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Land Use and Forestry in the Environmental Footprint

Prof. Dr. Philip Leistner | Prof. Dr. Klaus Peter Sedlbauer (Eds.)

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carried out on behalf of
Cepi (European association representing the paper industry)

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Content

Abbreviations and Acronyms 3

Executive Summary 5

1 Introduction 7
1.1 Goal of the report 7
1.2 Structure 7

2 Land use in LCA 8
2.1 State of the art 8
2.1.1 UNEP/SETAC Framework 8
2.1.2 LANCA® 13
2.1.3 Soil Quality Index in the EF 19
2.1.4 Evaluation of existing approaches by the UNEP Life Cycle Initiative 20
2.2 Summary of research gaps 22
2.3 Implications of LCA research gaps on forestry assessment in LCA 24

3 Forestry assessment 26
3.1 Forest specific issues 26
3.2 Land use models 28
3.2.1 EFISCEN Space 28
3.2.2 HANPP 33
3.2.3 SOC (IPCC) 33

4 Recommendations for improvement 34
4.1 Inventory 34
4.1.1 Land use flows 34
4.1.2 Land use modelling 34
4.1.3 Back- and foreground data 35
4.2 Impact assessment 35
4.2.1 Reference situation 35
4.2.2 Regeneration time 36
4.2.3 Cause-effect chain 36
4.3 Existing Characterisation factors 37
4.3.1 Erosion 37
4.3.2 Biotic Production 37
4.3.3 Mechanical filtration 37
4.3.4 Physicochemical filtration 38
4.3.5 Groundwater regeneration 38
4.4 Other Characterisation factors 38

5 LANCA characterisation factor improvement 39
5.1 General framework 39
5.1.1 Sealing factor 39
5.1.2 Geolocation 40
5.1.3 Nomenclature 40
5.2 SOC 45
5.2.1 Background Calculation procedure according to De Laurentiis et al. (in preparation) 45
5.2.2 Foreground Calculation procedure (based on EFISCEN Space) 47
5.3 HANPP 50
5.3.1 Background Calculation procedure according to Alvarenga et al. (2015) 50
5.3.2 Foreground Calculation procedure (based on EFISCEN space) 51

6 Case study 55
6.1 Inventory model 55
6.2 Impact assessment with existing characterization factors 58
6.3 Background calculation with new characterization factors 65
6.3.1 Existing characterization models with new factors 65
6.3.2 HANPP 70
6.3.3 SOC (foreground vs background) 70

7 Discussion 72
7.1 Inventory 72
7.2 Impact Assessment 73
7.3 Characterisation factor improvement 74

8 Guidance for practitioners and decision makers 76
8.1 Database development (background LCA) 76
8.2 Application (foreground LCA) 77
8.3 Result interpretation 77
8.4 Policy integration 78

Glossary 79

Publication bibliography 83

Abbreviations and Acronyms

CF	Characterization Factor
CORINE	Coordination Of Information On Environment
EF	Environmental Footprint
EFISCEN	European Forest Information Scenario
FSC	Forest Stewardship Council
GIS	Geographic Information System
GLAM	Global Guidance For Life Cycle Impact Assessment Indicators
HANPP	Human Appropriation Of Net Primary Productivity
HWSD	Harmonized World Soil Database
ILCD	International Reference Life Cycle Data System
IPBES	Intergovernmental Science-Policy Platform On Biodiversity And Ecosystem Services
IPCC	Intergovernmental Panel On Climate Change
JRC	Joint Research Centre
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
MCPFE	Ministerial Conference On Protection Of Forests In Europe
NFI	National Forest Inventory
NPP	Net Primary Productivity
OEF	Organisation Environmental Footprint
PEF	Product Environmental Footprint
PEFC	Programme For Endorsement Of Forest Certification Schemes
PNV	Potential Natural Vegetation

RUSLE	Revised Version Of Universal Soil Loss Equation
SETAC	Society Of Environmental Toxicology And Chemistry
SOC	Soil Organic Carbon
SQI	Soil Quality Index
UNEP	United Nations Environment Programme
USDA	United States Department Of Agriculture
USLE	Universal Soil Loss Equation

Executive Summary

Land occupation and transformation are at the core of many human activities with an impact on the environment. Among others, this is acknowledged in the 2030 Agenda for Sustainable Development, aiming for sustainable use of terrestrial ecosystems as well as to reduce environmental impacts throughout product life cycles. The Environmental Footprint (EF) framework developed by the European Commission strives to implement this overall targets using Life Cycle Assessment (LCA). It aims to provide a method for environmental performance assessment applicable to any product on the European market. For the calculation, the standardised LCA methodology considers the entire life cycle of the products, and covers most relevant impact categories. For land-use impact assessment the soil quality index (SQI) is recommended in EF, but specified as "to be applied with caution".

The applicability of the EF land use impact assessment method on wood-based products and forestry is investigated in this report. It builds on a structured investigation of the state of research, and improvement suggestions on several levels are provided and exemplarily applied. The report elaborates suggestions to improve the land-use framework and underlying modelling to tackle the limitations of land use assessment in LCA. After presenting research gaps, general recommendations are introduced with a focus on forestry and wood production. Additionally, the report suggests several improvements to calculate characterisation factors in the LANCA® model as well as additional indicators to be included. Furthermore, alternative modelling approaches are developed and tested at the inventory level and compared on their impact assessment results. The findings are discussed and summarized as guidance for method developers, practitioners and decision-makers.

The consideration of land use impacts in methods such as Life Cycle Assessment (LCA) is complex and oftentimes requires experts to perform studies and understand results. This report focuses on land use impact assessment methods in LCA studies applied to forestry. It presents an in depth investigation of the state of the art in forestry modelling and LCA, considering the EFISCEN space forest model, the UNEP/SETAC land use framework, the European Commissions' Environmental Footprint and the Fraunhofer LANCA® framework.

Building on these, recommendations are provided for the modelling framework for inventory and impact assessment as well as the improvement of existing and the introduction of new indicators. It is found that the existing flow nomenclature is not covering different management regimes and practices and lacks spatial differentiation. Furthermore, data gaps in inventory as well as impact assessment and the SQI weighting are identified as issues for the forestry sector. Improvements for LANCA® are presented and Soil Organic Carbon (SOC) as well as Human Appropriated Net Primary Production (HANPP) are suggested as future indicators.

The recommendations are used to propose LANCA® improvements on the sealing factor, the geolocation and the forestry related nomenclature. Furthermore, models for the calculation of characterisation factors for SOC and HANPP are presented and CFs are provided for the chosen case study. For both indicators, a background calculation approach as well as a GIS based foreground calculation is presented.

The improved framework is applied to an exemplary case study using different modelling approaches based on EFISCEN space data. A base forestry product (the volume of 1 cubic meter of wood) is assessed to compare the relevance of different locations (Netherland and Sweden) and different management regimes (low, medium, high intensities) as well as modelling assumptions (80-year rotation and 2010-2030) at inventory level (transformation and occupation). Impact assessment results calculated both using SQI and LANCA® 2.5 in GaBi directly as well as through manual characterization for the specifically calculated CFs are provided.

In the discussion section the results as well as the recommendations in general are critically reflected considering the different inventory and impact assessment assumptions. The report points out the necessity to provide clarifying guidance for practitioners and decision-makers by respective authorities such as the European Commission, and provides exemplary guidance building on the recommendations and their critical discussion. Furthermore, sector-specific needs and requirements for land-use modelling assumptions have to be clarified within EF. The findings are condensed in a recommendation section for developers, practitioners, stakeholders and policy makers.

1 Introduction

1.1 Goal of the report

In the first phase of the project "Land use and forestry in EF" a number of issues related to the land use framework were identified in the Environmental Footprint (EF), which limit the applicability of the EF framework for wood-based products. The aim of this report is to describe these constraints in detail and to provide recommendations for an improved framework setup that addresses the identified issues. Core elements are an improved nomenclature for inventory flows and a modelling guideline. The improved framework is exemplified by selected new characterisation factors (CFs) for the land use impact assessment framework LANCA®.

1.2 Structure

The work structures in three main parts. Section 2 and 3 present and critically assess the current state of land use modelling in Life Cycle Assessments (LCA) focusing on forestry related issues, resulting in general recommendations for improvement in Section 4. These recommendations are exemplified in the third part (section 5 to 8).

The land use framework in LCA as well as underlying models and methods are described in detail in chapter 2 and the research gaps that contribute to these limitations are presented based on an extensive literature review. In chapter 3 alternative models from the field of forest science are presented and their applicability for land use modelling in LCA is discussed. Based on the research gaps and the alternative models, chapter 4 gives recommendations to improve the land use framework and the underlying modelling approach with a focus on forests and timber production. Some of the alternative approaches are developed exemplarily in chapter 5 and are applied and tested in a case study in chapter 6, followed by a discussion on the results in chapter 7 with a focus on the transparency and reproducibility of the results as well as their transferability and robustness. Chapter 8 describes a short guide for decision makers and practitioners on land use modelling in EF.

2 Land use in LCA

2.1 State of the art

This chapter describes the state of the art of current modelling practices for land use impact assessment in LCA. It first describes how the quality of land is being assessed for transformation and occupation impacts in the framework of the United Nations Environment Programme (UNEP) and the Society of Environmental Toxicology and Chemistry (SETAC) Life Cycle Initiative, which provides the current state of practice. Secondly, the current land use and land cover classification practices in LCA are described. This classification is summarised in the EF flow list, which is the standardised approach of the Environmental Footprint (EF) for describing the elementary flows of land use as input in the LCA model. Furthermore, current policy recommendations and guidelines on land use impact assessment of the UNEP/SETAC Life Cycle Initiative and the European Commission Joint Research Centre (JRC) are elaborated. The LANCA® method is described in more detail, highlighting the current modelling practices, the indicators used as well as the Soil Quality Index (SQI), which is recommended by the European Commission for inclusion in the EF. In the last subchapter, the research gaps of current modelling approaches are discussed with a focus on the specific implications for the forestry assessments in LCA.

2.1.1 UNEP/SETAC Framework

The assessment of impacts on soil quality caused by land using activities in LCA differs fundamentally from most other impact assessment methods. Unlike most impact categories, soil quality changes are not following the linear correlative nature of emission based cause-effect chains where more emissions linearly correlate with a higher impact. Furthermore, the impact of land using activities is strongly depending on regional and local conditions such as soil properties and climate.

Facing these challenges, a comprehensive framework for land use in LCA was developed in a joint life cycle initiative by the UNEP/SETAC. The framework was presented in a special issue in the international journal of LCA and presents a general modelling guideline, a flow list and a number of case study applications. (Koellner et al. 2013b; Milà i Canals et al. 2007; Koellner et al. 2013a). The guideline describes the concepts of transformation and occupation as well as the choice of reference states and regeneration times. In the following these main elements are presented and critically evaluated based on their applicability and limitations.

2.1.1.1 Land use modelling framework

In Life Cycle Impact Assessment (LCIA) methods, characterisation factors (CF) are mainly calculated using the UNEP SETAC framework, based on the approaches of (Koellner et al. 2013b; Milà i Canals et al. 2007; Koellner et al. 2013a). In this, a comparison is made between the quality of land (ΔQ) that results from activities that occur on a land use type and a reference system. For example, the change in soil quality caused by pasture, cropland production or forestry is measured against the reference system of natural vegetation. The

CF is determined by this difference in soil quality. The impact is calculated by multiplying this CF by the area and time of land occupied. In Figure 1, the quality change of the land for occupation is presented. As can be seen, the occupation occurs between the two points in time t_1 and t_2 and is determined as the change in soil quality between the reference system and a land use type. The potential natural vegetation can serve as the reference situation. In accordance with the guidelines of the UNEP/SETAC framework, the quality of the soil remains at the same level during the occupation, although a higher intensity of land use could lead to an even greater degradation of the soil (Koellner et al. 2013a). Between t_2 and t_3, the reversible transformation after the end of the occupation happens and causes a change in soil quality depending on the time needed for regeneration. Calculating the difference between the soil qualities of two land use types gives the permanent transformation after the end of an occupation; it is not influenced by time.

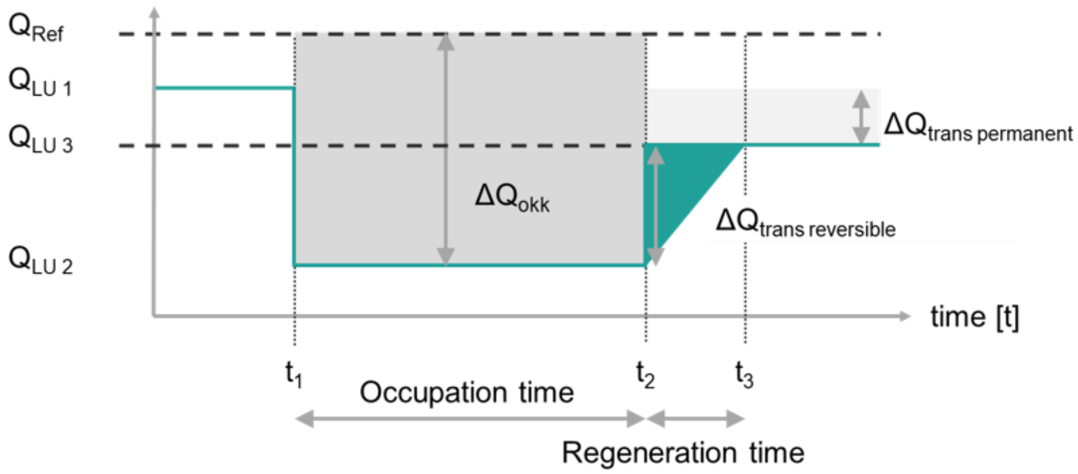

Figure 1: Transformation and occupation as simplified case of one intervention (based on Beck et al. 2010; Koellner et al. 2013b)

2.1.1.2 Inventory nomenclature

In order to carry out an LCA, information on all input and output flows of the system under consideration is required. The collection of the input and output data is carried out in the life cycle inventory (LCI) phase of the LCA. Depending on the scope of the analysis, different information has to be provided. For the assessment of land use impacts, the scope of information collection includes all land use types that are identified as input flows along a product's life cycle, as well as descriptions of the land use activity's time and the land use sites' location, which can be done by giving the name of the country or by stating the specific location (Taelman et al. 2016; Milà i Canals et al. 2014).

In the context of the UNEP/SETAC Life Cycle Initiative, the nomenclature of the land use flow classification in LCA has been developed and published by Koellner et al. (2013a). It is based on the concepts of geo-information modelling. Among the references cited are the Global Land Cover 2000 (Bartholomé and Belward 2005), GlobCover (Arino et al. 2010) or the CORINE land cover classification system (European Environment Agency 2007). The classification of land use types proposed by Koellner et al. (2013a) is utilised in order to model land use impacts in the EF when conducting an LCA. This classification is known as the EF flow list and was published by the EU in the Handbook of the International Reference Life Cycle Data System (ILCD) and recommended by the latter (JRC 2011).

The flow list applies a four-level approach for the classification of the various land use types where more information is provided at each level. It can be summarized as follows: [Common land use/ cover name (Level1)] + [Land status (Level 2)] + [Land management practices (Level 3)] + [Land use intensity (Level 4)]. The first level is used for describing the common land use or land cover name. Examples include „pasture" or „grassland". This elementary description is detailed on the second level by providing information on the status of the land. For example, the first level might classify a land use as "forest", which is then supplemented on the second level with further information such as "forest, used" or „forest, natural" (Koellner et al. 2013a). On the third level, more details on land management (e.g. arable, irrigated) is given and on the fourth level the classification is finalised by specifying the land use intensity (e.g. agriculture, arable, extensive) (Koellner et al. 2013a). A deviation from the four-level approach is made in the case of forestry and grassland, as for them the intensity is already provided on the third level without the fourth level. It should be noted that the flows of a lower level do not determine how missing information on lower level is chosen (either average or worst-case based). Besides, the flow name can be used to specify the location of the land use. There are different options for doing so. One option is the regionalisation based on biomes and climates proposed by Koellner et al. (2013a), however, as this information is often not available to practitioners, it has not been applied in modelling practice. Another option is to include the country code of the specific flow in the nomenclature for the EF. Where this information is available, this option is used instead. An example is „forest used, intensive (regionalized, FI)".

The EF flow list comes with both advantages and drawbacks. As the EF flow list presents a common nomenclature for land use flows that is used in the EF and that meets the approval of different stakeholders, it lays the basis for the LCA. This major advantage is in contrast to the fact that only a limited number of flows can be assessed. For forests, for example, only seven flows are available, and none of these are on the fourth level indicating forest management practices. As a result, for forestry there is only a distinction between used forests: 1) extensive, with selective logging, where timber extraction is followed by regrowth, including at least three naturally occurring tree species; or 2) with either even-aged stands and clear-cut patches, or less than three naturally occurring species at planting/seeding (Koellner et al. 2013a). Therefore, this flow list nomenclature is only of limited practicability, especially for modelling the impacts of forest use, as it does not do justice to the diverse management practices in the various forest management systems. A drawback of the EF list is that the flow list nomenclature is not always consistent. In some cases, the flow name specifies a type of land use while in other cases it gives a description of the land cover. As previously mentioned, there are also deviations from the four-level approach used in the nomenclature. As such, for some flows, details on the land use intensity or land management practices might be provided at different levels than defined in the approach, and for some flows, there is no such specific description available. For example, in the case of forest flows, the nomenclature does not include any management practices. Furthermore, a more precise location (than the country) of a land use flow, such as the region or geo-coordinates, would allow for a better foreground characterisation, but lead to an infinite number of flows (currently there are already ~15,000 flows due to the country information).

2.1.1.3 Occupation/Transformation

In order to model the impacts of land use, two kinds of flows are modelled: land occupation and land transformation flows. Land occupation is characterized as the current type of land use of an area per functional unit within a certain duration that affects the quality of the soil. It is therefore measured in units of area and time (e.g. m² and year) (Koellner et al. 2013a; Milà i Canals et al. 2007). Land transformation is the change in the quality between two specific types of land use. A distinction is made here between reversible and permanent transformation (Koellner et al. 2013a; Milà i Canals et al. 2007).

The quality of abandoned land during its regeneration is described by the reversible transformation. For the permanent and the reversible transformation only a "quasi-natural state" is assumed, based on the assumption that an abandoned land cannot achieve the quality of the primary, natural land cover (Koellner et al. 2013b). When calculating the reversible transformation, a regeneration factor is factored in for the time it takes the ecosystem to reach the quasi-natural state.

The quality of land between different types of land use is described by the permanent transformation. The two types of land use considered are the one before and the one after the occupation has occurred. For example, a chronological order of the different land use types could be as follows: natural forest (before the occupation), intensive forestry (during the occupation), and arable land (after the occupation). In this case, the originally naturally forested land was transformed by intensive forestry and will be transformed into agricultural land after the occupation. This type of transformation, the permanent transformation, is expressed as the area of the transformed land. When calculating the permanent transformation, no regeneration time is factored into the equation. Therefore, the permanent transformation is no time-dependent value and is expressed in a different measuring unit than the occupation and reversible transformation.

The distinction in transformation types is not represented in the flow nomenclature, nor is there a distinct guideline available for inventory modelling with regard to transformation. These differences in transformation flows lead to inconsistencies in land use modelling for different LCA software since the databases use the same flows but interpret them differently. For the "transformation to" flows, it is not specified whether this is considered a permanent transformation (as interpreted in GaBi DB and Ecoinvent) or a reversible transformation (as interpreted in the SQI) normalization model that is suggested for EF 3.0). This leads to ambiguity and systematic errors since the permanent transformation flows in GaBi and Ecoinvent models are interpreted as reversible transformation flows when applying the SQI. Therefore, this might lead to an underestimation of the SQI, for example, for very intensive land use activities.

2.1.1.4 Reference situation

The reference situation chosen impacts substantially on the results as it serves as benchmark against which the quality of the land under a particular type of land use is measured. Basically, three approaches can be distinguished that can be used to define the reference situation in LCA, according to Koellner et al. (2013b). The first method on this list uses the concept of potential natural vegetation (PNV). The PNV characterises the vegetation that could be expected to occur in areas where there are no human activities (Chiarucci et al. 2010). In the second approach, the reference situation is set as the "quasi-natural" vegetation in a particular ecological region, e.g., a biome or an ecoregion. The third possible approach sets the current land use situation in a particular region as a reference system (Koellner et al. 2013b). IPBES (2018) refers to this approach as the time-bound recent state approach. The defined initial situation is an ecosystem condition that still exists or existed in recent historical years. One further option can be added to this list of approaches. This approach is the so-called time-bound natural state, which has been described by IPBES (2018). It describes a historical state of ecosystems the way it was before a human-induced "degradation" took place, e.g., 600 years ago (IPBES 2018). While the approaches are quite different, they have in common that they all have some advantages and disadvantages. For example, the use of PNV as a reference situation results in high impacts in both temperate and tropical countries. A quite different outcome would be obtained when using the current land use situation as a reference situation. In this case, only the tropical areas would show a high impact in occupation as, in comparison to countries, e.g. in Europe, they still have bigger, intact areas with natural primary vegetation (Koellner and Geyer 2013). Consequently, the historical development of deforestation in industrialised countries is not adequately considered.

2.1.1.5 Cause-effect chain

Many methods that analyse the impacts in the LCIA phase use a type of presentation called cause-effect chain in order to depict the connections between an intervention, the impact indicators and the different areas of protection. The LCI provides the information on land use (occupation, transformation, land management). This information is classified and characterised into various midpoint categories, for example groundwater resistance or erosion. In the stage of damage assessment and normalisation, it is finally linked to the endpoint category ecosystem quality. It is possible to group all endpoint categories into a single index, such as the SQI, which is weighted to receive a joint entity.

The developed impact indicators reflect the specific ecosystem services or impairments. A cause-effect chain for impact indicators on biodiversity and ecosystem services has been presented and further developed, for example, by Lindeijer (2000) and Vidal-Legaz et al. (2016). Starting point is a specific land use as an intervention. This has a direct impact on biodiversity, life-supporting functions and land availability. Resources, ecosystem quality and biodiversity are indicated as areas of protection (also known as safeguard subjects). According to Koellner et al. (2013b), indicators such as erosion control and water purification are midpoints caused by interventions in land use such as fertilisation, soil sealing and irrigation. Examples of the direct consequences of interventions are the influence on soil fertility through intensive cultivation of field crops or the influence on infiltration through compaction of the soil by heavy machinery. According to Vidal-Legaz et al. (2016), there are two endpoints that can also be the midpoints of other impact indicators: ecosystem thermodynamics and ecosystem services. These two impact indicators can refer to the third endpoint, biodiversity, or independently influence the areas of protection of natural resources, natural environment and human health. In Koellner et al. (2013b), the cause-effect chain includes not only the endpoint damage to biodiversity but also the endpoint damage to ecosystem services, while the thermodynamics of the ecosystem is not considered in the cause-effect chain (Bos 2019).

As can be seen, there is neither an agreement on the type and number of mid- and endpoint indicators nor on a common cause-effect chain for modelling impacts on ecosystem services. However, this is part of the Global Guidance for Life cycle Impact Assessment Indicators (GLAM) phase 3 (see next subchapter). Furthermore, it is important to note that a single impact indicator does not do justice to the complex effects of land use analogous to the cause-effect chain (Bos 2019).

2.1.2 LANCA®

One of the land use assessment methods that is directly tailored to the guidelines of the UNEP/SETAC Framework is the LANCA® method. The LANCA® method allows for the calculation of characterised indicator values that describe the effects of processes on various ecosystem services. The calculations are based on geo-ecological classification systems and use site-specific input data. The method is intended for the calculation of LCA within the framework of the EU Environmental Footprint (EF). The following ecosystem functions can be considered within the LCA using the LANCA® method:

- Erosion resistance: The ability of a soil to prevent erosion beyond the natural erosion rate.
- Mechanical filtering capacity of groundwater: The ability of a soil to filter a suspension by mechanically binding pollutants to soil particles.
- Physicochemical filtration capacity of groundwater: The ability of a soil to absorb dissolved substances from the soil solution and thus prevent them from entering the groundwater.
- Groundwater recharge capacity: The ability of a soil to contribute to groundwater recharge.
- Biotic production potential: The ability of an area to produce biomass.

