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REVIEW ARTICLE

Non-market forest ecosystem services and decision support in Nordic countries

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ABSTRACT

The need to integrate non-market ecosystem services into decision-making is widely acknowledged. Despite the exponentially growing body of literature, trade-offs between services are still poorly understood. We conducted a systematic review of published literature in the Nordic countries (Denmark, Norway, Sweden and Finland) on the integration of non-market forest ecosystem services into decision-making. The aim of the review was two-fold: (1) to provide an overview of coverage of biophysical and socio-economic assessments of non-market ecosystem services in relation to forest management; (2) to determine the extent of the integration of biophysical and socio-economic models of these services into decision support models. Our findings reveal the need for wider coverage of non-market ecosystem services and evidence-based modelling of how forest management regimes affect ecosystem services. Furthermore, temporal and spatial modelling of ecosystem impacts remains a challenge. We observed a few examples of multiple non-market services assessments. Integration of non-market services into decision support was performed with either biophysical or socio-economic models, often using proxies and composite indicators. The review reveals that there is scope for more comprehensive and integrated model development, including multiple ecosystem services and appropriate handling of forest management impacts.

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Ecosystem services; trade-offs; valuation; decision support; forest management; review

Introduction

International policy commitments and substantial scientific efforts have fostered a debate on the need for modelling and the integration of ecosystem services into decision-making (e.g. Daily 1997; MEA 2005; Daily et al. 2009; Ten Brink et al. 2011; Goldstein et al. 2012). Recent examples include the establishment of, "Intergovernmental Platform on Biodiversity and Ecosystem Services" (IPBES 2015) and "Ecosystem Services Partnership" (ESP 2015) and projects such as, "Integrating Biodiversity Science for Human Well-being" (DIVERSITAS 2015), "The Economics of Ecosystems and Biodiversity" (TEEB 2015) and the current mapping of ecosystem services initiative within the Member States of the EU (Maes et al. 2011). However, the inclusion of ecosystem services into decision-making processes is still challenged by existing knowledge gaps. Some of these include: the quantification of relationships between landscape characteristics and their associated services; the impact of management on the provision of ecosystem services and mapping values (ecological, social and economic) for spatial landscape planning (MEA 2005; ICSU et al. 2008; De Groot et al. 2010). Given the exponentially growing number of publications on ecosystem services (Fisher et al. 2009; Vihervaara et al. 2010), it is important, first, to evaluate the existing literature to create a basis for addressing knowledge gaps and, thus, reduce challenges for their integration into decision-making.

We conducted a systematic review of published literature in the Nordic countries (Denmark, Finland, Norway and Sweden) on the integration of non-market forest ecosystem services (i.e. services provided by forests that are not subject to market transactions, e.g. recreation, aesthetics, biodiversity) into decision-making. As Nordic countries' traditions are closely related to nature (Beery 2013), forest ecosystems and their services are of economic, ecological and social importance (Hytönen 1995). This has been supported by a long tradition of research on the impact of forest management on the provision of ecosystem services (e.g. Christensen & Emborg 1996; Reunanen et al. 2000; Fossestøl & Sverdrup-Thygeson 2009; Gustafsson et al. 2010) and their valuation (e.g. Kellomäki & Savolainen 1984; Bostedt & Mattsson 1995; Nielsen et al. 2007; Jensen & Skovsgaard 2009; Ezebilo et al. 2015). However, the contribution of these findings to decision-making has often been questioned (Mazza et al. 2013). A number of thematic reviews covering various types and aspects of decision support tools integrating non-market ecosystem services exists (e.g. Mendoza & Martins 2006; Diaz-Balteiro & Romero 2008; Ananda & Herath 2009). However, review studies on trade-offs between ecosystem services and their integration into decision support are rare (Uhde et al. 2015). The dependence of trade-offs on the context suggests the need for more geographically targeted assessments. Recent attempts to generate information for

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decision-making on non-market ecosystem services in Nordic countries (e.g. Framstad et al. 2013; Kettunen & Vihervaara 2013) together with the fact that there is a lack of regional studies which cover both the assessment of trade-offs and their integration into decision support make this region important and relevant for review. The aims of this review are two-fold:

(1) To provide an overview of the coverage of assessments of selected non-market ecosystem services in relation to forest management in existing literature in the Nordic countries.
(2) To understand the extent of the integration of non-market forest ecosystem services into decision support in previously published papers in the Nordic countries.

The implications of the findings from the review are discussed and recommendations regarding future research are made. Although the focus is on forest ecosystem services studies in Nordic countries, discussions are also relevant to a larger geographical scale.

Materials and methods

Drawing upon the literature and practice of systematic reviews in social sciences (Gough, Oliver, et al. 2012; Petticrew & Roberts 2012), as well as the guidelines set in conservation (Pullin & Stewart 2006; Pullin & Knight 2009), a systematic review methodology was used to identify and collect relevant studies. This method allows large volumes of research on specific, well-defined question(s) to be synthesized and is regarded as being particularly useful in situations where there is a need to provide a systematic overview of the issue at hand. The systematic review process consisted of four stages:

- Establishing the scope of the review and research questions.
- Developing the search strategy.
- Literature search and selection of relevant publications.
- Data extraction and synthesis.

Scope of the review

For the purpose of this review, we assume that forest management decision-making is an adaptive cyclical process (Figure 1). The decision-making departs from the initial stand/forest characteristics that are the result of a combination of previous management and natural conditions. The decision is made based on knowledge regarding the effects of silvicultural regimes on the provision of different ecosystem services and goals set for the area. Once the decision has been implemented, the process starts again.

