Bernes *et al. Environ Evid (2015) 4:25*
DOI 10.1186/s13750-015-0050-7

Environmental Evidence

SYSTEMATIC MAP

Open Access

# What is the impact of active management on biodiversity in boreal and temperate forests set aside for conservation or restoration? A systematic map

Claes Bernes[1*], Bengt Gunnar Jonsson[2], Kaisa Junninen[3], Asko Lõhmus[4], Ellen Macdonald[5], Jörg Müller[6] and Jennie Sandström[2]


## Abstract

**Background:** The biodiversity of forests set aside from forestry is often considered best preserved by non-intervention. In many protected forests, however, remaining biodiversity values are legacies of past disturbances, e.g. recurring fires, grazing or small-scale felling. These forests may need active management to keep the characteristics that were the reason for setting them aside. Such management can be particularly relevant where lost ecological values need to be restored. In this review, we identified studies on a variety of interventions that could be useful for conserving or restoring any aspect of forest biodiversity in boreal and temperate regions. Since the review is based on Swedish initiatives, we have focused on forest types that are represented in Sweden, but such forests exist in many parts of the world. The wide scope of the review means that the set of studies is quite heterogeneous. As a first step towards a more complete synthesis, therefore, we have compiled a systematic map. Such a map gives an overview of the evidence base by providing a database with descriptions of relevant studies, but it does not synthesise reported results.

**Methods:** Searches for literature were made using online publication databases, search engines, specialist websites and literature reviews. Search terms were developed in English, Finnish, French, German, Russian and Swedish. We searched not only for studies of interventions in actual forest set-asides, but also for appropriate evidence from commercially managed forests, since some practices applied there may be useful for conservation or restoration purposes too. Identified articles were screened for relevance using criteria set out in an a priori protocol. Descriptions of included studies are available in an Excel file, and also in an interactive GIS application that can be accessed at an external website.

**Results:** Our searches identified nearly 17,000 articles. The 798 articles that remained after screening for relevance described 812 individual studies. Almost two-thirds of the included studies were conducted in North America, whereas most of the rest were performed in Europe. Of the European studies, 58 % were conducted in Finland or Sweden. The interventions most commonly studied were partial harvesting, prescribed burning, thinning, and grazing or exclusion from grazing. The outcomes most frequently reported were effects of interventions on trees, other vascular plants, dead wood, vertical stand structure and birds. Outcome metrics included e.g. abundance, richness of species (or genera), diversity indices, and community composition based on ordinations.

**Conclusions:** This systematic map identifies a wealth of evidence on the impact of active management practices that could be utilised to conserve or restore biodiversity in forest set-asides. As such it should be of value to e.g.


*Correspondence: claes.bernes@eviem.se
[1] Mistra Council for Evidence-Based Environmental Management, Royal Swedish Academy of Sciences, 104 05 Stockholm, Sweden
Full list of author information is available at the end of the article

conservation managers, researchers and policymakers. Moreover, since the map also highlights important knowledge gaps, it could inspire new primary research on topics that have so far not been well covered. Finally, it provides a foundation for systematic reviews on specific subtopics. Based on our map of the evidence, we identified four subtopics that are sufficiently covered by existing studies to allow full systematic reviewing, potentially including meta-analysis.

**Keywords:** Biodiversity, Boreal forest, Temperate forest, Disturbance legacy, Forest conservation, Forest restoration, Forest set-aside, Forest reserve, Habitat management, Partial harvesting, Prescribed burning, Thinning, Grazing, Browsing, Dead wood

## Background

### Conservation and restoration of forest biodiversity

Globally, forest cover has declined over many millennia, but extensive regions still remain mostly forested, not least in northern Eurasia and North America. In the latter areas, the proportion of the landscape covered by forest is currently stable or even expanding [1]. At the same time, however, impacts of large-scale forest management and other industrial activities have transformed forest ecosystems from being governed mostly by natural processes to being under strong human influence [2]. This transition has had far-reaching consequences for forest structure and dynamics, and it has been accompanied by a significant loss of forest biodiversity at all levels. Genetic diversity, species richness and ecosystem variability have all decreased [3].

The traditional way of compensating for such effects is to identify forest areas that have (or may develop) high natural values and set them aside as reserves, with restrictions on subsequent management and use. Protection of this kind is still seen as an indispensable tool for nature conservation—current global targets state that at least 17 % of the total land area should be protected for the benefit of biodiversity [4]. Such a target constitutes a major challenge, both because setting aside land is generally costly and because the proportion of forests that still have high natural values falls far short of the 17 % target in many regions. Today, 12 % of the entire forested area in Europe (excluding Russia) has been protected, and the corresponding figure for North America is 9 %. The proportion of primary forest is a mere 2.8 % in Europe, however, whereas it still exceeds 40 % in North America [1].

Of the 'western taiga' forest in Sweden, for instance, it has been estimated that only 2 million hectares, about 10 % of its original extent, fulfils the habitat criteria of the European Species and Habitat Directive [5]. Old-growth characteristics in particular (such as large old trees and dead trees) have been drastically reduced in forests around the world, and significant parts of the biodiversity that depends on such characteristics face local extirpation or extinction even in countries that remain largely forested [6].

In existing reserves too, past silvicultural use has in some cases impaired forest habitats to such a degree that they are unable to sustain a diverse flora and fauna. In many forests included in the EU Natura 2000 network of protected areas, habitat conditions are not better than in unprotected areas [7]. For example, the extensive forest-reserve networks that have been established in Estonia and Germany are still dominated by mid-aged second-growth forests, and 10 % of the area covered by the Estonian network has also been degraded by artificial drainage [8, 9].

In some areas still untouched by large-scale forestry, e.g. the montane natural forests that predominate in Sweden's protected forest areas, vegetation is shaped primarily by small scale internal dynamics, i.e. the ageing and death of fully grown trees and the establishment and growth of new seedlings. In most forest reserves in such areas, biodiversity can be preserved under a *non-intervention management* approach (also called *passive management*, *free development* or *benign neglect strategy*), intended to allow natural processes of internal dynamics to continue undisturbed.

In many protected forests, however, the remaining biodiversity values are legacies of past disturbance regimes that nowadays are suppressed. This situation is common e.g. in the boreal pine forest, which in its natural state is shaped by recurring fires that create an abundance of dead wood and keep the stands relatively sparse and mixed with a significant broadleaf component. In northern Europe, forest fires are now very rare. Pine forests in this region have therefore become denser, with an increasing preponderance of spruce [10, 11] and loss of natural values associated with more open habitats.

Even in seemingly intact European forests, many current biodiversity hotspots have experienced profound human disturbances in the past [12]. In some forest set-asides, for instance, existing conservation values are partly a result of earlier forest grazing (using the forest as pasture for livestock), coppicing with standards, small-scale felling or similar human influences. Since these activities were usually discontinued several decades ago, the forest has become denser and more shaded in such areas, to the detriment of a large number of species that are dependent on a semi-open forest landscape or early-successional stages of stand development. In Estonia, for example, the area of wooded grasslands has plummeted from 700,000 ha in 1940 to less than 10,000 ha today. As a consequence, many formerly common species are now threatened there [13].

Reserves in areas of these kinds may need some form of *active management* to keep the characteristics that were the reason for setting them aside. Such management could, for instance, involve partial harvesting, thinning, prescribed burning, creation or addition of dead wood, grazing or exclusion from grazing, and introduction or removal of species. Since active and non-intervention management can favour different sets of species (e.g. [14]), these approaches should always be carefully weighed against local and landscape-level conservation targets.

Active management for ecological purposes can be particularly relevant in regions where forests have already been degraded. In such areas, the creation of a network of forest reserves with high-quality habitats will require a combination of landscape-scale planning and stand-scale *restoration*. While, in this review, 'conservation' mainly refers to management intended to preserve existing natural values, 'restoration' may be defined as 'the process of assisting the recovery of an ecosystem that has been degraded, damaged or destroyed' [15]. In applied situations, however, conservation and restoration may simply be seen as two ends of a spectrum, ranging from the maintenance of ecological values at a certain level to the reintroduction of such values. Our review includes studies covering all parts of this spectrum.

In some places, exploited forest areas may be restored by allowing them gradually to return to a near-natural state through non-intervention, but elsewhere active measures may be required to accelerate natural recovery or to sustain or introduce desired natural processes or conditions [6, 16]. Nowadays, a multitude of restoration activities are performed to counteract losses of forest biodiversity (e.g. [17]). An ambitious goal set in the EU Biodiversity Strategy is that 15 % of degraded ecosystems are to be restored by 2020.

Solutions like afforestation and forest restoration could be particularly useful in historically deforested regions, such as Britain. There, the best starting point for protecting old-forest biota may be to manage mature planted forests in a way that facilitates the development of natural forest characteristics [18].

Finally, it should be noted that both conservation and restoration efforts must be approached with consideration of broader changes in the environment (e.g. climate change and variations in land use intensity, both of which are capable of fundamentally affecting species communities). For instance, the rationale for restoration of natural fire regimes may depend not only on specific biodiversity targets but also on an understanding of the environmental conditions that determine what is 'natural' [19].

### Scientific basis for the management of forest set-asides

Direct evidence of how active management has affected biodiversity in forest set-asides is relatively sparse, but there has been some improvement over the last few years. Recent reviews with a particular focus on forests set aside from commercial harvesting include a literature study by Götmark [20] of management options for protected areas and a systematic review by Davies et al. [21] of interventions intended to conserve saproxylic invertebrates (in old-growth forests as well as in younger stands).

Considerably more studies have been made on how commercial forest management can be modified to reduce its negative impacts on biodiversity. Many of the studies describe attempts to restore certain old-growth characteristics (e.g. the presence of dead wood or an uneven-aged forest structure), usually through some kind of partial harvesting, to stands that formerly were under even-aged management [22]. In North America, numerous studies have also been made on the ecological effects of fuel reduction, i.e. thinning, prescribed burning and other interventions intended to reduce the frequency, extent and severity of wildfires (e.g. [23]).

A large share of these studies have been made in forests where commercial timber production will continue, but a few have been conducted in protected forests. A minority of studies deal with old-growth forest with no history of large-scale harvesting. Nevertheless, even studies in timber-production forests may provide useful indirect evidence on how active management can affect biodiversity in areas entirely set aside from commercial forestry. Studies of how biodiversity is affected by various forestry practices (including fuel reduction) have recently been summarised in several literature reviews, e.g. [24–28]. Many such studies have also been included in meta-analyses, e.g. [29–41].

However, most of these summaries are restricted to certain geographical regions, to one or two types of intervention, and to specific aspects of biodiversity. Eleven of the nineteen reviews and meta-analyses cited above focus on forests in the United States and/or Canada, most of them are devoted to effects of burning, thinning or partial harvesting, and nearly half of them deal with effects on birds or other vertebrates only. Moreover, many of the reviewed studies compare silvicultural systems that are described in very general terms, with little or no information on specific interventions.

There is clearly a need for a more complete and explicit synthesis of the available evidence on how various management options may affect biodiversity in forests set aside for conservation or restoration. We initiated this review at the request of Swedish stakeholders, who wished to get an overview of the scientific support for different ways of managing protected forests (see Additional file 1). For that reason, our review is focused on the boreal and temperate forest types that are represented in Sweden, but these forests are parts of vegetation zones that extend over many parts of the world. Any study of active management that is used (or could be used) to maintain or restore forest biodiversity within these zones was potentially eligible for inclusion in the review. This also means that the evidence covered by our review should be relevant for managers of forest set-asides throughout the boreal and temperate zones.

Rather than reviewing a specific selection of interventions, we sought to cover a wide range of active forest-management options that could be useful for conserving or restoring biodiversity in protected forests. Similarly, rather than attempting to distinguish aspects of biodiversity with particular relevance to conservation, we considered the entire array of diversity measures presented in original sources, recognising that no such measure represents a universally meaningful conservation target.