In 2016, characterisation factors were developed for these functions. All factors are calculated in line with the UNEP/SETAC framework for the land-use relevant EF flows with globally available, spatially resolved data (Bos et al. 2016). LANCA® characterisation values are calculated for various land-intensive processes in the GaBi database so that a consistent evaluation of foreground and background systems can be performed (Bos et al. 2016). In the year 2018, an update of the characterisation factors took place by revising the reference system and adding the SQI (Horn and Maier 2018), developed in cooperation with the JRC of the European Commission (Laurentiis et al. 2019). The new reference values have been calculated using the PNV in each country based on an area-weighted average according to

FAO (2012). For land using activities the PNV was restricted to biologically productive areas (e.g. excluding bare areas).

2.1.2.1 Erosion Resistance

The ability to resist erosion is an important function of natural ecosystems and is therefore considered as an indicator of the impact of land use in LANCA® (Bos et al. 2016). According to Wischmeier and Smith (1987) soil erosion caused by water can be predicted using the Universal Soil Loss Equation (USLE). A revised version of USLE (RUSLE) is presented by Renard et al. (1997) which contains modified calculation methods for some of the parameters. The RUSLE model is used as a basis for the calculation of erosion resistance for the LANCA® characterisation (Bos et al. 2016). This model includes important soil parameters, such as soil texture (e.g., clay, silt and sand content of the soils), the mean grain size of the soil particles, soil permeability and soil structure class, gravel and humus content and a stoniness factor. For the LANCA® characterisation factors, information on these parameters is derived from the Harmonized World Soil Database (HWSD) and averaged per country (Bos et al. 2016). Further parameters refer to topographical and climatic variables, all of which have an influence on the degree of erosion, such as elevation and slope of an area or precipitation patterns and climate zones. In addition to soil properties and environmental variables, the management of the land also influences the erosion resistance potential. Therefore, the RUSLE calculations take into account land management parameters such as a crop management factor based on Kuok et al.(2013) and a conservation practice factor based on several literature sources (Trahan and Ouyang 2002; Kuok et al. 2013; Panagos et al. 2015) and complemented by internal expert estimations (Bos et al. 2016). Such practices can be according to Wischmeier and Smith (1978) contour tillage, strip cropping on the contour, and terrace systems. For forestry regimes, however, there is insufficient data on these two land management parameters. Therefore, the conservation practice value is always 1 for all forest land use flows, even for intensive forestry. Furthermore, there are only two values for the crop management factor, whereas the three land use flows "forest", "forests, natural" and "forests, extensive" have the same values, as do the land use flows "forest, intensive" and "forests, used". Therefore, forest management will have no effect on the erosion resistance. This means that there is still room for improvement for the indicator erosion resistance regarding the different land management regimes in the forest sector. The parameters and calculation procedure for erosion resistance are depicted in Figure 2.

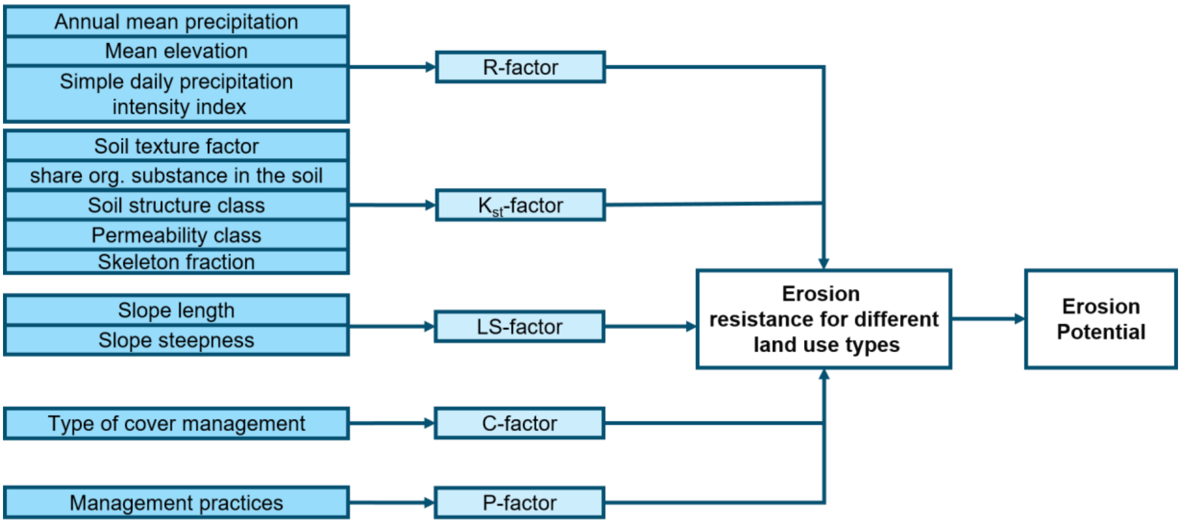

Figure 2: Input parameters for the calculation of erosion resistance (Bos et al. 2020)

2.1.2.2 Mechanical Filtration

Mechanical filtration is defined as the ability of a soil to filter a suspension mechanically (Marks et al. 1989; Bos et al. 2016). Mechanical filtration describes the amount of water that can be infiltrated into a given soil, whereas physical-chemical filtration takes into account the amount of adsorbable cationic pollutants (Bos et al. 2016). The infiltration capacity is expressed by the water permeability of the soil. This represents the amount of water that can seep through the soil at the investigated site per defined time interval (Klink and Leser 1988; Marks et al. 1989; Bastian and Schreiber 1999; Baitz 2002). In general, water permeability is influenced by soil texture at the study site, distribution of soil pores, soil type, sediment sequence, groundwater surface, distance to groundwater and type of land use (Bos et al. 2016). The characterisation factor infiltration-reduction potential in LANCA® is therefore calculated by the parameters soil type, depth to the groundwater table and a sealing factor according to Beck et al. (2010). The sealing factor, in particular, has some limitations for modelling the effects of land use on the forest. For the share of sealed soils in forests only a very generic assumption could be made, which states that intensively used and managed forests have a sealing factor of 5 percent, whereas natural forests and extensively managed forests do not have any sealed areas. Furthermore, apart from soil sealing, no additional forest management parameters are taken into account that also impact on important soil properties, such as soil texture, pH and humus content. These include soil compaction through heavy machines, nutrient removal, harvest management regimes or the composition and age structure of tree species.

The parameters and calculation process for mechanical filtration are depicted in Figure 3.

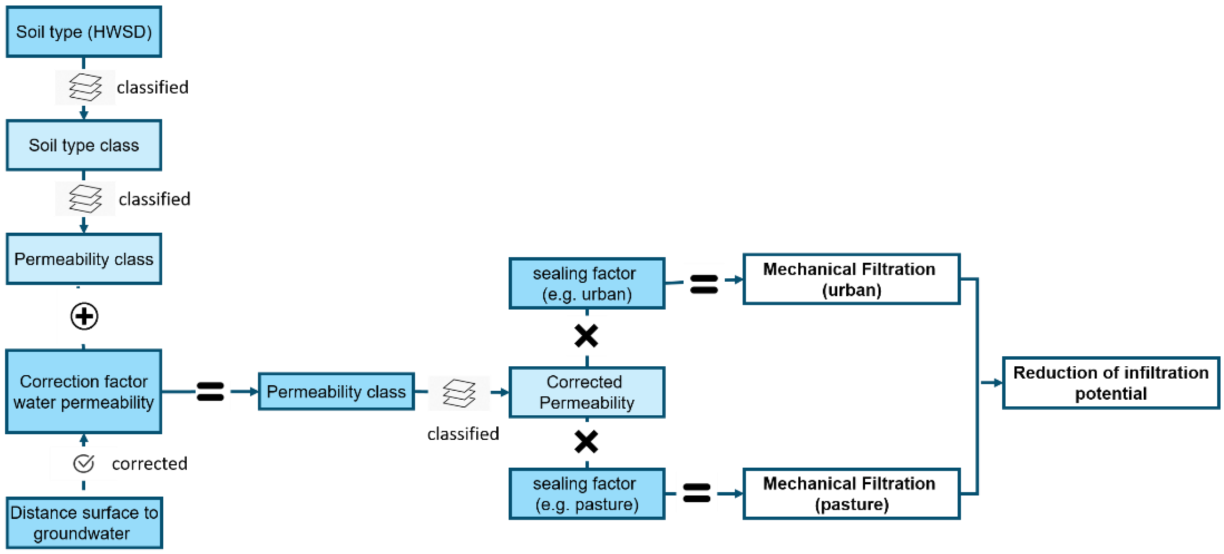

Figure 3: Calculation of mechanical filtration (Bos et al. 2020)

2.1.2.3 Physicochemical Filtration

The ability of a soil to fix and exchange cations on clay and humus particles is called physicochemical filtration. The pH dependence of the adsorption intensity on humus is an important factor for the physicochemical filtration capacity of a soil, which is referred to as effective cation exchange capacity. The physicochemical filtration-reduction potential is calculated in LANCA® using information on soil properties and surface sealing (Bos et al. 2016). For the calculation, first, the effective cation exchange capacity of the soil type is determined, based on the clay and silt content and type of the soil in an area. This classification is based on recommendations of the Environmental Atlas Berlin (Arbeitsgruppe Bodenkunde 2013) and the Federal Institute for Geosciences and Natural Resources (Bundesanstalt für Geowissenschaften und Rohstoffe 2005) according to Bos et al. (2016). Next, the pH factor is derived from the pH value of the soil, which represents the influence of the pH value on the potential cation exchange capacity. The pH factor is then multiplied by the potential cation exchange capacity, which gives the effective cation exchange capacity of the humus content. In the last step, the effective cation exchange capacity of the humus and the clay content are added to determine the physicochemical filtration reduction potential (Bos et al. 2016). Since this indicator is also mainly influenced by specific soil properties and the sealing factor, the limitations of modelling the impact of forest on land use are similar to those of the mechanical infiltration indicator. The limitations originate from the assumptions made on sealed areas in different forest management regimes and the absence of other forestry parameters that influence the various relevant soil properties, such as fertilizer use on the pH factor. Hence in the current system it is mainly the sealing factor that determines differences between management practices.

The calculation steps are depicted in Figure 4.

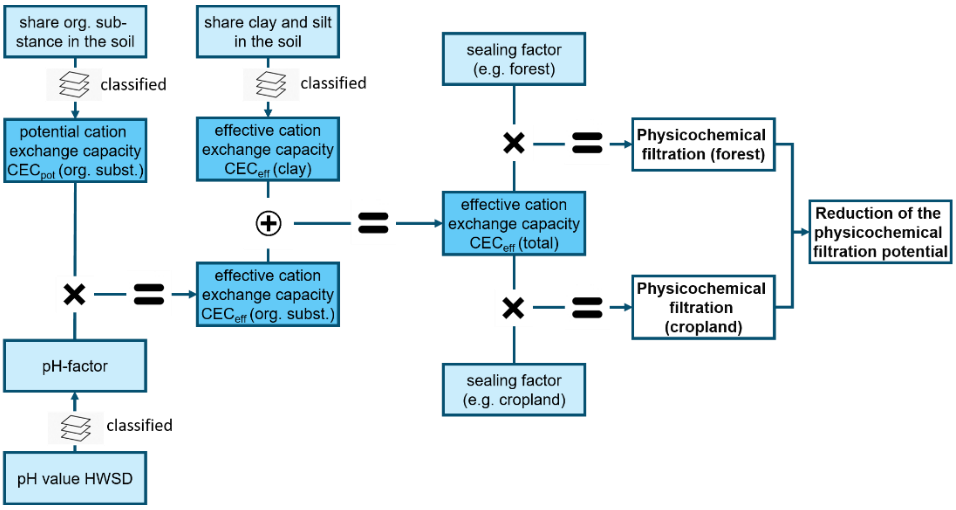

Figure 4: Calculation of physicochemical filtration (Bos et al. 2020)

2.1.2.4 Groundwater Regeneration

The ability of a soil to regenerate groundwater sources is another indicator in LANCA® and is represented as Groundwater Regeneration. Important factors influencing groundwater recharge are the existing surface vegetation, the climate zone and the structure of the soil (Bos et al. 2016). The indicator Groundwater Regeneration describes the potential of an area to regenerate groundwater. The infiltration of rainwater and the associated evapotranspiration is influenced by human land use activities such as sealing or the modification of vegetation.

In LANCA®, the groundwater regeneration reduction potential is calculated from parameters such as soil, slope and type of land use that influence runoff, precipitation and evapotranspiration. The characterisation model for groundwater regeneration is the runoff-corrected groundwater regeneration rate, expressed in millimetres per year (Bos et al. 2016). For this purpose, the mean annual precipitation (Hijmans et al. 2005; Hijmans et al. 2015) and the evapotranspiration (Allen 1998; Mu et al. 2011) in an area are determined. The runoff is calculated with runoff coefficients based on Williamson and Klamut (2001) and with the information on soil properties, slope and type of land use (Bos et al. 2016). Herein, the main limitations concern the few numbers of land-use types that can be assessed and that have a direct impact on the results. Since there is only one land use type for forest classifying the specific surface run off in LANCA®, the differently managed forest land use types are not presented in the calculation of the surface run off and therefore the calculation of the groundwater regeneration.

The steps for calculating the indicator groundwater regeneration are depicted in Figure 5.

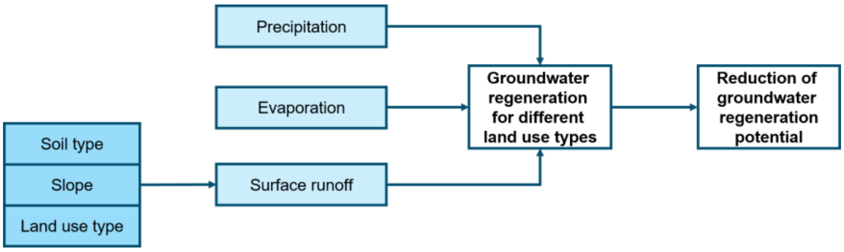

Figure 5: Calculation of groundwater regeneration (Bos et al. 2020)

2.1.2.5 Biotic Production

Biomass production is defined as the total amount of biomass produced by organisms in a given time, relative to an area. The production of biomass is influenced by the type of land use and depends on the climate, soil properties, type of vegetation and availability of nutrients at the location under investigation.

In LANCA®, biotic production is quantified as a standard value per land use type in [kg/(m2*a)] (Bos et al. 2016). Therefore, a certain net primary productivity (NPP) value is assigned to each land use type. These values are based on several literature sources (Lieth and Whittaker 1975; Schultz 1988; Kalusche 1996; Bick 1993; GLCC-EROS 1998). For some land use flows, the values are corrected for the type of land use and degree of sealing (Beck et al. 2010). The biotic production loss potential is calculated based on land use types and surface sealing (Bos et al. 2016). When modelling forest impacts, some limitations are induced by the assumption of a standard value for sealing and the limited default values for biotic production for different forest management regimes.

The calculation steps for the indicator biotic production are depicted in Figure 6.

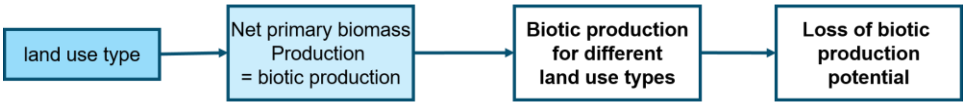

Figure 6: Calculation of biotic production (Bos et al. 2020)

2.1.2.6 Regionalisation

The LANCA® characterisation factors published in Bos et al. (2016) were further developed and improved in Horn and Maier (2018). Bos (2019) and Bos et al. (2020) were developing an approach to calculate spatially refined characterisation factors by using a geo-information system (GIS). The use of pixel-based information on, e.g. land use, soil properties and climate information instead of country averages also improves some of the limitations for land use impact modelling. As shown in Bos et al. (2020), more reliable results can be obtained by using regionalised characterisation factors, especially in large countries. However, as has been pointed out for some of the land use flows, such as forests, permanent crops, wetlands, arable or grassland, there are still no differences in the characterisation factor. Herein, the modelling always assumes a single land use type covering the whole world (Bos et al. 2020) and is presented in one map displaying the CFs as if the whole world or a region would be covered with e.g. forest. This limitation can be overcome by using more precise and refined land use and land cover maps (such as the forest management intensity maps for Europe, as described in the EFISCEN Space section) and by aggregating the values of the characterisation factors per country only in those areas where the type of land use occurs according to the land use model (Bos 2019; Maier et al. 2019; Bos et al. 2020).

2.1.3 Soil Quality Index in the EF

In 2013, within the Single Market for Green Products Initiative, the European Commission proposed the Product Environmental Footprint (PEF) and Organisation Environmental Footprint (OEF) or, more generally, EF. The European Commission issued a Recommendation (2013/179/EU) (European Commission 2013) that describes methods for a standardised measurement of the environmental life-cycle performance. The methodologies recommended in the framework have been adopted from the International Life Cycle Data (ILCD) system by the European Commission's JRC. Given the different needs and goals under the EF framework, LCIA characterisation models and indicators have been improved to fulfil the requirements of the EF over the reference package 2.0. Moreover, subsequently, the models have been refined in the EF reference package 3.0. One mandatory indicator, the SQI for the land use impact category from LANCA® bases on the model developed by Bos et al. (2016), and Horn and Maier (2018) is implanted for the reference packages 2.0 and 3.0, respectively (JRC 2018).

2.1.3.1 Soil Quality Index

To select the recommended default model, an evaluation has been done among pre-selected models (Sala et al. 2019). The LANCA® model is the most suitable model to calculate SQI. There are several reasons why the LANCA® model is chosen for the characterisation factor within the EF framework (Laurentiis et al. 2019):

- It follows a land use classification fully compatible with the ILCD system and the resulting EF flow list.
- It presents the highest coverage in terms of land use elementary flows (up to Level 4, according to the classification provided by (Koellner et al. 2013a)
- It allows for a global application of the characterisation and provides characterisation factors (CFs) both at global and country level
- It covers both occupation and transformation impacts
- It represents a robust attempt to model impacts on different soil properties and functions.

The SQI builds upon the aggregation of some of the selected indicators by covering distinct soil properties and simplifying the interpretation of the results (Sala et al. 2019): Erosion resistance, Mechanical filtration, Groundwater replenishment and Biotic production.

The SQI is aimed at the country scale, and CFs can be used to calculate the impacts of land occupation and permanent transformation flows. The development of the aggregation for calculating the SQI includes the following steps (as presented in De Laurentiis et al. 2019):

- Identification of the most representative indicators avoiding redundancy in the type of information they provide. In the case of the LANCA® model, physicochemical filtration and mechanical filtration showed a very high correlation (i.e. 1) on the global CFs. However, the CFs on a local level show differentiated effects. Therefore, both indicators should have been taken. In this aggregation, the physicochemical filtration was not taken into account.
- Identification, for each indicator separately, of the value corresponding to the 5th and 95th percentile of the distribution of characterisation factors for "occupation" elementary flows (CF5 and CF95) and application of a cut-off to all the characterisation factors smaller than CF5 and larger than CF95.
- Linear re-scaling of the remaining occupation CFs, obtained by calculating the ratio between each value and the CF95 and multiplying by 100.
- The re-scaled values obtained for each indicator were aggregated by adding them together in order to obtain just one characterisation factor for each elementary flow. This number represents the characterisation factor.

The outcome is a normalized index factor that contributes to each elementary flow in the range of -47 to 318 in the country-specific set. The SQI is expressed in Points/m^2. Higher values indicate higher impacts. For example, a high CF value in erosion resistance potential means a potentially higher soil loss. In other words, a negative CF value is associated with a potential improvement against the reference situation (Laurentiis et al. 2019).

2.1.4 Evaluation of existing approaches by the UNEP Life Cycle Initiative

The Life Cycle Initiative, hosted by UN Environment (formerly hosted by UNEP/SETAC), initiated reviews approaches and indicators to reach a consensus on recommended environmental indicators and CFs for life cycle impact assessment (LCIA).Land use impacts on biodiversity is one of four topics that was discussed in international task forces for GLAM Volume 1 (UNEP 2016). Then the second GLAM aims to address soil quality and related ecosystem services that one of the additional environmental topics introduced (UNEP 2019).

The continuous human interference on soil quality through land use and land use change (LULUC) and management practices make the inclusion of a soil quality indicator essential for many LCA studies of product systems that transform or occupy land. The LCI refers to land occupation and transformation under distinct land cover types and management practices (UNEP 2019). These human interactions involve processes that change soil properties like the sealing, acidification, and compaction of soils, which in turn cause direct modification of soil quality properties like the Soil Organic Carbon (SOC) content and soil loss through water erosion (UNEP 2019). Most models have in common that they use at least one of the indicators addressing SOC, soil erosion, and biological productivity. Only the LANCA® model (Bos et al. 2016) combines these three most-addressed indicators and additionally also includes groundwater regeneration, mechanical filtration and the effect of soil sealing on water infiltration capacity (UNEP 2019).

One approach for deriving a comprehensive measure for soil quality is through the SQI, which was developed by the European Commission's JRC (details in section 2.1.3). Even though several researchers have agreed on the needs of multiple indicators could be used to link soil quality attributes to a one-dimensional SQI (Andrews et al. 2002; Velasquez et al. 2007; Obriot et al. 2016), but the available approaches are not consensual (UNEP 2019).

As soil capacity to function can be linked to the SOC (Boone et al. 2018), change in Soil Organic Carbon (ΔSOC) is the provisional recommendation for a midpoint impact indicator of soil quality. SOC indicates the difference between inputs of organic matter originated from biotic production and the turnover that connected to soil biological activities (UNEP 2019). The SOC deficit potential, based on (Brandão and i Canals 2013), has a relative value to a reference state in a geographically distinct climate region (or country or even subnational level, where available). CFs for land occupation represent the ΔSOC (kg C * m^{-2}) between the reference land use and the current land use over the occupation time. Land transformation is defined as the time-integrated ΔSOC (kg SOC * m^{-2} * year) during the regeneration time between the previous land use and the new land use. At the moment, only national average CFs have been adapted, based on PNV, as the reference land use (UNEP 2019). CFs for SOC deficit potential are available for ten land use types in ten climate regions within six soil types (Long-term cultivated, Long-term cultivated full tillage, Long-term cultivated Reduced tillage, Long-term cultivated No tillage, Permanent grassland, Paddy rice, Perennial/Tree Crop, Set-aside (< 20yrs), Sealed Land, Forest). Additionally, different levels of management intensities are included (Brandão and i Canals 2013; UNEP 2019).

Erosion potential is the other recommended additional indicator from GLAM 2 (UNEP 2019) because SOC deficit potential does not cover all aspects of soil (Milà i Canals et al. 2007). For calculating soil erosion, the methods from Bos et al. (2016), Horn and Maier (2018) and Brandão and i Canals (2013) are combined based on the method (Renard et al. 1991) proposed. In order to be consistent with the approach used in the SOC CFs, the regeneration times were assumed as 20 years for biotic land uses and 85 years for sealed land (Brandão and i Canals 2013). Soil erosion for land occupation impact (kg soil loss) is computed by multiplying land occupation effects (kg soil * m^{-2} * $year^{-1}$) and occupation inventory flow (m^2/year). For land transformation impact (kg soil loss), land transformation effects (kg soil * m^{-2}) is multiplied by the inventory flow for land transformation (m^2) CFs are implemented at the global and country scale for a range of 58 land use types (Bos et al. 2016).

Currently, GLAM phase 3 initiated and aims to refine and develop robust LCIA methods that cover classification, midpoint and damage/endpoint characterisation, normalisation and weighting on natural resources and ecosystem services. Eventually, the method to consistently combine these environmental impacts into an aggregated score will be developed (Life Cycle Initiative 2020).

A draft with comprehensive and consistent LCIA methods will be ready by the winter of 2020. Expected targeted work period is between 2020 and 2022 for pre-recommendations of all category indicators, including additional and new categories. Finally, at the beginning of 2023, final integration, implementation and approval are planned.

The Natural Resources & Ecosystem Services Taskforce will focus on formulating endpoint indicator & link models to establish a wider applicability of the methods and parameters globally with different land practices, as well as operationalise newer methods. This will include updating the LANCA® method by Fraunhofer IBP with the SOC deficit potential and biotic production:

- Especially improvement in CFs for SOC that take into consideration current land use maps to calculate the country average CF to include different land management practices.
- For Biotic production, recalculation of CFs at an ecoregion (Olson et al. 2001) level and new aggregation that excludes contributions from "boreal tundra woodland", "polar", "subtropical desert", "temperate desert" and "tropical desert "for agriculture and forestry land uses.
- Plus, general improvement of the calculator of the reference system and the inclusion of regeneration times.

2.2 Summary of research gaps

The research gaps and limitations of current land use modelling approaches in LCA are summarised in this subchapter.

With regard to the modelling of transformation impacts, the results might be over- or underestimated, due to the different modelling approaches of reversible and permanent transformation. Herein, no clear distinction is made in the nomenclature whether a land use flow refers to reversible or permanent transformation, even though various methods use it differently.