This knowledge may originate from biophysical and/or socio-economic assessments and may be provided by decision support models. Biophysical studies provide insights into the capacity of an ecosystem to supply services and they focus mainly on biological and ecological relationships between ecosystem services (e.g. timber production and recreation or recreation and biodiversity) and/or the impacts of various forest management practices on the provision of non-market ecosystem services (e.g. Paillet et al. 2010; Framstad et al. 2013). Socio-economic studies address market and non-market priced ecosystem services from the human perspective in order to uncover the socially desirable levels of these services, but this review only focuses on the latter. Using a wide range of approaches, socio-economic studies supply information on public preferences concerning forest management practices (e.g. Ribe 1989; Edwards et al. 2012), and monetary values for non-market forest ecosystem services (e.g. Hörnsten & Fredman 2000; Zandersen & Tol, 2009). Together, these two domains (biophysical and socio-economic) can be combined to determine and assess trade-offs and synergies between ecosystem services for different conditions and forest management regimes. In this review, a trade-off between two services

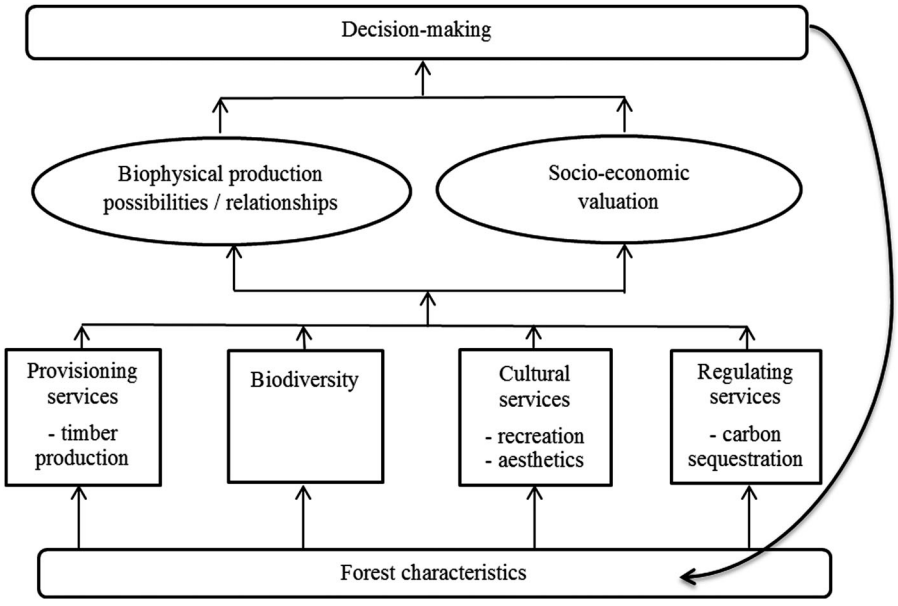

Figure 1. Chart depicting components of the decision-making process in forest management and their interactions adopted in this review.

refers to the increase in the provision of one ecosystem service combined with the simultaneous decrease in provision of the other service (win–lose), whereas the existence of a synergy implies that an increase in the provision of one service has no or a positive effect on the provision of the other service (win–win) (Raudsepp-Hearne et al. 2010). Studies on decision support include both computerized quantitative systems and conceptual models (Burstein & Holsapple 2008) that may consider timber production and non-market ecosystem services such as recreation and carbon sequestration when determining, for example, the optimal spatial and temporal allocation of final timber harvest, thinning and other forest management operations (e.g. Hartman 1976; Englin 1990; Wikström & Eriksson 2000; Asante et al. 2011). With this review, we aim to determine the coverage of both biophysical and socio-economic assessments of non-market ecosystem services as well as the extent of their integration into decision support models.

The terminology related to non-market ecosystem services has been shifting over the years from amenities (e.g. Cooper 1969), amenity services (e.g. Hartman 1976), to non-timber benefits (e.g. Stern 1985), non-market benefits/goods (e.g. Willis & Benson 1989), while in the last two decades they have been embedded in the concept of ecosystem services. The current review adopts the Millennium Ecosystem Assessment (2005) classification: supporting, provisioning, regulating and cultural ecosystem services (MEA 2005). Of the broad range of non-market ecosystem services provided by forests, this review focuses on carbon sequestration (a regulating service, i.e. the benefits obtained from the regulation of ecosystem processes), recreation and aesthetics (cultural services, i.e. nonmaterial benefits obtained from ecosystems) and biodiversity (both "as the source of ecosystem goods and services", and the ecosystem service and good itself) (MEA 2005; Mace et al. 2012). This selection of non-market ecosystem services was suggested as they were the most frequently identified services in the pilot search, which was conducted in November 2013. This meant that the final search only included other non-market services (e.g. those linked to water or soil) if they were in combination with biodiversity, carbon or recreation. Provisioning services (i.e. products obtained from ecosystems) were represented by timber production, and were only used as a reference.

Developing the search strategy

Developing the search strategy included elaborating the search terms and strings and identifying relevant sources. The extent of terms and synonyms (Figure 2) was finalized during the scoping stage – an iterative process which involves testing the proportional relevance (i.e. the proportion of the sample that appears to be relevant for the review) of the yielded publications from various search strings until the optimal level has been achieved. The search terms were kept broadly defined (e.g. "biodiversity", "recreation") to catch as many relevant studies as possible and to ensure a balanced representation of studies across ecosystem services. For example, the search for biodiversity did not include specific search terms related to individual taxonomic groups. The search was run through the following sources: general scientific article databases (ISI Web of Science (WoS), Science Direct), specialized databases both by subject and geographical location (EconLit, Research Papers in Economics, Environmental Valuation Reference Inventory, ValuebaseSwe), websites of relevant organizations (EFI, TEEB Initiative, Norden, FAO, Metla) and web search engines (Google and Google Scholar). With regard to the latter, the "first 50 hits" approach was adopted, since extending it further during scoping showed a higher degree of overlap of results with other sources and rapidly declining relevance of retrieved publications.

