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Assessing biodiversity impacts in Life Cycle Assessment framework - comparing approaches based on species richness and ecosystem indicators in the case of Finnish boreal forests

Abstract

Impacts of bioeconomy on climate change have been much discussed, but less attention has been given to biodiversity deterioration. One approach to assess biodiversity impacts is Life Cycle Assessment (LCA). Finland is a forested country with intensive forest industries, but only coarse biodiversity LCA methods are available. The aim of this study was to further develop and apply approaches to assess the biodiversity impacts of wood use in Finland. With the species richness approach (all taxons included), biodiversity impacts were higher in Southern than in Northern Finland but impacts in both regions were lower when mammals, birds and molluscs were included. With the ecosystem indicators approach, if the reference situation were forest in its natural state, biodiversity impacts were higher than in the case where the initial state of forest before final felling was used to derive biodiversity loss. In both cases, the biodiversity impacts were higher in Northern Finland. These results were not coherent as the model applying species richness data assesses biodiversity loss based on all species, whereas the ecosystem indicators approach considers vulnerable species. One limitation of the species richness approach was that there were no reliable datasets available. In the ecosystem indicators approach, it was noticed that the biodiversity of managed Finnish forests is substantially lower than in natural forests. Biodiversity LCA approaches are highly sensitive to reference states, applied model and data. It is essential to develop approaches capable of comparing biodiversity impacts of forest management practices, or when looking at multiple environmental impacts simultaneously with the LCA framework.

Keywords: biodiversity, boreal biome, forest, forest management, life cycle assessment

Highlights:

- A life cycle approach was applied to assess the biodiversity impacts of wood use.
- Characterisation factors were developed for boreal forests.
- Approaches based on different indicators are not coherent
- Biodiversity impacts depend on the reference situation, indicators and datasets.
- With the models, the biodiversity impact of forest products in LCA can be assessed.

1. Introduction

Bioeconomy has been given an important role as a means to achieve climate change mitigation, employment and economic growth in Finland (The Bioeconomy Strategy 2014). However, increasing bioeconomy often implies increasing harvesting levels, which can lead to adverse environmental impacts (e.g. Seppälä et al. 2019). The climate change impacts of the Finnish bioeconomy have been actively debated, but less attention has been given to the protection of biodiversity (Mustalahti 2018). A wood-based bioeconomy can have highly negative impacts on forest biodiversity as land use change sand land occupation for anthropogenic use are among the key drivers of loss and degradation of biodiversity (Steffen et al. 2015). In Finland, about half of the approximately 45 000 species known live in forests and 36% of endangered species are forest species (Rassi et al. 2010). The most common threat for threatened species is the decreasing amount of decaying wood, forest management activities, changes in the composition of tree species and decreasing amount of old-growth forests (Rassi et al. 2010). The utilisation of forests in Finland is already intensive with roundwood removals of over 65 million m^3 (Sevola, 2013). To minimise impacts of increased wood use on forest biodiversity, operational approaches for assessing impacts from forest management are needed. However, due to the complexity of measuring biodiversity, its integration into decision support remains challenging (Helin et al. 2014).

Environmental impacts related to goods and services in a bioeconomy can be assessed using life cycle assessment (LCA; Curran 2014). However, biodiversity is seldom included in standard LCA due to methodological limitations and data scarcity (Helin et al. 2014). As LCA is commonly used to assess e.g., climate change impacts of wood use (see e.g., Seppälä et al. 2019, Soimakallio et al. 2016), approaches to enhance the assessment of biodiversity impacts in the same framework could contribute to a more comprehensive understanding of the environmental sustainability of a wood-based bioeconomy.

Biodiversity includes three components: ecological, functional and structural compositions and multiple levels of organisations (genetic, species, population, community and ecosystem) (Curran et al. 2014). Many biodiversity LCA models rely on species diversity data (Winter et al. 2017, Curran et al. 2016). Species richness approaches are based on the widely accepted assumption that there is a linear relationship between species diversity and land area, and that land use change directly influences biodiversity. In a study by Chaudhary et al. (2015), data on five taxa and six land use types in 804 terrestrial ecoregions was applied. The vulnerability scores for each ecoregion based on the fraction of each species' geographic range (endemic richness) hosted by it and the assigned threat. Also DeBaan et al. (2013) assessed relative changes in species richness in different land use types compared to a (semi-) natural regional reference situation.

Biodiversity degradation could also be measured by using ecosystem indicators. According to Gao et al. (2015), ecosystem indicators such as dead wood volume and diversity, tree canopy cover and age of canopy trees, indicate biodiversity more accurately than species indicators. Michelsen (2008) compared different forestry management regimes for the ecoregions Scandinavian and Russian taiga and Scandinavian coastal coniferous forests. His approach was based on certain key factors and consequent biodiversity impacts were determined according to a simple scale ranging from no impact to major impact. In the similar approach applied by Lindner et al. (2014), regionally relevant ecosystem functions were determined based on expert judgements. Lindqvist et al. (2016) tested the methods developed by de Baan et al. (2013) and Lindner et al. (2014) at a regional level in Sweden. Winter et al. (2018) developed a methodological framework allowing an assessment of currently missing impacts on biodiversity on a global scale. Their approach is a further development of the methods of Michelsen (2008) and Lindner et al. (2014), in which various indicators besides species diversity are applicable. As yet, case studies do not exist because biodiversity impact functions are not available.