Further limitations concern the EF flow list, which only allows the analysis of a limited number of flows. There are inconsistencies in the flow list nomenclature, such as inconsistent classifications of land use, land cover, land use intensity or land management practices. For some flows, information is available for all four levels, while other flows, like the forest related flows, are limited to the type and intensity of land use and do not provide information on land management practices. For some of the indicators available in LANCA®, there is still room for improvement regarding the use of generic data or the limited data availability for some of the input parameters. For example, for the indicator erosion resistance, there is insufficient data on land management parameters such as crop or forest management and conservation practices. Some further limitations result from the assumption of a default value for sealing and the limited number of default values for biotic production for different forest management regimes. The generic assumption of a sealing factor for the different types of land use creates also some limitations in modelling the effects of land use for the indicators of mechanical filtration and physicochemical filtration. The lack of other land management parameters that also influence soil properties and thus soil-related impact indicators is another drawback of current modelling approaches to assess the impacts of land use. These include, for example, soil compaction through heavy machines, nutrient input or removal and harvest management regimes or the composition and age structure of tree species.

SOC deficit is a frequently cited indicator for soil quality that is also recommended in GLAM 2. SOC is recognised as a critical indicator to examine soil quality, due to strong links to endpoints including carbon cycling, biotic production potential and other ecosystem services (Cowie et al. 2018). However, the ability of SOC to reflect soil quality is limited because it might not promote endpoints like biotic production and other ecosystem services when SOC is very high or other critical soil threats such as compaction, salinisation happened in the areas. Besides, in the case of an already very high SOC, a small change of the SOC would not influence significantly in quality in organic soils (UNEP 2019).

Furthermore, currently, there is no differentiation in major land use types, for example intensive and extensive production forests and permanent crops are regarded as the same SOC level as "natural forests" (UNEP 2019). Even for flows that cover all four levels that mentioned above, the current assignment of the same characterisation factor values to all arable land use types can be improved. Also, some models that deal with the critical threat to the soil quality that brings permanent transformation, cannot be implemented to build a global set due to limited geographical occurrences or insufficient data (Verones et al. 2016). In terms of adjustment of characterisation factors, geo-differentiated characterisation factors would require a smaller geographical scale such as states or ecoregions for large countries. Often land management practice factors that has influence to the SOC data offered by IPCC have no direct corresponding elementary flows provided by Koellner et al. (2013a). In addition, in terms of greenhouse gas accounting, 'default data set' by IPCC (climate regions and soil types under different land use and management practices) can be applied when more specific data are applicable as tier 2 and tier 3 approaches are recommended by IPCC. Currently, only national average characterisation factors have been developed based on PNV.

Regarding the mapping of the impacts of land use interventions on midpoint indicators as well as the area of protection, there is no common agreement on a cause-effect chain for modelling impacts on ecosystem services. As pointed out by Rugani et al. (2019), existing models for impact characterisation in LCIA do not cover the full breadth of ecosystems potentially impacted throughout the life cycle of a product. Furthermore, only a few specific ecosystem services are presented without considering their links in the cause-effect chain (Rugani et al. 2019).

In view of current aggregation practices, the use of country averages carries the risk of over- or underestimating the impacts of land use, especially in larger countries. This risk has been reduced by calculating the indicators in a GIS environment, but the assumption of a single land use type covering the whole world still leaves room for improvement.

Furthermore, there is still no agreement on a common reference situation for modelling the effects of land use on, e.g. soils or biodiversity. Since several methods use different reference situations, it is not possible to compare and aggregate the results across the different methods.

In the case of reversible transformation according to Koellner et al. (2013a), the impact needs to take into account the regeneration time. Although several publications proposed estimations of regeneration times (Koellner and scholz 2008; Müller-Wenk 1998; van Dobben et al. 1998; Koellner et al. 2013b; Saad et al. 2013; Koellner and scholz 2008; Saad et al. 2013), there is limited knowledge for the reality. Additionally, researchers have still have not drawn a generally harmonised agreement on regeneration times of ecosystems. Moreover, there is a lack of CFs to include considerations of the regeneration time.

2.3 Implications of LCA research gaps on forestry assessment in LCA

The main classification for forests in the UNEP/SETAC framework (Koellner et al. 2013b) is between Natural (primary or secondary) and Used (extensive or intensive) forests. This is an important constraint for assessing the impact of forestry as there are actually only two types of forestry, intensive or extensive, where country information may further define how intensive or extensive are specified. Although implicitly it appears that in the current application extensive is being interpreted as lower environmental impacts and intensive is interpreted as being higher impacts, these actually represent (from their definition) two very different types of use, which both could be sustainable (or unsustainable) depending on the actual management practices applied and precautions taken to reduce or prevent impact to vulnerable soils and other relevant forest functions. To further expand on this and to allow further differentiation in management practices and different level of impacts, the flow list would need to be adjusted. In the current implementation intensive and extensively used forest partially receive the same characterisation factors for the ecosystem functions included in LANCA®. This characterisation represents a certain impact per unit of land required to continuously produce the required amount of wood. Since at the inventory level extensively used forests will produce less wood per unit of land, more land is required to produce a certain amount of wood. Then to assess the impact of the wood extraction the required area is multiplied by the characterisation factor. As a result, the calculated impact of the use of a certain amount of wood from extensively used forests per definition might be higher than the impact of using the same amount of wood from intensively used forests depending on the underlying characterisation factors. In reality trade-offs between intensity of wood production, area needed and impact are expected that require more specific characterisation factors for different intensities of forest use, or management practices. At the same time the ecosystem functions in LANCA® represent important aspects in which forest management would differentiate. In sustainable management practices particularly, practices aimed to protect vulnerable soils (i.e. erosion on slopes, soil compaction in skid trails) and to reduce damage to residual stands are considered important elements. This would then require specific characterisation factors for different practices as well as a comprehensive consideration of the multifunctionality of forest systems and a consistent choice of inventory modelling and characterization.

The current framework assumes that to continuously produce a certain amount of wood an area is needed that given by the annual wood harvest times the rotation cycle of harvesting. For example, if annually 300 m3 of wood is produced per ha of forest in a rotation cycle of 40 years, to continuously produce 300 m3 of wood, 40 ha would be required. Each of these hectares is in a different stage of the cycle. The characterisation factor then would be determined on the average effect in the whole area of 40 ha. However, it represents only an ideal theoretical situation. While in forestry the forest management units would be divided in blocks that are harvested in turn and then are given time to regrow in reality disturbances appear that will have an effect on age class distributions and do not necessarily follow the theoretical assumptions. These two approaches differ systematically and the choice should be made transparent and comparable between assessments.

3 Forestry assessment

3.1 Forest specific issues

With the rise of the concept of sustainable development in the 1990s, the concept of sustainable forest management became commonly accepted for managing forests. Forest Europe, formerly the Ministerial Conference on the Protection of Forests in Europe (MCPFE), leads the promotion and implementation of sustainable forest management in Europe. Forest Europe has laid the basis for sustainable forest management in 1993 by defining the concept (Forest Europe 1993):

"The stewardship and use of forests and forest lands in a way, and at a rate, that maintains their biodiversity, productivity, regeneration capacity, vitality and their potential to fulfil, now and in the future, relevant ecological, economic and social functions, at local, national, and global levels, and that does not cause damage to other ecosystems".

To further define and promote the concept of sustainable forest management, there was a need for criteria. In 1998, Forest Europe defined the Pan-European criteria for sustainable forest management (Forest Europe 1998):

1. Maintenance and appropriate enhancement of forest resources and their contribution to global carbon cycles;
2. Maintenance of forest ecosystems' health and vitality;
3. Maintenance and encouragement of productive functions of forests (wood and non-wood);
4. Maintenance, conservation and appropriate enhancement of biological diversity in forest ecosystems;
5. Maintenance, conservation and appropriate enhancement of protective functions in forest management (notably soil and water); and
6. Maintenance of other socio-economic functions and conditions.

Together with those criteria, a set of indicators was adopted. The indicators enable monitoring, assessing and reporting the progress of sustainable forest management in the signatory countries of Forest Europe. Every 5 years the progress is reported in the Series State of Europe's Forests. Both the criteria and indicators have been updated during the Ministerial Conferences in the past two decades.

Also voluntary sustainability certification schemes, like the Forest Stewardship Council (FSC) and the Programme for Endorsement of Forest Certification Schemes (PEFC) have similar lists of criteria and indicators defining sustainable forest management.

As part of its action plan on financing sustainable growth in 2020 the EU adopted an EU Taxonomy providing a common classification system for sustainable economic activities. This taxonomy also covers forestry activities, identifying sustainable forest management requirements (EU-TEG 2020). These requirements are similar to other SFM criteria and include requirements for applying management practices. These SFM requirements use EU legislation as minimum baseline and build on the Recast of the Renewable Energy Directive and existing industry best practice criteria including those of Forest Europe.

In order to take into consideration sustainable forest management into the outcomes of LCA studies, the effects of applying sustainable forest management principles need to be reflected in the characterization factors. Within the context of the LCA and EF land use modelling, this means that information is needed on how sustainable forest management will affect the characterization factors considered in the land-use models. Currently such data is not widely available. Moreover an assessment of possible ways to model or implement sustainability criteria in land use models. Table 1 below shows a selection of the criteria and indicators for which possible translations to implement them in modelling could be identified. The full list of indicators which was endorsed at the 7th Ministerial Conference, is provided in Forest Europe (2015).

Table 1: Forest Eur.ope criteria and indicators for sustainable forest management (Forest Europe 2015). The indicators don't have limits provided on what would be sustainable practice. This will need to be developed depending on forest specific conditions. In the last column examples are provided on how the indicators are implemented or used in modelling studies.

Criteria	No.	Indicator	Translation to modelling/implementation
Criterion 1: Maintenance and Appropriate Enhancement of Forest Resources and their Contribution to Global Carbon Cycles	C.1	Policies, institutions and instruments to maintain and appropriately enhance forest resources and their contribution to global carbon cycles	
	1.1	Forest area	No net decrease in forest area (reference year 2015) over the simulation period.
	1.2	Growing stock	No net decrease in growing stock (reference year 2015) over the simulation period
	1.4	Forest carbon	If the emissions from harvesting are lower than the removals and avoided emissions from wood use, a negative emissions balance results, which proves the C-sustainability.
Criterion 2: Maintenance of Forest Ecosystem Health and Vitality	C.2	Policies, institutions and instruments to maintain forest ecosystems health and vitality	
	2.2	Soil condition	C:N ratio not higher than 25:1. A maximum wheel load of 4-4.5 ton should not be exceeded on compaction sensitive (fine textured) soils.
	2.5	Forest land degradation	20 to 25% maximum slope is recommended to avoid excessive erosion.
Criterion 3: Maintenance and Encouragement of Productive Functions of Forests (Wood and Non-Wood)	C.3	Policies, institutions and instruments to maintain and encourage the productive functions of forests	
	3.1	Increment and fellings	Fellings-to-annual-increment ratio of approximately 70% is recommended.

Criteria	No.	Indicator	Translation to modelling/implementation
Criterion 4: Maintenance, Conservation and Appropriate Enhancement of Biological Diversity in Forest Ecosystems	C.4	Policies, institutions and instruments to maintain, conserve and appropriately enhance the biological diversity in forest ecosystems	
	4.5	Deadwood	Leave as many large standing dead trees at harvest as possible.
	4.9	Protected forests	No net decrease in ratio of protected forests (reference year 2015) over the simulation period

3.2 Land use models

Generally, this section describes models that can provide input to land use impact assessment in advance to the existing framework and potentially close some of the research gaps). For each of the model a description is given with focus on forestry related information, as well as potential output data for LCA.

3.2.1 EFISCEN Space

EFISCEN Space was developed as a successor for the European Forest Information Scenario (EFISCEN) model that has been in use for decades (Nabuurs et al. 2001; Schelhaas et al. 2007; Verkerk et al. 2016; Sallnäs 1990) to provide projections of forest resource development at national and European level. While the EFISCEN model was designed to work on aggregated national forest inventory (NFI) data for essentially even-aged forests, EFISCEN Space is designed for all types of forests, can handle a wide range of management systems and works with detailed NFI data. A more complete description of the model can be found in (Arets Eric and Schelhaas 2019). However, EFISCEN Space is a model under development, with currently a lack of validation of some of the newly added sub-modules. In particular these are the time/cost estimation of harvesting activities and the soil carbon module. It was used in this study to demonstrate that such a model would be able to provide useful information for the impact assessment methods, by differentiating wood sourced from areas with different management and harvesting routines.

In a national forest inventory (NFI), the whole of the forest is represented by a certain number of inventory plots. Each plot is considered to be representative of a specific forest area, typically in the range of 100–2,000 ha, depending on the density of inventory plots. Similarly, in EFISCEN Space, the future development of the forest is modelled through the development of the same set of inventory plots. The state of the forest in each of the inventory plots at a certain point in time is depicted as the number of trees per diameter class, distinguishing 20 species or species groups. These 20 groups are constructed in such a way that the most important species in Europe are covered, including species with an important share in Europe as a whole, as well as important species in a certain region of Europe, either in terms of production (like poplar plantations) or in coverage (like Quercus ilex (L.) and Quercus suber (L.) in the Mediterranean region). Growth is simulated by moving trees to a higher diameter class, while harvest and mortality are modelled as the removal of trees from the simulation. Regeneration or ingrowth is simulated by adding new trees to specific diameter classes.

The model forest stands can be initialised using forest inventory data from local inventories or NFIs. Transitions to a higher diameter class are derived from species-specific growth functions that are calibrated using a large set of observed diameter increment data all over Europe (Schelhaas et al. 2018b). The growth functions are sensitive to diameter, basal area in the stand and a number of abiotic variables. Harvest can be applied as a set of observed frequencies, for example from repeated observations in an NFI or other inventory, or as a set of harvesting rules mimicking the supposed behaviour of the forest manager, for example as derived from handbooks or management guidelines. However, as shown by Schelhaas et al. (2018a), the observed patterns of harvesting usually differ considerably from the handbook management. Similarly, mortality can be applied as a set of observed frequencies or by applying a dynamic mortality model, which is currently under development. Ingrowth is governed by simple rules, with a dynamic ingrowth module under development.

Diameters are converted to volume using local volume functions, usually derived from NFI data. The model produces annual output on the forest state, mortality and harvest, expressed in terms of tree numbers, basal area and whole stem volume, per plot, per species and per diameter class. The stem volumes can be translated into commercial volumes, biomass and carbon content. These outputs can be aggregated to yearly overviews per plot and on the total modelled area scale. The soil carbon module Yasso15 (Järvenpää et al. 6/8/2015) is coupled to EFISCEN Space for providing estimates of soil carbon development. Inputs to the soil model are calculated from the turnover of living biomass and input from mortality and harvest residues. Decomposition of the litter depends on its size and differs for each of its chemical components, and is climate dependent. Recently also a new module was integrated that allows the estimation of harvesting costs via estimates of the time needed to fell and extract the trees to the roadside. EFISCEN Space can be applied to any set of inventory plots, ranging from forest reserves (den Ouden et al. 2020) to the national and European level (Arets Eric and Schelhaas 2019).

Nabuurs et al. (2019) present a forest management intensity map for Europe, which hypothetically estimates management intensity based on a number of predictors like tree species, slope, elevation, soil type, occurrence of national parks/reserves, distance to cities, etc. in a Bayesian Belief Network (Figure 7). These patterns and the underlying rules have been validated with an expert panel during 2 interactive sessions. Labelling certain areas as having a more intensive management is thus not caused by any observation of real harvest intensity or the occurrence of natural events such as storms. Ideally these management classes reflect a real gradient across the country, and we can use these classes to extract the real harvest pattern per management class based on repeated NFI data. The EU-funded project TreeMort collected repeated observations for permanent NFI plots in 9 countries. All plots were assigned a forest management intensity class according to the map, and management and mortality patterns were extracted for all combinations of species, countries and management intensity classes. Harvesting probabilities seem to show a positive correlation with management intensity classes (Figure 8), which would provide a basis for extrapolation to other countries. Based on the TreeMort dataset, management and mortality sets were derived for the 20 species groups in EFISCEN Space for each of the countries, for three management intensity classes: low, (combining strict nature management, close-to-nature management and low-intensity management), medium (multifunctional management) and high (intensive and very intensive management). In addition, a set was derived from all observations together for application in case the management class was unknown. Now, for any country where we have initialisation data, we can run EFISCEN Space, given the European increment model, and the possibility to apply harvest and mortality frequencies according to the management intensity as shown by the map, as derived from observations from the country itself or a suitable neighbouring country. A key assumption in EFISCEN space is that the management map stratifies the forest in areas that are managed in a different way, particularly related to management intensity. In addition to the assumption on management intensity, we have assumed that in the low intensity management class tree felling is done manually.

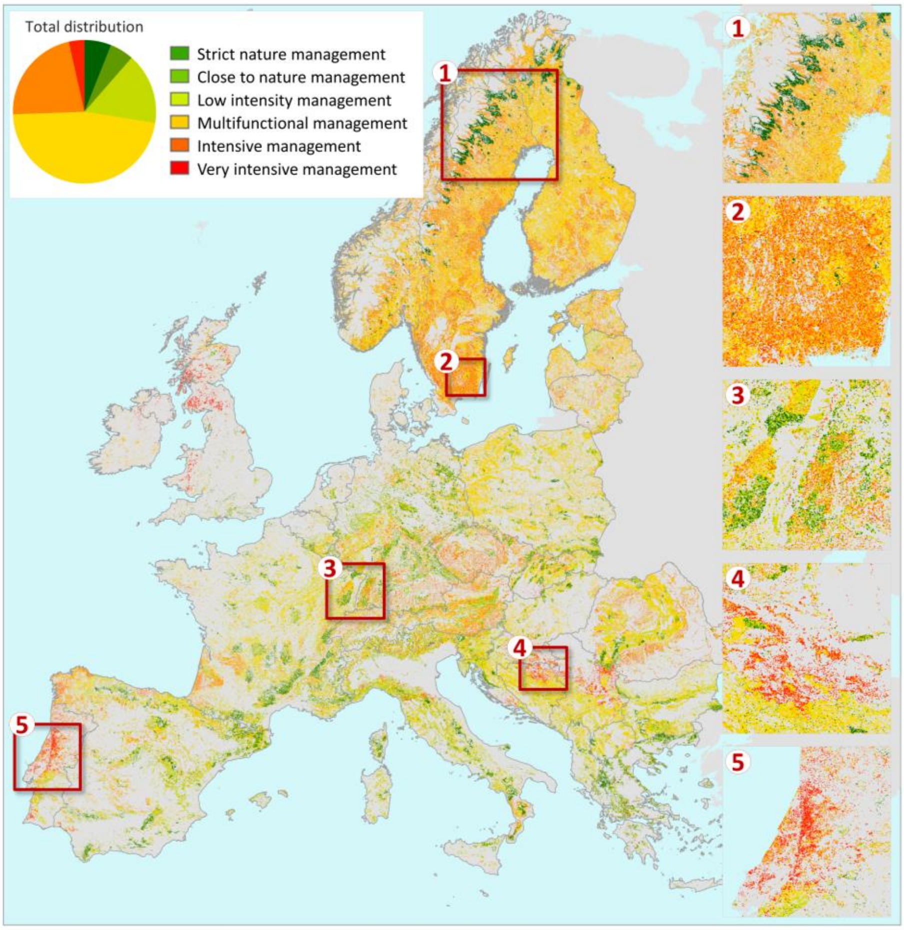

Figure 7: Forest management intensity map (Nabuurs et al. 2019)

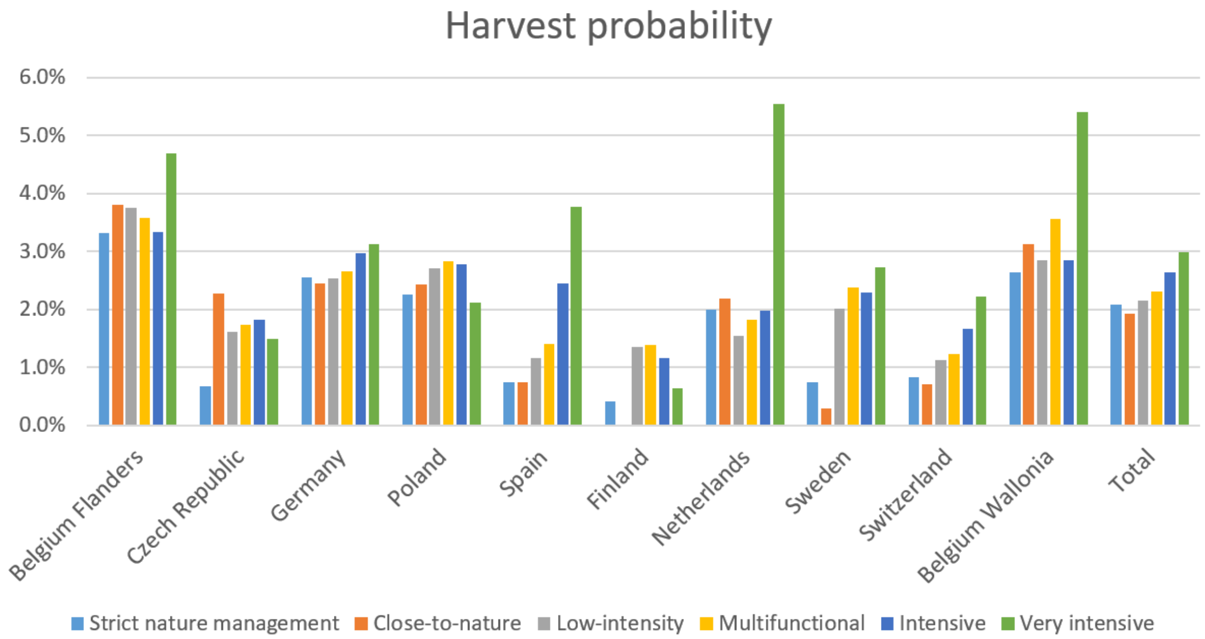

Figure 8: Annual harvest probability per management class as derived from the TreeMort dataset

To illustrate this approach and for further use in this project, we applied the above framework to the Netherlands and Sweden. For Sweden, the simulation is based on 7668 NFI plots (covering 19.6 million ha), of which 628 were managed as low intensity (8%), 3468 as medium intensity (46%), 2503 as high intensity (33%), and for 1069 plots the management was undetermined (14%). For the Netherlands, the simulation is based on 3046 plots 0.37 million ha), of which 1795 were managed as low intensity (59%), 963 as medium intensity (32%), 287 as high intensity (9%) and for 1 plot the management was undetermined (0%). All simulations were done for the period 2010-2030, assuming a stable climate. In addition, a full rotation of one stand was simulated. This was a Douglas fir stand located on richer sandy soils in the Netherlands, assuming a medium management and a rotation length of 80 years, based on plot D04 from Het Leesten (Figure 9:), as presented in den Ouden et al. (2020). Results were calculated for the forest as a whole, as well as separately for the low, medium and high intensity classes. Table 2 gives an overview of the simulation results.