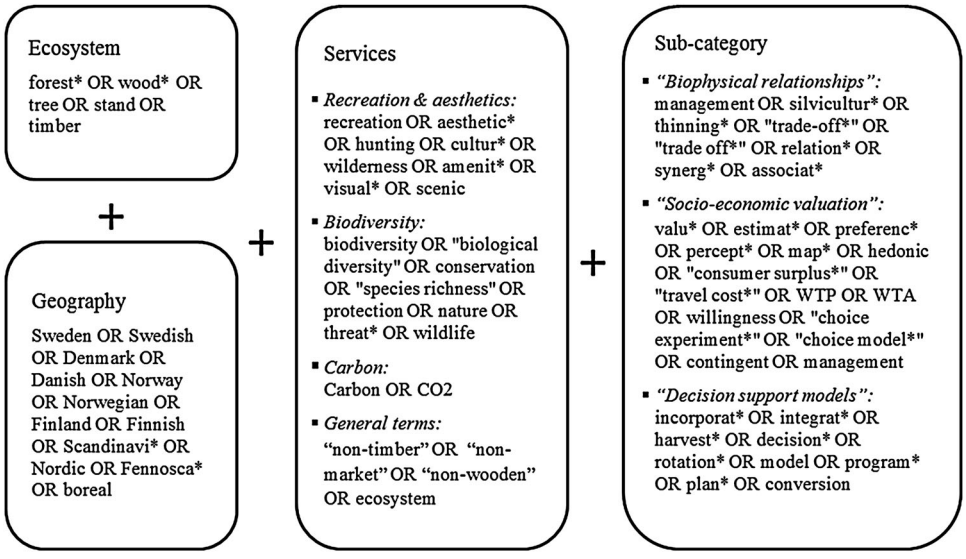

Figure 2. Search keywords and construction of search strings. Search strings are made by combining sub-strings from all four boxes and using Boolean operator "AND" between.

Literature search and selection of relevant publications

The literature search was conducted in all sources in the period December 2012 to February 2013. The search of the WoS yielded the majority of the publications (24,984 – app. 80%) some of which were relevant, while others were irrelevant for the review. In order to automatically exclude a portion of the irrelevant studies, the "refine by research area" function in WoS was applied. Only publications in the fields of "forestry", "ecology", "social sciences interdisciplinary", "biodiversity conservation", "remote sensing", "multidisciplinary sciences" and "economics" were selected, which reduced the pool of publications to 6994. The remaining pool was then exposed to two stages of relevance screening. First, based on an examination of titles and abstracts, all publications were categorized into three groups: "relevant", "not clear" and "irrelevant", the latter being discarded from further considerations for the review. During the second stage, full texts of the publications in the remaining two groups were subject to a relevance examination, and the final list of publications for the review was compiled. In both stages, a study was only considered to be relevant if all of the following criteria had been met:

- The study had been performed in the context of forestry in one of the Nordic countries.
- It was concerned with at least one of the selected non-market ecosystem services (recreation, aesthetics, biodiversity and carbon sequestration/storage).
- It examined the impacts/consequences of a forest management decision (e.g. optimal rotation age, thinning programme, types of harvest, fertilization, spatial allocation, choice of/transformation to a different silvicultural regime, etc.) on one or more of the selected non-market ecosystem services.

After all irrelevant publications had been excluded, each of the remaining studies was assigned to one of the three domains (biophysical relationships, socio-economic valuation and decision support models). The final sample amounted to 96 publications (consisting of 89 journal articles, 3 book chapters, 3 reports and 1 doctoral thesis), which were included in the current review (the full list of reviewed studies is presented in the Supplemental data).

Data extraction and synthesis

The data extraction and synthesis were based on systematic mapping and dynamic synthesis of findings. The latter builds on a framework synthesis approach, which allows new concepts to emerge from the data thereby developing the initial conceptual framework as reviewers become more familiar with the reviewed literature (Gough, Oliver, et al. 2012; Gough, Thomas, et al. 2012). This approach has been applied to reviews of studies with diverse designs and contexts. It is initiated by exploring abstracts followed by the full texts to identify the key issues and reoccurring themes (both originating from the initial conceptual framework and those emerging from the data in the process). Once most of the key themes had been identified, each publication was coded in a set of tables. The tables included descriptive information about the studies (location, authors, year of publication, etc.), as well as details of the methodology, context and main findings and any knowledge gaps relevant to this review.