Currently available biodiversity LCA approaches to evaluate forest management in Finland are severely underdeveloped. For forest biodiversity in LCA, most of the values to convert the impacts within one environmental impact category into commensurable units (characterisation factors, CFs) can currently be applied only at a very coarse (biome) level. (Holma et al. 2013, Koellner et al. 2013, de Baan et al. 2015, Helin et al. 2014).
Moreover, several approaches underestimate the biodiversity deterioration as they are developed only to assess impacts on a global level, or do not take into account the features of boreal forests. Regionally applicable biodiversity impact assessment approaches, such as those proposed by Lindqvist et al. (2016), have not been applied for Finnish forest management.

Species richness and ecosystem indicator approaches are, according the literature review, the two main approached to assess biodiversity impacts in an LCA-framework. As there are no direct measurements for biodiversity, species richness and ecosystem indicators are often considered as proxies to measure biodiversity. However, the consistency of these approaches has not been systematically assessed..
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In this study, the aim is to improve the quantification of land use-related biodiversity impacts of Finnish forest products and services in LCA. To achieve this:
1. CFs for forest management in Southern and Northern Finland are developed
2. Two often applied approaches: species richness and ecosystem indicators are applied
3. Biodiversity impacts of forest management caused by wood use of $1m^3$ in Southern and Northern Finland are assessed

4. Usability and data requirements of the two approaches (species richness and ecosystem indicators) are critically assessed
5. How the two approaches characterise biodiversity and how they could be applied and further developed to support more sustainable decision making are assessed.

2. Material and methods

2.1 Case study area

Almost all the forests in Finland belong to the boreal coniferous forest zone and nearly half of the volume of the growing stock consists of pine *(Pinus sylvestris)* and 30% of spruce *(Picea abies)* (Finnish Statistical Yearbook of Forestry 2014). The other common species are downy birch *(Betula pubescens)* and silver birch *(Betula pendula)* and the share of the broadleaved tree species is about 20% (Finnish Statistical Yearbook of Forestry, 2014). Due to regional differences in climate and soil, species diversity, forest structure and annual increment are distinctly different in Southern and Northern Finland (Figure 1). Therefore, biodiversity assessment approaches were constructed separately for these two regions.

Figure 1. Map of Southern and Northern Finland.

2.2. LCA methodology and biodiversity assessment

Biodiversity impact assessment of land use occupation through forest management in Finland were studied. Land transformation or permanent impacts were not included. Occupational impacts include three dimensions: area, quality and time, where the basic idea is that a stretch of land, normally after transformation from some previous stage, is used for a period of time (Michelsen et al. 2014). Land occupation refers only to use of land, i.e., the time when a particular land is used by humans for a specific purpose, e.g., commercial forestry, and its properties are assumed to remain constant throughout that period. The impact on biodiversity is calculated as the difference between biodiversity quality during land occupation and between a reference situation and after forest management.

CFs were developed to be used in attributional LCA (ALCA). ALCA) aims to describe a production system as it is, using average data, whereas so-called consequential LCA describes how environmentally relevant flows would change in response to possible decisions, using marginal data (Finnveden et al. 2009). In ALCA, the principle for a land use baseline setting is proposed by the United Nations Environment Programme (UNEP)/Society for Environmental Toxicology and Chemistry (SETAC) initiative.

2.2.1 Species-richness approach

CFs were calculated using a species richness approach (de Baan et al 2013) that assesses the deterioration of biodiversity in terms of species richness before (reference situation) and after forest management. Maximum species diversity in the reference situation was determined using information from several studies (Table 1). The diversity and distribution of mammals, birds and molluscs in Finland are well studied. Species diversity and distribution of ampyllophoroid, mosses, agarics and boletes are moderately well studied, but information on the forest species inhabiting Northern and Southern Finland was not available, so the distributions of these taxons are based on estimates. The species diversity and distribution of arthropods is currently not well known, hence these were omitted. The species diversity after land alteration was estimated by subtracting the species which have become vulnerable or endangered because of forest management, the modern practice of this (changes in the forest tree species structure, removal of old growth forests and large trees and/or removal of dead wood) being the primary cause.

Table 1. Species diversity in Finland in the reference situations and critically vulnerable (CR), vulnerable (VU) and endangered (EN) forest species in Finland. The species diversity after land alteration was estimated by subtracting the species which have become vulnerable or endangered because of forest management.

Southern Finland						**Northern Finland**				
	Number of species in the reference situation	**CR**	**VU**	**EN**	**Number of species after land alteration**	**Number of species in the reference situation**	**CR**	**VU**	**EN**	**Number of species after land alteration**
Mammals	59[1]	1	5	2	51	43[1]	1	4	1	37
Birds	92[2]	3	7	2	80	76[2]	1	7	0	68
Molluscs	62[3]	2	11	7	42	28[3]	2	11	8	7
Mosses	100[4]	9	15	10	66	121[4]	1	5	4	111
Vascular plants	375[5]	8	6	21	340	100[5]	0	18	4	78
Ampyllophoroid	777[6]	14	54	15	694	423[6]	8	27	6	382
Agarics and boletes	1016[7]	15	31	22	948	831[7]	0	4	0	827