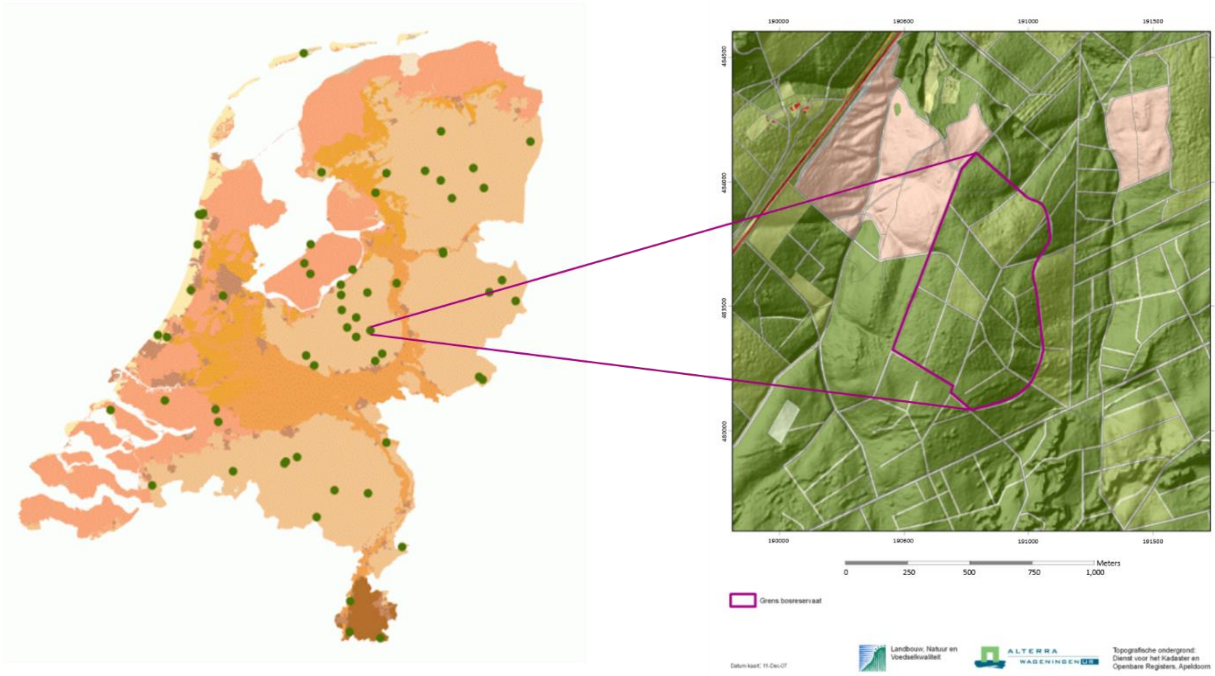

Figure 9: Location of forest reserve het Leesten, basis for the specific scenario (den Ouden et al. 2020)

Table 2: Simulated values for gross increment, mortality and harvest (m^3 ha^{-1} yr^{-1}) for all cases

Case	Management	Area covered (1000 ha)	Gross increment	Mortality	Harvest
Netherlands all species 2010-2030	all	373	6.6	1.0	2.4
	low	220	6.5	1.0	2.5
	medium	118	6.6	1.0	2.5
	high	35	7.9	1.1	1.4
Netherlands Douglas fir 80 year rotation	medium	0.001	10.1	0.6	9.4
Sweden all species 2010-2030	all	19556	7.4	0.7	4.5
	low	1610	8.4	0.9	4.3
	medium	8869	7.6	0.7	4.6
	high	6394	8.0	0.8	5.2

3.2.2 HANPP

Human Appropriation of Net Primary Productivity (HANPP; Haberl et al. 2007) is a metric developed to quantify the human impact on the environment. The HANPP approach would quantify how land use alters energy flows in ecosystems via land conversions and biomass harvest. It compares the Net Primary Productivity (NPP) of the Potential Natural Vegetation with the NPP of the current land-use minus the part of the NPP that is removed as a result of harvesting under the condition of human interactions. If the NPP in the current system is the same as the NPP in the reference system HANPP would be 0. If all NPP is lost, or harvested, HANPP will be 100%. In situations where the NPPP capacity of the current land-use is higher than the reference situation, HANPP may become a negative value. The higher the value of HANPP the stronger the impact of human land-use is.

The comparison with the NPP in the PNV should be possible with the current system. Quantification of NPP in different forest management systems could for instance be characterized with forest models like EFISCEN (space), as illustrated above.

3.2.3 SOC (IPCC)

Soil organic carbon (SOC) is a relevant part of the global carbon cycle. As an important soil characteristic, the SOC content has a direct impact on soil productivity, biodiversity and erosion. SOC should be considered for its impact on the climate system and the soil quality (Lefèvre et al. 2017). In the LCA, in a first approach, CF of Brandão and i Canals (2013) based on IPCC factors were provided for a limited number of land use types without country-specific regionalisation. The CFs of Brandão and i Canals (2013) are provisionally recommended by the UN in the current GLAM 2 (2019). In 2019, a group of experts worked on improved factors. The results are not yet publicly available, but a joint publication is currently being prepared together with the JRC. For the CEPI project, an exemplary application of the IPCC values to illustrate the general applicability of SOC characterisation factors in LANCA® could be considered. Here, the EFISCEN Space soil module could provide a potential input for SOC in LANCA®. The calculation of CFs for SOC could then be performed on the basis of forest management regimes for European forests as shown above, for an improved forest classification in environmental flows. However, for the general application of SOC in the EF, other land use categories and forests outside Europe need to be characterised.

4 Recommendations for improvement

4.1 Inventory

Several challenges and research gaps have been identified that need to be addressed in the future for a more consistent modelling of land use impacts in LCA. With regard to the Life Cycle Inventory, these research gaps are related to the revision and refinement of land use flows, harmonisation of current land use modelling practices, as well as the handling of background and foreground data. A description of recommendations for improvements regarding these issues will be given in the next subchapters.

4.1.1 Land use flows

As highlighted, the provision of a new nomenclature and a common classification of land use flows is of crucial importance, which has also been pointed out by other authors see (Vidal-Legaz et al. 2016). This includes the need for a harmonised method with a framework that allows to analyse impacts on the four levels of land use: location, land use type, intensity and management practices as it has been suggested by Maier et al. (2019). Furthermore, there is a need for a harmonised solution to the question of the number of flows. Thus, in future developments of databases and the implementing softwares features to consider flow properties on location, land use type, intensity and management practices should be taken into consideration. Furthermore, the differences in the transformation from/to and the occupation flows should be made explicit in the nomenclature.

4.1.2 Land use modelling

There is no consistent approach to land use modelling practices in LCI. One of the inconsistencies lies in the different ways of looking at and interpreting "transformation to" modelling, where the same flows are used to represent different points in time in different databases for the modelling of reversible transformation and permanent transformation. This leads to systematic differences due to ambiguity of flows and interpretation of database providers. Besides, the consideration of time aspects during transformation is handled differently. Here it is not clear to which point in time the flows refer. In addition, a clear indication of land use inventory quantities would be needed.

One possible solution is to determine representative input data per country and land use type. In addition, a uniform LCI modelling guideline for land use processes would be needed, especially in the EF context. This should be part of the EF guidelines and could, for example, be developed as part of the agricultural working group currently established by the European Commission. An additional possibility would be to provide user guidance, for example in the form of video tutorials, to ensure a consistent approach to land use modelling.

4.1.3 Back- and foreground data

With regard to different use cases, land use modelling and resulting necessary CFs are different. For specific applications with primary data available (foreground system), specific inventory information and specific CFs are necessary to allow depicting the actual land use.

For the foreground system, the CFs can be calculated from coordinate-exact input data depending on the goal and scope of the study or the country-specific characterisation factors are also used (Bos 2019). This includes the consideration of specific management practices and geolocation as well as underlying pedoclimatic conditions. As these characterisation models are too specific to be provided in the LCA software for all potential cases, an integrated solution using GIS maps for characterisation is recommended for foreground application.

In background system and for missing primary data, representative locations have to be automatically selected for each land use type and country according to a defined procedure including the climatic, pedological and topographical conditions. From this, input data characteristic for this specific land use type and country are determined, and the corresponding characterisation factors are calculated. Thus, representative average data for the background system can be presented for a specific land use type. However, the data should be calibrated with national ground-based measurements to be reliable.

This dual approach – providing average pre-calculated CFs for country and land use type and complementing them when further information is available – still faces several challenges. For comprehensive global background CFs and inventory model there is a lack of monitoring data. Furthermore, the underlying inventory quantities (area and areatime) requires a harmonisation in inventory modelling to ensure consistency between fore- and background models. This also includes open questions on defining the plot of land that is considered in inventory.

4.2 Impact assessment

With regard to the Life Cycle Impact Assessment, there are mainly three points that need to be addressed and require further improvements. These are related to the agreement on a common reference situation, regeneration time and cause effect-chain, as well as the integration of further impact indicators within the method in order to get a broader coverage of effects within the cause-effect chain.

4.2.1 Reference situation

Since evaluating the environmental effects of land use is always in comparison to a reference situation, this land use reference state needs to be clearly defined. However, there is still a discussion on which reference situation is the most suitable and an agreement has yet to be reached. A different choice of reference states influences the impact categories (Bos et al. 2016). Even, different impact categories often use different reference states despite the need for consistency. The reference situation could be calculated as a weighted average of the values of ecosystem quality based on all the types of PNV that can be found in a country considering all existing ecological zones by FAO (2012). Furthermore, the reference situation is not necessarily static (Bos et al. 2016) as Bork et al. (1998) mentioned natural areas are in a dynamic state of development.

In response to on-going debates among LCA experts on the question of which reference state is the most suitable to assess land use impacts, we propose a new multi-perspective approach bringing for the first time LCA experts, policymakers, ecologists, forestry experts and (environmental) historians on the table. The purpose of the workshop is to discuss the historical imperial and post-imperial developments of the ecological transformations and destruction (over the past 500 years) and today's implications when choosing one reference state over another. During its course, the participants will deal with the question of how a globally applicable reference (thus meeting LCA criteria) can meet with a thorough historical analysis which accounts for resulting post-imperial "injustices". The workshop shall have a working character and might result in a joint paper with conclusive recommendations.

4.2.2 Regeneration time

In order to be able to calculate comparable land use effects in life cycle assessments, the reference situation, modelling and regeneration time as well as the allocation of the transformation effects have to be determined uniformly. The uniform choice of the reference situation shall be made as a specification to ensure consistent and comparable results of different methods (Bos 2019). Still, the regeneration times underestimate reality (Brandão and i Canals 2013), therefore, the regeneration times that estimate different ecosystem types and impact pathways should be in a comprehensive way in many occasions (Saad et al. 2013). The reference situation, modelling time, regeneration time and allocation of transformation effects are independent of the development of the characterisation factors. The allocation of transformation effects can be assumed to take 20 years.

We suggest harmonisation, and an approach taking into account land use type, pedoclimatic conditions.

4.2.3 Cause-effect chain

As also emphasised by Vidal Legaz et al. (2017), the assumption of a common land use cause-effect chain and the definition of common areas of protection are of crucial importance in the impact assessment (Vidal Legaz et al. 2017). Therefore, further indicators need to be integrated into existing land use impact assessment methods in order to develop an integrative model that includes a comprehensive set of indicators that can assess impacts of land use on ecosystem services and other endpoint indicators.

A suggestion for such a common land use cause-effect chain has been proposed by Fraunhofer IBP in the GLAM 3 discussions and is depicted in Figure 10.

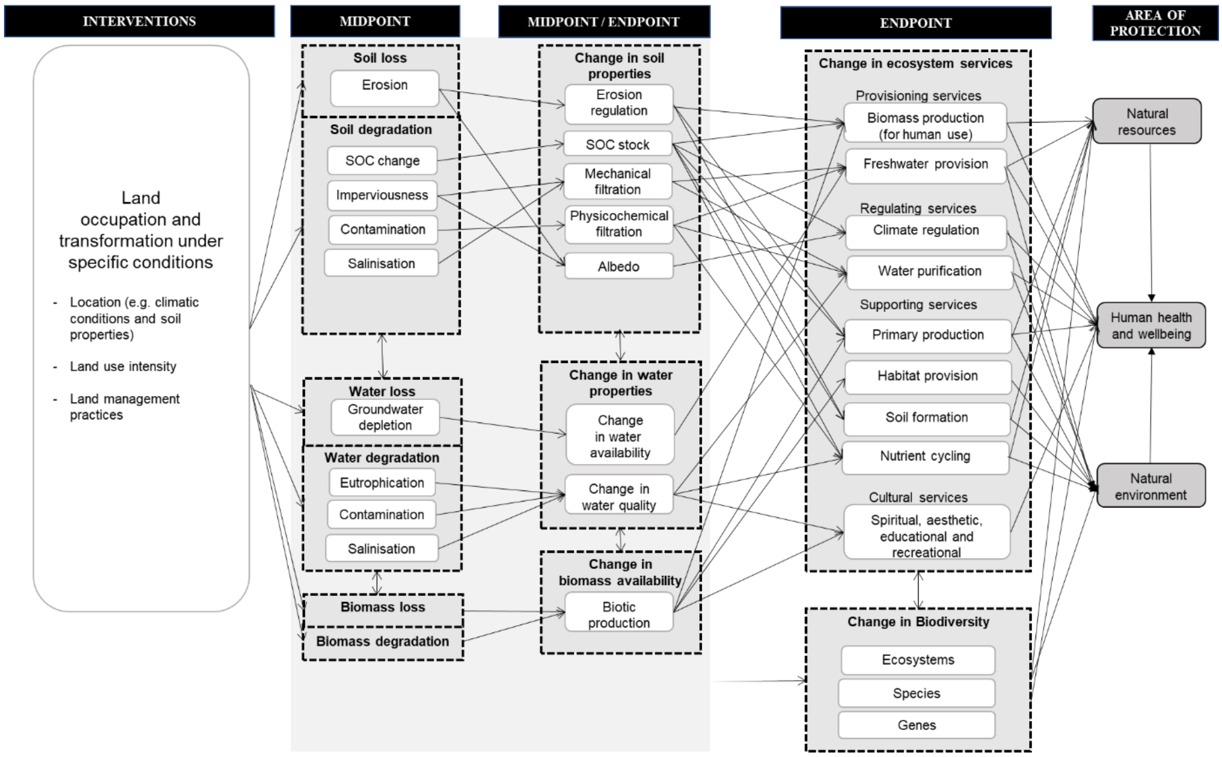

Figure 10: Schematic impact pathway of land using interventions in the context of ecosystem services adapted from Vidal Legaz et al. (2017) and Millennium Ecosystem Assessment and World Resources Institute (2005) and proposed in the GLAM 3 discussions

4.3 Existing Characterisation factors

4.3.1 Erosion

The greatest room for improvement lies in the update and integration of better data for the conservation practice factor and the crop management factor such as provided by Panagos et al. (2015). Extensive research on other data sources could provide more precise results for the different forest management regimes. Furthermore, the development of spatially refined CFs with the help of GIS will lead to better results for individual land use locations than the country average values assumed so far.

4.3.2 Biotic Production

The method currently implemented in LANCA® for the impact category biotic production follows very simple assignments. We propose to replace this impact indicator with other suitable indicators such as HANPP, which is currently under development.

4.3.3 Mechanical filtration

The sealing factor, in particular, has great potential for improvement. As only very generic assumptions could be made for the share of sealed areas in different land use types so far, an update of the factor would have substantial effects on the results. Especially since the sealing factor shows the largest influence on the overall results. One possibility would be to use sealing maps and to overlay them with land use maps to determine the proportion of sealed area per land use type. Since the CFs of mechanical filtration are already spatially differentiated, the effects of individual land use locations can already be determined more precisely. For the aggregation of the values, however, we recommend the overlay of land use models with the characterisation map in order to calculate more precise average values per land use type and country.

4.3.4 Physicochemical filtration

The recommendations for improving the characterisation factors of the impact indicator physical-chemical filtration are the same as for mechanical filtration since both have the same underlying limitations (see previous subchapter).

4.3.5 Groundwater regeneration

The effects on groundwater regeneration are directly related to soil properties, elevation and type of land use. Since only a few land use types can be evaluated so far, the potential for improving this characterisation factor lies mainly in the integration of further and finer land use types into the method. Furthermore, the development of spatially refined CFs with the help of GIS will also provide improved results, since better-resolved input data on, for example, soil properties or elevation can be used.

4.4 Other Characterisation factors

The LANCA® method can be supplemented by further impact indicators in order to get a broader coverage of the cause-effect chain. For example, indicators can be integrated to estimate changes in soil carbon, HANPP, biodiversity, change in albedo effects or changes in water quality. Three impact indicators are currently under development for the integration into the LANCA® method:

- SOC: Spatially refined characterisation factors have been calculated for all flows of the EF flow list using the new aggregation approach. A publication is currently being prepared together with the JRC.

- HANPP: More precise methods and data for the calculation of HANPP will be integrated into the LANCA® method in order to substitute the impact category biotic production.

- Biodiversity: A biodiversity multi-scale assessment method (BioMAss) for LCA was developed jointly at the University of Stuttgart and Fraunhofer IBP (Maier et al. 2019). The land use classification can be mapped to the classification system used in LANCA®, making it suitable for future integration (Maier, Horn 2020).

Potential further categories include the impact indicators of salinization, compaction and contamination of both soils and groundwater, as well as changes in albedo effects.

5 LANCA characterisation factor improvement

5.1 General framework

As one of the purposes of the report, in this chapter describes improvements of identified issues in the framework LANCA®. In the general framework section, sealing factor improvement, a suggestion of an approach to connect LCA software and geolocations, and nomenclature for inventory flows will be discussed. The core solutions are on SOC and HANPP as regionalised characterisation factors that are integrated with a geo information system (GIS), within the existing EF land use flow list.

5.1.1 Sealing factor

The Sealing factor has the largest influence on the mechanical filtration and physicochemical filtration indicators (Bos 2019). If soils are sealed with artificial materials, the filtration performance will decrease, which results in indicator values that are also small (e.g. the filter properties or the effective cation exchange capacity). That means the characterisation factor becomes accordingly large. Low sealing factor appears in the land use types of forest and scrubland as well as grassland. So far, one default value and no geolocation differences for entire used forests for calculation of sealing factor on land use on forestry. To solve the limitations, the characterisation factors map from Bos (2019) for mechanical filtration and physicochemical filtration can be used as a new base map as starting point. The sealing factor adjusts the permeability values in mechanical filtration and the effective cation exchange capacity in physicochemical filtration as a last step of the calculation (Bos 2019). The map with the property "Sealing factor" originated from the global land cover map "GLC 2000 (Fritz et al. 2003)" is assigned with the ELCD land use types. In the calculation of the maps of characterisation factors, the permeability value (the effective cation exchange capacity in physicochemical filtration) is corrected on the basis of the specific land use type or the corresponding sealing: the permeability map is multiplied by the sealing factor map. In order to calculate different characterisation factors maps in each land use type, the maps with different sealing factors in the different land use types are created separately. Next, these two maps are multiplied by (1-sealing factor). For example, for the reference situation under natural land use, the sealing factor is 0, for arable land 0.05 and so the permeability map is multiplied by (1 – 0) for the reference situation, or (1 – 0.05) for arable land. For all other land use types, the same procedure is followed.

Furthermore, the EFISCEN Space model excludes non-forest areas like roads. As sealing in LANCA® indicates artificial materials that covers the surface, when the EFISCEN space leaves out non-forest areas, there is no sealed area left in forests. Therefore the sealing factor in forestry may need other complementary CFs that can adjust water permeability of the soil. In this light, soil compaction due to harvest activities has a high potential together with the sealing factor. The USDA Forest Service mentioned that in general a bulk density increase of more than 15 % (response ratio > 0.14) after machine traffic leads to detrimental soil compaction (Powers et al. 1998). However, still, the relations between forest management and compaction-sealing characterisation need further investigation.

Note that in LANCA®, geo-ecological landscape analysis and landscape assessment methods are used (Baitz 2002; Bastian and Schreiber 1999; Marks et al. 1989). The concept of calculating the characterization factors assume that the area of interest is entirely covered by the same land use type. Furthermore, not every land use type can occur in every country. For instance, forests in Germany may only be transferred to other purpose with permission (Gesetz zur Erhaltung des Waldes und zur Förderung der Forstwirtschaft 2015).

5.1.2 Geolocation

Within current LCA databases, regionalized methods are only partly implemented and restricted to territorial units, mainly countries. Especially soil parameters and climatic conditions are very site-specific, therefore there is a need for regionalized CFs. Bos et al. (2020) describe the global spatial calculation of CFs is feasible by using a geoinformation system (GIS) for mechanical filtration and physicochemical filtration in the conceptual framework in LANCA®. Using this methodology, the location of land use impacts can be determined more specifically. In comparison between country-specific CFs and the regional GIS-CFs, site-specific CFs are far more beneficial, especially for large countries. The region-specific CFs were calculated in a GIS environment and generate a map with values for mechanical filtration and physicochemical filtration per grid cell for various land use types.

As most pedological features vary and refer to site-specific conditions, country-specific CFs are often too unspecific for huge countries or long north-south countries such as Chile, Brazil, Russia, Canada, the USA, and China. The study by Bos et al. (2020) shows large differences in the results of arable land in Brazil.

5.1.3 Nomenclature

The current nomenclature for the environmental flows and its drawbacks were described in section 2.1.1.2. Particularly the management intensity level currently does not very well link to forest management practice and nomenclature used in forestry. We propose an updated nomenclature for the land use flows used for forests, where the basis as presented in Koellner et al. (2013b) remains intact but with an additional level indicating forest management intensity and management practice. Various alternatives would be available to do this. For instance Cardellini et al (2018) have developed a nomenclature that identifies seven different sylvicultural systems (see Table 3) and combines this with a number of tree species used in European forestry.

Table 3: Silvicultural systems identified by Cardellini et al. (2018)

ID	System	Definition
1	Unmanaged forests	No management
2	Continuous cover forest management	Continuous cover forest management - Selection cuttings based on target diameter
3	Even-aged forest management with shelterwood	Even-aged forest management - Regeneration: natural - Thinning - Shelterwood cut after a certain mean diameter (or age) has been reached
4	Even-aged forest management: uniform clearcutting system	Uniform forest management - Regeneration: planting or natural - Thinning - Clear-cut after certain target diameter (or age) has been reached
5	Coppice	Woodland which has been regenerated from shoots formed at the stumps of the previous crop trees, root suckers, or both, i.e., by vegetative means
6	Coppice with standards	Coppice system under low-density uneven-aged high forest
7	Short rotation Plantation	forestry including exotic species

Nabuurs et al. (2019) have developed an approach to map forest management strategies. They identified six management strategies that differ in forest management intensities and are related to different silvicultural systems.

Table 4: Forest Management Strategies as identified by Nabuurs et al. (2019)

ID	Forest management strategy	Definition
1	Strict nature management	No forest management is applied, with natural processes being the most important shaping process (e.g. strictly protected areas)
2	Close to nature management	Areas with restricted forest management foremost aimed at conservation and restoration of biodiversity and nature values (e.g. protected areas)
3	Low intensity management	Management mostly aimed at nature conservation or carbon sequestration, (co-)aimed at wood and timber production with a low intensity in space and or time
4	Multifunctional management	Forest management aimed at more than one objective occurring in varying degrees and where possible, simultaneously in space

		and time. E.g. timber, water production, erosion protection, biodiversity, climate mitigation and adaptation and recreation occurring spatially integrated
5	Intensive management	Forest management aimed predominantly at wood and timber production, using clear cuts (small and medium scale) and regular periodic harvest techniques over larger areas, not necessarily in large contiguous blocks but taking duly into account the other functions of forests as well
6	Very intensive management	Forestry aimed at (pulp/fibre) wood and timber production in short rotation periods and clear cuts over (mostly) semi-large areas. In most cases fast growing tree species are used (poplar, eucalypt and Sitka spruce)

Additionally the flows for used forest are further subdivided using the forest management strategies as presented in Nabuurs et al. (2019). For Europe the identified management strategies were mapped Nabuurs et al. (2019), see Figure 7 in Chapter 3.2.1. This information is also used in the case study described in Chapter 6. While the strategies defined and mapped by Nabuurs et al. (2019) only cover European forests, similar information could be derived and mapped for a global context as shown in Schulze et al. (2019).