Results

The results of this review showed that studies that focused on biophysical relationships had the highest number of publications followed by socio-economic valuation and decision-support models (Figure 3). Of the Nordic countries, Sweden had the highest number of publications associated with biophysical relationships and socio-economic valuation, while Finland had the highest number of publications on decision support models. A general upward trend in the number of publications devoted to non-market ecosystem services was

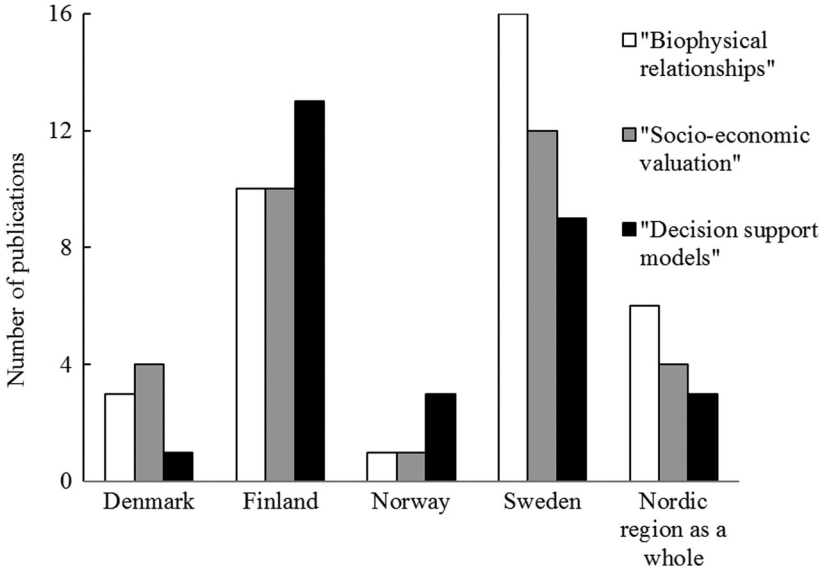

Figure 3. Distribution of the reviewed publications between geographical areas and research domains.

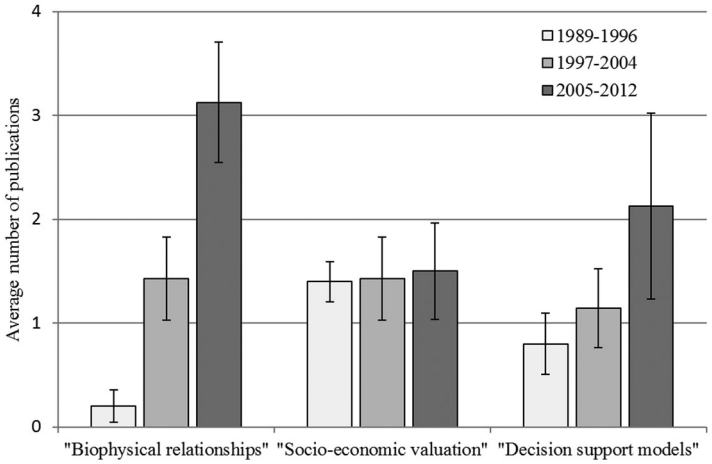

Figure 4. Average number of reviewed publications for 7-year periods for each research domain (with standard errors).

observed in the reviewed literature from the Nordic countries. The increase was most prevalent for the biophysical relationship research domain (Figure 4).

Eleven review publications were captured in this review (Table 1). Seven of the publications covered biophysical relationships between timber production and non-market ecosystem services, and four focused on socio-economic values for non-market ecosystem services. An assessment of both biophysical and socio-economic domains of non-market ecosystem services was performed using indicators that either directly or indirectly (proxies) reflect the status of the service. The following proxies (indirect indicators) have been used in the review publications captured in this review: "deadwood", "coarse woody debris" (Gustafsson et al. 2010) as well as composite indicators such as the ability to maintain "natural habitat structures" (Kuuluvainen et al. 2012), or by targeting requirements for specific taxa such as invertebrates (Niemelä 1997). The review publications mainly examined a single non-market ecosystem service at a time (Table 1).

The same trend was observed in the original research studies captured by this review. Only 15 publications focused on two non-market ecosystem services, while three publications focused on three or more services (Table 2). The highest number of non-market services as well as the presence of other services than those selected for this review (e.g. reindeer husbandry, watershed regulation) was observed in publications on decision support models. Biodiversity as a single output or in combination with other services dominated the focus of the reviewed publications, followed by cultural services (recreation and aesthetics). In general, the underrepresentation of regulating services was observed in the reviewed literature (Figure 5).

Biophysical relationships between forest ecosystem services

Publications in the biophysical relationships group mainly featured trade-offs and synergies between timber production and one of the non-market forest ecosystem services, for example, biodiversity and carbon storage and/or sequestration. Various components of biodiversity have been assessed: from specific species, for example, flying squirrels or reindeer (Reunanen et al. 2000; Berg et al. 2008) to groups of species, for example, beetles or lichens (Martikainen et al. 2000; Johansson et al. 2007). A wide range of measures and their effect on biodiversity and/or carbon sequestration have been addressed in the publications of this group such as the retention of trees and snags after tree felling (Gustafsson et al. 2010), management

Table 1. Previous review publications captured in the current review.

Reference	Geography	Object of the study	Issue at focus
Framstad et al. (2013)	Nordic	Biodiversity and carbon sequestration	Old forests
Kuuluvainen et al. (2012)	Boreal Fennoscandia	Biodiversity	Even-aged versus uneven-aged stands
Bouget et al. (2012)	Boreal	Biodiversity	Management for fuelwood
Gustafsson et al. (2010)	Nordic	Biodiversity	Tree retention in clear-cuts
Felton et al. (2010)	Sweden	Biodiversity	Coniferous monocultures versus polycultures (Norway spruce and birch)
Niemelä (1997)	Fennoscandia	Biodiversity	Forest management
Hakkarainen (1997)	Finland	Biodiversity	Forest management
Fredman et al. (2012)	Sweden	Recreation	Economic values
Gundersen and Frivold (2008)	Nordic	Recreation	Preferences for different silvicultural regimes
Lindhjem (2007)	Fennoscandia	Various non-timber outputs	Economic values
Lindgren (1995)	Nordic	Aesthetics	Preferences for various stand characteristics

Table 2. Number of publications in relation to selected non-market forest ecosystem services and research domains.