[1]Rassi et al. 2010
[2] Valkama et al. 2011
[3] Koivunen et al. 2014
[4] Ulvinen et al. 2002
[5] Hallanaro et al. 2002
[6] Kotiranta et al. 2009
[7]Kytövuori et al. 2005

CFs for Northern and Southern Finland were calculated by use of equations 1 and 2.

$$S_{rel,LUi,j,g} = \frac{S_{LUi,j,g}}{S_{ref,j,g}} \quad (1),$$

where

$S_{rel,LU}$= CF, Relative species richness on the land used
S_{LU} = Species richness on the land used
S_{ref} = Species richness in the reference situation
i= Land use type
j=Region
g=Taxonomic group

The CFs were calculated as follows

$$CF_{occ,LUi,j,g} = S_{ref,j} - S_{LUi,j} = 1 - S_{rel,LUi,j} \qquad (2),$$

The CFs for boreal forest management in Southern and Northern Finland were calculated including: 1) all taxons except arthropods, and 2) taxons whose distribution is based on observational data (i.e. mammals, birds and molluscs). For both of these, CFs were calculated in two distinct manners: assuming 1) equal weights for taxons and 2) equal weights for species. For both cases, the natural situation of Finnish forests was the reference situation, i.e., it was assumed that all known Finnish forest species could inhabit such forest. The numerical value of CF is between 0 and 1 (1 implying total removal of biodiversity and 0 implying no impact on biodiversity), but negative values are also possible (beneficial biodiversity impact).

2.2.2 Ecosystem indicators

The second biodiversity assessment approach applied was based on the method developed by Lindner et al. (2014) using ecosystem indicators. Expert judgments were applied to identify regionally specific indicators for biodiversity, the importance of each indicator and its relation to biodiversity, and questions about quantities, including amount and intensity of the indicators (Lindner et al., 2014; Lindqvist et al., 2016). Selecting the appropriate indicators and defining the respective contribution functions requires literature reviews and expert interviews or workshops (Lindner et al., 2014). The expert interviews consist of a qualitative and a quantitative discussion about the importance of each indicator and its relation to biodiversity, and questions about quantities including the amount and intensity of the indicators (Lindner et al., 2014; Lindqvist et al., 2016).

The preliminary indicators were chosen among the structural features that were identified in literature as important for forest biodiversity and that should be maintained in managed boreal forests. The preliminary indicators included old-growth forests, share of broadleaved trees, amounts of decaying wood and retention trees (Äijälä et al. 2014). Preliminary biodiversity potential functions for the selected indicators for Southern and Northern Finland were fitted based on literature (e.g. PEFC Finland 2014).

The biodiversity contribution functions were calculated as according to eq. 3:

$$y_i(x_i) = e^{-0.5\left(\frac{x_{i-k}}{l}\right)^r} \qquad (3),$$

where y_i is the biodiversity potential of each indicator, x_i is an indicator important for biodiversity and k, l, and r are fitted constants based on expert judgements. The biodiversity potential function for each indicator links the value of the indicator to a biodiversity contribution value. The biodiversity potential (BP) of each indicator is aggregated into a total multivariate biodiversity potential function according to equation 4:

$$BD = \frac{1}{n}[y_1(x_1) + y_2(x_2) + y_3(x_3) + \cdots + y_n(x_n)], \qquad (4),$$

where n is the number of contributions or indicators. Finally, the CF is calculated by subtracting the total biodiversity contribution from a hypothetical reference situation with maximum quality of biodiversity based on expert opinions.

Five biodiversity and forest management specialists working at the Finnish Environment Institute (SYKE) were selected as experts to ensure the sufficient amount of expertise. First, a set of preliminary indicators and fitted functions were sent to the expert group so that they could get acquainted with the methodology. Then a workshop was arranged where the preliminary functions, graphs and critical points and issues were presented to the experts. After the discussions with the experts, proposed adjustments were made, and the resulting indicators, graphs and values of the biodiversity potential functions were again sent for a review to be modified and/or accepted by the experts. In addition to formulating the shapes of the biodiversity potential functions, the experts determined the maximum quality of biodiversity, i.e., the reference situation for this approach (Figure 2).