From a forestry perspective additional information could be derived from a more specific silvicultural description as presented by Cardellini et al. (2018), but currently no spatial information is available on these classes. Nevertheless including silvicultural systems into the nomenclature would make sense. Different silvicultural systems could be applied under the different management strategies identified by Nabuurs et al. (2019). A complete nomenclature, with the main structure provided by Koellner et al. (2013a) as a basis and with additional information on management intensity in Nabuurs et al. (2019) and silvicultural systems (Cardellini et al. 2018) is provided in Table 5:

Table 5: Proposal for a nomenclature for the forest flows based on the original land-use classes, combined with management strategies and silvicultural systems

ID	Land use/cover class from Koellner et al. (2013a)	Management strategy (Nabuurs et al. 2019)	Silvicultural system (Cardellini et al. 2018)
1.1.	Forest, natural		
1.1.1	Forest, primary	Strict nature management	-
1.1.2	Forest, secondary	Close to nature management	-
		Strict nature management	
1.2	Forest, used		
1.2.1	Forest, extensive		
(a)		Low intensity management	Continuous cover forest management (selection felling, or selective logging)

(b)		Multifunctional management	Continuous cover forest management (selection felling, or selective logging)
(c)			Forest management with shelterwood Forest management with clearcutting systems combined with nature considerations in all operations and set aside areas with no management or management in order to maintain or enhance biodiversity values or other values.
1.2.2	Forest, intensive		
(a)		Intensive management	Forest management with shelterwood
(b)			Uniform clearcutting system
(c)			Coppice
(e)		Very intensive management	Uniform clearcutting system
(f)			Short rotation plantations

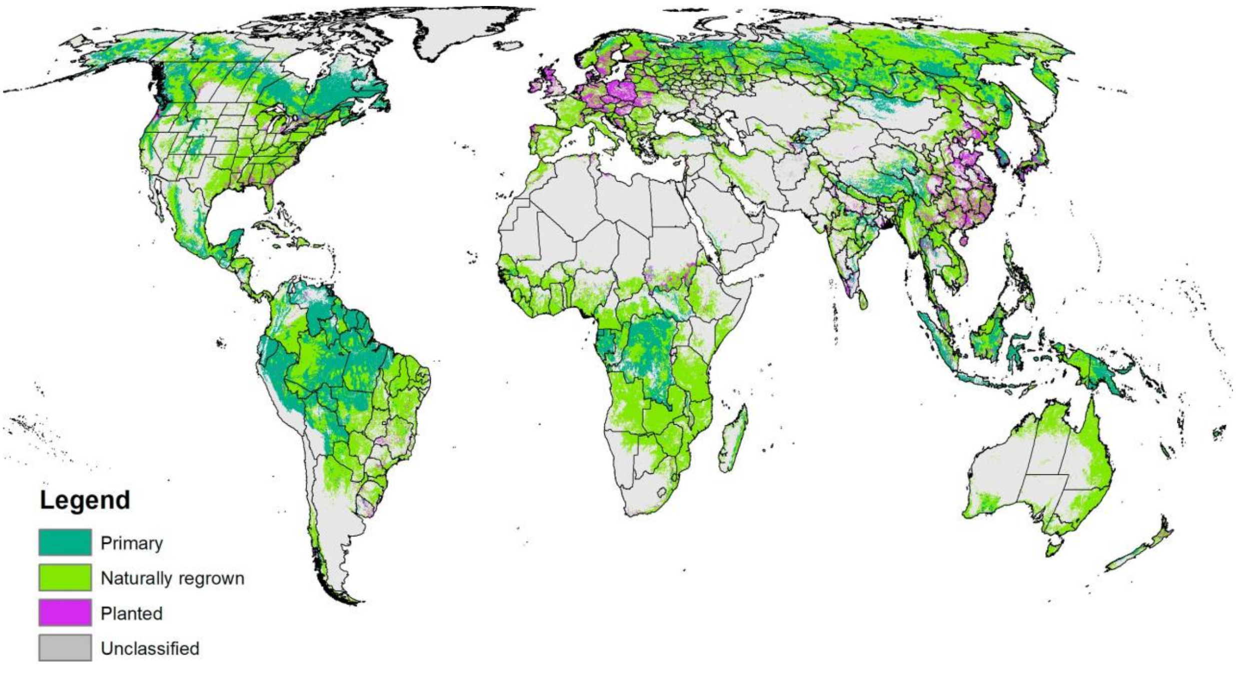

Figure 11: Global patterns of forest classes as presented in Schulze et al. (2019)

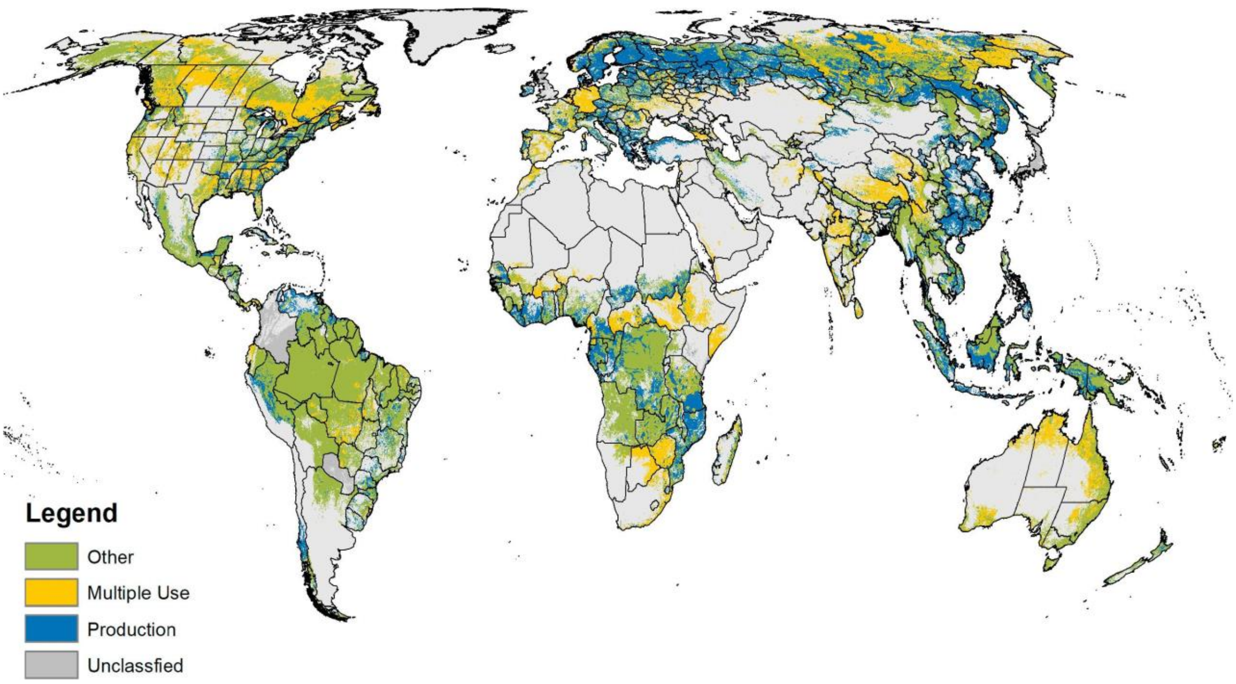

Figure 12: Global patterns of forest uses as presented in Schulze et al. (2019). The combination of these two elements provides similar information on forest management strategies as identified and mapped by Nabuurs et al. (2019)

The incorporation of sustainable management practices is not straightforward as potentially all of the mentioned intensities and silvicultural systems could be either sustainable or unsustainable. There could be a distinction between forest management that is certified according a sustainable forest management certification system like FSC or PEFC and uncertified forest management. But wood from uncertified sources is not necessarily produced unsustainably. Nevertheless this aspect (certified vs uncertified) could be added as a flow property (if flow properties are applicable). This would mean that for each region characterization factors for the different management strategies need to be elaborated for certified and non-certified forest management and an average value in case the certification standard is not known. In regions where non-certified forest management already meets sustainability criteria, like in large parts of the EU forests, the differences between those characterization factors will be limited.

A further possibility of classifying land use flows is described in Maier's forthcoming dissertation (Maier 2022 submitted) for the development of a biodiversity impact assessment method in LCA (Maier et al. 2019), which can also be used for the other land use impact assessment methods (Horn and Maier 2018). As proposed here the land use flows are hierarchically structured, similar to Koellner et al. (2013a), according to the levels *land use type, land use sub type, land use intensity, land management parameters and geolocation*. However, instead of naming individual land use flows, an approach based on flow properties is being used. This approach defines a set of land use type-specific management parameters that characterize each broad land use class and thus its intensity by calculating a so-called land use intensity index (Maier et al. 2019). With the help of this nomenclature based on flow properties, an infinite number of land use flows can thus be assessed in the life cycle impact assessment phase (Maier 2022 submitted; Maier, Horn 2020). Furthermore, this approach allows a direct connection between the life cycle inventory and the life cycle impact assessment. Therefore, changes in land management parameters or the land use intensity in the nomenclature directly lead to a change in the characterization factor and thus in the overall impact such as in the soil related indicators (e.g. erosion), biodiversity and other areas of protection. Furthermore, by using the geolocation as one property of the flow nomenclature further information on the most likely land use intensity and the specific land management parameters in a given country or region can be derived based on statistical data (Maier, Horn 2020; Maier et al. 2019). This is particularly important for background processes if a company only knows the locations (country/region/coordinates) and types of land use that are part of the life cycle of a product, but has no further knowledge about the intensity of land use or the specific land management parameters in a region. A set of land use type specific management parameters has been suggested by (Maier et al. 2019) for six broad land use classes and is being further refined and made operational using a GIS environment. The new nomenclature based on the flow properties can easily be adapted to the existing EF flow list used in LANCA® in order to make this approach applicable within the EF framework (Maier, Horn 2020).

5.2 SOC

Soil organic carbon is one of the indicators recommended by the Life Cycle Initiative to be used in LCA as mid-point indicator to measure the impact of land use on soil. Within a collaboration of the Joint Research Centre and the Fraunhofer IBP, background characterization factors have been developed based on the requirements of the GLAM 2 report (De Laurentiis et al. in preparation). In the following, the general calculation procedure for country specific characterization factors on global level as well as an exemplary calculation of specific characterization factors based on EFISCEN space are presented.

5.2.1 Background Calculation procedure according to Laurentiis et al. (in preparation)

To calculate spatially refined characterization factors for SOC, several input data are required:

1. A base map of SOC stocks under natural vegetation (in kg/C per ha)
2. A climate map depicting the IPCC climate zones
3. Factors for the change in SOC content under different types of land use, land use intensity and land management practices as provided by the (Calvo Buendia E. et al. 2019)
4. Land use maps depicting the occurrence of the main land use types, e.g. (Kehoe et al. 2017)
5. Country shape file for the aggregation of CF values per country for the background database.

The first step in calculating the SOC CFs is to match the IPCC factors for SOC inventory changes under different land use regimes and in different climate zones with the existing EF land use flow list in the LCA. Maps for each land use flow are derived from the matching table and IPCC SOC change factors per climate zone and land use flow are generated (Calvo Buendia E. et al. 2019). These maps are then multiplied by the SOC stock map (under natural vegetation) to obtain specific results for the SOC content for each land use flow. To obtain the CFs, the delta between the SOC content under natural vegetation and the SOC content under each land use flow is calculated. To aggregate the CF per country for the background database, an average CF value per country and type of land use is calculated, masking out all areas where the specific land use type does not occur, similar to the approach of Maier et al. (2019).

The SOC content under land use is calculated according to the following equation:

SOCLU = SOCref * FLU * FMG* FI [kg C/m^2] (according to Laurentiis et al. (in prepa ration)

where

SOCLU = SOC content under a specific land use type

SOC ref = SOC content under natural vegetation

FLU = SOC stock change factor for a land use type

FMG = SOC stock change factor for land management

FI = SOC stock change factor for land use intensity

Based on this equation a scaling factor for forest flows could be calculated by dividing the SOC value under land use by the SOC value under natural vegetation.

FLU * FMG* FI = Scaling_factor (for different land use types, management practices and intensities)

Scaling_factor=SOCLU/SOCref

The calculation steps for the indicator change in soil organic carbon are showed in Figure 13.

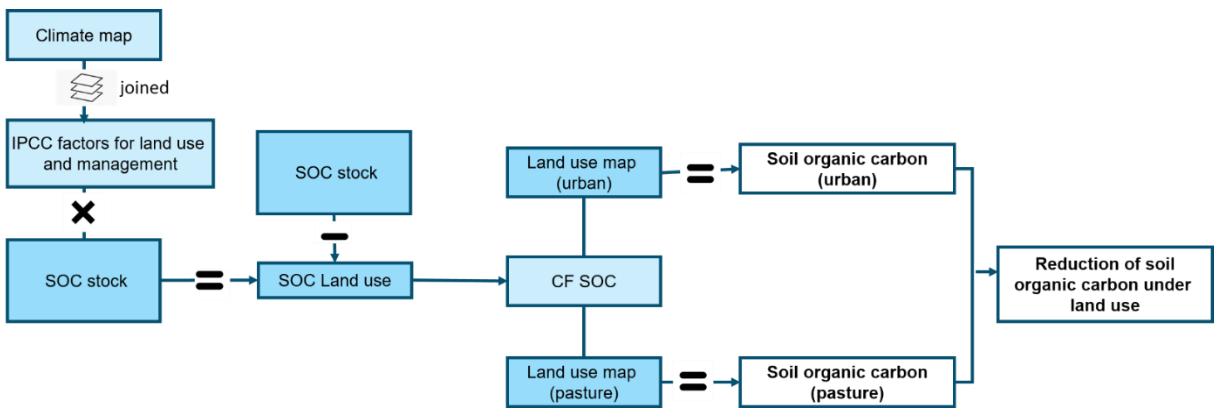

Figure 13: Calculation of CFs for soil organic carbon

As has been shown in (De Laurentiis et al. in preparation) , using the calculation approach described above, characterization factors can be obtained for each elementary flows of the EF flow list on a global scale. For some regions, however, no SOC CF factor is available, because either no information about the SOC content in soils or no information about land use is available in the map. Furthermore, the values for some of the SOC CFs and some of the land use flows are the same, because the IPCC does not provide further refined SOC stock change factors that could be matched with the EF flow list (e.g. some of the flows of the land use type urban). Another drawback is that some of the land use flows have negative signs (e.g. arable, non-irrigated, intensive or arable, flooded crops). The use of this CF leads to a generally positive impact. Moreover, the differences in SOC CF values in some regions are due only to soil characteristics and climate and not to soil management and intensity. Furthermore, with regard to the forest flows, the IPCC makes no distinction between SOC changes in different forest management systems. Since the IPCC assumes that the SOC content under different forest management regimes does not change compared to the SOC content in natural forests, it gives a SOC change factor of 1 for forests in general and for all forest management systems (Calvo Buendia et al. 2019). Since the SOC content under natural vegetation is the same as the SOC content under managed forests, the result is a characterization factor of 0 for all forest related land use flows.

5.2.2 Foreground Calculation procedure (based on EFISCEN Space)

The link between EFISCEN Space and the Yasso15 module has been established only recently, and is not thoroughly tested yet. It is highly dependent on an accurate estimation of the biomass per compartment (stems, foliage, branches, roots), in combination with the parameters that govern the turnover of these biomass compartments. For the majority of the simulated plots, simulated carbon values are in a reasonable range, while for some plots the simulated values are very high. The latter is connected to a few species (mainly broadleaves) where the parameterization has to be improved. Overall, more work is still needed to get a better calibration of the modelled soil carbon values against observations. We here present the results as they currently are, only meant for demonstration purposes. Rather than presenting averages, we present median values, as the median is not so much influenced by outliers in the underlying population (Table 6). A spatial representation was made by averaging the simulated individual plot values in 0.125 degree grid cells (Figure 14 and Figure 15).

Table 6: Median simulated soil carbon stock (Mg C/ha) values for the different cases as simulated by EFISCEN Space (preliminary results)

Case	Management	SOC (Mg C/ha)
Netherlands all species 2010-2030	all (low-medium-high)	211
	low	204
	medium	214
	high	277
Netherlands Douglas fir 80 year rotation	medium	144
Sweden all species 2010-2030	all (low-medium-high)	174
	low	194
	medium	177
	high	178

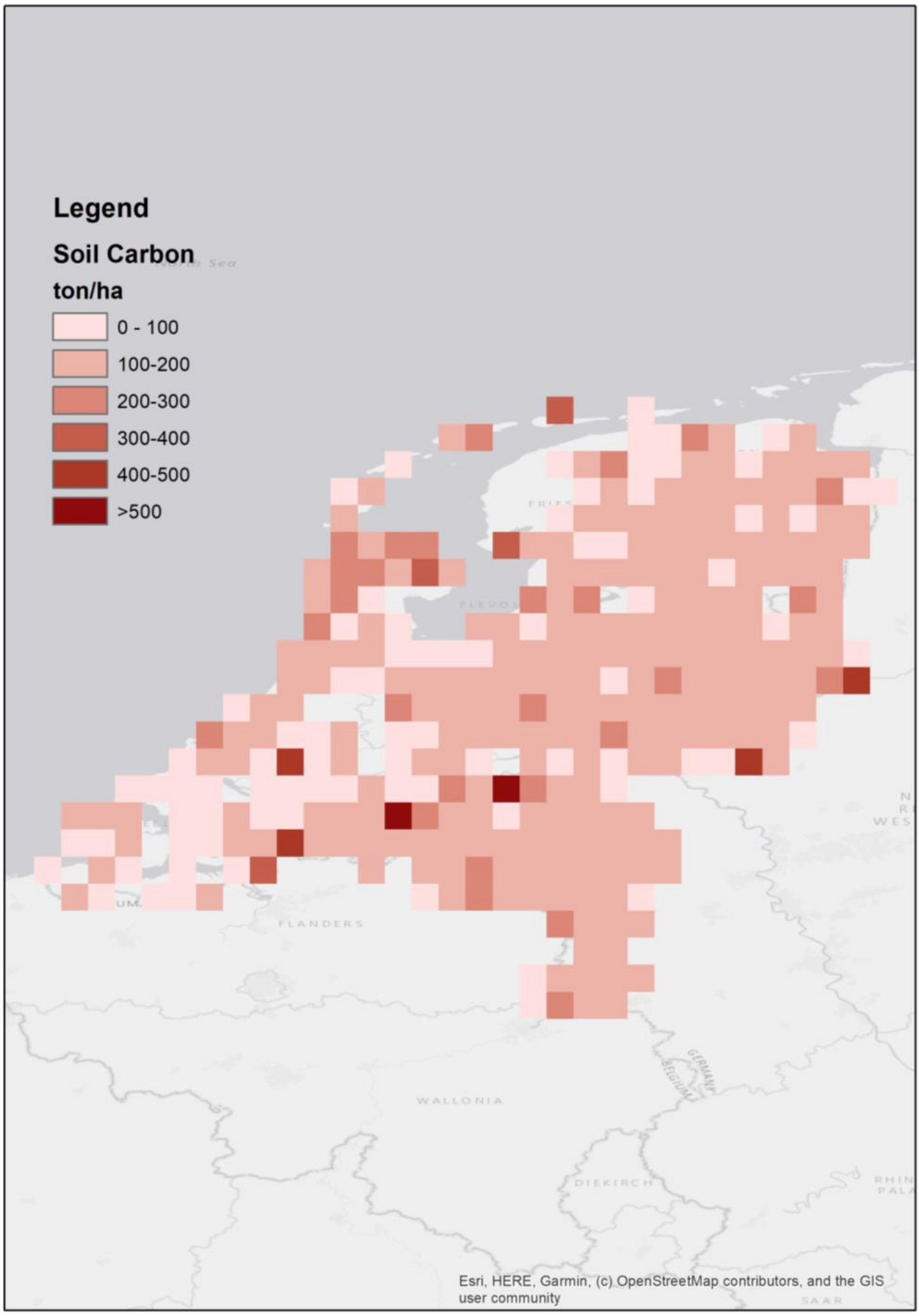

Figure 14: Average simulated forest soil carbon stock values (g C/ha) per 0.125-degree grid cell for the Netherlands as simulated by EFISCEN Space (preliminary results)

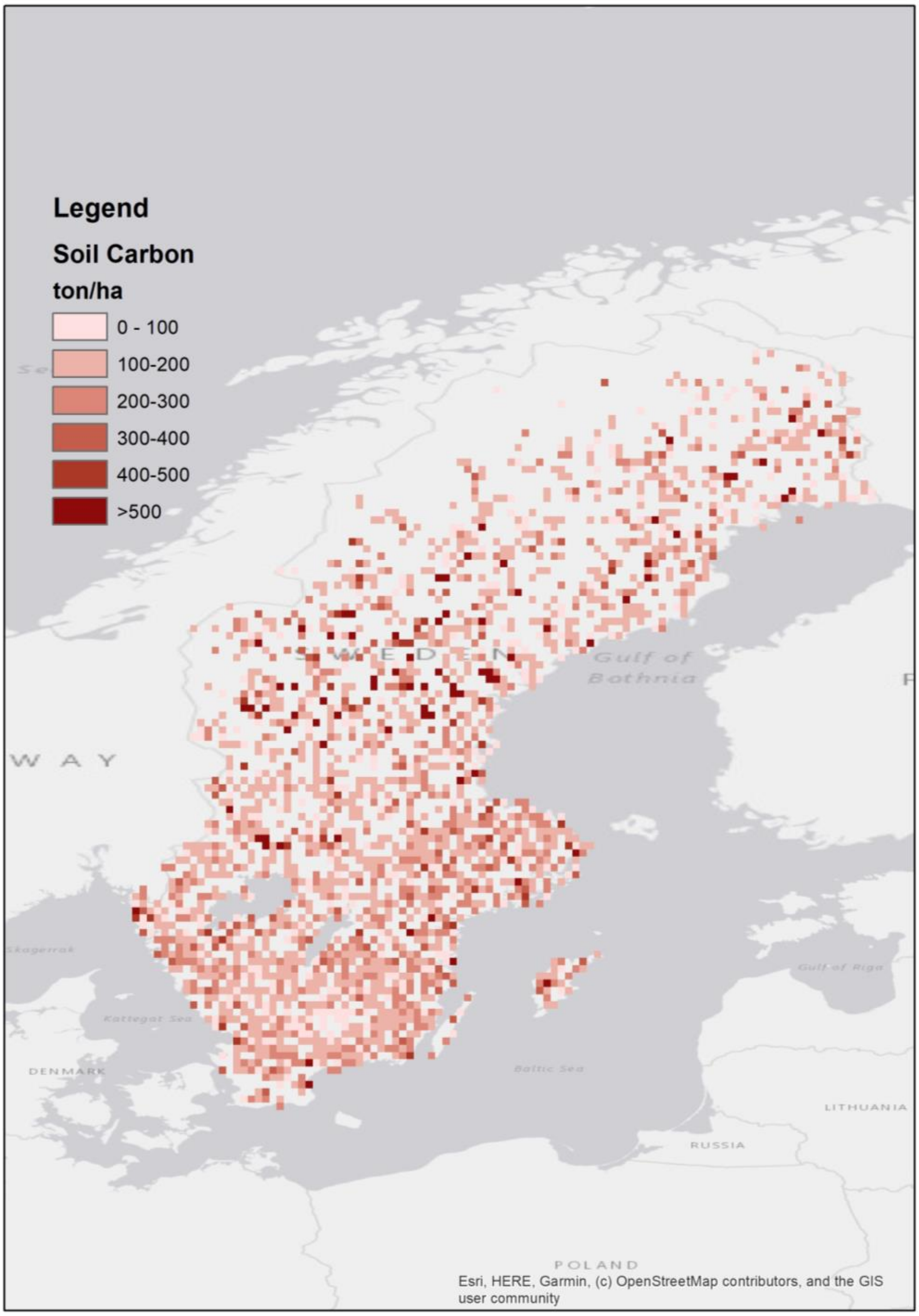

Figure 15: Average simulated forest soil carbon stock values (g C/ha) per 0.125-degree grid cell for Sweden as simulated by EFISCEN Space (preliminary results)

5.3 HANPP

HANPP is a socio-ecological indicator (Vitousek et al. 1986) that measures the proportion of net primary production (NPP) that humans have appropriated. It is a measure of the impact of anthropogenic land use on the biosphere. It quantifies the biomass harvested and the difference between the potential productivity of ecosystems and current productivity caused by land use processes such as land conversion or land degradation (Figure 16). The concept of HANPP has been further developed by including aspects of the fraction of HANPP consumed (cHANPP) as well as embodied HANPP (eHANPP) (Ma et al. 2012).

5.3.1 Background Calculation procedure according to Alvarenga et al. (2015)

In LCA, the concept has been applied by several authors and CFs have been calculated by comparing the NPP of plants occurring under current land use types with the NPP of potential natural vegetation (Alvarenga et al. 2015). Taelman et al. (2016), calculate site-dependent CFs for terrestrial land cover for 3680 zones both country and land use specific, expressed as mean NPP (MJex m^{-2} yr^{-1}) in that specific zone. However, current models that apply HANPP in LCAs have very limited coverage of land use elemental flows and do not capture different land management practices. In addition, as shown by Vidal-Legaz et al. (2016), cropland production is considered beneficial in terms of the HANPP indicator, so they recommend evaluating other soil quality indicators that are necessary. Regarding forestry assessment, CFs calculations for forest are not yet possible due to lack of data on changes in NPP due to global forest managements.