Research domain and ecosystem service	Number of publications
"Biophysical relationships"	36
Biodiversity	28
Biodiversity and carbon	1
Biodiversity versus recreation[a]	2
Carbon	5
"Socio-economic valuation"	31
Aesthetics	3
Aesthetics and biodiversity	1
Aesthetics and recreation	3
Biodiversity	7
Biodiversity and recreation	2
Recreation	13
Various[b]	2
"Decision support models"	29
Aesthetics	1
Aesthetics and recreation	1
Aesthetics and water	1
Aesthetics, biodiversity, nature tourism and recreation	1
Amenity/general	1
Biodiversity	12
Biodiversity and carbon	1
Biodiversity and reindeer husbandry	1
Biodiversity, nature tourism, recreation and reindeer husbandry	1
Biodiversity, recreation and reindeer husbandry	1
Carbon	3
Recreation	3
Recreation and reindeer husbandry	1
Carbon and recreation	1
Total	96

[a]These items are exploring biophysical relationships between two non-market services.
[b]Refers to previous review publications where more than one service was investigated across the reviewed literature.

for fuel wood (Melin et al. 2010), managed versus old-growth stands (Penttilä et al. 2004), nature-based management (Mielikäinen & Hynynen 2003), etc. Pooling information from the reviewed publications into a matrix revealed the frequent presence of the same few stand attributes (number of publications in parenthesis):

- Deadwood (both quality and quantity) and coarse woody debris (17).
- Tree species composition and especially the presence of broadleaves (aspen, willow, rowan) in the mixture (10).
- Variation/structural diversity (8).
- High stumps/snags (7).
- Old stands (including veteran trees) (6).

These attributes were used in different ways. In a portion of the studies, they acted as proxies for non-market ecosystem services, for example, one-fourth of the reviewed publications focused on the capacity of various silvicultural regimes to provide desired stand characteristics for supporting biodiversity, whereas other publications determined the relationship between non-market ecosystem services and these proxies (stand characteristics). Among the publications reviewed, there was a consensus that there is a positive relationship between the use of retention trees, snags, high stumps and dead wood and biodiversity. However, there was a lack of agreement on the effect of stump harvesting, thinning and final harvest regimes and rotation length on the provision of biodiversity or carbon sequestration or storage.

In general, the studies confirm that synergies exist between timber production and carbon sequestration, whereas timber production and biodiversity and timber production and recreation tend to compete and represent clear trade-offs. Two studies (Törn et al. 2009; Kangas et al. 2010), which focused on the relationship between non-market ecosystem services (i.e. how measures for recreation influence biodiversity), suggest a synergetic relationship between recreation and biodiversity. However, increasing recreational pressure as well as high-impact recreation may have negative effects on various species which are sensitive to a high level of disturbance.

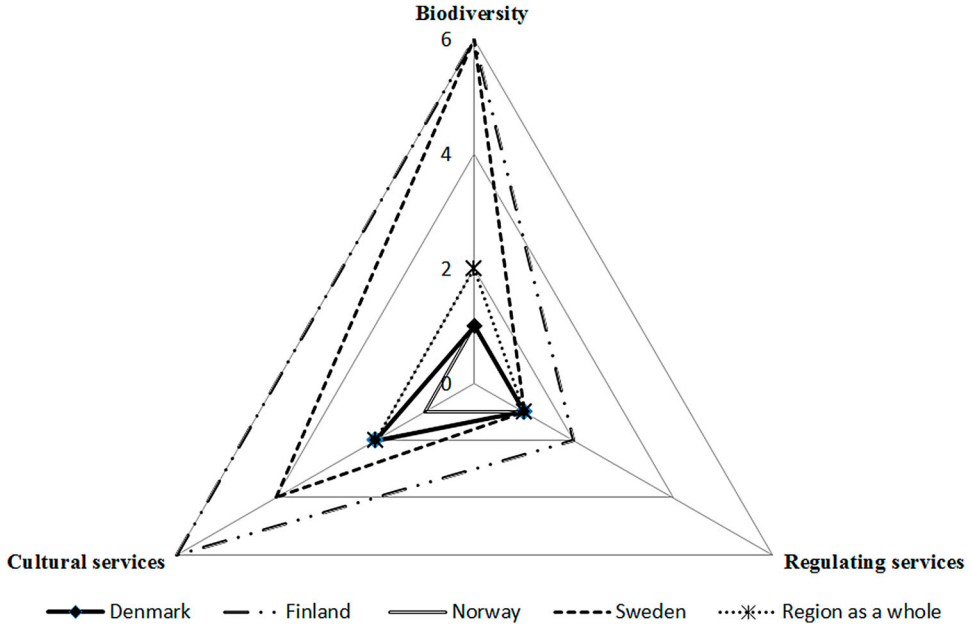

Figure 5. Relative frequency of categories of non-market ecosystem services studied in the reviewed literature per country ("0", no studies; "1", 1–4 studies; "2", 5–8 studies; "3", 9–12 studies; "4", 13–16 studies; "5", 17–20 studies and "6", 21–24 studies).

Trade-offs within ecosystem services or between proxies that are used to represent the services may also occur, for example, different land uses support different taxonomic groups of biodiversity. Emphasis on replacing coniferous monocultures with mixed species stands in Southern Sweden has positively affected general biological diversity, albeit at the expense of bryophytes as well as the number of protected red-listed species (Felton et al. 2010).