Furthermore, we searched for available studies and screened them for relevance using a 'systematic' approach in the sense established by the Collaboration for Environmental Evidence (CEE) [42]. The rigour and transparency of this approach is intended to avoid bias and facilitate quantitative and repeatable evaluation by means of meta-analysis. Some of the existing reviews cited above are based on systematic literature searches, but only one of them [35] is actually endorsed by the CEE.

The wide scope of our review means that the set of relevant studies is quite heterogeneous. Forest types, management options and biodiversity outcomes can be combined in numerous ways, and it was not clear from the outset how well various combinations would be covered by existing studies. As a first step towards a more complete and quantitative synthesis, we compiled a *systematic map*. A systematic map gives an overview of the evidence base by providing a database with descriptions of the design, scope and focus of relevant studies, but it does not synthesise reported results [42].

Based on our map of the evidence, we then identified subtopics that are sufficiently covered by existing studies to allow full systematic reviewing, potentially including meta-analysis. The map can also be used as a tool for identifying knowledge gaps and research needs.

## Objective of the systematic map

The primary aim of this systematic map is to provide an overview of available evidence on how biodiversity in forest set-asides may be affected by various forms of active management. We searched not only for studies of interventions in actual forest reserves and other kinds of set-asides, but also for appropriate evidence from non-protected and commercially managed forests, since some of the practices commonly applied in commercial forestry may be useful for conservation or restoration purposes too.

### Primary question

What is the impact of active management on biodiversity in boreal and temperate forests set aside for conservation or restoration?

### Components of the primary question

- Population/subject: Boreal and temperate forests set aside for conservation or restoration of biodiversity
- Intervention: Active management (e.g. partial harvesting, thinning, prescribed burning, creation or addition of dead wood, grazing or exclusion from grazing, and introduction or removal of species)
- Comparator: Non-intervention or alternative types of intervention
- Outcomes: Measures or indicators of biodiversity

It may be noted that in the context of conservation, the primary comparator (non-intervention) can be regarded as a management option as relevant to study in detail as any kind of active management.

## Methods

### Planning the review

The design of this systematic map was established in detail in an a priori protocol [43]. It follows the guidelines for systematic reviews and evidence synthesis issued by the Collaboration for Environmental Evidence [42].

As described in the protocol, we established the scope and focus of the map in close cooperation with stakeholders, primarily in Sweden. Before submission, peer review, revision and final publication of the protocol, a draft version was open for public review at the website of the Mistra Council for Evidence-Based Environmental Management (EviEM) in May 2014. Comments were received from scientists, environmental managers and other stakeholders, and the protocol was revised accordingly.

### Searches for literature

When searching for relevant literature, we used online publication databases, search engines, specialist websites and literature reviews. Whenever possible, we applied the search terms specified below. In many cases, however, the search string had to be simplified as some sites could handle only a limited number of search terms or did not allow the use of 'wildcards' or Boolean operators.

No time, language or document type restrictions were applied.

#### *Search terms*

Initially, we conducted a scoping exercise to assess alternative search terms, testing them against a set of about 20 articles known to be relevant. This resulted in a preliminary search string that was used for the main part of the literature searches. Based on suggestions by stakeholders and on the terminology in relevant papers found with the preliminary search terms, a few terms were later added to the search string and used in a set of supplementary searches. The final selection of search terms was as follows:

- Subject: forest*, woodland*, "wood* pasture*", "wood* meadow*"
- Forest type: boreal, boreonemoral, hemiboreal, nemoral, temperate, conifer*, deciduous, broadlea*, "mixed forest", spruce, "Scots pine", birch, aspen, beech, "*Quercus robur*", Swed*
- Intervention: conserv*, restor*, rehabilitat*, "active management", (prescribed OR control* OR experiment*) AND (burn* OR fire*), thinn*, (partial OR selecti* OR gap OR retention) AND (felling OR cutting OR harvest*), "green-tree retention", *introduc*, remov*, graz*, brows*, girdl*, ditch*, flood*, fenc*, exclos*, pollard*, coppic*
- Outcomes: *diversity, species AND (richness OR focal OR target OR keystone OR umbrella OR redlist* OR threatened OR endangered OR rare), "species density", "number of species", indicator*, abundance, "dead wood", "woody debris", "woody material", "forest structure", habitat*

The terms within each of the categories above ('subject', 'forest type', 'intervention' and 'outcomes') were combined using the Boolean operator 'OR'. The four categories were then combined using the Boolean operator 'AND'. An asterisk (*) is a 'wildcard' that represents any group of characters, including no character.

The 'forest type' category of search terms was included in order to keep the number of articles at a manageable level—without these terms, the amount of literature to be screened would have increased about fourfold. The 'forest type' search terms were chosen to optimise the likelihood of finding relevant studies in Sweden or in forests elsewhere that are dominated by tree species commonly occurring in Sweden. However, the terms were also judged to be capable of identifying a satisfactory share of relevant studies carried out in other boreal and temperate forest types throughout the world.

At some of the websites mentioned below, searches were also made for relevant literature in Finnish, French, German, Russian and Swedish, using search terms in these languages. A translation of the full English search string was used when French literature was searched for in publication databases. In other cases, the selection of search terms had to be reduced and customised to individual websites, since few of these accept long and complex search strings and some of the English terms could not be translated to other languages.

About 10 months after the main searches for literature in English, an update was made using Web of Science and Google Scholar.

Full details of the search strings used for each search are recorded in Additional file 2, together with search dates and the number of articles found.

#### *Publication databases*

The search utilised the following online publication databases:

1. Academic Search
2. Agricola
3. Biological Abstracts
4. GeoBase + GeoRef
5. JOSKU (University of Eastern Finland library)
6. JSTOR
7. Libris
8. eLIBRARY.ru (Научная электронная библиотека)
9. Science Citation Index
10. Scopus
11. SwePub
12. Web of Science
13. Wiley Online Library

The main searches for literature in English were made with the preliminary search string in ten of these databases. Supplementary searches for English literature using the additional search terms in the final search string were made in Academic Search, Scopus and Web of Science (except for one addition, "brows*", which was searched for in Web of Science only). Literature in Finnish, French, Russian and Swedish was searched for in subsets of the publication databases listed above (see Additional file 2 for details).

#### *Search engines*

Internet searches were performed using the following search engines:

Google (http://www.google.com)
Google Scholar (http://scholar.google.com)

In most cases, the first 200 hits (sorted by relevance) were examined for appropriateness.

#### *Specialist websites*

Websites of the specialist organisations listed below were searched for links or references to relevant publications and data, including grey literature.

Ancient Tree Forum (http://www.ancient-tree-forum.org.uk)
Bureau of Land Management, US Dept. of the Interior (http://www.blm.gov)
Environment Canada (http://www.ec.gc.ca)
European Commission Joint Research Centre (http://ec.europa.eu/dgs/jrc)
European Environment Agency (http://www.eea.europa.eu)
Food and Agriculture Organization of the United Nations (http://www.fao.org)
Finland's environmental administration (http://www.ymparisto.fi)
International Union for Conservation of Nature (http://www.iucn.org)
Metsähallitus (http://www.metsa.fi)
Natural Resources Canada (http://www.nrcan.gc.ca)
Nordic Council of Ministers (http://www.norden.org)
Norwegian Environment Agency (www.miljødirektoratet.no)
Norwegian Forest and Landscape Institute (http://www.skogoglandskap.no)
Norwegian Institute for Nature Research (http://www.nina.no)
Parks Canada (http://www.pc.gc.ca)
Society for Ecological Restoration (http://www.ser.org)
Swedish County Administrative Boards (http://www.lansstyrelsen.se)
Swedish Environmental Protection Agency (http://www.naturvardsverket.se)
Swedish Forest Agency (http://www.skogsstyrelsen.se)
Swedish University of Agricultural Sciences (http://www.slu.se)
UK Environment Agency (http://www.environment-agency.gov.uk)
United Nations Environment Programme (http://www.unep.org)
United States Environmental Protection Agency (http://www.epa.gov)
US Forest Service (http://www.fs.fed.us)

### Other literature searches

As a check of the comprehensiveness of our searches, relevant articles and reports were also searched for in literature reviews. Moreover, each member of the review team used national and international contacts to get information on current research related to the topic of the review, and also to find non-peer-reviewed literature, including reports and theses published in e.g. Swedish, Finnish, Estonian or Russian.

### Screening of literature

#### *Screening process*

Articles found by searches in publication databases were evaluated for inclusion at three successive levels. First, they were assessed by title by a single reviewer (primarily CB or JS). In cases of uncertainty, the reviewer chose inclusion rather than exclusion. As a check of consistency, a subset of 100 titles was assessed by both of the primary reviewers and also by four other members of the review team (BGJ, KJ, AL and JM). Of the 76 titles in this subset that had been excluded by one of the primary reviewers (or both), 69 were also excluded by at least two of the additional reviewers. Four of the remaining seven titles were excluded by only one of the additional reviewers, and three titles by none of them. After discussions and agreements on whether to include or exclude certain borderline topics that had been identified by this exercise, the title screening was allowed to continue.

Next, each article found to be potentially relevant on the basis of title was assessed for inclusion on the basis of abstract, again by a single reviewer (CB, JS or BGJ) who in cases of uncertainty tended towards inclusion. At an early stage, a subset consisting of 100 abstracts was assessed by all three reviewers involved in this part of the screening process, and the consistency of their assessments was checked with kappa tests. The outcomes ranged between $\kappa = 0.50$ (CB vs. JS) and $\kappa = 0.78$ (CB vs. BGJ), indicating 'moderate' to 'substantial' agreement [44]. Discussion of the discrepancies between the primary reviewers (CB and JS) resulted in additional specifications of how the inclusion criteria were to be interpreted. When a second subset of 100 abstracts was screened by the two primary reviewers, the kappa statistic relating to their assessments was found to be 0.63, indicating 'substantial' agreement [44].

Finally, each article categorised as potentially relevant on the basis of abstract was assessed for inclusion by one reviewer who studied the full text. This task was shared by all members of the review team. The articles were randomly distributed within the team, but some redistribution was made to avoid having reviewers assess studies authored by themselves or articles written in an unfamiliar language. Articles found using search engines, specialist websites, literature reviews or stakeholder contacts were entered at this stage in the screening process.

Almost 90 % of the full-text assessments were double-checked by a second reviewer (primarily CB). Where the first and second reviewers disagreed on whether to include a study or not, they discussed and reconciled their assessments on a case-by-case basis. Certain categories of studies identified as doubtful during this stage of the screening were discussed by the entire team. Based on these discussions, some of the inclusion criteria were specified further.

### *Study inclusion criteria*

Each study had to pass each of the following criteria in order to be included:

- Relevant subjects: Forests in the boreal or temperate vegetation zones.

Any habitat with a tree layer was regarded as forest, which meant that studies of e.g. wooded meadows and urban woodlands could be included.

As an approximation of the boreal and temperate vegetation zones we used the cold Köppen-Geiger climate zones (the D zones) and some of the temperate ones (Cfb, Cfc and Csb), as defined by Peel et al. [45] (see Fig. 1). The other temperate Köppen-Geiger climate zones are often referred to as subtropical and were therefore considered to fall outside the scope of this systematic map.

Nevertheless, forest stands dominated by ponderosa pine (*Pinus ponderosa*) were considered as relevant even if located outside the climate zones mentioned above. These forests constitute a well-studied North American habitat type that shares several characteristics with the pine forests in boreal and temperate regions.