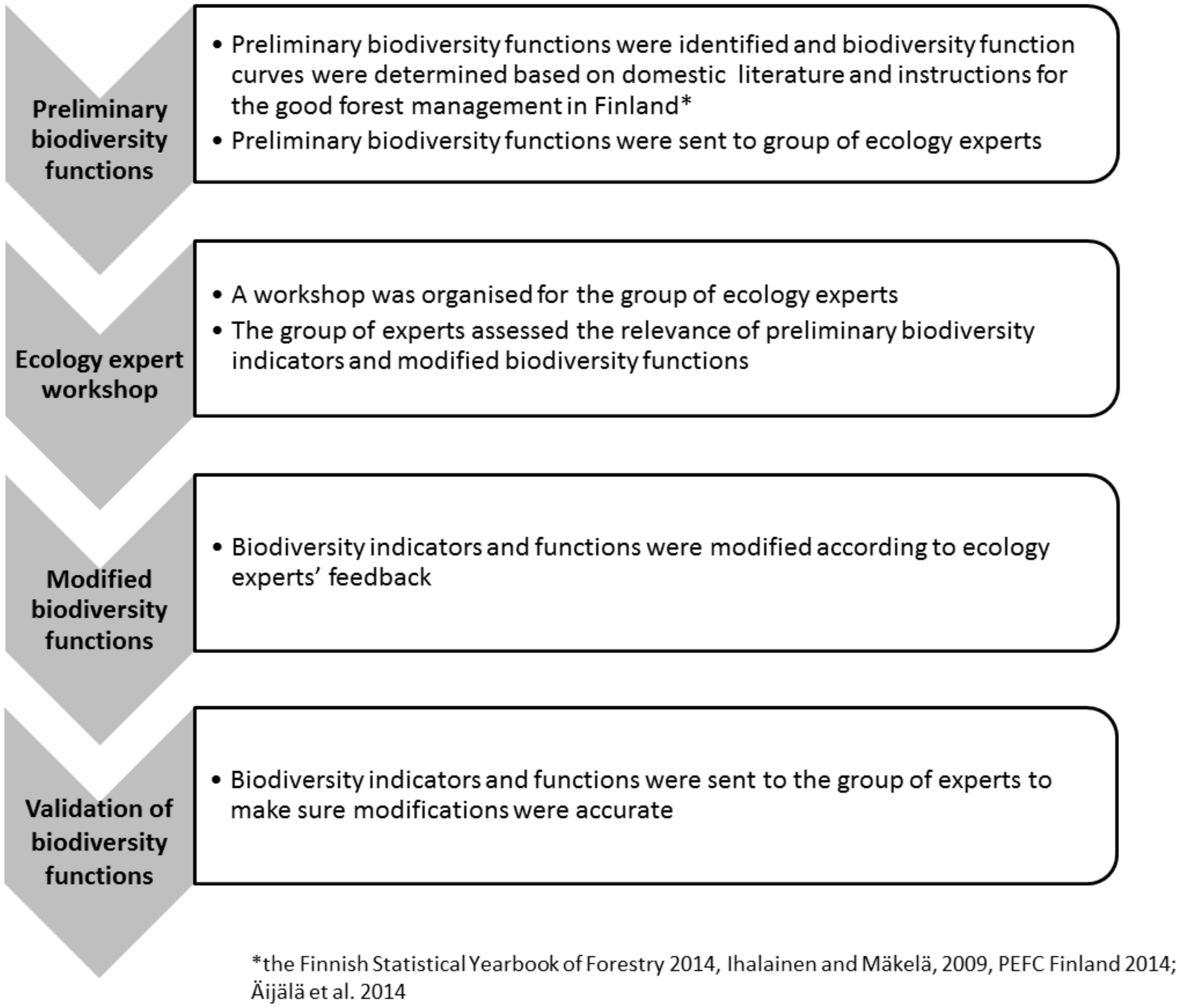

Figure 2. A flowchart of the process of determining ecosystem indicators and contribution functions.

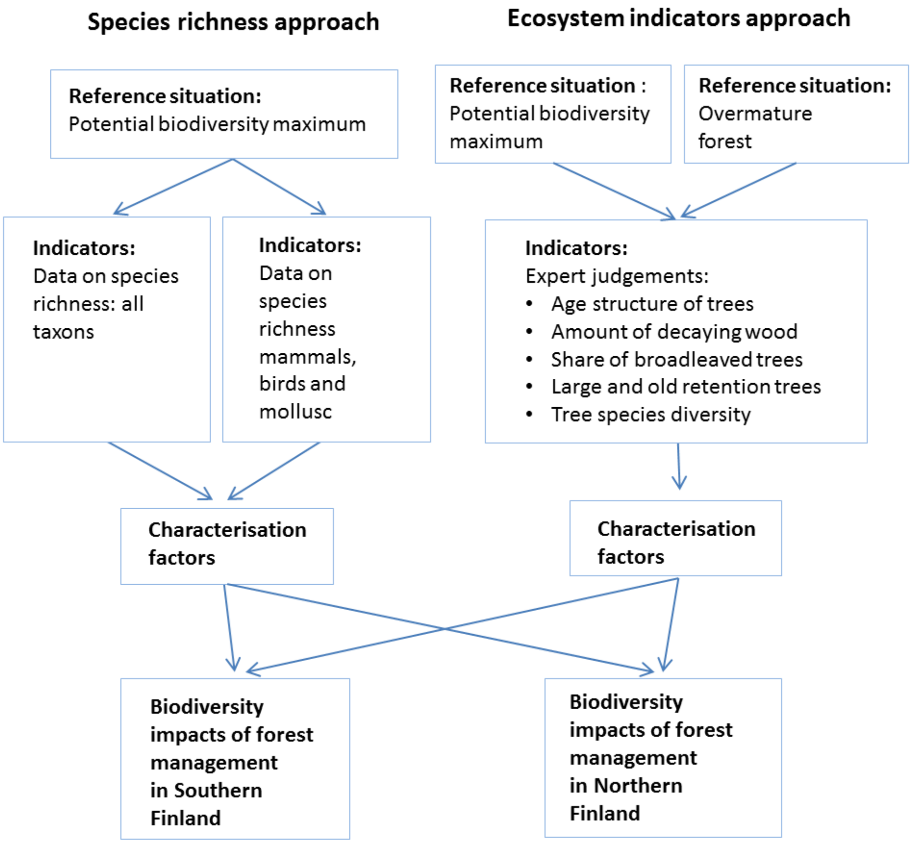

Figure 3. The summary of the data sources and assumptions underlying the two biodiversity assessment approaches.