Socio-economic valuation of non-market forest ecosystem services

Approximately one-third of the reviewed publications that focused on the socio-economic valuation of non-market ecosystem services were concerned with biodiversity. The remaining publications dealt with the valuation of cultural services, that is, aesthetics and recreation (Table 2). An even split between eliciting monetary values in the form of willingness to pay or accept and non-monetary preferences and attitudes was observed. Only 2 out of 31 studies used expert judgements, while the rest surveyed the general public (both forest owners and lay people). Values of non-market services were estimated to contribute a substantial portion to the total forest value that is comparable with that of timber production (Mattsson & Li 1993; Löf et al. 2010; Fredman et al. 2012).

The publications revealed strong recreational preferences for advanced stages of stand development, that is, larger trees (Edwards et al. 2012) and variation (both in terms of species composition and age structure) (Lindgren 1995; Nielsen et al. 2007). The shelterwood system was found to be the most preferred silvicultural regime from a recreational point of view in Sweden (Holgén et al. 2000). The general acceptance of clear-cuts has been identified in the literature, although with a preference for multiple small ones as opposed to several large ones (Mattsson & Li 1994; Gundersen & Frivold 2008) (see review publications in Table 1, e.g. Lindhjem 2007; Gundersen & Frivold 2008, for a more detailed account of public preferences).

The publications covered preferences and values regarding a change in the provision of services as a result of shifts between different silvicultural regimes and treatments, conservation measures and forest stand characteristics similar to those from studies on biophysical relationships (e.g. which silvicultural system is favoured by recreationists or what value does the public place on adding extra units of forests for conservation). The majority of the reviewed publications, however, reported case-specific results, that is, values and preferences confined to the demographic groups, region and context of case.

Integration of non-market forest ecosystem services into decision support models

More than one-third of the studies focusing on forest decision support models which incorporated non-market forest ecosystem services were devoted to biodiversity, while the rest were concerned with aesthetics, recreation and carbon. The most prevalent level of planning was the forest (a set of stands), which constituted half of the models. The remainder were allocated between stand and landscape levels. The reviewed publications were concerned with a range of forest management decisions from classical rotation age and specific stand treatments to the more general selection of tree species and management regimes (e.g. even-aged versus uneven-aged). A number of models focused on the spatial aspects of planning such as the allocation of conservation and recreation sites (e.g. Juutinen et al. 2004; Öhman et al. 2011), while others included participatory aspects (e.g. Mustajoki et al. 2011; Nordström et al. 2011) and land owners' perspectives (e.g. Fries et al. 1998).

Most of the studies addressed the issue of the integration of non-market ecosystem services using a range of decision support models, including integer and linear programming (e.g. Næsset et al. 1997; Juutinen et al. 2004), analytic hierarchy process (e.g. Kuusipalo & Kangas 1994), multi-attribute and multi-criteria decision support (e.g. Kangas et al. 2005; Mustajoki et al. 2011). In these models, non-market services were often represented as being either a combination of desirable stand characteristics (proxies of targets) or as composite indicators (e.g. habitat suitability or scenic beauty indices). Notably, biodiversity and carbon were represented in the models in the form of biophysical relationships, where recreational and aesthetic – in the form of socio-economic valuation (Table 3). In a third of the publications on decision support models, both domains of research were included, which coincided with the integration of more than one non-market service (e.g. biophysical domain for biodiversity, and socio-economic for recreation). The inclusion of both domains for the same non-market service was not observed. The monetary socio-economic value component of non-market ecosystem services was only introduced into the model in the form of willingness to pay or accept in a few of the reviewed publications that used cost-benefit analysis (e.g. Holgén & Bostedt 2004; Koskela et al. 2007).

Table 3. Representation of selected non-market forest ecosystem services in reviewed publications on decision support models.

Research domain and ecosystem service(s)	Number of publications
Biophysical	12
Biodiversity	10
Biodiversity and carbon	1
Carbon and recreation	1
Socio-economic	8
Aesthetics	1
Aesthetics and recreation	1
Aesthetics and water	1
Amenity/general	1
Biodiversity and reindeer husbandry	1
Recreation	3
Both (biophysical and socio-economic)	9
Aesthetics, biodiversity, nature tourism and recreation	1
Biodiversity	2
Biodiversity, nature tourism, recreation and reindeer husbandry	1
Biodiversity, recreation and reindeer husbandry	1
Carbon	3
Recreation and reindeer husbandry	1

Discussion

The assessment and operationalization of trade-offs between ecosystem services is one of the main challenges for integrating the services into decision-making. Ecologists and social scientists whose work is related to ecosystem services have expressed the need for more integrated and comprehensive assessments that combine the biophysical and socio-economic domains to help strengthen links between science, policy and forest management (Hooper et al. 2005; ICSU et al. 2008; Bennett et al. 2009; Rudd et al. 2011; Kettunen & Vihervaara 2013). In such inter and trans-disciplinary settings, the interactions and mutual use of knowledge between research domains are becoming even more paramount. This review confirms that most studies are mainly concerned with covering knowledge within each research domain separately (e.g. Lindhjem 2007; Gundersen & Frivold 2008; Kinell et al. 2010; Timonen et al. 2011; Kuuluvainen et al. 2012; Gamfeldt et al. 2013). It also reveals that most of the studies presenting decision support models in Nordic countries have either focused on integrating biophysical or socio-economic models/data. Even in the few studies where both perspectives are applied, they seldom focus on the same service.