- Relevant types of intervention: Active management which is used or could conceivably be used to conserve or restore biodiversity in forest set-asides. The following types of management were judged to be relevant:

  - Prescribed burning
  - Thinning
  - Partial harvesting
  - Removal of woody understorey or ground-layer vegetation
  - Removal or addition of litter or humus
  - Creation of dead wood
  - Addition (translocation) of dead wood
  - Exclusion or other deliberate manipulation of wild cervids and similar grazers/browsers
  - Livestock grazing and traditional mowing, coppicing and pollarding
  - Underplanting of trees and (re)introduction of native non-tree species
  - Control of exotic and/or invasive species
  - Hydrological restoration
  - Liming and use of herbicides, if the primary goal was conservation

Clearcutting was not included, since we did not find this intervention useful for the conservation of forest biodiversity (although we admit that clearing of an established stand may be relevant in very specific cases, e.g. when the aim is to substitute a plantation with an alternative forest type). We did, however, include coppicing, because this is in many regions a traditional forest

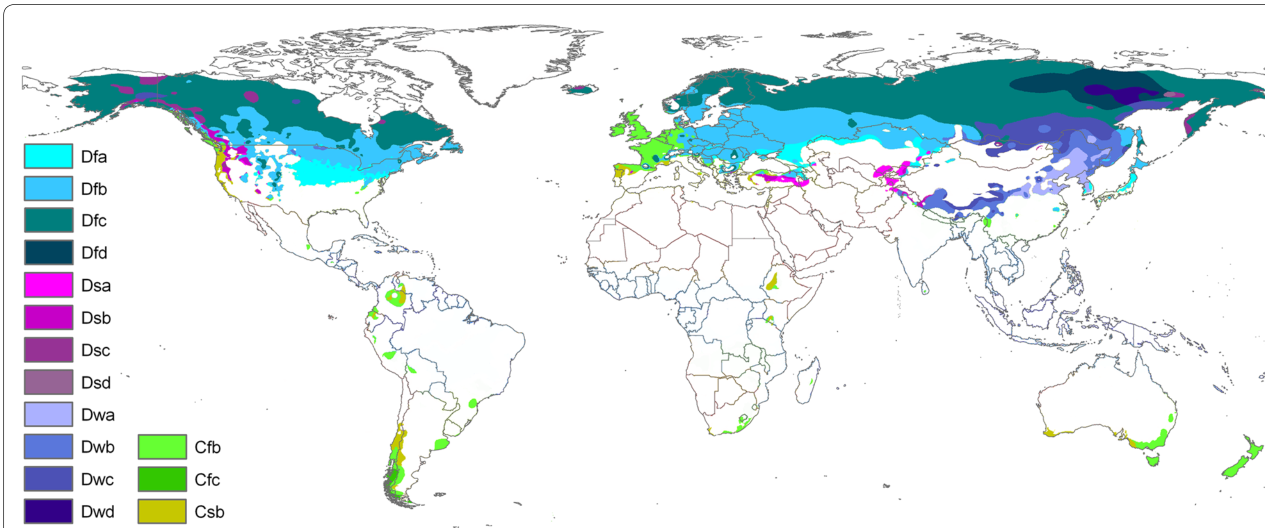


**Fig. 1** Köppen-Geiger climate zones judged as relevant to the subject of this review. Relevant zones include all of the cold climate types (D) and some of the temperate ones (C). The map is modified from Peel et al. [45]

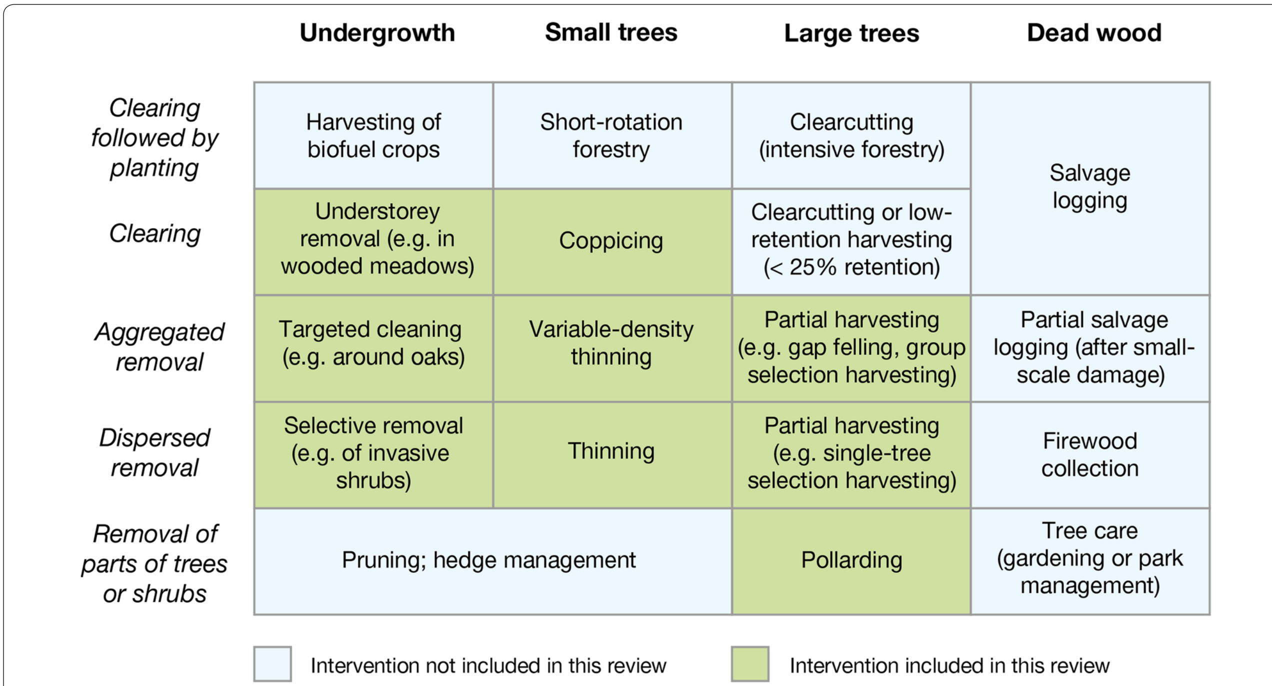


**Fig. 2** Interventions involving removal of trees and other woody material. The figure provides an overview of harvesting options and other techniques for removal of woody material that we encountered when searching for relevant literature on forest management. Interventions in *green boxes* were included in the review

management system with specific biodiversity values worth maintaining. Pollarding (a traditional harvesting technique that affects large trees across entire stands) was included for similar reasons, but not other kinds of pruning that are applied in gardening and for managing single trees, often for aesthetic reasons (see Fig. 2).

Studies of partial harvesting were not included if less than 25 % of the volume or basal area of living and dead trees was retained, or if the intervention consisted of gap felling with an average gap size exceeding 0.5 ha. Existing meta-analyses have concluded that harvested stands start to function as clearcuts (from a biodiversity point of view) when the retention level drops to somewhere between 15 and 40 % [46, 47]. Nevertheless, studies of 25–50 % retention levels may provide some conservation insights, e.g. into the possibilities of combining management for forest biodiversity with management for wooded-grassland diversity and/or for species favoured by disturbances. The threshold we chose for gap sizes was based on the FAO definition of forest as land with a certain minimum tree cover and an area of more 0.5 ha [48]—hence we considered gaps larger than 0.5 ha as clearcuts.

When in doubt about the relevance of interventions intended to benefit particular species (notably tree species), we generally included or excluded studies based on whether study authors described the interventions as being made for the purpose of conservation or not.

Several of the stakeholders that we consulted when developing the protocol [43] suggested that studies of wildfires should be included, but we decided not to do so. Wildfire is usually not a management option, although it may be possible to choose whether to suppress a fire or not. Moreover, while there is an extensive literature on the effects of unplanned and uncontrolled fires (e.g. [49, 50]), their consequences for biodiversity cannot be assumed to be identical to those of prescribed burning. We judged that including only studies of prescribed burning was appropriate for the purposes of this review.

- Relevant type of comparator: Non-intervention or alternative types of intervention.

Both temporal and spatial comparisons of how different kinds of forest management affected biodiversity were considered to be relevant. This means that we included both ‘BA’ (Before/After) studies, i.e. comparisons of the same site prior to and following an intervention, and ‘CI’ (Control/Impact) studies, i.e. comparisons of treated and untreated sites (or sites that had been subject to different kinds of treatment). Studies combining these types of comparison, i.e. those with a ‘BACI’ (Before/After/Control/Impact) design, were also included.

Most CI and BACI studies that are relevant to the subject of this systematic map compare different forest stands or different parts of a single stand. However, studies of how creation or addition of dead wood affects biodiversity may be based on comparisons of individual trees (logs or snags) that have been subject to different treatments (e.g. girdling vs. other ways of killing trees), and we included such comparisons as well.

Moreover, we found a number of seemingly useful dead-wood studies that did not compare effects of different kinds of intervention but were based on other types of comparison instead, and we therefore decided to extend the comparator criterion by also including studies of the three following categories:

(A) Studies comparing biodiversity effects of dead-wood creation/addition in different kinds of forest stands (e.g. stands of different age or stands subject to different kinds of management).
(B) Studies comparing biodiversity effects of creation/addition of different kinds of dead wood (e.g. wood of different species or sizes).
(C) Studies comparing biodiversity aspects of created/added vs. naturally occurring dead wood.

- Relevant types of outcome: Measures or indicators of biodiversity in the terrestrial environment.

The following types of outcome were considered to be relevant:

- Abundance of single species or taxonomic or functional groups of terrestrial organisms (including the soil seed bank)
- Species richness, diversity index and composition of taxonomic or functional groups of terrestrial organisms (including the soil seed bank)
- Performance and population viability of target species
- Tree mortality
- Abundance and diversity of dead wood
- Stand structure (horizontal and/or vertical distribution of trees)
- Occurrence of tree microhabitats (e.g. cavities)

- Relevant type of study: Primary field studies.

Based on this criterion, we excluded e.g. simulation studies, review papers and policy discussions.

- Language: Full text written in English, French, German, Danish, Norwegian, Swedish, Finnish, Estonian or Russian.

During the screening process, we sometimes found it necessary to specify the inclusion criteria further by deciding whether to include or exclude certain borderline topics or study categories, based on their relevance to conservation or restoration. The final set of criteria, including all specifications, is listed in Additional file 3.

### Study quality assessment

No quality appraisal was made of studies subsequent to their inclusion in the review, since this is not considered necessary for the purposes of a systematic map [42]. Nevertheless, the screening for relevance described above did involve certain quality aspects. Since we required studies to present 'useful' data on interventions, we excluded investigations of the effects of silvicultural systems (such as 'uneven-aged' or 'near-natural' forestry) if they provided insufficient information on how the forest had been managed, e.g. no data on the specific interventions on which these kinds of forestry were based. Similarly, since comparators were also required to be 'useful', we excluded studies where the ages or species compositions of treated and untreated stands were entirely different (e.g. studies of interventions in young plantations where mature or old-growth stands were used as controls).

If studies included in the map are later selected for full systematic review, they will have to undergo full critical appraisal. The data on study design that are provided in the map may be relevant when such an assessment is made. For instance, studies with a CI or BACI design are likely to be more useful than BA studies in the context of forest management. This is because a forest set-aside that has been subject to some kind of active management may also be affected by other influences (e.g. changes in weather, climate or atmospheric pollution, or ecological succession following earlier land-use changes). Such influences can be controlled for in CI and BACI studies, but not in BA studies. On the other hand, it should be noted that CI studies can be misleading if confounding differences between treated and untreated sites (due e.g. to interventions in the past) are not known and described well enough. Other relevant quality aspects of the study design include the size of treatment/intervention units and the degree of replication. Such aspects may well be taken into account in a full systematic review, but they have not been used as criteria for exclusion in the present systematic map.

### Systematic map database

The database that constitutes the core of this systematic map provides basic information on each study found to be relevant. This information is available in an Excel file (Additional file 4), and also in an interactive GIS application. The GIS application plots study locations on a zoomable world map, and data on the studies can be retrieved by clicking on the symbols in the map. The application also provides a table with the same content as the Excel file. Both the GIS application and the Excel file allow data to be filtered and sorted.