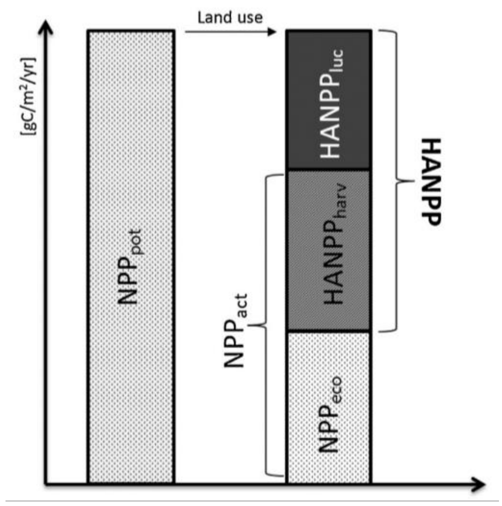

Figure 16: Representation of the HANPP constituents as provided by Niedertscheider and Erb (2014)

To calculate CF for HANPP in forestry, Alvarenga et al. (2015) differentiated between (1) the NPP of PNV that produced biomass by plants in certain circumstances under no land use activity (so called NPP_{pot}) and (2) remaining NPP of current land use with or without after harvest (so called NPP_{act}). The difference between NPPs and NPP of PNV denote as $\Delta HANPP_{luc}$. As the first step, HANPP map delivered from the NPP maps (e.g., Imhoff et al. 2004). The different land use regimes (e.g., Kehoe et al. 2017) maps are multiplied by obtained HANPP map to calculate specific HANPP values for each land use flow. For the midpoint CF for HANPP, the delta between the natural potential NPP and actual NPP per land use flow is calculated. To aggregate the CF within each country for the background calculation, a country specific average CF value and type of land use is calculated, excluding areas where the specific land use type does not occur, similar to the approach of Maier et al. (2019). The calculation steps for the indicator change in NPPs are depicted in Figure 17.

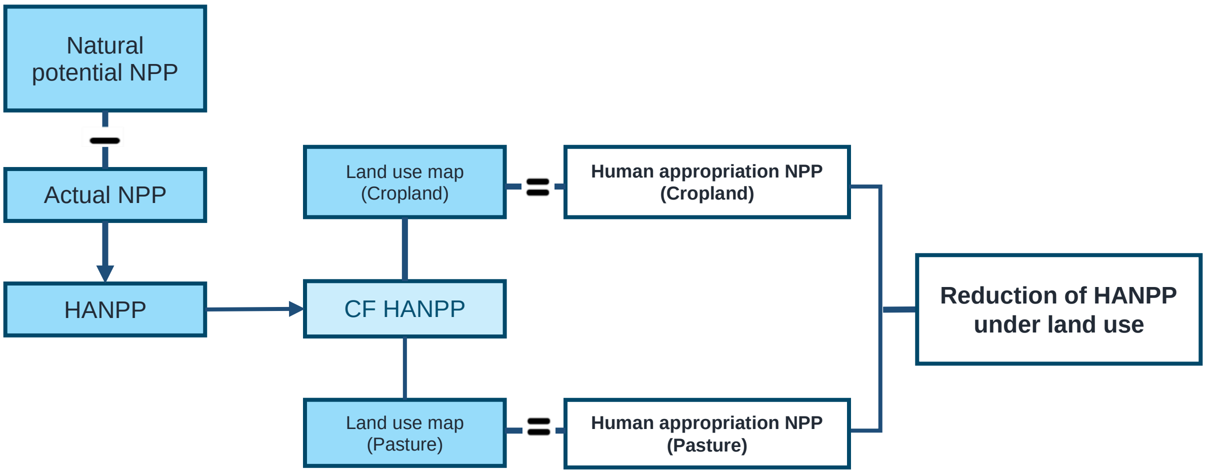

Figure 17: Calculation of HANPP for LANCA®

One way forward in improving the CFs for forest related flows in LCA would be the calculation of CFs for HANNP based on different forest management regimes and changes in NPP derived from different forest models, e.g. EFISCEN model for European forests for improved forest classification in the environmental flows. This could also include the consideration of regional specificities in nutrient supply or other growth determining factors (Högberg et al. 2021). However, for the application in EF also other land use categories and forests outside Europe need to be characterized.

Therefore in order to receive a global background database a simplified GIS based approach could by applied by calculating quality values derived from global HANPP and NPP maps (e.g. as provided by Imhoff et al. 2004). These could be overlaid with land use models to calculate characterization factors for the specific forest areas and management regimes.

5.3.2 Foreground Calculation procedure (based on EFISCEN space)

EFISCEN Space provides estimates of biomass in living trees, and biomass for trees that die or are harvested. The HANPP methodology requires different NPP components that are calculated as follows:

- Total NPP = stock1-stock0 + turnover + harvest + mortality
- NPP harvested = all biomass removed during harvest
- NPP remaining = total NPP - all biomass (stems) removed during harvest

Each of these components are calculated per year, and then averaged over the full rotation or projection period. Table 7 shows the simulated values for each of the case studies. Figure

18 and Figure 19 show the average actual NPP, as average of all plots per 0.125-degree pixel for respectively the Netherlands and Sweden.

Table 7: Values for NPP components (g C m^{-2} yr^{-1}) for the different cases as simulated by EFISCEN Space

Case	Management	Actual NPP	Remaining NPP	Harvested NPP
Netherlands all species 2010-2030	all	1000	886	180
	low	923	806	185
	medium	985	865	189
	high	1559	1484	117
Netherlands Douglas fir 80 year rotation	medium	793	368	648
Sweden all species 2010-2030	all	702	514	305
	low	745	565	290
	medium	732	538	314
	high	749	531	353

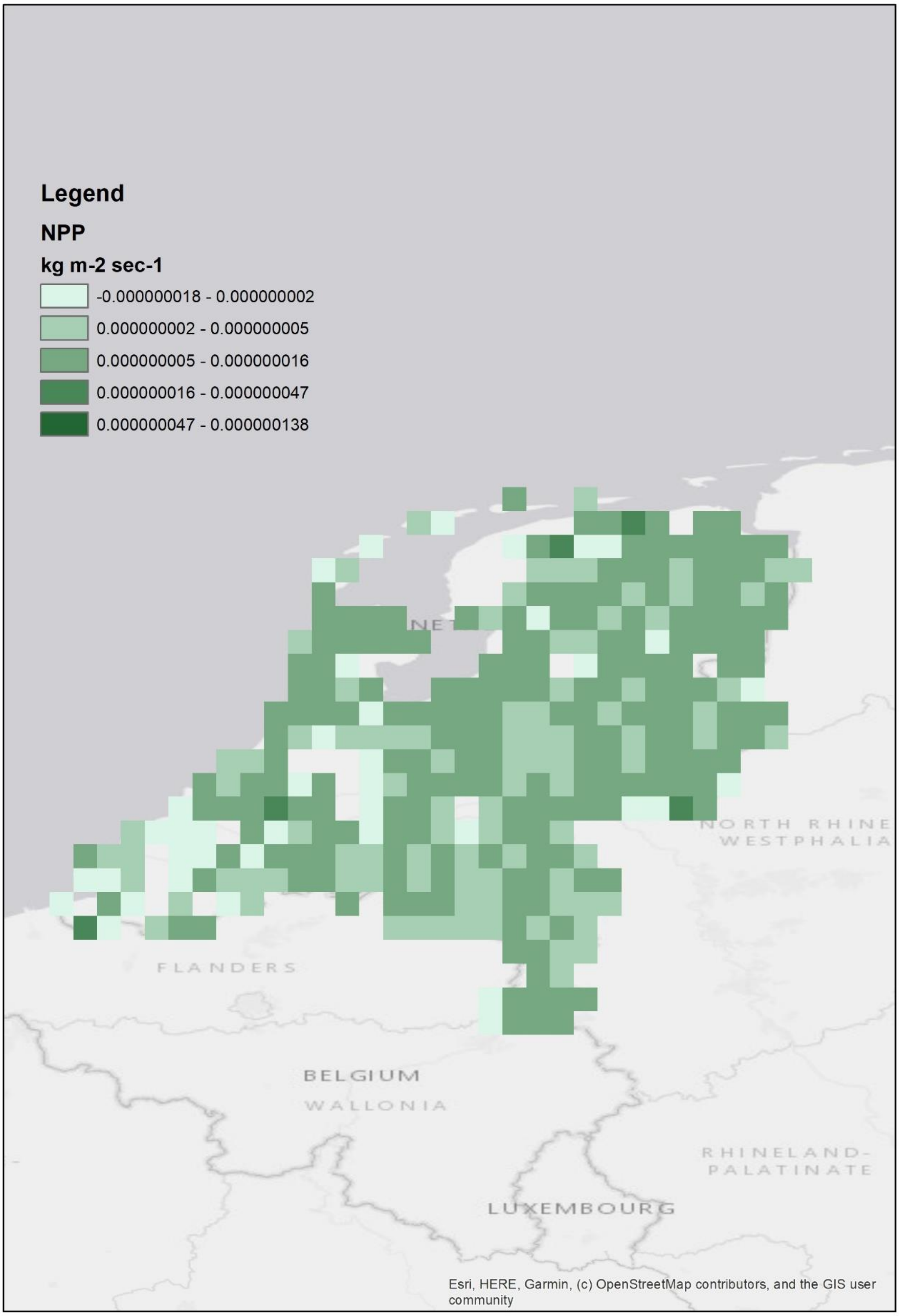

Figure 18: Average simulated forest NPP values (kg m^2 s^{-1}) per 0.125-degree grid cell for the Netherlands as simulated by EFISCEN Space (preliminary results)

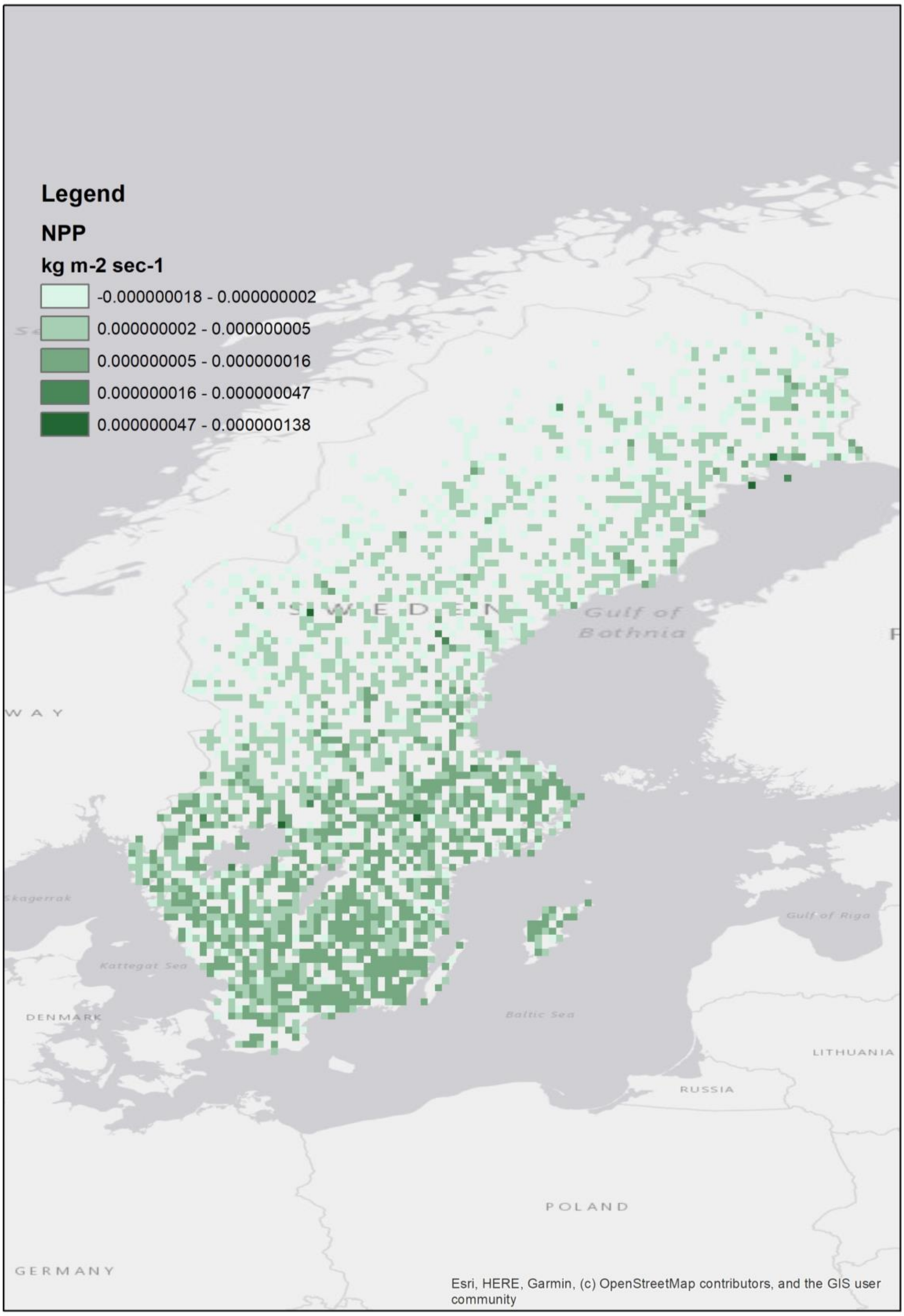

Figure 19: Average simulated forest NPP values (g C/ha) per 0.125-degree grid cell for Sweden as simulated by EFISCEN Space (preliminary results).

6 Case study

To showcase the recommendations for improvement, a base forestry product deals as exemplary assessment to compare the relevance of different locations and different management regimes as well as modelling assumptions in inventory and impact assessment.

The cases as simulated with EFISCEN Space show some important differences. The specific case of Douglas fir over a full rotation cycle shows a high increment (10.1 m^3 ha^{-1} yr^{-1}) and a high harvest (9.4 m^3 ha^{-1} yr^{-1}). This full rotation cycle includes all development stages, i.e. the regeneration phase where the forest is open and increment still low; the dense stage where trees mainly grow in height, mortality is higher and harvest is absent; the mature phase where trees mainly grow in diameter and thinnings are done regularly; and the final harvest stage when the trees reach their target diameter and where all or most of the trees are harvested. In addition, this forest stand is located on a relatively rich soil, and is assumed to be dedicated to forest production, with only limited attention for other functions like recreation and nature conservation. The generic case of the Netherlands as a whole shows a much lower increment and harvest (6.6 and 2.4 m^3 ha^{-1} yr^{-1}, respectively). The lower increment can be explained by having a large share of less productive species, and the forest being located mostly on the most unproductive soils in the country. In contrast to the full rotation cycle of the specific case, some phases are more common across the country than others. Due to the large afforestation efforts in the period 1920-1960, forests in the mature phase are overrepresented. The actual management in these forests deviate considerably from the "ideal" management as assumed in the specific case for Douglas fir. About one third of the forest in the Netherlands is designated for nature conservation, with little or no harvesting. The rest is considered to be multi-purpose forest, where wood production is only one of the aims. In practice, much of the area that would be ready for final harvesting because the target diameter is reached, is not harvested or only partially. This leads to continued accumulation of growing stock, a declining increment, delayed regeneration and rather low harvesting levels.

6.1 Inventory model

The case study contains a comparison of different forest management and wood harvest scenarios for a simple wood-based product. The underlying LCA model was developed within GaBi Software as parameterized model, which can be applied for different wood types and harvesting conditions. Its assumptions and modelling choices are based on the UNEP/SETAC land use framework as well as the forestry specific modelling frameworks of Klein et al. (2015) as well as Cardellini et al. (2018) The functional unit of this product system corresponds to the volume of 1 cubic meter. The model itself is scaled to the reference flow harvested wood, which corresponds to the assumed wood density and is thus defined as the mass equivalent to one cubic meter harvested wood. Details on the wood density within the different scenarios can be seen in Table 8. In principle all models are related to the dried wood quantity. Nevertheless, if applicable and relevant (i.e. calculation of the transportation efforts, heat value consideration, etc.) the wood moisture quantity can be integrated through the parameter settings. The product system is a cradle to gate system and refers to harvested wood at forest. The transportation and storage of wood as well as irrigation systems are not included within this model scope.

Table 8: Wood Density [kg/m³] of different scenarios

Management Scenarios	Wood density [kg/m³]
NL - low management intensity	472
NL - medium management intensity	470
NL - high management intensity	528
NL - all cases	474
NL - specific case	450
SE - low management intensity	419
SE - medium management intensity	419
SE - high management intensity	419
SE - all cases	419

As can be seen in Figure 20, the model is based on different modules: (1) biological production, (2) Chainsaw (forest model), (3) Harvester (forest model), (4) Forwarder (forest model), and (5) several supporting and background system modules.

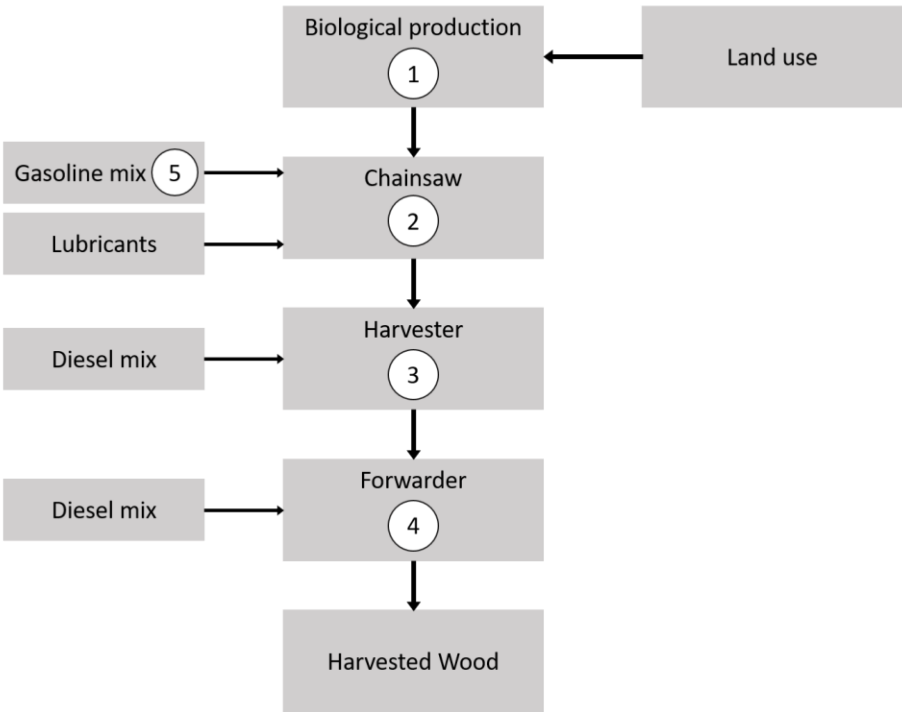

Figure 20: Generic flow chart of forest LCA-model.

The biological production module contains mass balance information on the growth of wood and production of oxygen. Within this module land use change, the carbon (dioxide) uptake via photosynthesis (i.e. 1,851.0 kg CO_2/t abs. dry wood), as well as the resulting primary energy uptake (18,112.0 MJ/t abs. dry) are modelled.

The modules Chainsaw (forest model), Harvester (forest model), and Forwarder (forest model) contain mass balance information on the fuel consumption and environmental impacts of the machinery used for the forest management and wood harvest. In combination with the background system processes (i.e. Gasoline mix, Lubricants, Diesel mix) the total environmental impacts of the used machinery is calculated. Information on the machine productivity and fuel consumption as simulated by EFISCEN Space and can be found in Table 9.

Table 9: Simulated values for productivity and fuel consumption for the case study scenarios

		Productivity (hour/m³)			Fuel consumption (l/m³)		
Country	Management	harvester	forwarder	chainsaw	harvester	forwarder	chainsaw
Netherlands all species 2010-2030	all	0.01	0.09	0.28	0.12	0.83	0.24
	low	0.00	0.09	0.38	0.00	0.83	0.32
	medium	0.03	0.09	0.15	0.37	0.84	0.13
	high	0.06	0.08	0.00	0.78	0.78	0.00
Netherlands Douglas fir 80 year rotation	medium	0.02	0.06	0.06	0.19	0.58	0.05
Sweden all species 2010-2030	all	0.03	0.07	0.22	0.35	0.68	0.19
	low	0.00	0.07	0.35	0.00	0.69	0.30
	medium	0.04	0.07	0.16	0.49	0.68	0.13
	high	0.04	0.07	0.16	0.42	0.66	0.14

Table 10 provides an overview on the land use related inventory values of the investigated scenarios. The chosen flow types reflect the available land use nomenclature, as only these flows are available in the modelling software. The occupation quantities are based on the considered forest area necessary in the EFISCEN space model to provide the expected annual yield. The transformation quantities consider a rotation length of 80 years. For all flows the same land use type is assumed, which is resulting in a foreground transformation impact of 0. The different yields of the management intensities show the expected correlation for Sweden and for Netherlands except for the high management intensity, where the simulated yield is significantly lower due to the modelled forest status in the simulation. Also, the yield of the full rotation scenario varies significantly.

Table 10: Land use related inventory values of the investigated scenarios

Country	Manage-ment	Transformation			Occupation	
		(m2)	Flow name(from)	Flow name (to)	(m2a)	Flow name
Netherlands all species 2010-2030	all	52.08	From forest, used	To forest, used	4166.21	Forest, used
	low	50.41	From forest, extensive	To forest, extensive	4032.74	Forest, extensive
	medium	49.19	From forest, used	To forest, used	3935.62	Forest, used
	high	88.57	From forest, intensive	To forest, intensive	7085.54	Forest, intensive
Netherlands Douglas fir 80 year rotation	medium	13.24	From forest, used	To forest, used	1059.44	Forest, used
Sweden all species 2010-2030	all	27.82	From forest, used	To forest, used	2226.00	Forest, used
	low	29.05	From forest, extensive	To forest, extensive	2324.02	Forest, extensive
	medium	27.04	From forest, used	To forest, used	2163.69	Forest, used
	high	23.96	From forest, intensive	To forest, intensive	1916.57	Forest, intensive

6.2 Impact assessment with existing characterization factors

The life cycle impact assessment results have been calculated both in GaBi directly as well as through manual characterization of the inventory results. This allows to create standard results based on current EF 3.0 recommended methods as well as to provide a detailed investigation of the EF 3.0 results through looking at the separate LANCA® indicators as well as their contribution to the SQI in normalized form. Furthermore, a sensitivity analysis on nomenclature and framework related assumptions can be made.

Figure 21, Figure 22 and Figure 23 show the GaBi based results of the scenario comparison of this case study. In order to assess the product systems with regard to their global warming potential, this case study uses the IPCC AR5 GWP100 (including and excluding biogenic carbon). Land use is assessed via EF3.0 Land Use.

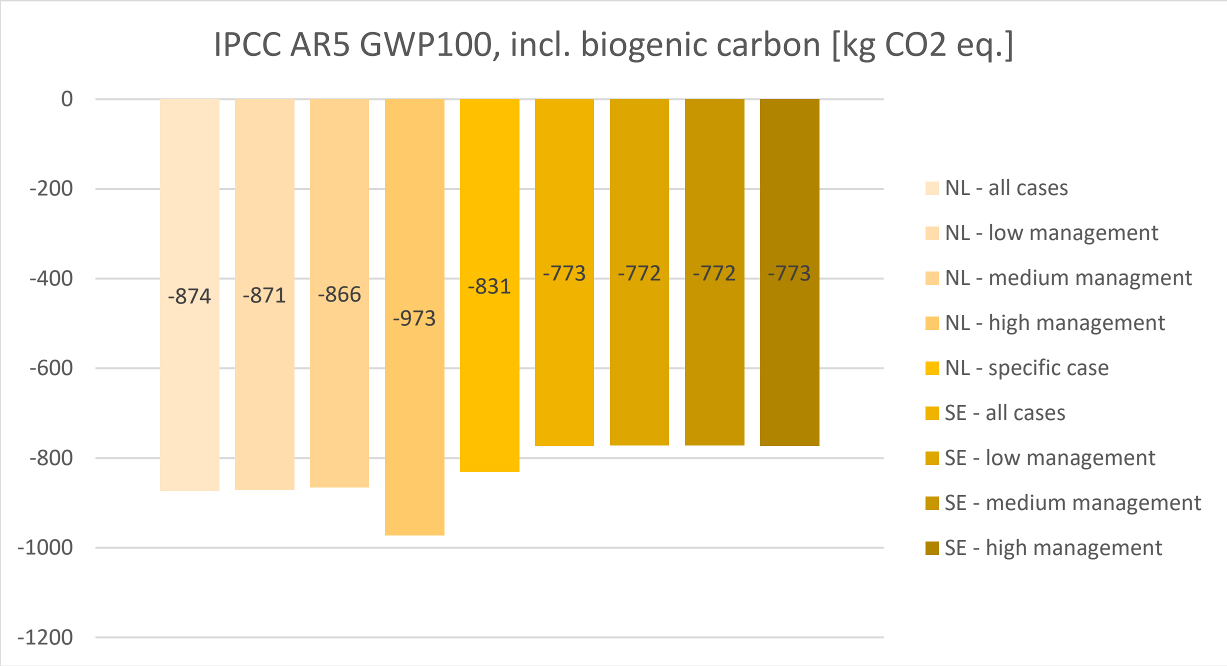

Figure 21: Scenario comparison - GWP100 incl. biogenic carbon

When comparing the scenarios in Figure 21, it can be seen that the results are robust. The minor variation can be explained due to the assumed wood densities. The higher the wood density, the lower the IPCC AR5 GWP100, including biogenic carbon, as more carbon dioxide is captured by denser wood.