This review suggests that there is a limited and unevenly distributed coverage of non-market forest ecosystem services in published literature of Nordic countries, which is also consistent with findings in global reviews on ecosystem services (e.g. Vihervaara et al. 2010). The most prominent non-market forest ecosystem services are biodiversity and recreation. This may be attributed to geographical location and landscape, characteristics and roles of the forest sector in the local economy, proportion of forests in land cover, funding priorities, or the socio-political and cultural context. For example, the importance of recreation, berry and mushroom picking and hunting in the Nordic countries may be spurred by the cultural identity of the region and free public access to forest land (Hytönen 1995). Moreover, relatively low attention to regulating services in the reviewed literature may be the result of the decision to focus, in this review, on carbon sequestration/storage and the rather simple assessment of its provision due to the existence of direct indicators. Even though this review focused explicitly on specific services, a need for a wider coverage of non-market forest ecosystem services has been observed.

The single non-market ecosystem service focus of the majority of reviewed studies may be well suited for more detailed assessments in biophysical and socio-economic domains. However, when applied to the decision support (management of a single non-market service), it entails the risk of compromising the provision of other ecosystem services and resilience of the managed landscapes (Foley et al., 2005). This risk has also been observed in practical policy as authors have discovered conflicting goals, for example, for Swedish conditions it has been observed that the goal of biodiversity protection may counteract the goal of reducing the impact of climate change (Geijer et al. 2011). Thus, it is not surprising that global research on ecosystem services has been advocating the assessment of the impact of different land use regimes on multiple non-market services (e.g. Nelson et al. 2009; Duncker et al. 2012; Scolozzi et al. 2012). Moreover, research to identify bundles of ecosystem services (sets of services that consistently appear together across space and time) has provided important implications for decision-making (e.g. Raudsepp-Hearne et al. 2010; Turner et al. 2014). For example, on a landscape scale, greater diversity of services has been shown to positively correlate with the provision of regulating services (Raudsepp-Hearne et al. 2010). Thus, more studies that assess management scenarios with regard to multiple non-market ecosystem services are needed in order to make more informed decisions.

The reviewed literature in biophysical and socio-economic domains in the Nordic region addressed a range of forest management regimes and actions. However, a number of knowledge gaps in both domains have been observed. One knowledge gap in biophysical studies of forest ecosystem services is the need for a more comprehensive evaluation of the effects of alternative forest management regimes on biodiversity and ecosystem services. There is a lack of understanding regarding the effects of converting monoculture forest stands into mixed uneven-aged stands (Kuuluvainen et al. 2012; Gossner et al. 2013). Another knowledge gap is more detailed and integrated assessments of the services themselves, for example, differences in carbon content within tree species, sizes and components (Matala et al. 2009) or quantitative relation between saproxylic insects and the amount and quality of deadwood (Müller & Bütler 2010). Similarly, knowledge gaps in socio-economic valuation indicate a general need to recognize and investigate the full range of socio-economic values such as the effect of forest recreation on human health, cultural landscape values, etc. A more integrated approach to assessments providing a mix of monetary and non-monetary estimates may support this and has been recommended by other studies (e.g. Ninan & Inoue 2013; Ruckelshaus et al. 2015). Even when the relationships between services have been extensively documented, for example, timber production and biodiversity, a lack of approaches and data for the inclusion of temporal and spatial dimensions has been identified as being one of important knowledge gaps in the reviewed literature. Biodiversity conservation generally requires planning on a landscape scale and/or is tied to the location of specific species (Polasky et al. 2005), whereas demand for carbon storage is global which allows relative flexibility regarding allocation (Chan et al. 2006). In a socio-economic context, it may also be necessary to perform the quantification and valuation at the landscape level in order to account for substitution effects. For example, the recreational value of a site not only depends on its characteristics, but also on how the recreational demand for the site affects the value of existing alternatives and vice versa (Termansen et al. 2008). The lack of studies on spatial and temporal trade-offs as well as biophysical and socio-economic responses to various management regimes calls for more comprehensive assessments of forest ecosystem services (ICSU et al. 2008; De Groot et al. 2010).

The presence of insignificant trade-offs and in some instances synergies between biodiversity conservation and the provision of other non-market ecosystem services has

been suggested (Hooper et al. 2005; Chan et al. 2006; Harrison et al. 2014). On the other hand, trade-offs between provisioning and non-market ecosystem services, for example, biodiversity and cultural services, have been extensively documented (e.g. Chan et al. 2006; Geijer et al. 2011; Kettunen & Vihervaara 2013; Turner et al. 2014). However, some management regimes also enhance synergies between these groups of services. One example is timber production and recreation, where studies demonstrate that in a Nordic context people in general tend to prefer recreation in managed forests compared to unmanaged forests (Gundersen & Frivold 2008; Löf et al. 2010).

Since non-market ecosystem services are often assessed using indicators and proxies, their selection also has an effect on the revealed trade-offs and synergies (Harrison et al. 2014), which means the selection requires careful consideration. The fact that relatively little attention has been given to operationalizing the relationship between non-market forest ecosystem services in the reviewed studies can be attributed to the challenges of finding a common set of indicator(s) to assess the provision of different services. Moreover, while indicators are useful in providing biophysical relationships and socio-economic valuation data, none of the available indicators are capable of reflecting the overall sustainability of the long-term use of non-market ecosystem services on their own (Kettunen & Vihervaara 2013). Therefore, this suggests that there is a need to develop indicators and proxies in inter and trans-disciplinary settings, and confirms the previous call for more comprehensive assessments.