Each included study is described and categorised based on the following types of data (to the extent that they were available):

- Full reference,
- article language,
- location of study area (country, state/province, region or site(s), geographical coordinates, altitude),
- research programme to which the study belonged,
- forest type (coniferous/mixed/deciduous),
- dominant tree species,
- stand age,
- stand origin,
- type of comparison (BA/CI/BACI),
- number of true replicates,
- intervention type(s) categorised using codes listed in Additional file 4,
- intervention(s) specified using free text,
- outcome type(s) categorised using codes listed in Additional file 4,
- focal species, communities and/or biodiversity indicators.

In addition, the database contains links that search Google Scholar for the title of each included article. They will return links to abstracts and full-text versions of the articles if these are available through Google Scholar.

Descriptions recorded in the database were normally extracted from the included articles, but if no geographical coordinates were given, we recorded approximate coordinates based on published site names, maps or verbal descriptions of study locations (or coordinates provided in another article describing the same site). Not uncommonly, moreover, coordinates given by study authors were clearly incorrect (e.g. confusing minutes of arc with decimals of degrees, or confusing latitude and longitude with coordinates based on national grid systems). In such cases, too, we recorded coordinates based on other information.

In cases where some of the data reported by a study fell outside the scope of our review (e.g. where some of the study sites were located outside relevant vegetation zones), we recorded information only on those parts of the study that fulfilled our inclusion criteria.

The number of true replicates recorded in the database was strictly based on the extent to which the intervention was replicated, regardless of the scale of the intervention (and even if study authors stated that they had avoided pseudoreplication by spacing sampling sites widely enough). For instance, studies of exclusion from grazing were considered to be non-replicated if they were based on one exclosure only, even if the exclosure was large and contained many sampling sites. If treated sites and controls were not replicated to the same extent, we always recorded the lowest number of replicates.

The first round of data recording was shared by all members of the team. Two of us (CB and JS) then added some supplementary data, mainly on locations of study areas. Finally, one reviewer (CB) double-checked all entries in the map database for consistency.

## Results

### Literature searches and screening

The main searches for literature using the initial English search string were conducted on 4–5 May 2014. A total of 31,805 articles were returned from ten of the thirteen publication databases listed in the Methods section. Subsequent supplementary searches in publication databases using the additional search terms in the final search string yielded 2137 more articles, for a total of 33,942—see Fig. 3. Removal of duplicates left 16,484 unique articles. After title screening, 5871 of these articles remained included. When the searches were updated in March 2015, 271 additional articles were included based on titles, for a total of 6142.

Screening based on abstracts left 1570 articles that were still considered as potentially relevant. Most of the articles rejected at this stage were excluded because they did not cover relevant types of intervention.

Searches with Finnish, French, Russian and Swedish search terms in online publication databases yielded 0, 0, 7 and 1 potentially relevant publications in these languages, respectively. Searches using search engines (Google and Google Scholar) returned 38 potentially relevant articles (13 found with English search terms, 11 with Finnish, 8 with French, 2 with German and 4 with Swedish ones) in addition to those that had already been identified.

Similarly, searches at specialist websites located another 64 potentially useful publications (60 found using English search terms, 3 using Finnish and 1 using Swedish ones). Of these publications, 50 were retrieved at a single website, that of the US Forest Service. Many of the articles found at the specialist websites can be characterised as grey (non-peer-reviewed) literature.

An additional 54 articles were found in existing literature reviews that presented relevant meta-analyses. Two articles were found by checking the full contents of Finnish or Russian journals or report series, and 26 more publications (in English, Estonian, Finnish or Russian)

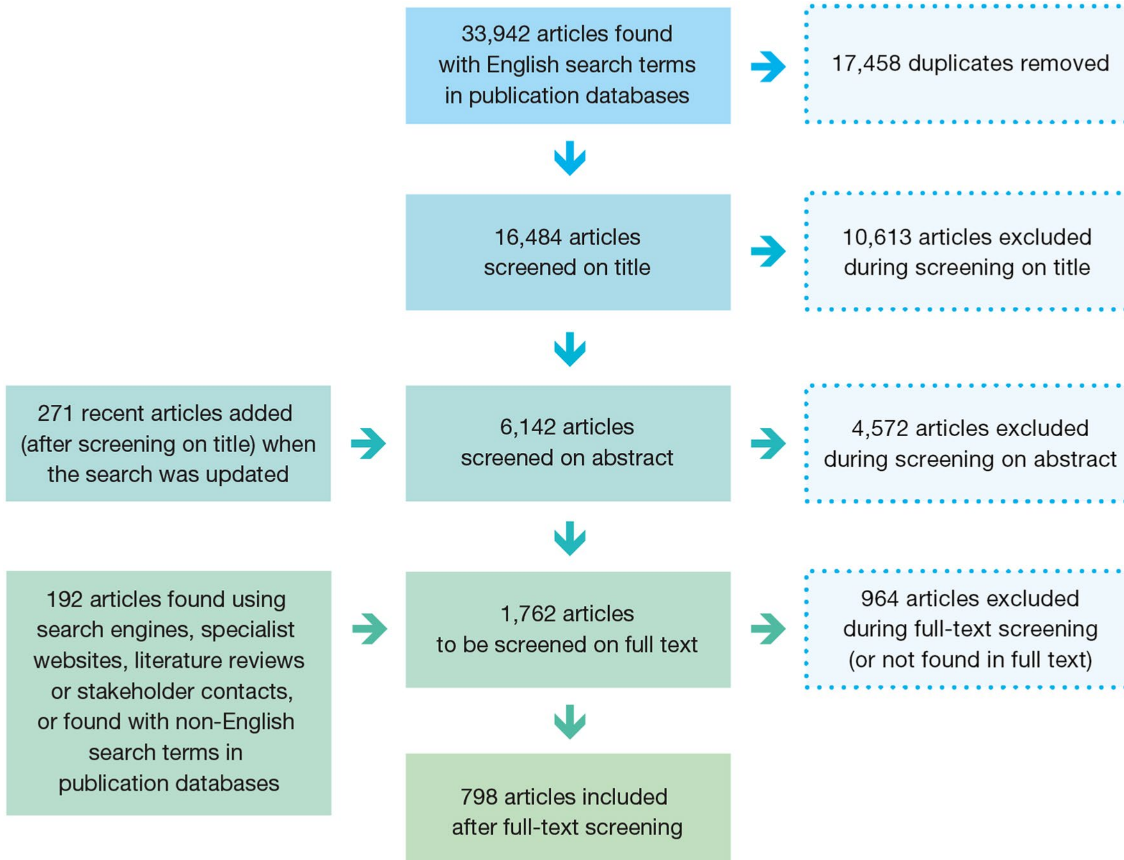


**Fig. 3** Overview of article inclusion and screening

**Table 1 Reasons for exclusions of articles at full-text screening**

| Reason for exclusion | No. of articles |
|---|---|
| Not a study of forests, woodlands or other terrestrial habitats with a tree layer | 44 |
| Not a study made in boreal or temperate vegetation zones | 180 |
| Not a field study | 42 |
| Not a study of interventions intended (or potentially useful) for the conservation or restoration of forest biodiversity (or no useful data on such interventions) | 447 |
| No useful comparator data | 101 |
| No useful measures of biodiversity or conditions known to influence diversity | 108 |
| No useful primary data, but potentially useful as a review | 49 |
| Redundant (data also reported elsewhere) | 5 |
| Full text not in English, French, German, Swedish, Norwegian, Danish, Finnish, Estonian or Russian | 25 |
| Full text not found | 51 |

Some of the articles appear more than once in the table, since they were excluded for more than one reason

were supplied by members of the review team. The most common reason why these articles had not been found in publication databases was that their title and abstract did not contain any of the 'forest type' search terms that we applied when searching online.

In all, the searches resulted in 1762 articles to be assessed in full text. After full-text screening, 798 of them remained included. Again, the most common reason for exclusion was that studies did not cover relevant types of intervention (see Additional file 5 and

Table 1). In 51 cases, publications had to be excluded because they were not found in full text. Nevertheless, this means that we were able to retrieve 97 % of the articles that had been judged as potentially relevant based on their abstracts.

Most of the included articles (766, or 96 %) were written in English. The other ones were written in Finnish (13), Swedish (7), Russian (5), German (4), French (2) or Estonian (1). Only 34 (4 %) of the articles were published earlier than 1995, and 561 of them (70 %) appeared in 2005 or later.

A few of the included articles reported on more than one relevant study. The total number of studies included in this systematic map is 812. Data on each of these studies are available in an Excel file (Additional file 4), and also in an interactive GIS application that can be accessed at the EviEM website (http://www.eviem.se/en/projects/Managing-protected-forests-original/).

#### Characteristics of included studies

Almost two-thirds (529) of the 812 studies included in the map were conducted in North America, whereas 237 were performed in Europe, 17 in Asia, 22 in Australia/New Zealand and 7 in South America (see Figs. 4, 5). Of the European studies, 58 % were conducted in Finland or Sweden.

More than half of the studies (58 %) presented data on forests that were mainly coniferous, whereas 35 % included data on predominantly broadleaf forests and 16 % reported on stands with a mixture of coniferous and broadleaf trees (since some studies included data on more than one of these forest types, the total percentage exceeds 100 %).

The tree genera most commonly dominant (or co-dominant) in the studied stands were *Pinus, Picea, Quercus, Pseudotsuga* and *Acer* (Table 2). The tree species that most frequently dominated were all conifers: Douglas-fir (*Pseudotsuga menziesii*; dominant in 15 % of the studies), ponderosa pine (*Pinus ponderosa*; 15 %), Norway spruce (*Picea abies*; 12 %) and Scots pine (*Pinus sylvestris*; 10 %).

Stand ages were reported by only about half of the studies. Of these, 29 % had examined stands aged 60 years or less, while 71 % reported on stands older than 60 years or stands described as 'mature' or 'old-growth'.

The interventions most commonly studied were partial harvesting (alternatively referred to as selective harvesting, group or single-tree selection harvesting, retention or green-tree retention harvesting, patch cutting, gap