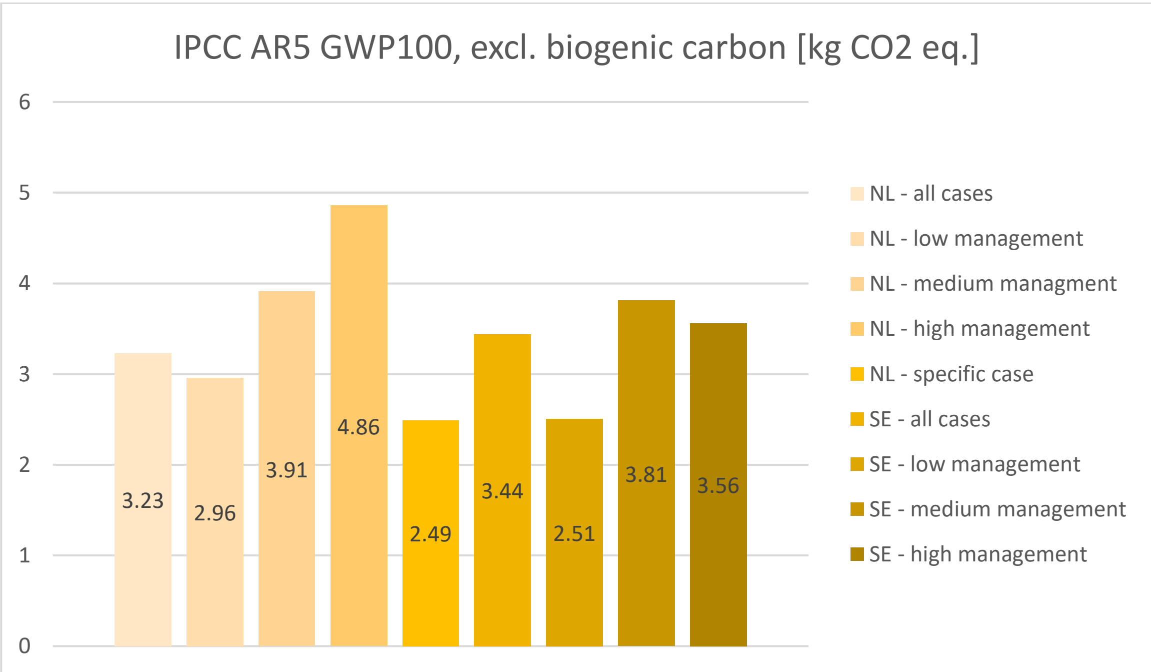

Figure 22: Scenario comparison - GWP100 excl. biogenic carbon

The variation presented in Figure 22 when considering the IPCC AR5 GWP100, excl. biogenic carbon, can be explained by heterogeneous degrees of machine usage in these scenarios. Thus, it can be concluded: the more intense the machine usage (chainsaw, harvester, forwarder), the higher the carbon dioxide equivalent emissions.

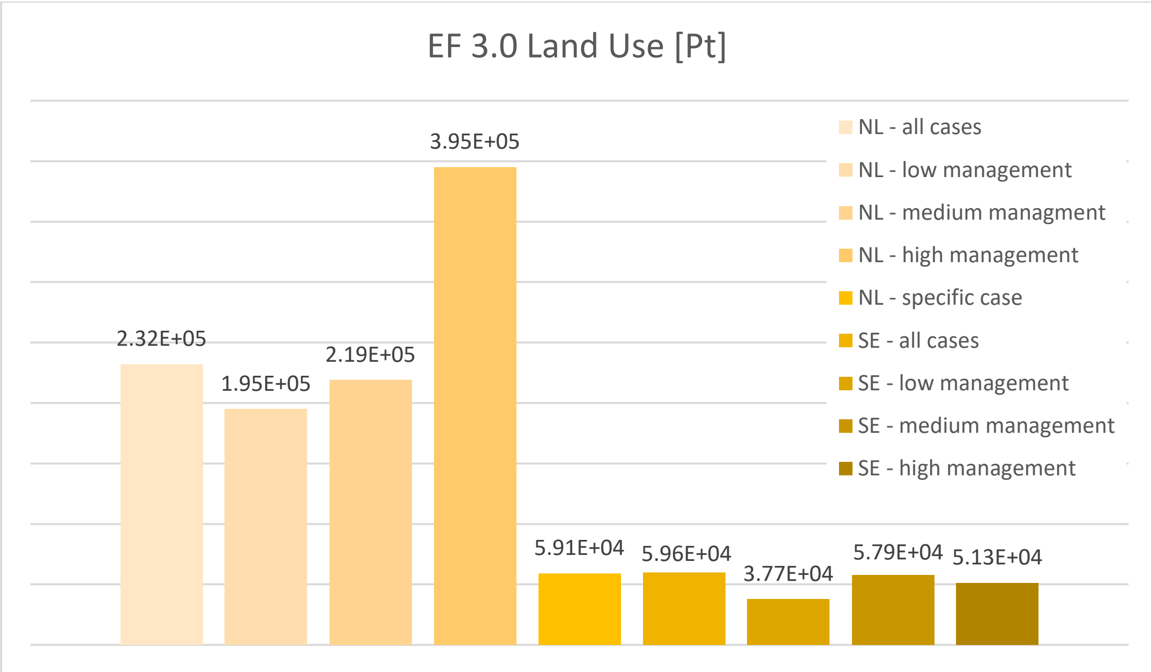

Figure 23: Scenario comparison - Land Use

The variation presented in Figure 23 can be separated into two aspects. The results reflect the underlying occupation and transformation areas that originate from the expected yields of the EFISCEN space model. In addition to this, several further observations can be made on the impact assessment results. Firstly, a country-specific variation is observed as the Dutch scenarios exceed the results of all Swedish scenarios. This can be explained with varying regionalized characterization factors in EF3.0 for the land use SQI. Secondly, the analysis indicates more or less stable results for the Swedish scenarios when compared domestically to each other, but shows increasing deviation for the Dutch cases. Hence, it can be concluded that increasing management intensity leads to higher Land Use impacts in case of the Dutch scenarios. From a modelling point of view, this can be explained with the differing input parameters the model is fed with and the underlying characterization factors.

In the following, this assessment deals as a basis for a detailed investigation of the SQI results. In Figure 24, the EF3.0 Land Use results are depicted based on a manual characterization of the inventory results. Here, the SQI value is further differentiated in the underlying LANCA® characterization models. For all scenarios the dominant LANCA® model is the occupation – biotic production loss potential. While the SQI result does not provide this information, its normalization and weighting algorithm makes this composition plausible: While transformation is nullified through the chosen land use flows (same for transformation to and from), the occupation results of forestry systems do have only relatively small impacts on infiltration reduction and very small impacts on erosion or groundwater regeneration compared to other land use systems. As the normalization is based on the distribution of characterization factors, the biotic production loss potential is the main contributor to the SQI impact.

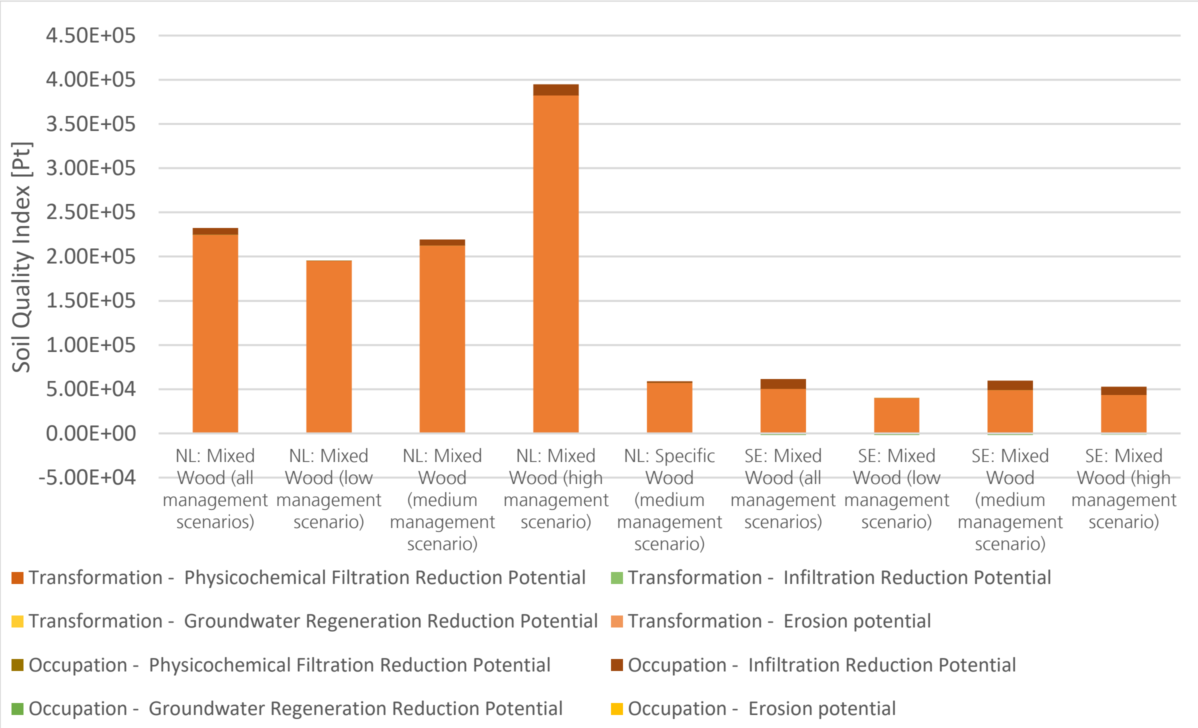

Figure 24: Land use Impact Assessment results (Soil Quality Index as recommended in EF 3.0 Land Use) differentiated by the underlying normalized LANCA® 2.5 results

Figure 25 and Figure 26 provide scenarios on nomenclature level based on the normalized LANCA® 2.5 CFs as applied in EF 3.0 Land Use. In Figure 25 the land use flow differentiation of the baseline scenarios is removed and replaced by level 2 land use flows (forest, used for all scenarios). Figure 26 provides the result for a land use change scenario, where for the low management scenario a land use change from forest, used to forest, extensive is assumed.

While the main differences due to yield and location are still dominant for these scenarios, the comparison of the different scenarios within the countries changes in Figure 25. While the lower yield in the low management scenario is overcompensated by the lower CF in the baseline scenario, this is not the case when only level 2 flow nomenclature is applied. The low management scenario, having the least impact in the baseline scenarios, is now exceeding the impact of the medium management scenario for both the Dutch and the Swedish case.

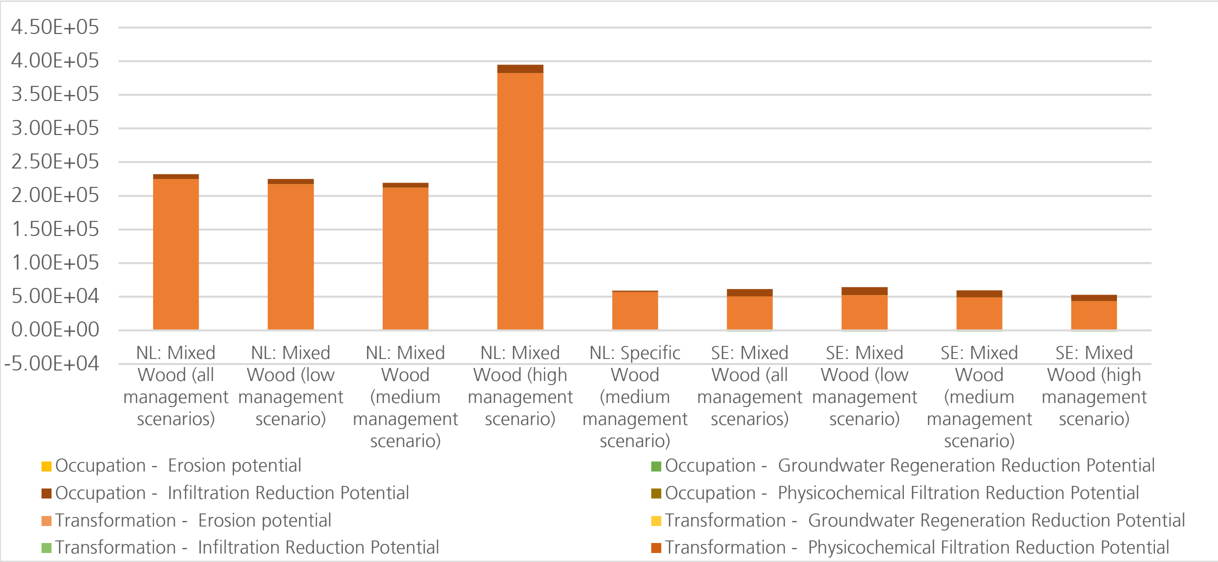

Figure 25: Land use Impact Assessment results (Soil Quality Index as recommended in EF 3.0 Land Use) differentiated by the underlying normalized LANCA® 2.5 results, scenario with level 2 land use flows (only "forest, used")

In the baseline scenarios, transformation is only relevant for background processes, as the transformation from and to flows of the forestry model are of the same type and quantity (resulting in a transformation impact of zero). For an assumed land use change and a point in time of the chosen land use transformation flows as suggested by Laurentiis et al. (2019), the transformation impact can result in a negative impact for the normalized transformation impact and for the chosen scenarios change reduce the impact of EF 3.0 Land Use by 9,6% for the Dutch scenario and by 79,3% for the Swedish low management scenario (Figure 26). When tracing back the results to the LANCA® model, the impact in transformation does not originate in biotic production loss but in infiltration reduction potential.

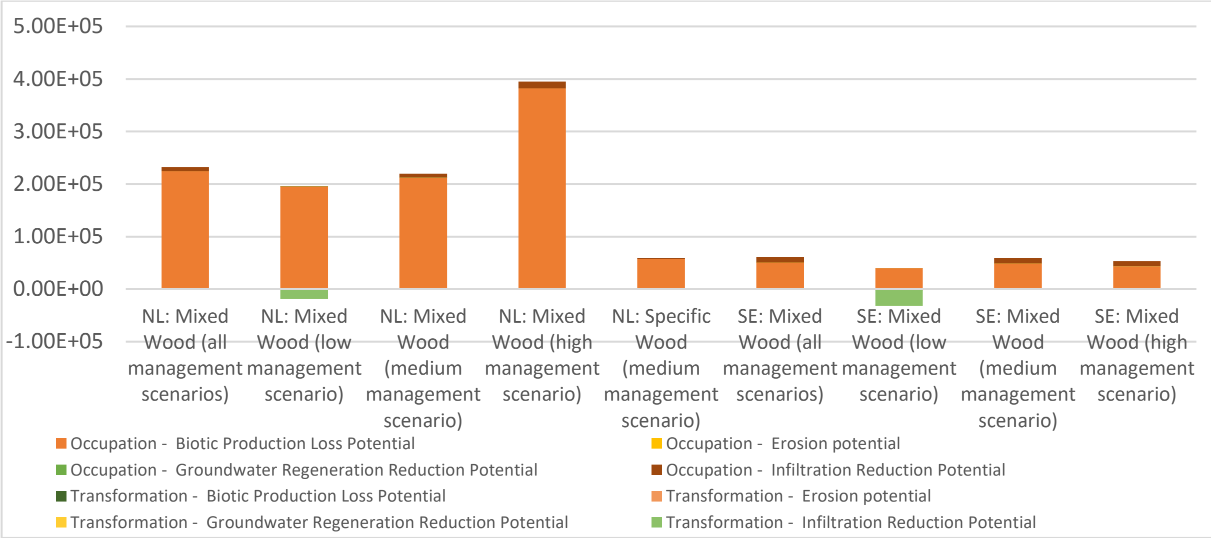

Figure 26: Land use Impact Assessment results (Soil Quality Index as recommended in EF 3.0 Land Use) differentiated by the underlying normalized LANCA® 2.5 results, assumed land use change for the low management scenario from forest, used to forest, extensive

In addition to the analysis of the normalized LANCA® results, Figure 26 provides detailed results of all LANCA® categories, including occupation and permanent transformation. The results on category level show higher heterogeneity than the normalized results, and findings vary between occupation and transformation. Overall, differences between locations as well as between the management scenarios are available for most categories, but with heterogeneous tendencies. While the occupation impact for all scenarios and categories except for groundwater regeneration reduction potential in the Swedish scenarios, the transformation impact of erosion potential, infiltration reduction potential and physicochemical filtration reduction potential is negative for all investigated scenarios. The difference in management scenarios shows similar tendencies for all occupation categories, with a significantly higher differentiation for the Dutch scenarios between low, medium and high management in the categories erosion potential, infiltration reduction potential and physicochemical reduction potential. In general, the impacts of the low management scenario is significantly lower than the average one, which is mainly caused by the choice of input parameters for the CF calculation for “forest, extensive”, that are close to the PNV parameters. The choice not to consider physicochemical filtration reduction due to redundancy to infiltration reduction for the SQI is not fully supported by the detailed results, as there are major differences between the country results while the differences of the management scenarios within countries show high similarities.

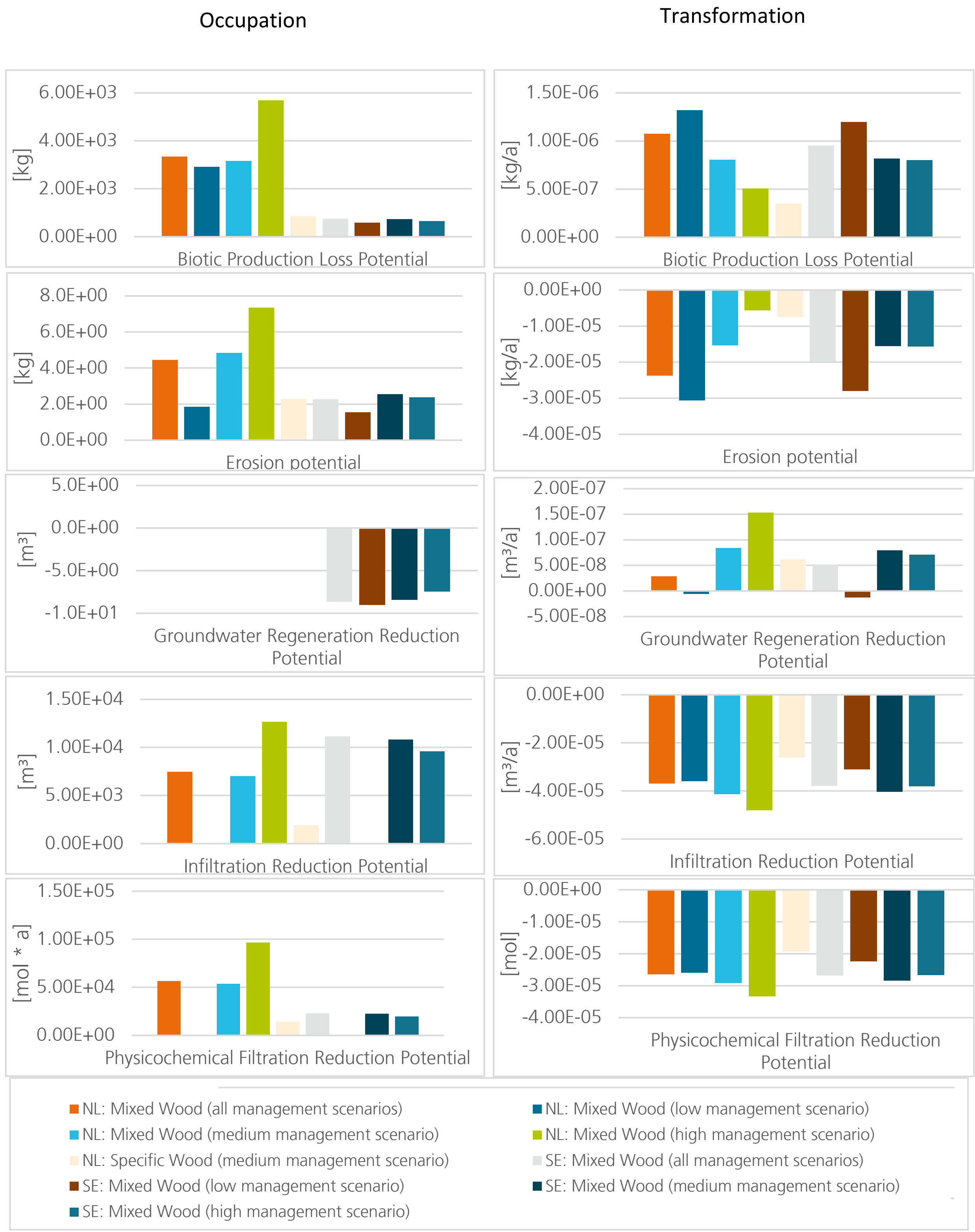

Figure 27: Land use Impact Assessment results for the baseline scenarios (LANCA® categories for occupation and transformation of biotic production loss potential, erosion potential, groundwater regeneration reduction potential, infiltration reduction potential and physicochemical filtration reduction potential)

6.3 Background calculation with new characterization factors

6.3.1 Existing characterization models with new factors

Based on the calculation framework provided by Bos (2019) a spatially refined map for characterization factors for mechanical filtration with 1km resolution has been calculated. Furthermore, the new weighting approach as suggested by Maier et al. (2019) has been applied where all areas that are not classified as forest where excluded from the calculations for both mechanical and physicochemical filtration (see Figure 28 and Figure 34). With regard to the case study a closer look is given to the characterization factors for the Netherlands and Sweden for the different forest management regimes of low, medium and high intensive forest management. The characterization factors derived from the new map and the new weighting approach are compared to the country average values in both countries as they are currently being implemented in LANCA® provided by Horn and Maier (2018).

Figure 29 and Figure 30 show the maps of the characterization factors for mechanical filtration for all of Sweden and the Netherlands and Figure 31 and Figure 32 for only the areas that have been classified as forests by Kehoe et al. (2017).