The valuation of decision alternatives may support the decision-making process. The case-specific nature of valuation exercises may, however, be problematic in terms of their usefulness for decision-making and especially in establishing national and regional estimates (Bujosa Bestard & Riera Font 2010; Kettunen & Vihervaara 2013). The ongoing country-level assessments of ecosystem services within the EU (e.g. Maes et al. 2011, TEEB 2015) emphasize the need to develop indicators for the national level and improve the integration of values of non-market forest ecosystem services into decision-making. The reviewed literature on decision support models in the Nordic countries showed little evidence of the use of monetary valuation estimates. A need to develop more "soft systems" in decision support that enable the inclusion of various values has been expressed (Mendoza & Martins 2006). Despite the growing attention to non-market ecosystem services and multiple uses of forests, models that are used in forest planning are largely concentrated on timber-related issues (Borges et al. 2014). When non-market ecosystem services are included in the decision support models (e.g. the Swedish decision support system "Heureka"), proxies and composite indicators, for example, habitat suitability and recreational indices, are often used due to a lack of data (Wikström et al. 2011). Decision analysis theory demands that such proxies be well defined, comprehensive, directly relevant to the decision and understandable to participants in the decision-making process (Keeney & Gregory 2005).

The results of economic valuation studies are seldom put into direct use in actual decision-making (Pearce & Seccombe-Hett 2000; Laurans et al. 2013). The studies often contain a simple reference of values being potentially useful in decision-making, however, with no further context or specifics on the appropriate implementation being provided. In order to be more appropriate for decision support, it is important that valuation exercises maintain a balance between rigorous and contextual analysis (Laurans & Mermet 2014). In a recent study of challenges from over 20 demonstration cases of the integration of biodiversity and ecosystem services in decision models from around the world, Ruckelshaus et al. (2015) found that decision-makers are often best served by relatively simple models, provided they are clearly documented, published and that validation tests reveal limitations. The quality of stakeholder engagement in the development of decision support and other knowledge is important, and research needs to be user-inspired and provides user-useful knowledge (Cowling et al. 2008). Even for the models that include a participatory component (e.g. "Mesta" in Finland), authors have called for the wider consideration of socio-cultural values (Borges et al. 2014). For the interaction between science, policy and practice, a shift from "knowledge-transfer (a unidirectional 'bridging of gaps') to knowledge-exchange (dialogue between collaborating partners) and knowledge interaction (shared cultures and institutions)" is needed (Stewart et al. 2013). This should help to identify the immediate needs of managers and the challenges they face in an attempt to integrate multiple ecosystem services in forest management and produce more operational decision support.

Poorly understood relationships between ecosystem services are a limiting factor not only for the integration of ecosystem services into decision-making, but also for the production of reliable valuation estimates. Quantifying the economic value of ecosystem services requires the continuous development of natural science-based models that can describe and quantify the production of ecosystem services and changes in these resulting from changes in management, climate or environment. This, together with the need for more integrated and comprehensive indicators and assessments, strengthens the argument for multi, inter and trans-disciplinary research. Reliance on one domain of knowledge provides single-sided solutions. Thus, when dealing with a complex socio-ecological concept, in order to make well-informed decisions, it is necessary to investigate the full array of services from the biophysical and socio-economic domains (Carpenter et al. 2009; Vihervaara et al. 2010; Martín-López et al. 2014).

The limitations of this review are mostly concerned with three issues. First, the ability of the review process to capture and select all relevant studies in order to answer the posed research questions, which is closely linked to the developed search strategy and adopted inclusion criteria. We deliberately chose to only concentrate on literature written in English, recognizing that it entailed losing the nation-specific studies published in other languages. This was partially compensated by including previous review studies, which to certain extent covered literature in other languages. Moreover, regional and other differences regarding the use of terminology and its evolution as well as

specifics of search engines for each source (database) (McComb et al. 2006) could have led to the exclusion of some relevant studies. The second limitation concerns methodological and conceptual issues of the individual studies that formed our sample. This may have limited the scope for comparison between studies. Finally, confining the review to a selected set of non-market ecosystem services poses a third limitation.

Trade-offs between ecosystem services and their operationalization are highly complex and multi-faceted. The existing and emerging literature in the Nordic countries has the potential to offer insights into how non-market ecosystem services can be integrated into decision-making. However, this knowledge remains patchy and confined to the boundaries of separate research domains, ecosystem services and sets of methods. This results in insufficient decision support. However, inadequate data should not be a limiting factor or be used as an excuse to not to integrate non-market forest ecosystem services into decision-making at various levels, especially in the light of concerns for biodiversity and ecosystem functioning and the call for sustainability. Much can be learned from case studies when it comes to understanding the perspectives of and challenges facing decision-makers when handling the complexity of biodiversity and ecosystem services. In addition, we suggest complimenting existing methodologies with a stepwise approach, which involves an interdisciplinary group of researchers. First they jointly develop indicators or other measures to estimate change in the provision of ecosystem service(s) that are relevant for both domains of research (biophysical and socio-economic). Then, the assessment is performed starting with the biophysical domain followed by the socio-economic. The inclusion of both perspectives in such an order would provide management with a comprehensive assessment of the issue. To sum up, focusing on multiple non-market ecosystem services instead of in isolation and providing both ecological and socio-economic assessments in decision support instead of one or the other makes the difference between more- and less-informed decisions. Even though one has to be cautious not to look for a panacea solution to such complex issues as socio-ecological interactions (Ostrom 2007), implementing these principles in research will facilitate more comprehensive and integrated assessments thereby strengthening forest management decision support.

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Supplemental data

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