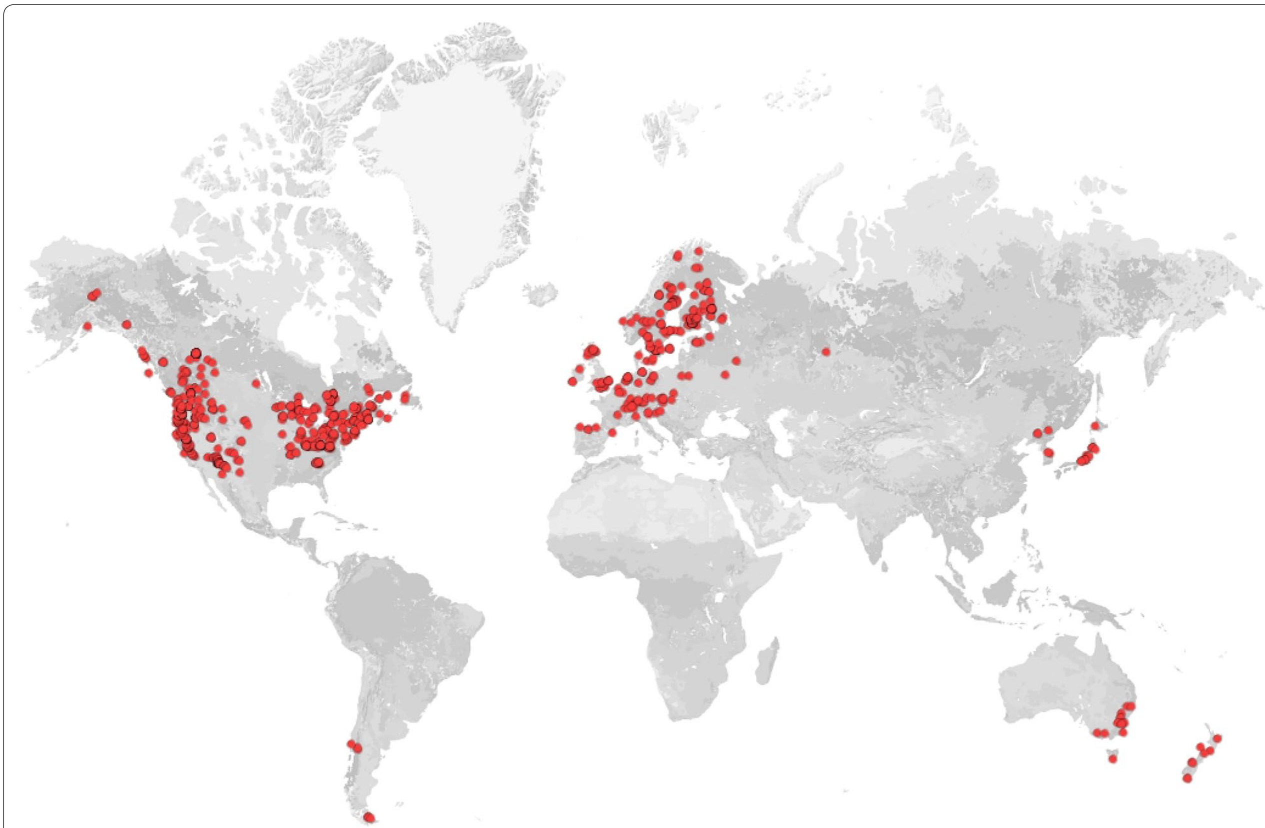

**Fig. 4** Locations of included studies

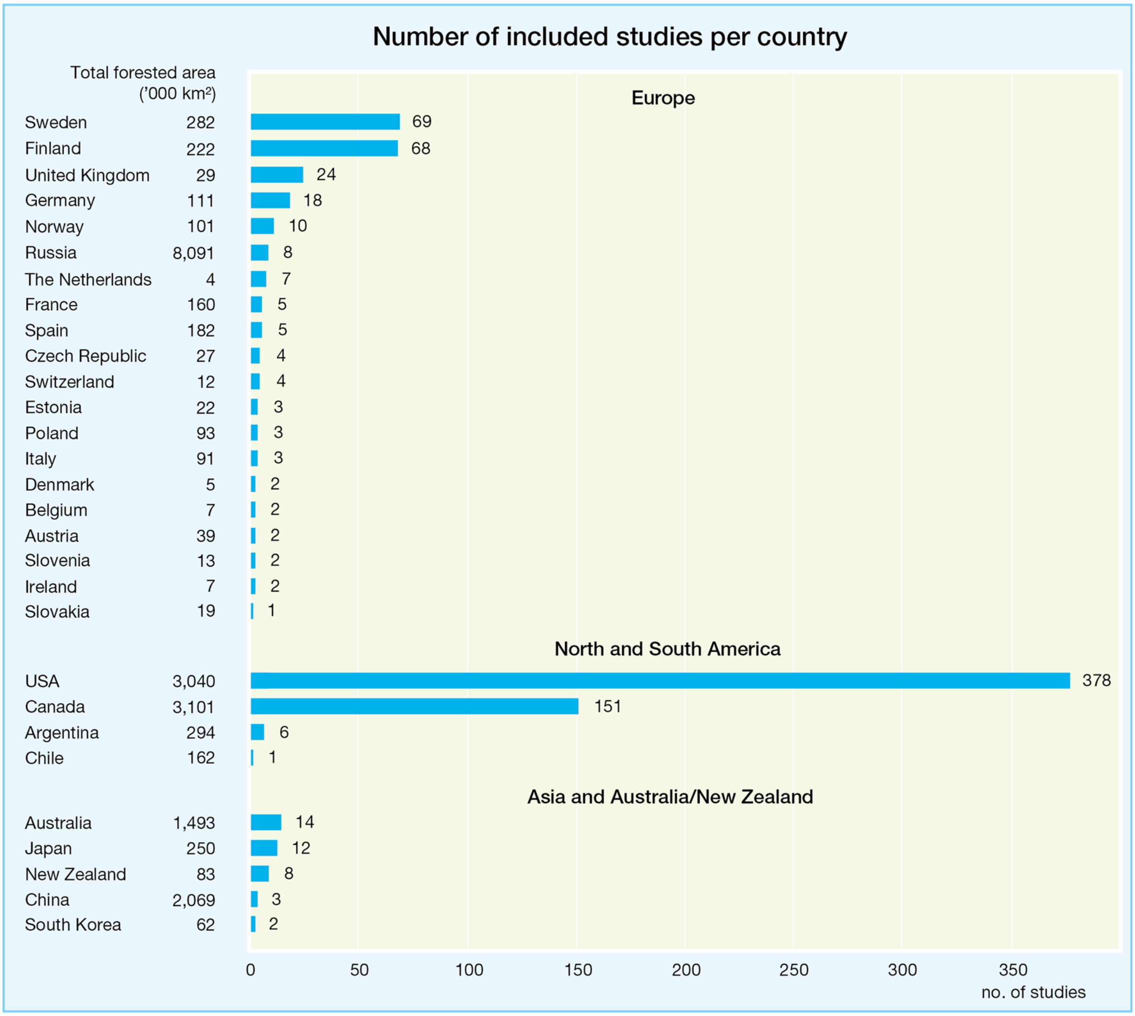


**Fig. 5** Number of included studies per country. Data on total forested areas include forests outside as well as within temperate and boreal zones [1]

felling etc.), thinning, prescribed burning, and grazing or exclusion from grazing (mainly by cattle, sheep or deer)—see Tables 2 and 3. Many studies investigated several different kinds of intervention, individually and/or in combination.

The outcomes most frequently reported were effects of interventions on trees, other vascular plants, dead wood, vertical stand structure and birds (Table 3). Data on the abundance of individual species, groups of species or dead wood were reported in 92 % of the studies, whereas 49 % of the studies included data on the richness of species (or genera), 19 % reported diversity indices such as Shannon indices, and 29 % presented data on community composition based on ordinations.

About 15 % of the studies described the effects of interventions on individual focal species. Some of the focal species constituted primary conservation targets, while others were characterised as invasive and had been selected as targets of control efforts.

Most of the studies had a CI or BACI design (65 and 29 %, respectively), while 4 % had a BA design and 2 % combined different designs. True replication of interventions had been carried out in 87 % of the studies, whereas 10 % of them were pseudo- or non-replicated and 3 % did not describe the study design clearly enough for us to assess replication.

## Discussion

This systematic map illustrates that substantive research has been conducted on some management interventions which could conceivably be used to conserve or restore biodiversity in forest set-asides. Although few of the studies were actually carried out in protected areas, many of the interventions assessed are compatible with

**Table 2 Combinations of interventions and dominant genera of trees (number of studies)**

| Intervention | Genus | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | *Abies* | *Acer* | *Alnus* | *Betula* | *Carya* | *Eucalyptus* | *Fagus* | *Fraxinus* | *Larix* | *Liriodendron* | *Picea* | *Pinus* | *Populus* | *Prunus* | *Pseudotsuga* | *Quercus* | *Thuja* | *Tilia* | *Tsuga* | All studies |
| Burning | 40 | 14 | 1 | 6 | 18 | 6 | 4 | 2 | 1 | 4 | 35 | 143 | 8 | 2 | 43 | 58 | 0 | 3 | 3 | 227 |
| Thinning | 42 | 13 | 0 | 0 | 0 | 0 | 6 | 1 | 7 | 1 | 26 | 119 | 6 | 4 | 80 | 46 | 4 | 1 | 18 | 229 |
| Partial harvesting | 46 | 68 | 1 | 33 | 12 | 2 | 38 | 9 | 2 | 5 | 108 | 53 | 42 | 3 | 53 | 47 | 8 | 4 | 34 | 311 |
| Removal of woody understorey | 11 | 8 | 4 | 5 | 5 | 0 | 3 | 2 | 0 | 2 | 6 | 18 | 2 | 1 | 10 | 32 | 0 | 2 | 0 | 57 |
| Removal of ground vegetation | 1 | 0 | 0 | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 3 | 5 | 0 | 0 | 0 | 1 | 0 | 1 | 0 | 9 |
| Litter manipulation | 1 | 3 | 1 | 1 | 2 | 1 | 1 | 2 | 0 | 2 | 2 | 11 | 1 | 0 | 1 | 5 | 0 | 0 | 1 | 20 |
| Creation of dead wood | 1 | 3 | 1 | 3 | 0 | 1 | 1 | 0 | 1 | 0 | 40 | 13 | 6 | 0 | 5 | 4 | 1 | 0 | 2 | 66 |
| Addition of dead wood | 2 | 0 | 0 | 0 | 0 | 2 | 3 | 0 | 0 | 0 | 16 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 19 |
| Grazing or exclusion from grazing | 12 | 20 | 8 | 27 | 2 | 8 | 22 | 13 | 1 | 1 | 21 | 42 | 15 | 6 | 4 | 46 | 3 | 3 | 11 | 157 |
| Mowing | 0 | 1 | 3 | 1 | 0 | 0 | 1 | 3 | 0 | 0 | 0 | 3 | 1 | 0 | 0 | 4 | 0 | 1 | 0 | 10 |
| Coppicing | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 3 | 0 | 0 | 0 | 4 |
| Pollarding | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 0 | 1 | 0 | 4 |
| Underplanting | 0 | 0 | 2 | 2 | 0 | 0 | 0 | 1 | 0 | 0 | 4 | 6 | 2 | 0 | 12 | 1 | 0 | 0 | 3 | 25 |
| Introduction of non-tree species | 1 | 2 | 0 | 0 | 1 | 0 | 1 | 2 | 0 | 0 | 3 | 2 | 1 | 0 | 2 | 4 | 0 | 0 | 0 | 11 |
| Control of exotic/invasive species | 1 | 8 | 0 | 0 | 3 | 0 | 8 | 5 | 0 | 1 | 0 | 2 | 2 | 1 | 0 | 8 | 0 | 0 | 1 | 21 |
| Hydrological interventions | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 4 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 4 |
| Other interventions | 0 | 2 | 0 | 1 | 3 | 0 | 1 | 0 | 0 | 3 | 2 | 5 | 1 | 0 | 0 | 5 | 0 | 0 | 0 | 13 |
| All interventions | 102 | 107 | 18 | 73 | 31 | 13 | 77 | 25 | 11 | 11 | 195 | 277 | 69 | 13 | 121 | 171 | 13 | 13 | 52 | |

The table shows the number of included studies with a given combination of intervention and dominant (or co-dominant) genera of trees. Data are presented for genera covered by a total of 10 studies or more. Many of the studies have listed more than one genus as dominant broad management objectives and paradigms in forest set-asides.

### Interventions

A major portion of the studies originate in concepts of forest ecosystem management and assess practices that were designed or modified to produce or sustain multiple forest values, e.g. timber and biodiversity. Beginning in the early 1990s, such practices became a focus of attention with the development of 'The New Forestry', ecosystem management and the natural-disturbance-based management paradigm [51, 52]. In Europe, these ideas influenced emerging landscape perspectives on reserve networks, including the understanding that non-intervention should be complemented with active management in reserves and with modified forestry practices outside reserves [53]. The active management approach was particularly highlighted in discussions on how to restore 'natural woodland' in regions with highly impoverished forests, such as Britain [54].

As these ideas developed, the research community responded with efforts to test the effectiveness of various practices designed to maintain and conserve biodiversity in managed forests—including maintenance or creation of important forest structural characteristics and features such as dead wood (e.g. [39]). It is thus not surprising that there was a notable increase in the number of publications on such interventions beginning in the mid-1990s, and that the vast majority of studies included in the systematic map have been published since 2000.