To generate the CFs from the model based on ecosystem indicators, the biodiversity potential was calculated for the situations before and after forest management in Southern and Northern Finland (Table 3 and Figure 3). The changes in CFs were calculated both between the reference situation, i.e., forest representing the potential biodiversity maximum determined by the experts and the initial situation of the forests before forest management. The initial situation of the forest stand was an overmature managed mixed forest with a high amount of decaying wood. The following assumptions were made: the stands in their initial state had substantial amounts of old and large retention trees; that there was a diversity of tree species; and that the stands were clear-felled, although about half of the retention trees as well as decaying wood remained after felling.

2.3 Relative biodiversity impacts

The CFs were generated to assess the relative biodiversity impacts of producing 1 m^3 of wood. The mean growing stock in Southern and Northern Finland was 6.6 m^3/ha and 3.2 m^3/ha (Finnish Statistical Yearbook of Forestry 2014) (Figure 1). To produce the functional unit (1 m^3 of wood), 0.18 ha·y land is needed in Southern Finland and 0.30 ha·y in Northern Finland. The biodiversity impacts were calculated by multiplying the required land areas by the generated CFs.

3. Results

3.1 Characterisation factors in the species richness approach

The results show that when using the species richness approach (all taxons included) the biodiversity quality because of forest management was 11-20% lower in Southern and 6-9% lower in Northern Finland than the reference situation. The deterioration in biodiversity, including only well-studied taxons (mammals, birds and molluscs), was slightly higher: 14-17% for Southern and 12% for Northern Finland (Table 2). The variability is further increased by the weights attributed to the taxons. The CFs based on species richness data were higher in Southern than in Northern Finland. This was the case in all variations of the calculation methods used. For both geographical areas, CFs based on equal weights for species were lower than CFs based on equal weights for taxons. The differences between the geographical areas were due to higher total species diversity and the number of vulnerable, critically vulnerable and endangered species in Southern Finland.

Table 2. Characterisation factors for forest management land occupation impacts based on species richness data.

	Southern Finland	Northern Finland
All taxons included		
Equal weights for species		
BD at the reference	100%	100%
BD after forest management	89%	94%
CF	0.11	0.06
Equal weights for taxons		
BD at the reference	100%	100%
BD after forest management	80%	91%
CF	0.20	0.09
Mammals, birds and molluscs included		
Equal weights for species		
BD at the reference	100%	100%
BD after forest management	86%	88%
CF	0.14	0.12
Equal weights for taxons		
BD at the reference	100%	100%
BD after forest management	86%	88%
CF	0.14	0.12

3.2. Characterisation factors in the ecosystem indicators approach

The maximum potential biodiversity is achieved only in a forest in its natural state, as stated by all five interviewed biodiversity experts. In their opinion, the age of natural forests in Finland considered to have maximum biodiversity potential should be much older than those currently designated old-growth forests; they should contain close to 100 m^3/ha of decaying wood as well as very large and old retention trees. Thus, the 100% contribution of the age of trees to 400 years was increased and the 100% contribution of the amount of decaying wood was increased to 100 m^3/ha. Otherwise, the experts considered that all the preliminary indicators were relevant. However, the maximum contributions and minimum values (where the biodiversity gains begin) were modified. The experts agreed that each of the indicators should be considered based on the endangered species depending on or specialised with regard to that particular indicator. The experts considered that only large and old retention trees are relevant with respect to biodiversity. Also, the maximum contribution of the share of broadleaved tree species was increased to almost 100%.

The minimum value for decaying wood based on the experts' opinions was 20 m^3/ha, age of trees 100 years, amount of large and old retention trees about 5-10 m^3/ha, and the share of broadleaved tree species 20-30%, depending on whether the contribution functions for Southern or Northern Finland were considered. In addition, the experts included a simple indicator to reflect tree species diversity, including the tree species groups that are recorded in the national forest inventory. The biodiversity contribution function for each indicator was modified according to the experts' opinions and sent for a final evaluation round (Appendices A and B). Estimated biodiversity potentials for the situations before and after forest management for Southern and Northern Finland calculated based on Equation 4 are presented in Table 3. The contribution (%) shows the intermediate contribution of the particular indicator to the biodiversity before weighting and the total contribution (%) shows the weighted value. The total biodiversity potential is generated as a weighted arithmetic mean over all the indicators.

Table 3. Biodiversity potentials and indicator contributions based on ecosystem indicators before and after forest management of the hypothetical stands in Southern and Northern Finland.

Southern Finland	**BD potential before forest management**					**BD potential after forest management**				
Indicator	Value	Normalised value	Contribution (%)	Weight (%)	Total contribution (%)	Value	Normalised value	Contribution (%)	Weight (%)	Total contribution (%)
Age structure of trees x_1	140	0.358	14.85	20	2.97	0	0	0	20	0
Amount of decaying wood x_2	7.5	0.08	0.336	20	0.077	3.6	0.04	0.06	20	0.01
Share of broadleaved trees x_3	26	0.267	0.057	20	0.017	0	0	0	20	0
Large and old retention trees x_4	10	0.4	2.117	20	0	6	0.24	0	20	0
Tree species diversity x_5	4.5	1	100	20	20	2.5	0.56	30.52	20	6.10
Total BD potential					23.47					6.11
Northern Finland										
Age structure of trees x_1	160	0.401	29.50	20	5.9	0	0	0	20	0
Amount of decaying wood x_2	18.4	0.181	4.058	20	0.81	10.1	0.010	0.71	20	0.14
Share of broadleaved trees x_3	18	0.181	0.61	20	0.12	0	0	0	20	0
Large and old retention trees x_4	16	0.64	98.157	20	20	8	0.320	10	20	2
Tree species diversity x_5	3.5	0.78	97.56	20	19.51	2	0.44	33.96	20	6.79
Total BD potential					45.98					8.95

