(12): 2078-2091.

Persson, T., Lenoir, L., Vegerfors, B., 2017. Long-term effects of stump harvesting and site preparation on pools and fluxes of soil carbon and nitrogen in central Sweden. Scandinavian Journal of Forest Research, 32(3): 222-229.

Pumpanen, J., Westman, C.J., Ilvesniemi, H., 2004. Soil CO2 efflux from a podzolic forest soil before and after forest clear-cutting and site preparation. Boreal Environment Research, 9(3): 199-212.

Roth, E.M., Karhu, K., Koivula, M., Helmisaari, H.S., Tuittila, E.S., 2023. How do harvesting methods applied in continuous-cover forestry and rotation forest management impact soil carbon storage and degradability in boreal Scots pine forests? Forest Ecology and Management, 544: 13.

Saari, P. et al., 2009. DOC and N2O dynamics in upland and peatland forest soils after clear-cutting and soil preparation. Biogeochemistry, 94(3): 217-231.

Seedre, M., Taylor, A.R., Brassard, B.W., Chen, H.Y.H., Jogiste, K., 2014. Recovery of Ecosystem Carbon Stocks in Young Boreal Forests: A Comparison of Harvesting and Wildfire Disturbance. Ecosystems, 17(5): 851-863.

Simard, D.G., Fyles, J.W., Paré, D., Nguyen, T., 2001. Impacts of clearcut harvesting and wildfire on soil nutrient status in the Quebec boreal forest. Canadian Journal of Soil Science, 81(2): 229-237.

Strukelj, M., Brais, S., Paré, D., 2015. Nine-year changes in carbon dynamics following different intensities of harvesting in boreal aspen stands. European Journal of Forest Research, 134(5): 737-754.

Strömgren, M., Hedwall, P.O., Olsson, B.A., 2016. Effects of stump harvest and site preparation on N2O and CH4 emissions from boreal forest soils after clear-cutting. Forest Ecology and Management, 371: 15-22.

Strömgren, M., Mjöfors, K., Olsson, B.A., 2017. Soil-surface CO2 flux during the first 2 years after stump harvesting and site preparation in 14 Swedish forests. Scandinavian Journal of Forest Research, 32(3): 213-221.

Sundqvist, E., Vestin, P., Crill, P., Persson, T., Lindroth, A., 2014. Short-term effects of thinning, clear-cutting and stump harvesting on methane exchange in a boreal forest. Biogeosciences, 11(21): 6095-6105.

Taylor, A.R., Wang, J.R., Chen, H.Y.H., 2007. Carbon storage in a chronosequence of red spruce (Picea rubens) forests in central Nova Scotia, Canada. Canadian Journal of Forest Research, 37(11): 2260-2269.

Teepe, R., Brumme, R., Beese, F., Ludwig, B., 2004. Nitrous oxide emission and methane consumption following compaction of forest soils. Soil Science Society of America Journal, 68(2): 605-611.

Wu, X. et al., 2011. Long-term effects of clear-cutting and selective cutting on soil methane fluxes in a temperate spruce forest in southern Germany. Environmental Pollution, 159(10): 2467-2475.

Yanai, R.D., Siccama, T.G., Arthur, M.A., Federer, C.A., Friedland, A.J., 1999. Accumulation and depletion of base cations in forest floors in the northeastern United States. Ecology, 80(8): 2774-2787.

Yildiz, O. et al., 2010. Effects of different site preparation methods on soil carbon and nutrient removal from Eastern beech regeneration sites in Turkey's Black Sea region. Applied Soil Ecology, 45(1): 49-55.

Appendix 2, Data extraction forms

The data extraction forms can be found in an Excel file available at https://zenodo.org/records/17608418.