The studies on various types of partial harvesting fall into this research category. Such practices often aim to balance removal of timber with retaining some forest cover or creating specific structural attributes that are important as habitats for forest species. Also in this category is the group of studies on creation or addition of dead wood. Since the early 1990s, the growing understanding of the ecological importance of dead wood has led to the development of new management approaches designed to maintain or increase the amount of dead wood in managed forests (e.g. [55, 56]). This has been a particularly important issue in forests which have been managed through multiple rotations and are thus very depauperate of dead wood, e.g. in central and northern Europe [57].

There were a number of other studies which examined practices designed to manipulate stand structure or composition in some way, and these mainly related to practices which could increase the openness of the stand (e.g. thinning or removal of understorey) or increase diversity (underplanting, species introductions). These studies have been undertaken for a variety of reasons, notably concern over conifer monocultures in intensive forestry systems, but also interest in alternative forest uses, such as berry production (e.g. in Russia).

Another large portion of studies, those pertaining to prescribed burning, are also related to forest ecosystem management but more from the perspective of regeneration, restoration and fuel reduction. Managers have increasingly turned to prescribed burning to restore forests that have become degraded due to a lack of fire disturbance (e.g. [22, 58]). Burning is also employed as a silvicultural tool within the natural-disturbance-based management paradigm, where regeneration and succession of forests are driven by a regime of low-, mixed- or high-frequency fire.

The final intervention that was well represented by studies included in the map is grazing/browsing, mainly by livestock or wild ungulates, or exclusion of such herbivores. Research on this kind of intervention has usually been motivated by issues arising from overgrazing, such as impaired regeneration of trees [59]. On the other hand, re-introduction of grazing (mainly by domesticated animals) can be of equal interest for forests where the grazing pressure is currently lower than it was in the recent past. Management interventions to deal with both excess and insufficient grazing are of interest for biodiversity management in forest set-asides.

Some of the interventions that we had included as relevant were covered by very few studies. Notably, the map contains only a handful of studies that examine hydrological interventions, although we had included "ditch*" and "flood*" as search terms to find studies on forests that had been drained but then restored. Environmental issues related to forest drainage are complex [60], and there is a clear need for experimental research on terrestrial biota in forested wetlands. The obvious lack of such research is largely due to the fact that efforts to restore wetlands so far have focused on open mires rather than forested areas (e.g. [61]).

We also found very few studies on coppicing and pollarding. These silvicultural systems have declined strongly over the past century, and since they are restricted to specific regions and to certain tree species such as willows or oaks, they have not attracted global attention in environmental conservation research. Nevertheless, recent attempts to restore or re-establish coppices and pollarded stands have been followed by an increasing number of studies. Full development or restoration of coppiced or pollarded stands may require decades to centuries, however. So far, these processes have rarely been investigated beyond pure observations [62].

While our systematic map does include a large number of studies, about 50 % of potentially useful studies were rejected during screening on full text. Most frequently, exclusions were made because the interventions did not

**Table 3 Combinations of interventions and outcomes (number of included studies)**

| Intervention | Outcome | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Vertical stand structure | Horizontal stand structure | Tree micro-habitats | Dead wood | Trees | Vascular plants except trees | Bryophytes | Lichens | Fungi | Mammals | Birds | Amphibians | Reptiles | Saproxylic beetles | Ground beetles | Other beetles | Insects except beetles | Arthropods except insects | Invertebrates except arthropods | Invasive species | All outcomes |
| Burning | 34 | 1 | 7 | 60 | 123 | 105 | 11 | 7 | 15 | 12 | 31 | 3 | 1 | 34 | 16 | 9 | 10 | 13 | 3 | 30 | 227 |
| Thinning | 57 | 1 | 4 | 55 | 129 | 113 | 26 | 13 | 11 | 36 | 34 | 4 | 0 | 19 | 10 | 7 | 16 | 14 | 1 | 22 | 229 |
| Partial harvesting | 48 | 4 | 7 | 73 | 153 | 113 | 37 | 26 | 12 | 26 | 49 | 10 | 3 | 29 | 25 | 17 | 38 | 34 | 3 | 15 | 311 |
| Removal of woody understorey | 7 | 0 | 0 | 7 | 35 | 27 | 4 | 4 | 2 | 3 | 7 | 0 | 0 | 4 | 3 | 3 | 5 | 5 | 0 | 9 | 57 |
| Removal of ground vegetation | 0 | 0 | 0 | 0 | 2 | 7 | 5 | 4 | 3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 9 |
| Litter manipulation | 0 | 0 | 0 | 0 | 4 | 17 | 5 | 4 | 4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 5 | 20 |
| Creation of dead wood | 2 | 0 | 4 | 16 | 21 | 9 | 3 | 2 | 10 | 0 | 6 | 0 | 0 | 31 | 1 | 5 | 6 | 4 | 0 | 0 | 66 |
| Addition of dead wood | 0 | 0 | 0 | 3 | 3 | 1 | 1 | 1 | 5 | 0 | 0 | 0 | 1 | 11 | 1 | 2 | 3 | 1 | 0 | 0 | 19 |
| Grazing or exclusion from grazing | 18 | 0 | 1 | 8 | 84 | 110 | 18 | 12 | 5 | 9 | 13 | 3 | 2 | 2 | 15 | 7 | 18 | 12 | 5 | 15 | 157 |
| Mowing | 0 | 0 | 0 | 0 | 6 | 8 | 0 | 2 | 0 | 0 | 2 | 0 | 0 | 0 | 1 | 0 | 1 | 1 | 0 | 3 | 10 |
| Coppicing | 0 | 0 | 0 | 1 | 2 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 1 | 0 | 0 | 0 | 4 |
| Pollarding | 0 | 0 | 1 | 0 | 2 | 1 | 0 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 4 |
| Underplanting | 4 | 0 | 0 | 3 | 13 | 16 | 6 | 1 | 2 | 3 | 0 | 2 | 0 | 0 | 3 | 1 | 3 | 5 | 1 | 2 | 25 |
| Introduction of non-tree species | 0 | 0 | 0 | 0 | 4 | 7 | 0 | 0 | 1 | 0 | 1 | 0 | 0 | 4 | 0 | 0 | 0 | 0 | 0 | 6 | 11 |
| Control of exotic/invasive species | 0 | 0 | 0 | 0 | 10 | 14 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 1 | 0 | 2 | 3 | 0 | 12 | 21 |

**Table 3 continued**

| Intervention | Outcome | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Vertical stand structure | Horizontal stand structure | Tree microhabitats | Dead wood | Trees | Vascular plants except trees | Bryophytes | Lichens | Fungi | Mammals | Birds | Amphibians | Reptiles | Saproxylic beetles | Ground beetles | Other beetles | Insects except beetles | Arthropods except insects | Invertebrates except arthropods | Invasive species | All outcomes |
| Hydrological interventions | 0 | 0 | 0 | 1 | 2 | 2 | 3 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 4 |
| Other interventions | 0 | 0 | 0 | 1 | 5 | 9 | 2 | 1 | 3 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 13 |
| All interventions | 115 | 5 | 18 | 153 | 401 | 373 | 88 | 56 | 52 | 71 | 115 | 17 | 6 | 78 | 54 | 36 | 75 | 64 | 13 | 69 | |

meet our criteria. For example, in harvested stands the level of retention was often lower than the 25 % limit set for inclusion. We admit that such stands can temporarily sustain some early-successional species [31], but low-retention harvesting is normally not a useful alternative to non-intervention in forest set-asides. In several cases, a study was excluded because the intervention was not described clearly enough; sometimes, for example, stands were merely described as being under 'natural' or 'near natural' management. Such management could be useful in a forest set-aside, but the research results cannot be easily applied if details of the interventions are not available.

#### Geographic distribution of studies

The vast majority of included studies were conducted in North America. The greatest number of studies were performed in the United States, and this is likely due to three factors: the large expanses of boreal and temperate forest in the US (including Alaska), the number of researchers, and the considerable attention that has been given to ecological management and biodiversity conservation in forests. The number of studies conducted in Canada was about 40 % of that in the US. Thus, even with a much smaller population of researchers than the US, obviously extensive research is being made on forest ecosystem management and conservation, particularly in the boreal forest, which is by far the dominant forest type in Canada. In both Canada and the US public pressure, locally and from abroad, on forest companies and governments has been a driving force behind evolution of forest management practices. This has motivated research testing interventions that are relevant to the management of forest biodiversity.

The predominance of North American studies in this review was somewhat surprising given the fact that Europe also has many active researchers in the area of forest management, ecology and conservation, and that issues of ecological management and biodiversity conservation in forests have received great attention from scientists, managers and the public there as well. Different research traditions may be part of the explanation. Particularly in central Europe, many of the studies assessed by us were observational rather than experimental, often with so little specific information about past interventions that we had to exclude them. One reason for this pattern could be that much less forest is available for experimentation there than in North America, due both to the limited size of forested areas and to a more fragmented ownership pattern.

Within Europe the bulk of included studies were conducted in Finland and Sweden, both countries being equally represented. The total number of studies from all other European countries was about 60 % of that for Finland and Sweden combined. This is more or less congruent with the distribution of forest types we included. The distribution of studies likely also reflects, to some extent, the languages we were able to include.

We found few relevant studies from Russia despite the considerable expanse of boreal and temperate forest types in that country. This fact can be explained by (1) the prevailing non-intervention policy in Russian reserves, which are also much more intact than those in western Europe, and (2) a lack of experimental biodiversity research traditions in managed forests. Intact Russian forests could provide important reference areas for active management practices in the future, particularly for assessing the broad-scale effectiveness of interventions in impoverished European forests (see also [63]). Unfortunately, the development of experimental approaches for sustainable forest management remains a marginal issue for the Russian forestry sector [64].

#### Forest types and outcomes

The dominant conifer genera in the forests studied were pine (*Pinus*), spruce (*Picea*), Douglas-fir (*Pseudotsuga*) and fir (*Abies*), with oak (*Quercus*) and maple (*Acer*) being the most frequent dominants in broadleaf stands. There was also good representation of studies in stands dominated by beech (*Fagus*), birch (*Betula*) and aspen (*Populus*). There are several ecological similarities between species of these genera throughout the circumpolar region. Thus, many studies included in the systematic map likely have considerable applicability to forest management across different areas.

Outcomes reported in included studies were dominated by data on trees and other vascular plants (e.g. size/growth, abundance, diversity, composition). This likely reflects the fact that many of the relevant interventions directly manipulate these components of the forest. Studies reporting on bryophytes were also fairly well represented, with somewhat fewer studies reporting on lichens or non-lichenised fungi. There were also a considerable number of studies that reported on vertical stand structure and dead wood, both of which can be important components of habitat for a variety of biota [65]. Together, information on physical structure (including dead wood) and species composition and diversity of forest vegetation could be used to infer the impact of the tested intervention on other biota which can be linked to these forest characteristics through their known habitat requirements.

The animal groups most frequently recorded as outcomes were beetles and birds, followed by mammals. Researchers often focus on these groups because they are considered indicators of forest condition or because they are of interest to forest managers and the public [66, 67]. Likewise, these species groups are often of considerable concern in forest set-asides. However, there are still obvious gaps in our knowledge even on these taxa; for example, bird studies included in the map were conducted almost exclusively in areas that had been subject to harvesting or burning. Also, invertebrates have not been studied as broadly as one might anticipate on the basis of their very significant contributions to forest biodiversity. More generally, the range of interventions covered by studies of animals appears to be narrower than that covered by studies of plants. In particular, while one could expect causal links between terrestrial fauna and the forest floor, we found only one litter-manipulation study that explored impacts on animals [68] and no study of ground-vegetation removal with that kind of focus.

#### Limitations of the systematic map

The map is limited to the studies we were able to find using our established protocol. Despite our efforts to be inclusive with search terms, databases and languages, we have undoubtedly missed some important studies. In particular, there may be grey literature (such as reports from government agencies) that is not catalogued in publication databases or on the specialist websites we searched.

We will also have missed literature published in languages that we do not master, most notably Chinese. China incorporates a notably-sized band of the climate zones we included, and there likely exists some relevant research that is published in Chinese. There is also likely relevant literature from Japan that we did not find or were unable to use. Indeed, 22 papers identified as potentially relevant based on their English abstracts were subsequently excluded because they were written in Chinese or Japanese.