The CF for the potential maximum quality of biodiversity was calculated from the maximum values based on the experts' opinions. The biodiversity value of the reference situation was given a value of 1 and the biodiversity potentials of after forest management were considered as relative changes from this (Table 4). The CFs were 0.94 and 0.91 in Southern and Northern Finland, respectively, thus, almost all biodiversity is lost compared to the natural situation with maximum biodiversity. Usually, the CFs are acquired only by subtracting the biodiversity potential after land use or forest management from the reference situation with maximum quality of biodiversity. However, as the reference situation differed markedly from the initial state, CFs from the initial state before forest management were also compared and calculated, representing a more typical forest under active management, i.e., an overmature forest. This led to markedly lower CFs, i.e., 0.23 and 0.69 for Southern and Northern Finland, respectively. This implies that the biodiversity quality at the initial point before felling was 76.5 % lower than the maximum quality of biodiversity in Southern and 54% lower in Northern Finland.

Table 4. The biodiversity potentials for the reference situation and initial situation, changes in biodiversity potentials from the initial state to the state after forest management, and CFs for forest management land use occupation impacts as relative biodiversity deterioration/ha.

	Potential maximum quality of biodiversity (natural state)	Biodiversity at initial point before forest management (overmature forest)	Biodiversity value after forest management	Change from the initial state before forest management to state after felling	CFs (natural state as reference)	CFs (calculated from initial state)
Southern Finland						
Value	1	0.23		0.17	0.94	0.23
%	100	23	6.1	17		
Northern Finland						
Value	1	0.46		0.37	0.91	0.69
%	100	46	8.5	37		

3.3. Biodiversity impacts of forest management

The relative decline in biodiversity was also examined as the impact is allocated to harvested wood. CFs described in previous chapters were used to assess the biodiversity impacts from forest management as caused by using 1m^3 wood (Table 5, Figure 4). When applying the species richness approach (all taxons included), the biodiversity impacts were higher in Southern than in Northern Finland. The impacts in both regions were lower when only mammals, birds and molluscs were included. The biodiversity impacts using the ecosystem indicators approach were highly dependent on the reference situation. If the natural situation is taken as a reference, biodiversity impacts are higher than they are when an overmature forest is used as a reference. In both cases, the biodiversity impacts were higher in Northern Finland.

Table 5. Biodiversity impacts as relative deterioration of biodiversity per 1m^3 wood in Southern and Northern Finland using a species approach and an ecosystem indicators approach

		Biodiversity impacts as relative biodiversity deterioration/1m^3 wood	
Applied approach	**Description**	**Southern Finland**	**Northern Finland**
Species richness approach	All taxons included, equal weights for species	0.019	0.019
	Mammals, birds and molluscs included, equal weights for species	0.025	0.035
	All taxons included, equal weights for taxons	0.036	0.028
	Mammals, birds and molluscs included, equal weights for taxons	0.025	0.033
Ecosystem indicators approach	Calculated from maximum quality of biodiversity (natural situation as reference)	0.169	0.273
	Calculated from initial state of the forests	0.041	0.206

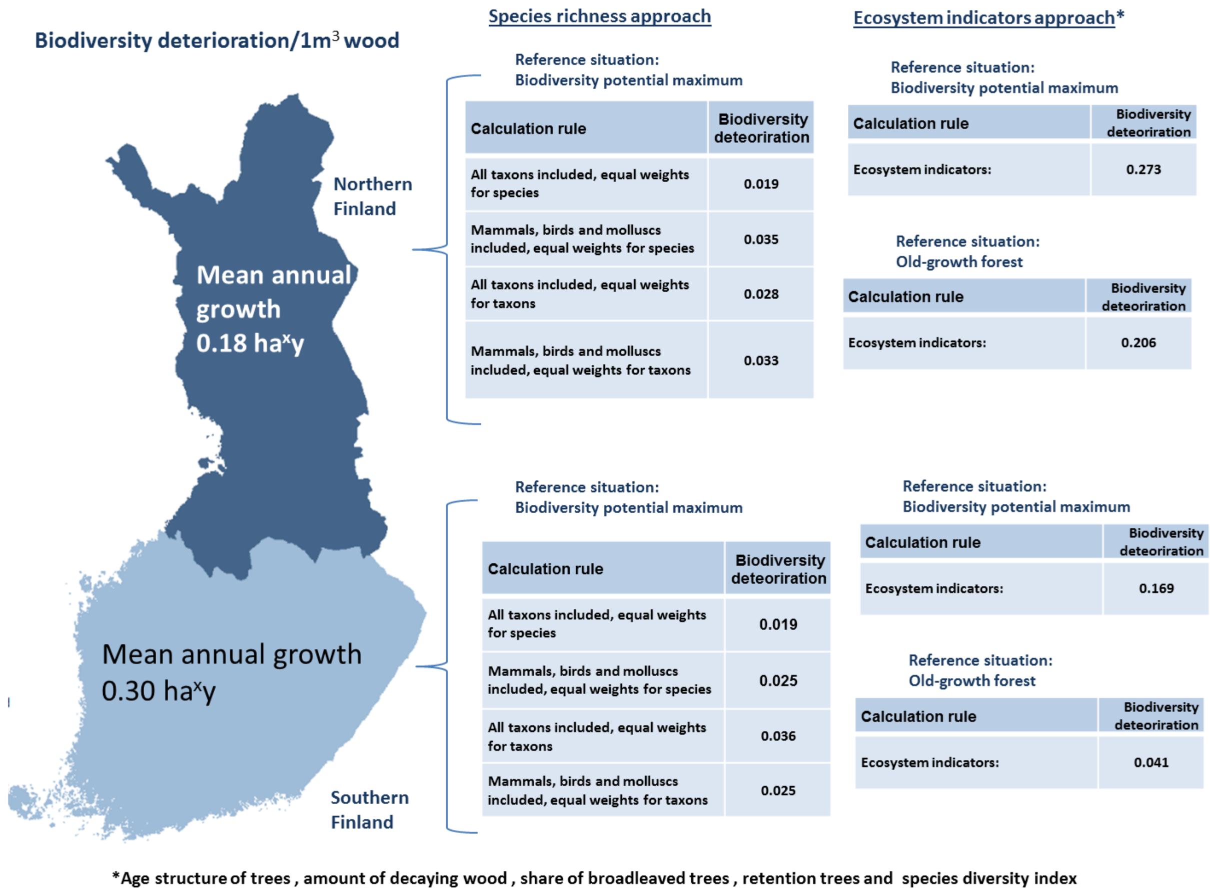

Figure 4. Biodiversity impacts of wood use in Southern and Northern Finland with species diversity and ecosystem indicators approaches.

4. Discussion

Finland is a forested country with the current bioeconomy strategies relying on increasing wood use (Seppälä et al. 2019). Operational models to assess environmental impacts such as biodiversity are highly relevant. In this study, approaches to assess biodiversity impacts of Finnish forest management in an LCA framework were applied for the first time. The results show that the biodiversity impacts are substantial when the ecosystem indicators approach is applied using a natural situation as a reference. Anticipated biodiversity impacts with the species diversity approach were much smaller.

Approaches in this paper could be applied and developed to assess biodiversity impacts of, e.g., increasing the level of harvests or applying alternative forest management regimes. It is also important to analyse trade-offs and/or synergies between objectives such as climate change mitigation and adaptation, as well as biodiversity, in a unified framework where both ecosystem and technosystem impacts are taken into account simultaneously (Leskinen et al. 2018). As LCA is the most commonly used method to assess environmental impacts such as impacts on climate change of a wood based bioeconomy (Seppälä et al. 2019, Leskinen et al. 2018), it is important to include also biodiversity impacts in the LCA framework.

4.3 Comparison of different approaches

CFs included variation between the regions and approaches as the CFs based on the species richness approach ranged from 0.11 to 0.20 in Southern and 0.06 to 0.12 in Northern Finland, whereas CFs based on the ecosystem indicators approach were much higher, from 0.23 to 0.94 in Southern and from 0.69 to 0.91 in Northern Finland. The CFs were significantly higher than in a study by Lindqvist et al. (2016) although similar kinds of approaches were applied to assess biodiversity impacts in Swedish spruce forest. However, in their study, a semi-natural situation was used as the reference situation, maximum biodiversity was lower than in this study.

Using the species richness approach, the relative biodiversity deterioration per 1 m^3 of wood ranged from 0.019 to 0.036 in Southern and from 0.019 to 0.035 in Northern Finland, depending on the taxons included and their weights. Biodiversity impacts using ecosystem indicators were highly dependent on the reference situation: using an overmature forest as the reference resulted in lower impacts. The relative biodiversity deterioration in was 0.041 per m^3 of wood in Southern and 0.206 in Northern Finland, but when a natural situation was the reference, the impacts were higher: 0.169 and 0.273, respectively.

Differences occur because the species richness approach includes all species (regardless of their vulnerability), whereas the ecosystem indicators approach was constructed considering requirements of vulnerable and endangered species. In the ecosystem approach, the interviewed biodiversity experts were unanimous that biodiversity impacts should be assessed considering the requirements on endangered and vulnerable species, not all species. In the species richness approach, CFs were constructed considering the change in the species diversity before and after forest management. In the ecosystem approach, the experts determined the natural state as old-growth forest with a large amount of dead wood. If total species diversity is used as an estimate of biodiversity, the CFs and the generated results underestimate the actual biodiversity impacts as some species can in fact benefit from the current forest management or do not have many special requirements on their forest habitat (e.g.Vierikko et al. 2010).

The interviewed biodiversity experts were unanimous that forests with maximum quality of biodiversity are forests in their natural state. Since forests in Finland have been utilised for a long time, there are no extensive natural forests in Finland (Finnish statistical yearbook of forestry 2014). In the ecosystem indicators approach, commercially managed forests appear to have a marked loss of biodiversity when compared to the natural state. Furthermore, the difference between the situation before and after forest management becomes quite small, since in both situations the biodiversity value is small compared to maximum biodiversity quality.