#### How the systematic map may be used

Management of forests set aside for conservation or restoration is commonly organised at a local or regional scale. Many protected areas have a small staff of managers who juggle a diversity of responsibilities and would find it challenging to read scientific papers. Although most managers are unlikely to find direct use for studies included in this systematic map, the database can quickly answer whether any relevant research has been done on a given intervention, outcome and geographic region/forest type. This could provide managers with ideas for monitoring the impact of current interventions or establishing new test systems in forest set-asides, and it could direct them to information on the efficacy of such interventions.

Further, the map provides a basis for targeted efforts to summarise existing knowledge for local or regional purposes, as well as for students who write their thesis on the management of forests set aside for conservation or restoration. The map offers possibilities to check to what extent the interventions and aspects of biodiversity under consideration have been investigated. The information about forest types that is recorded in the database allows filtering for studies in selected ecosystems. If relevant studies are found, it may be relatively simple to synthesise the results at least qualitatively in a review or leaflet aimed at managers. Such a strategy has recently been proposed as a way in which the staff of a national park can bridge the gap between science and conservation management [69].

The systematic map thus provides a means for moving from the completion of individual research projects to the 'extra tasks for conservationists' suggested by Arlettaz et al. [70]: knowledge transfer, implementation and efficiency testing. These tasks require considerable efforts beyond research as such, but only if they are fulfilled can the evidence be used as a basis for new or revised policies.

The map is also a potential tool for mitigating the 'disciplinary gap' within conservation research itself, i.e. the lack of communication and cooperation between different disciplines that results from traditional training and specialisation [71]. Guided by the map, researchers can find studies focused on taxa, interventions or regions that they are not familiar with.

#### Possible systematic review topics

On the basis of the availability of studies on different interventions and outcomes we have identified four subtopics on which it would be feasible to complete a full systematic review:

1. *What are the impacts of thinning, partial harvesting and understorey removal on the diversity of ground vegetation in mature temperate and boreal forest?* This review would provide information on the effectiveness of such practices, all of which result in opening up the forest canopy, presumably leading to increased abundance and diversity of ground-level vascular plants and bryophytes. At the same time, these practices can lead to some loss or reorganisation of shade-tolerant or desiccation-sensitive assemblages. In particular, it would be valuable to examine whether removal of trees is required to achieve the desired outcomes, or if it is sufficient to remove some understorey vegetation (e.g. shrubs). Removal of spruce in particular is highly relevant for the management of herb-rich forest set-asides in Finland and

Sweden. Although there are some existing reviews and meta-analyses relating to this topic, e.g. [24, 25, 30, 31], a full systematic review with more complete coverage is possible.

2. *What are the impacts of temperate and boreal forest stand- and tree-scale interventions on dead wood and saproxylic species?* The current lack of dead wood in forests with a history of commercial management makes any review of deadwood-related interventions highly relevant. Our systematic map has identified many studies of how the abundance and composition of dead wood and saproxylic species are affected by a variety of interventions, not only deliberate creation or addition of dead wood but also burning, thinning, partial harvesting, understorey removal, manipulation of grazing and browsing etc. It would be valuable to examine the impact of each of these interventions on dead wood and species affected by dead wood. It may also be possible to identify different responses by deadwood-dependent species to different ways of producing dead wood. We have found two published meta-analyses within this subject area, one of them focused on thinning and burning in western USA pine forests [34], the other one focused on experimental creation or addition of dead wood [39].
3. *What is the effect of prescribed burning in temperate and boreal forest on biodiversity, beyond tree regeneration, pyrophilous and saproxylic species?* While the effects of prescribed burning on tree regeneration and on pyrophilous and/or saproxylic species have been well studied, effects on non-target organisms are less well known. Importantly, such effects could be either negative or positive. It would be valuable to broaden the knowledge of how prescribed burning affects forest biodiversity, particularly because this practice is now fairly common.
4. *What are the impacts of manipulating the pressure of grazing and browsing by livestock or wild ungulates on the diversity of temperate and boreal forest plants and invertebrates?* We found more than 150 studies of how forest biodiversity is affected by manipulation of grazing and browsing. These mainly related to exclusion of deer and other wild cervids but also included studies on resumption of old-style forest grazing by cattle, sheep or other livestock. Both of these types of intervention are highly relevant to forest conservation in Sweden, and a review of grazing effects has been explicitly proposed by Swedish stakeholders. A broad quantitative review of large herbivore impacts on the species richness and abundance of other animal assemblages has recently been carried out by Foster et al. [33], and there are several narrative reviews of grazing/browsing effects on various aspects of biodiversity (e.g. [59, 72–79]. However, there is probably a need for an explicitly practice-oriented analysis that considers biodiversity targets relevant to the active-management context (i.e. manipulation of the grazing pressure in boreal and temperate forest set-asides).

## Conclusions

### Implications for management and policy

This systematic map is based on a comprehensive and systematic screening of all available literature on a range of interventions and outcomes relevant to biodiversity conservation in boreal and temperate forests. It identifies a wealth of information on the impact of active management practices that could conceivably be utilised to achieve objectives for biodiversity maintenance and conservation in forest set-asides. As such it should be of value to a range of actors, including conservation managers, researchers, and policymakers. It is challenging for practitioners to read and synthesise the evidence on individual interventions and biodiversity outcomes, but the map provides a key to finding concrete guidance from published research. A fundamental question for policymakers is whether to financially support and legally allow active management in protected areas. When such questions emerge, the systematic map allows for an overview of the available evidence and may guide the establishment of policy [80].

### Implications for research

Although significant research exists, the map also highlights important knowledge gaps. For instance, we found little data on certain interventions (such as hydrological restoration, coppicing and pollarding), on some geographical regions (such as Russia and Eastern Europe) and on outcomes such as effects on certain groups of invertebrates.

It is critical for managers to understand that there are often gaps in our knowledge on specific management issues. Such insight should serve as an incentive to establish more structured monitoring programs on initiated interventions [81, 82]. The map could be used by funding organisations, researchers and managers of protected areas to inspire new primary research on topics that have so far not been well covered. The objective overview provided by this systematic map reduces the risk of being influenced too much by strong lobbying, and it facilitates the identification of research topics where there are significant knowledge gaps. In combination with dialogues with the scientific community and stakeholder groups, this may allow for better allocation of available resources.

Finally, by identifying those areas where a substantive body of scientific knowledge has been accumulated, the systematic map provides a foundation for systematic reviews on specific subtopics. Such reviews would provide a synthesis of available evidence, making the information more accessible and easily applicable by managers and policy-makers.

## Additional files

**Additional file 1.** Swedish perspectives on active management of forest set-asides.

**Additional file 2.** Literature searches.

**Additional file 3.** Full set of criteria for inclusion/exclusion of articles.

**Additional file 4.** Systematic map database (descriptions of included studies).

**Additional file 5.** Articles excluded based on full-text screening.

**Authors' contributions**

All authors participated in literature searches, literature screening and extraction of metadata from included articles. CB double-checked the full-text screening, compiled the map database and checked all entries in the database. CB, BGJ, KJ, AL, EM and JM drafted the manuscript. All authors read and approved the final manuscript.

**Author details**

[1] Mistra Council for Evidence-Based Environmental Management, Royal Swedish Academy of Sciences, 104 05 Stockholm, Sweden. [2] Department of Natural Sciences, Mid-Sweden University, 851 70 Sundsvall, Sweden. [3] Metsähallitus Parks & Wildlife Finland, c/o UEF, P.O. Box 111, 80101 Joensuu, Finland. [4] Institute of Ecology and Earth Sciences, Tartu University, Vanemuise 46, 51014 Tartu, Estonia. [5] Department of Renewable Resources, University of Alberta, 751 General Services Building, Edmonton, AB T6G 2H1, Canada. [6] Department of Conservation and Research, Bavarian Forest National Park, Freyunger Str. 2, 94481 Grafenau, Germany.

**Acknowledgements**

We are grateful for valuable comments and advice received from a considerable number of stakeholders, both at meetings in the initial phase of this project, during the public review of the protocol and during our work with the systematic map. We would also like to thank Neal Haddaway, who suggested several valuable improvements of the map.

This review was financed by the Mistra Council for Evidence-Based Environmental Management (EviEM). EviEM is funded by the Swedish Foundation for Strategic Environmental Research (Mistra) and hosted by the Royal Swedish Academy of Sciences. The review process has been approved by the EviEM Executive Committee, but the authors are solely responsible for the contents and conclusions of the review.

**Competing interests**

The authors declare that they have no competing interests.

Received: 8 October 2015 Accepted: 2 December 2015
Published online: 29 December 2015

**References**

1. FAO. Global forest resources assessment 2010: Main report. FAO Forestry Paper, vol 163. Rome: Food and Agriculture Organization of the United Nations; 2010.
2. Schelhaas MJ, Nabuurs GJ, Schuck A. Natural disturbances in the European forests in the 19th and 20th centuries. Glob Change Biol. 2003;9:1620–33.
3. Secretariat of the Convention on Biological Diversity. Global Biodiversity Outlook 3. Montréal: UNEP/Earthprint; 2010.
4. Convention on Biological Diversity. Strategic plan for biodiversity 2011–2020. COP Decision X/2. Aichi: 2010.
5. Eide W. Arter och naturtyper i habitatdirektivet—bevarandestatus i Sverige 2013. Uppsala: ArtDatabanken, SLU; 2014.
6. Hanski I. Extinction debt and species credit in boreal forests: Modelling the consequences of different approaches to biodiversity conservation. Ann Zool Fenn. 2000;37:271–80.
7. Zehetmair T, Müller J, Runkel V, Stahlschmidt P, Winter S, Zharov A, et al. Poor effectiveness of Natura 2000 beech forests in protecting forest-dwelling bats. J Nat Conserv. 2015;23:53–60.
8. Lõhmus A, Kohv K, Palo A, Viilma K. Loss of old-growth, and the minimum need for strictly protected forests in Estonia. Ecol Bull. 2004;51:401–11.
9. Meyer P, Schmidt M, Spellmann H, Bedarff U, Bauhus J, Reif A, et al. Aufbau eines Systems nutzungsfreier Wälder in Deutschland. Natur und Landschaft. 2011;86:243–9.
10. Linder P. Structural changes in two virgin boreal forest stands in central Sweden over 72 years. Scand J For Res. 1998;13:451–61.
11. Hedwall P-O, Mikusiński G. Structural changes in protected forests in Sweden: implications for conservation functionality. Can J For Res. 2015;45:1–10.
12. Bradshaw RHW, Jones CS, Edwards SJ, Hannon GE. Forest continuity and conservation value in Western Europe. Holocene. 2015;25:194–202.
13. Sammul M, Kattai K, Lanno K, Meltsov V, Otsus M, Nõuakas L, et al. Wooded meadows of Estonia: conservation efforts for a traditional habitat. Agric Food Sci. 2008;17:413–29.
14. Nascimbene J, Dainese M, Sitzia T. Contrasting responses of epiphytic and dead wood-dwelling lichen diversity to forest management abandonment in silver fir mature woodlands. For Ecol Manage. 2013;289:325–32.
15. SER. The SER International Primer on Ecological Restoration. Tucson: Society for Ecological Restoration International; 2004.
16. Bernes C. Biodiversity in Sweden. Monitor 22. Stockholm: Swedish Environmental Protection Agency; 2011.
17. Halme P, Allen KA, Auniņš A, Bradshaw RHW, Brumelis G, Čada V, et al. Challenges of ecological restoration: Lessons from forests in northern Europe. Biol Conserv. 2013;167:248–56.
18. Humphrey JW. Benefits to biodiversity from developing old-growth conditions in British upland spruce plantations: a review and recommendations. Forestry. 2005;78:33–53.
19. Clear JL, Molinari C, Bradshaw RHW. Holocene fire in Fennoscandia and Denmark. Int J Wildland Fire. 2014;23:781–9.
20. Götmark F. Habitat management alternatives for conservation forests in the temperate zone: review, synthesis, and implications. For Ecol Manage. 2013;306:292–307.
21. Davies ZG, Tyler C, Stewart GB, Pullin AS. Are current management recommendations for saproxylic invertebrates effective? A systematic review. Biodivers Conserv. 2008;17:209–34.
22. Stanturf JA, Palik BJ, Dumroese RK. Contemporary forest restoration: a review emphasizing function. For Ecol Manage. 2014;331:292–323.
23. Stephens SL, McIver JD, Boerner REJ, Fettig CJ, Fontaine JB, Hartsough BR, et al. The effects of forest fuel-reduction treatments in the United States. Bioscience. 2012;62:549–60.
24. Abella SR, Springer JD. Effects of tree cutting and fire on understory vegetation in mixed conifer forests. For Ecol Manage. 2015;335:281–99.
25. Elliott KJ, Harper CA, Collins B. Herbaceous response to type and severity of disturbance. In: Greenberg CH, Collins BS, Thompson FR, editors. Sustaining young forest communities: ecology and management of early successional habitats in the central hardwood region, USA., Managing Forest Ecosystems, New York: Springer; 2011. p. 97–119.
26. Kennedy PL, Fontaine JB. Synthesis of knowledge on the effects of fire and fire surrogates on wildlife in U.S. dry forests. Special report 1096. Corvallis, Or.: Oregon State University Agricultural Experiment Station; 2009.
27. Meggs JM. Wildlife responses to stand-level structural retention practices in the boreal forest. Technical Bulletin 964. Research Triangle Park: NCASI; 2009.
28. Nascimbene J, Thor G, Nimis PL. Effects of forest management on epiphytic lichens in temperate deciduous forests of Europe—a review. For Ecol Manage. 2013;298:27–38.
29. Alba C, Skalova H, McGregor KF, D'Antonio C, Pysek P. Native and exotic plant species respond differently to wildfire and prescribed fire as revealed by meta-analysis. J Veg Sci. 2015;26:102–13.
30. Duguid MC, Ashton MS. A meta-analysis of the effect of forest management for timber on understory plant species diversity in temperate forests. For Ecol Manage. 2013;303:81–90.

31. Fedrowitz K, Koricheva J, Baker SC, Lindenmayer DB, Palik B, Rosenvald R, et al. Can retention forestry help conserve biodiversity? A meta-analysis. J Appl Ecol. 2014;51:1669–79.
32. Fontaine JB, Kennedy PL. Meta-analysis of avian and small-mammal response to fire severity and fire surrogate treatments in U.S. fire-prone forests. Ecol Appl. 2012;22:1547–61.
33. Foster CN, Barton PS, Lindenmayer DB. Effects of large native herbivores on other animals. J Appl Ecol. 2014;51:929–38.
34. Fulé PZ, Crouse JE, Roccaforte JP, Kalies EL. Do thinning and or burning treatments in western USA ponderosa or Jeffrey pine-dominated forests help restore natural fire behavior? For Ecol Manage. 2012;269:68–81.
35. Kalies E, Covington W, Chambers C, Rosenstock S. How do thinning and burning treatments in southwestern conifer forests in the United States affect wildlife density and population performance? CEE review 09-005 (SR66). Bangor: Collaboration for Environmental Evidence; 2010.
36. Kalies EL, Chambers CL, Covington WW. Wildlife responses to thinning and burning treatments in southwestern conifer forests: a meta-analysis. For Ecol Manage. 2010;259:333–42.
37. Paillet Y, Bergès L, Hjältén J, Ódor P, Avon C, Bernhardt-Römermann M, et al. Biodiversity differences between managed and unmanaged forests: meta-analysis of species richness in Europe. Conserv Biol. 2010;24:101–12.
38. Pastro LA, Dickman CR, Letnic M. Fire type and hemisphere determine the effects of fire on the alpha and beta diversity of vertebrates: a global meta-analysis. Glob Ecol Biogeogr. 2014;23:1146–56.
39. Seibold S, Bässler C, Brandl R, Gossner MM, Thorn S, Ulyshen MD, et al. Experimental studies of dead-wood biodiversity—a review identifying global gaps in knowledge. Biol Conserv. 2015;191:139–49.
40. Vanderwel MC, Maicolm JR, Mills SC. A meta-analysis of bird responses to uniform partial harvesting across North America. Conserv Biol. 2007;21:1230–40.
41. Verschuyl J, Riffell S, Miller D, Wigley TB. Biodiversity response to intensive biomass production from forest thinning in North American forests—a meta-analysis. For Ecol Manage. 2011;261:221–32.
42. Collaboration for Environmental Evidence. Guidelines for systematic review and evidence synthesis in environmental management. Version 4.2. Bangor: Environmental Evidence; 2013.
43. Bernes C, Jonsson BG, Junninen K, Lõhmus A, Macdonald E, Müller J et al. What is the impact of active management on biodiversity in forests set aside for conservation or restoration? A systematic review protocol. Environ Evid. 2014;3(22):1–9.
44. Landis JR, Koch GG. The measurement of observer agreement for categorical data. Biometrics. 1977;33:159–74.
45. Peel MC, Finlayson BL, McMahon TA. Updated world map of the Köppen-Geiger climate classification. Hydrol Earth Syst Sci. 2007;11:1633–44.
46. Rosenvald R, Lõhmus A. For what, when, and where is green-tree retention better than clear-cutting? A review of the biodiversity aspects. For Ecol Manage. 2008;255:1–15.
47. Aubry K, Halpern C. CE P. Variable-retention harvests in the Pacific Northwest: a review of short-term findings from the DEMO study. For Ecol Manage. 2009;258:398–408.
48. FAO. FRA 2000 on definitions of forest and forest change. Appendix 1: Definitions as in FRA Working Paper 1 and comments. Rome: Food and Agriculture Organization of the United Nations; 1998.
49. Kuuluvainen T, Aakala T. Natural forest dynamics in boreal Fennoscandia: a review and classification. Silva Fennica. 2011;45:823–41.
50. Gromtsev A. Natural disturbance dynamics in the boreal forests of European Russia: a review. Silva Fennica. 2002;36:41–55.
51. Franklin JF. Toward a new forestry. Am For. 1989;95(11/12):37–44.
52. Lindenmayer DB, Franklin JF, Lõhmus A, Baker SC, Bauhus J, Beese W, et al. A major shift to the retention approach for forestry can help resolve some global forest sustainability issues. Conserv Lett. 2012;5:421–31.
53. Hansson L. Ecological principles of nature conservation: applications in temperate and boreal environments. London: Elsevier; 1992.
54. Peterken GF. Natural woodland: ecology and conservation in northern temperate regions. Cambridge: Cambridge University Press; 1996.
55. Samuelsson J, Gustafsson L, Ingelög T. Dying and dead trees. A review of their importance for biodiversity. Report 4306. Stockholm: Swedish Environmental Protection Agency; 1994.
56. Jonsson B, Kruys N, Ranius T. Lessons from species ecology for dead wood management at a landscape scale. Silva Fennica. 2005;38:289–309.
57. Bauhus J, Puettmann K, Messier C. Silviculture for old-growth attributes. For Ecol Manage. 2009;258:525–37.
58. Kuuluvainen T, Aapala K, Ahlroth P, Kuusinen M, Lindholm T, Sallantaus T, et al. Principles of ecological restoration of boreal forested ecosystems: Finland as an example. Silva Fennica. 2002;36:409–22.
59. Côté SD, Rooney TP, Tremblay JP, Dussault C, Waller DM. Ecological impacts of deer overabundance. Annu Rev Ecol Evol Syst. 2004;35:113–47.
60. Lõhmus A, Remm L, Rannap R. Just a ditch in forest? Reconsidering draining in the context of sustainable forest management. Bioscience. 2015. doi:10.1093/biosci/biv136.
61. Similä M, Aapala K, Penttinen J. Ecological restoration in drained peatlands—best practices from Finland. Vantaa: Metsähall Nat Serv; 2014.
62. Sebek P, Altman J, Platek M, Cizek L. Is active management the key to the conservation of saproxylic biodiversity? Pollarding promotes the formation of tree hollows. PLoS One. 2013;8(3):e60456.
63. Angelstam P, Axelsson R, Elbakidze M, Laestadius L, Lazdinis M, Nordberg M, et al. Knowledge production and learning for sustainable forest management on the ground: Pan-European landscapes as a time machine. Forestry. 2011;84:581–96.
64. Ulybina O. Model forests in the Russian federation: Local perspectives, challenges and outcomes. Environ Policy Gov. 2015. doi:10.1002/eet.1679.
65. Lindenmayer DB, Margules CR, Botkin DB. Indicators of biodiversity for ecologically sustainable forest management. Conserv Biol. 2000;14:941–50.
66. Nilsson SG, Hedin J, Niklasson M. Biodiversity and its assessment in boreal and nemoral forests. Scand J For Res Suppl. 2001;3:10–26.
67. Caro T. Conservation by proxy: indicator, umbrella, keystone, flagship, and other surrogate species. Washington, DC: Island Press; 2010.
68. Osler GHR, Korycinska A, Cole L. Differences in litter mass change mite assemblage structure on a deciduous forest floor. Ecography. 2006;29:811–8.
69. Müller J, Opgenoorth L. On the gap between science and conservation implementation—a national park perspective. Basic Appl Ecol. 2014;15:373–8.
70. Arlettaz R, Schaub M, Fournier J, Reichlin TS, Sierro A, Watson JEM, et al. From publications to public actions: When conservation biologists bridge the gap between research and implementation. Bioscience. 2010;60:835–42.
71. Habel JC, Gossner MM, Meyer ST, Eggermont H, Lens L, Dengler J, et al. Mind the gaps when using science to address conservation concerns. Biodivers Conserv. 2013;22:2413–27.
72. Gerhardt P, Arnold JM, Hackländer K, Hochbichler E. Determinants of deer impact in European forests—a systematic literature analysis. For Ecol Manage. 2013;310:173–86.
73. Gill RMA, Beardall V. The impact of deer on woodlands: the effects of browsing and seed dispersal on vegetation structure and composition. Forestry. 2001;74:209–18.
74. Gordon IJ, Hester AJ, Festa-Bianchet M. The management of wild large herbivores to meet economic, conservation and environmental objectives. J Appl Ecol. 2004;41:1021–31.
75. Rooney TP, Waller DM. Direct and indirect effects of white-tailed deer in forest ecosystems. For Ecol Manage. 2003;181:165–76.
76. Suominen O, Danell K. Effects of large herbivores on other fauna. In: Danell K, Bergström R, Duncan P, Pastor J, editors. Large herbivore ecology, ecosystem dynamics and conservation. Cambridge: Cambridge University Press; 2006. p. 383–412.
77. Mitchell FJG, Kirby KJ. The impact of large herbivores on the conservation of semi-natural woods in the British uplands. Forestry. 1990;63:333–53.
78. Putman RJ. Grazing in temperate ecosystems, large herbivores and the ecology of the New Forest. London: Croom Helm; 1986.
79. Russell FL, Zippin DB, Fowler NL. Effects of white-tailed deer (*Odocoileus virginianus*) on plants, plant populations and communities: A review. The American Midland Naturalist. 2001;146:1–26.
80. Bilotta GS, Milner AM, Boyd I. On the use of systematic reviews to inform environmental policies. Environ Sci Policy. 2014;42:67–77.
81. Mascia MB, Pallier S, Thieme ML, Rowe A, Bottrill MC, Danielsen F, et al. Commonalities and complementarities among approaches to conservation monitoring and evaluation. Biol Conserv. 2014;169:258–67.
82. Sutherland WJ, Peel MJS. Benchmarking as a means to improve conservation practice. Oryx. 2011;45:56–9.