4.3. Sensitivity to key methodological choices

The CFs generated were based on different biodiversity indicators, reference situations and methods. Our observations support the findings of several other studies (e.g., Lindqvist et al. 2016, Michelsen et al. 2014) that the assessment of biodiversity impacts in LCA is highly sensitive to methodological choices and in particular to the choice of reference situations. In this case study, the biodiversity impacts were higher in Southern than in Northern Finland in two calculation setups (species richness approach based on all taxons), and lower in the other four setups. The biodiversity impacts assessed using the species richness approach were quite similar in Southern and Northern Finland. The ecosystem indicator approach resulted in biodiversity impacts that were higher in Northern than in Southern Finland. When overmature forest was used as a reference instead of natural state, the relative change in the biodiversity impact in Northern Finland was higher than in Southern Finland.

Choosing a reference situation is a much discussed topic in ALCA land use studies (Soimakallio et al. 2015). Using the ecosystem indicators approach, it was demonstrated that generated CFs and subsequent biodiversity impacts in Southern Finland are higher when the natural situation was used as a reference instead of initial state of forest. In a review by Soimakallio et al. (2015), four references were identified: zero baseline (ecosystem quality 0 in the baseline), business as usual, natural or quasi-natural state and natural regeneration. Soimakallio et al. (2015) and Mila I Canals et al. (2007) also considered natural regeneration, i.e., land left without any further human intervention the most suitable reference as land alteration postpones natural regeneration of land, which should be accounted for. It is not always necessary to define a reference situation: e.g. if the aim is to compare different forest harvesting scenarios. For example, in the case of the Finnish forest bioeconomy discussion, the question of interest could be the impacts of increasing the current forest harvesting level. In this setup, the reference state cancels out in the calculations where all the scenarios are compared to the same analogous reference state.

4.2. Alternative data sources

For the reference situation applied in the species richness approach, it was assumed that all recorded forest species in Finland could inhabit unmanaged forests. A drawback in this approach is focusing on the currently recognised taxons, which amount to less than half of the species diversity in Finland. (Rassi et al. 2010). As half of the species in Finland are insects (Rassi et al. 2010) using biodiversity models that exclude this taxon can cause biased results. This problem could be avoided by using e.g. expert judgements to fill data gaps connected to less studied taxons. Another drawback connected to the species richness approach is that other biodiversity aspects (such as genetic and ecosystem diversity) are not considered. The biodiversity could also be assessed by e.g., field surveys. However, fieldwork consumes time and resources, which is why only certain species groups such as game animals are surveyed in Finland (Vierikko et al. 2011).

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4.3. Global contribution of regional biodiversity assessments

Species richness is a suitable approach for biodiversity impact assessment of forest management for any region and geographical scale (see, e.g., Chaudhary et al. 2015). In the ecosystem indicators approach, ecosystem indicators are not globally applicable as the indicators and the generated results are not directly comparable over different areas. In global assessments, selecting a suitable reference is also a fundamental step. Species diversity in Finland, even in its natural state, is much lower than in biodiversity hotspot areas. Therefore, in global assessments, the biodiversity impacts of land use in countries such as Finland appear negligible, as demonstrated in a study by Di Fulvio et al. (2019). When the global perspective is dominating the LCA framework, local impacts tend to be overlooked, which makes complementary approaches such as those described in this paper important.

CFs typically describe the relative decline in biodiversity per land area, but annual growth is another fundamental factor. Eventual biodiversity impacts can be greater in countries where the annual increment is low, regardless of smaller CFs. When both relative decline in biodiversity as well as annual increment are considered simultaneously, it could be possible to assess the implications for the forest biodiversity of, e.g., international trade transfers of wood products, or for making cross-country comparisons of wood use. Determination of one reference situation is essential to making such assessment meaningful.

5. Conclusions

A transition to a wood-based bioeconomy will inevitably have impacts on forest biodiversity. Operational models and datasets are needed to assess these impacts. These models should provide reliable and understandable information on biodiversity for decision makers when e.g. level of harvests, are considered. Such models have previously been applied, but they are coarse and typically require regional adjustments. In this study, approaches based on species richness and ecosystem indicators were applied to assess biodiversity impacts of forest management in Finland. These approaches can be utilised when comparing different products and looking at various other environmental impacts at the same time. The approaches used in this study were not coherent as the species richness approach resulted in smaller CFs and biodiversity impacts than the ecosystem indicators approach.. The approach applying species richness data consider biodiversity loss including all species, whereas the ecosystem indicators approach only considers the impacts on vulnerable species. These two approaches measure different aspects of biodiversity complementing one another. This finding support the conclusions of similar studies that the current biodiversity LCA approaches are highly sensitive when it comes to reference state, applied model and data sources. To reduce uncertainties different approaches need to be developed simultaneously

Despite the uncertainties, the results show that Finnish forests are currently far from the biodiversity maximum as regards endangered species. Although it appeared that anticipated additional biodiversity impacts are not significant this does not imply that forest management practices do not influence forest biodiversity, but that the current state of Finnish forests is already well under the biodiversity maximum. Current practices that aim to improve the biodiversity value of managed forests (e.g., retention trees and dead wood) appear insufficient, and much more efficient practices along with more specific methods and approaches to evaluate progress are needed.

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