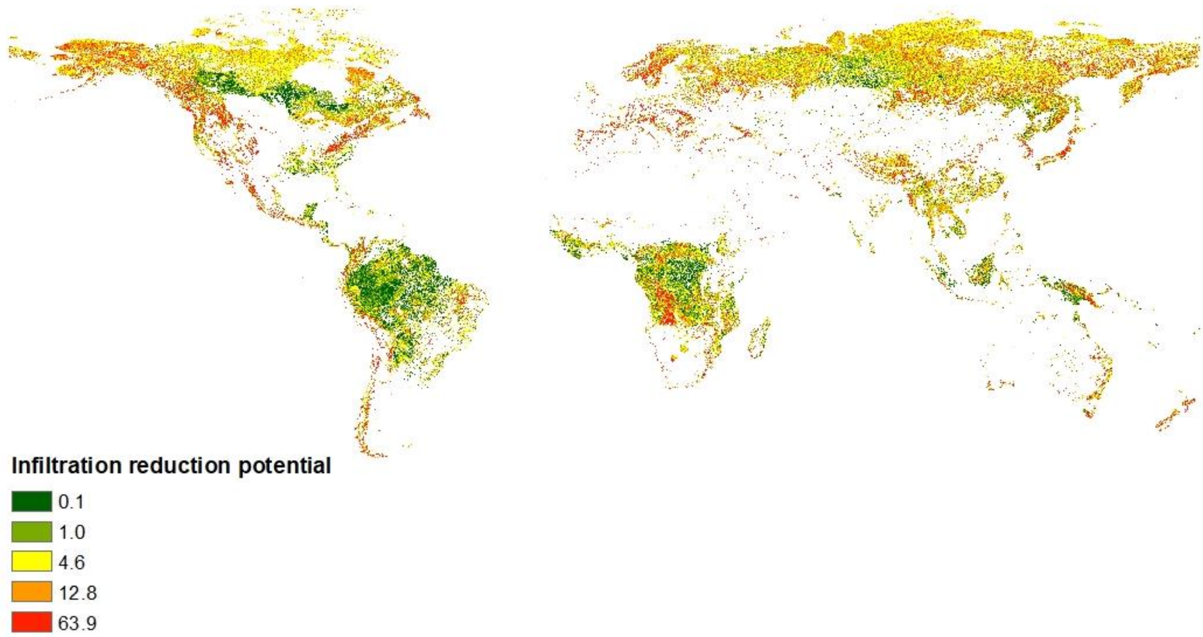

Figure 28: Global characterization factors for mechanical filtration (1km resolution)

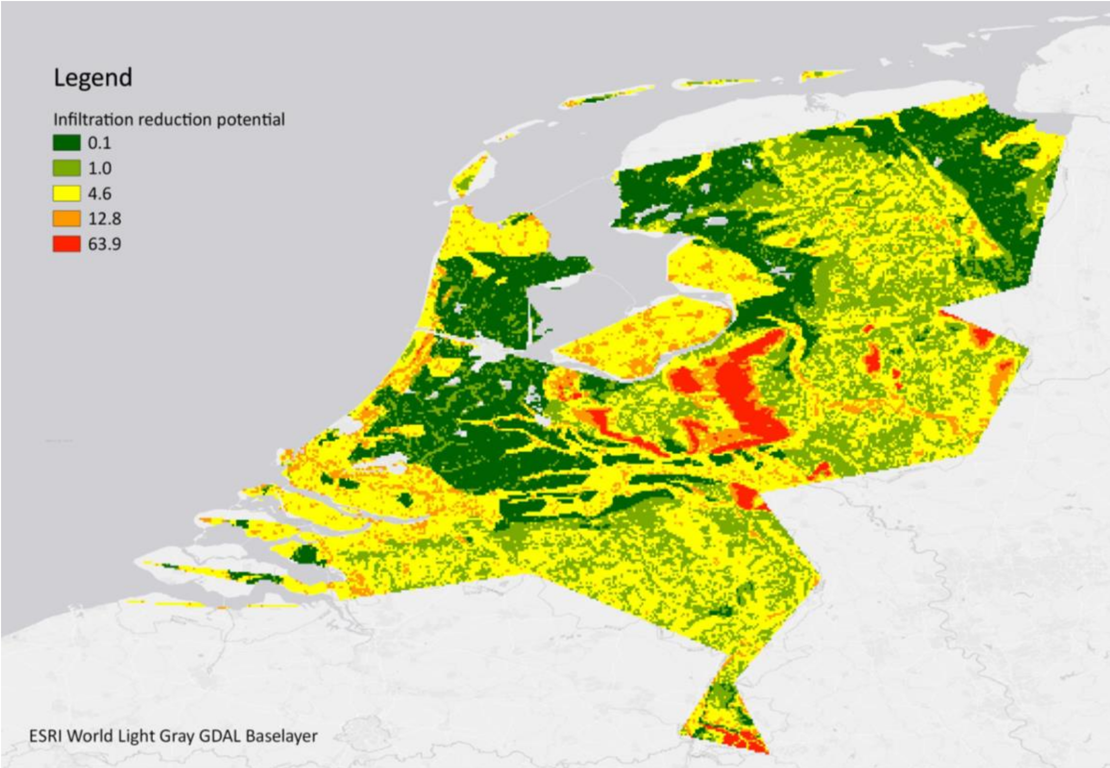

Figure 29: Characterization factors for mechanical filtration in the Netherlands

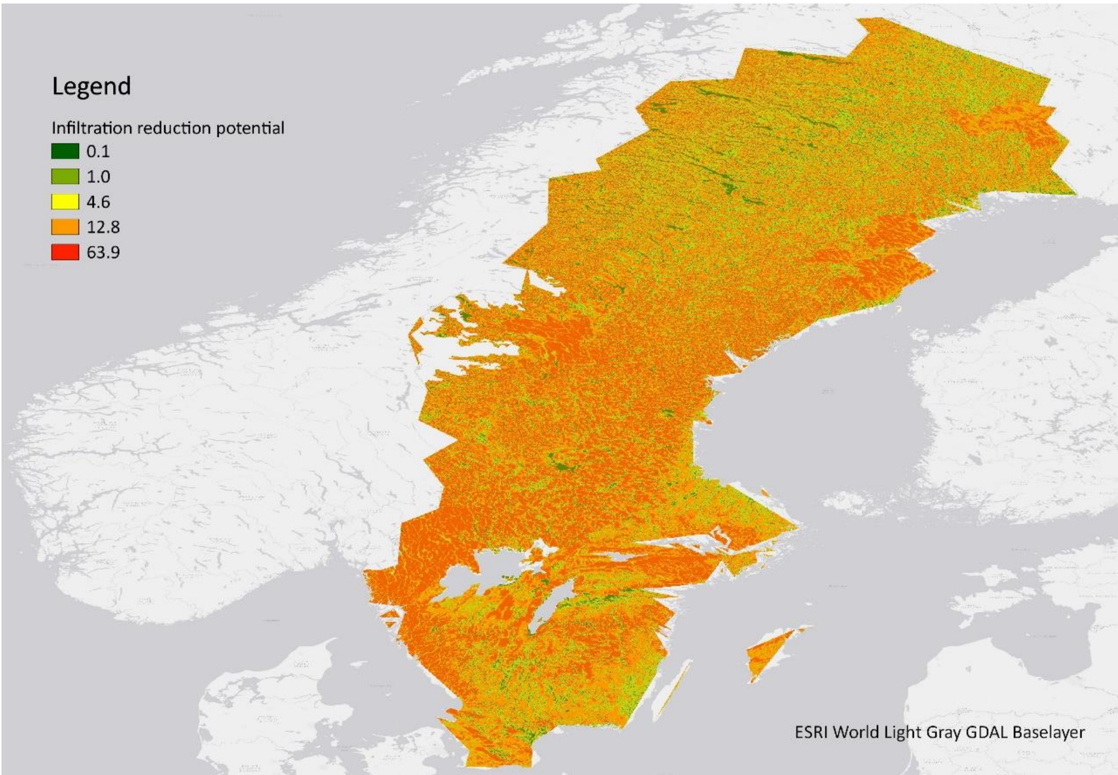

Figure 30: Characterization factors for mechanical filtration in Sweden

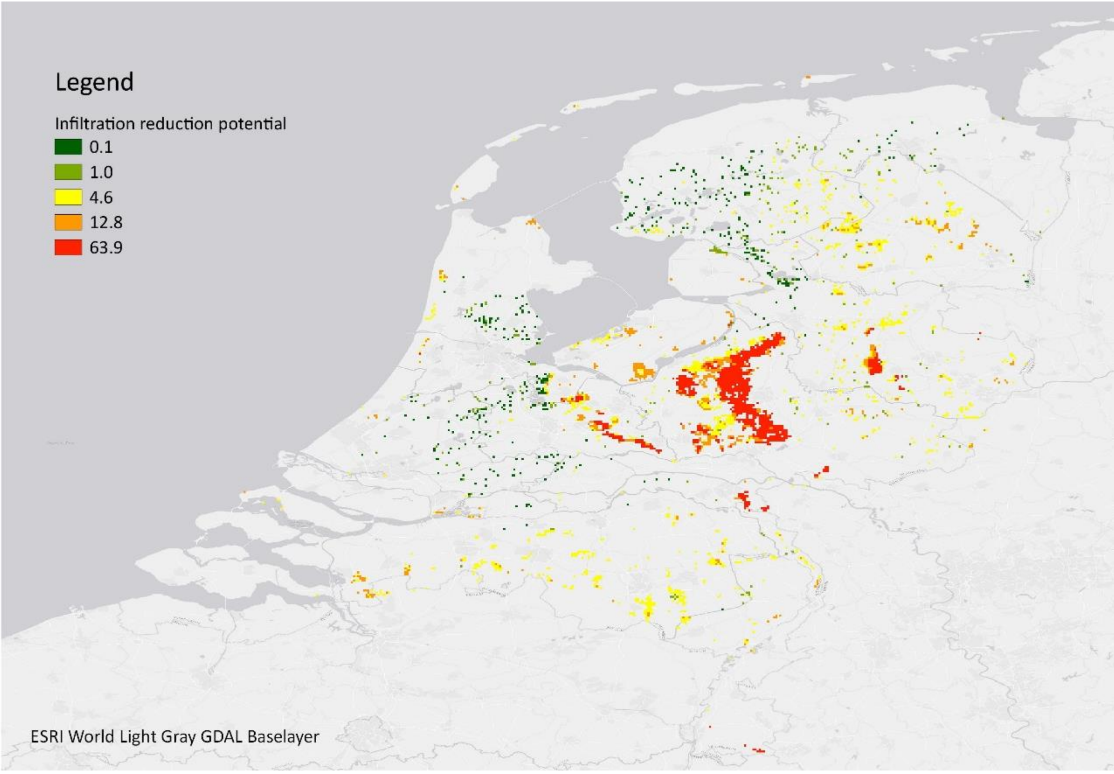

Figure 31: MF Characterization factors in the Netherlands for areas classified as forest by Kehoe et al. (2017)

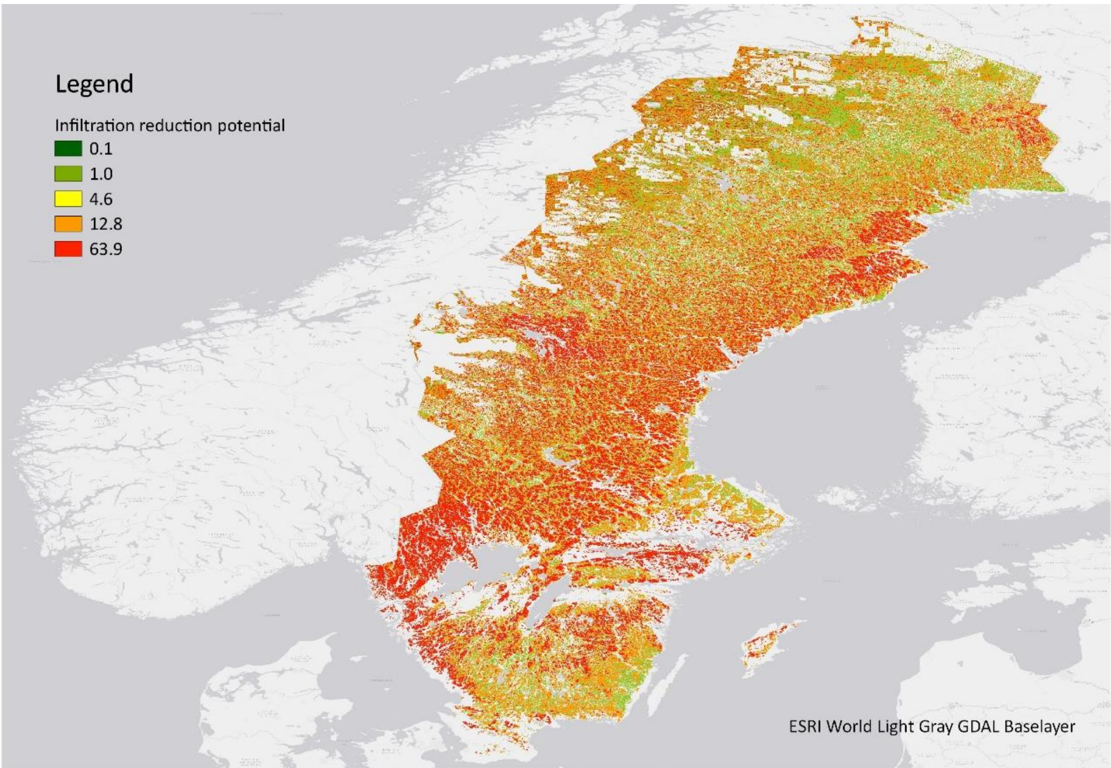

Figure 32: Characterization factors for mechanical filtration in Sweden for areas classified as forest by Kehoe et al. (2017)

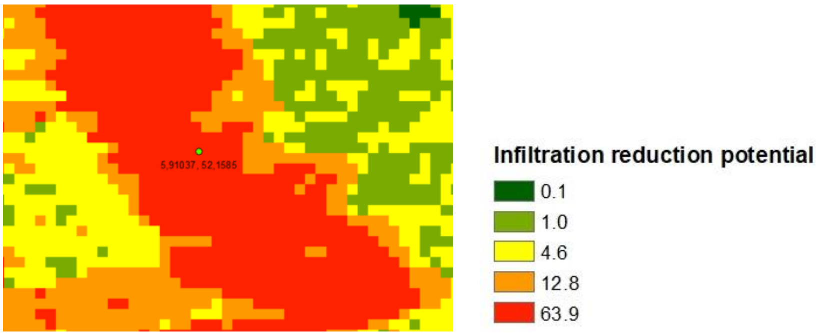

Figure 33: Characterization factors for mechanical filtration in the Netherlands for the case study area

As shown in Table 11, the GIS based analysis and the new weighting of characterization factors shows more refined and reliable results, than using an overall average value for the characterization factor per country. This is especially the case for the Netherlands where the impact on mechanical filtration is much higher when using the GIS based foreground data compared to the average data currently being used in LANCA® database.

Table 11: Impact on infiltration reduction potential for the case study sites derived from the new characterization factor map and the new weighting approach as well as the country average currently being implemented in LANCA® provided by Horn and Maier (2018).

Country	Management	Infiltration reduction potential (Horn and Maier 2018) [m^3]	Infiltration reduction potential: GIS based country average [m^3]	Infiltration reduction potential: GIS based with new weighting regarding Maier et al. (2019) [m^3]	Infiltration reduction potential (Coordinates) [m^3]
Netherlands all species 2010-2030	all	1.90E+04	2.08E+04	8.94E+04	2.66E+05
	low	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	medium	1.80E+04	1.97E+04	8.44E+04	2.51E+05
	high	3.23E+04	3.54E+04	1.52E+05	4.53E+05
Netherlands Douglas fir 80 year rotation	medium	4.83E+03	5.30E+03	2.27E+04	6.77E+04
Sweden all species 2010-2030	all	2.84E+04	5.39E+04	6.00E+04	N/A
	low	0.00E+00	0.00E+00	0.00E+00	N/A
	medium	2.76E+04	5.24E+04	5.83E+04	N/A
	high	2.45E+04	4.64E+04	5.16E+04	N/A

Figure 34 shows the map for the characterization factor physicochemical filtration for the areas that are classified as forest by Kehoe et al. (2017)

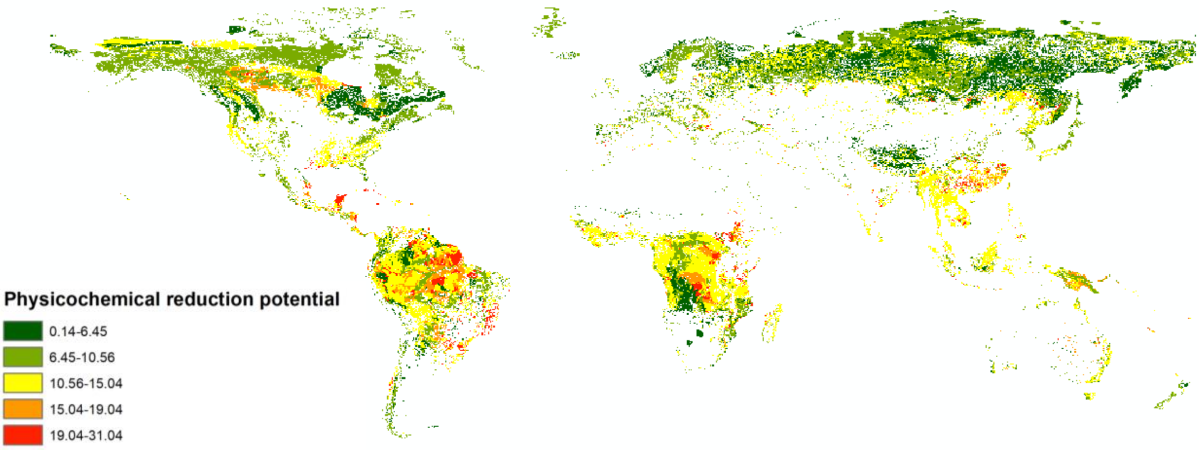

Figure 34: Global characterization factors for physicochemical filtration based on Bos et al. (2020) for the areas classified as forest by Kehoe et al. (2017).

Table 12: Impact on physicochemical reduction potential for the case study sites derived from the new characterization factor map and the new weighting approach as well as the countr y average currently being implemented in LANCA®.

Country	Management	Physicochemical reduction potential (Horn and Maier 2018) [mol*a]	Physicochemical reduction potential: GIS based country average based on Maier et al. (2019) [mol*a]	Physicochemical reduction potential: GIS based new weighting [mol*a]
Netherlands all species 2010-2030	all	5.67E+04	3.29E+04	2.59E+04
	low	0.00E+00	0.00E+00	0.00E+00
	medium	5.36E+04	3.11E+04	2.45E+04
	high	9.64E+04	5.60E+04	4.41E+04
Netherlands Douglas fir 80 year rotation	medium	1.44E+04	8.37E+03	6.60E+03
Sweden all species 2010-2030	all	2.28E+04	2.02E+04	2.02E+04
	low	0.00E+00	0.00E+00	0.00E+00
	medium	2.22E+04	1.97E+04	1.96E+04
	high	1.97E+04	1.74E+04	1.74E+04

6.3.2 HANPP

To compare the new CF improvement for HANPP from EFISCEN Space to the biotic production in LANCA® 2.5, HANPP values are calculated based on the previous section 6.3 in each scenario. For the LANCA® values, the background calculation based on the GaBi database. Due to not all of management land use flows are available, 'forest, extensive' flow for low management scenario and 'forest, intensive' flow for medium and high management scenario are adapted to the scenarios in the case study (Table 13).

Table 13: CF on HANPP for the case study sites derived from the new characterization factor map and the country average currently implemented in LANCA®.

Country	management	HANPP CF (g C/m²/yr)	Biotic Production (g C/m²)
Netherlands all species 2010-2030	all	934	650
	low	855	700
	medium	916	650
	high	1517	650
Netherlands Douglas fir 80 year rotation	medium	570	650
Sweden all species 2010-2030	all	585	650
	low	635	700
	medium	612	650
	high	614	650

Many studies on HANPP have developed only at the global level or with a high uncertain (Imhoff et al. 2004; Núñez et al. 2013). The CF values of the chosen scenarios have been derived by EFISCEN Space from Wageningen University. This allows to have more agreed and accurate data and model. Table 13 presents the improvement of data quality in geolocation and land use flow (information for land use intensity, level 3) compared to biotic production. Furthermore, HANPP could be applicable for foreground calculation as well while biotic production can be applied only for the background calculation.

6.3.3 SOC (foreground vs background)

Since the EFISCEN Yasso model is not able to run SOC content under potential natural vegetation the calculation of CFs in a foreground system cannot be demonstrated here. The SOC content under PNV would be essential to calculate the quality differences between the natural state and the SOC content for the different forest management regimes and to derive the characterization factors (see Table 14).

Table 14: SOC values based on the EFISCEN Space model

Country	Management	SOC (Mg C/ha)	SOC under PNV (Mg C/ha)	SOC CFs foreground (Mg C/ha)
Netherlands all species 2010-2030	all	211	N/A	N/A
	low	204	N/A	N/A
	medium	214	N/A	N/A
	high	277	N/A	N/A
Netherlands Douglas fir 80 year rotation	medium	144	N/A	N/A
Sweden all species 2010-2030	all	174	N/A	N/A
	low	194	N/A	N/A
	medium	177	N/A	N/A
	high	178	N/A	N/A

As has been stated by the IPCC (Calvo Buendia E. et al. 2019), soil C stocks are assumed equal to the reference values for managed as well as unmanaged forest lands for all climate zones. This assumption results in a SOC stock change factor of 1 for all land use flow. Therefore, as described in the previous chapter, the characterisation factor for all forest related land use flows is equal to 0 for the background database, since no change in SOC content is assumed between natural vegetation and managed forests, regardless of the management intensity and the country (see Table 15).

Table 15: SOC CF values based on Calvo Buendia E. et al. (2019) and De Laurentiis et al. (in preparation)

Country	Management	SOC CF background (Mg C/ha) based on (De Laurentiis et al. in preparation)
Netherlands all species 2010-2030	all	0.00
	low	0.00
	medium	0.00
	high	0.00
Netherlands Douglas fir 80 year rotation	medium	0.00
Sweden all species 2010-2030	all	0.00
	low	0.00
	medium	0.00
	high	0.00

7 Discussion

The findings from the state of research and practice investigation and the thereupon proposed recommendations have been exemplified in section 5 and 6. While some recommendations offer straightforward application potentials, others require significant developments on underlying data and the applied methods and tools. In the following, the three levels of inventory modelling, existing impact assessment and improved characterization factors are discussed focusing on robustness, applicability and ease of implementation.

7.1 Inventory

On inventory level, the main input data was provided by the forestry model EFISCEN space. For the inventory modelling the consideration of simulation based input data has proven to be robust and to provide data of high specificity. Depending on the availability of a forestry model such as EFISCEN space, this allows to better consider the actual forest status compared to the current state of practice to use average production volumes for modelling. Generally, the framework of Cardellini et al. (2018) and Klein et al. (2015) proved to be applicable and robust to identify relevant processes as well as cut offs and specify temporal and spatial boundary conditions. The simulated productivity (extracted wood) has shown to be the most dominant input parameter, which also varied significantly between management practices, countries and modelling approaches. For comparable results, the modelling approach as well as the underlying data and simulation models should be consistent and transparent, as different assumptions could overlay the differences between the compared systems. While the annual simulation approach better represents the current situation in forests, as age distribution and growth as well as harvest patterns are considered, the full rotation simulation allows to allocate both impacts and function (harvested wood) of a full rotation period over time and thus create assessment models independent to the forest status.

For land use flow nomenclature two options have been discussed. While the first option aims to make use of forestry specific classification systems to specify adequate forestry land use flows, the latter one proposes to add properties to basic land use flows to flexibly consider varying levels of geo-information, intensity and management practices. The first option provides an improvement within the Koellner framework (Koellner et al. 2013b) and the recent modelling regime and allows to differentiate between typical management intensities and silvicultural systems based on the frameworks of Nabuurs et al. (2019) and Cardellini et al. (2018). The underlying assumptions have been identified to be compatible with the LANCA® background data, and could be addressed with specific characterization factors. The flow property approach would facilitate the consideration of plot level characterization and therefore a consistent system boundary between inventory and impact assessment level. This would allow to take the high spatial heterogeneity of land systems into account and has been exemplarily applied in the case study for the full rotation scenario. However, as the main LCA database and software providers do not support this approach yet, this option is not directly applicable.

The choice of the *transformation to* approach has shown to be relevant especially under the assumption of land use change. To apply the SQI and to allow for a single point creation for land use, transformation has to be specified as reversible, and the according land use types should be chosen as for t1/t2 (Figure 1) to allow comparability and to ensure compatibility with the SQI. As the flow nomenclature does not provide information on the point in time (t1, t2 or t3), a distinct specification of the chosen transformation type in addition to the flows themselves is required. This should be represented in the flow name (e.g. "to grassland, reversible"). Regeneration times are not necessary for inventory modelling, as the SQI includes the regeneration time directly in the CF.

7.2 Impact Assessment

For the impact assessment of land use the only information available is the flow name and its quantity. Thus, for comprehensive characterization it is necessary to also differentiate the flows in an adequate level of detail. This requires to identify the potential levels of detail that can be expected in land use modelling in LCA. For the case study, three levels have been investigated: country average, management intensity average and plot specific. All three have been exemplarily provided with specific characterization factors using the same spatial boundaries than for the inventory. As land use impacts are mainly of local nature, the consideration of these levels are suggested to characterize the impacts of land using activities. However, as this does not align with current database and software solutions, such an approach should be tested comprehensively and introduced in a robust and harmonized approach.

The GIS-based analysis and new weighting of characterization factors for mechanical filtration and physicochemical filtration shows more refined and reliable results when using foreground data compared to using a general average value for the characterization factor per country (background data). This is particularly true for the Netherlands in the case study, where the impact on mechanical filtration is much higher when using the GIS-based foreground data than when using the average data currently used in the LANCA® database. This can be mainly attributed to the fact that the previous approach of aggregating the characterization factors takes into account all land area in a country, even if in some areas a particular land use type does not take place at all. This can be demonstrated by the results of the case study, where we also see a larger deviation of the values in the Netherlands than in Sweden, since in the common averaging approach in the Netherlands a lot of areas are included that do not represent forest at all. According to Global forest watch, the Netherlands has only 19% forest area, while in Sweden almost 70% of the land is covered by forest (Global Forest Watch 2021). Furthermore, when using land use maps for weighting the characterization factors for the background database, it is also essential to take into account the accuracy of the land use models, as there are still considerable gaps in the locations and management types of the various forests at the global level, especially for forests under management (Schulze et al. 2019).

The impacts depicted by the LANCA® model represent the soil properties, the locations and the management types as expected. The complexity of the results with five indicators for occupation and transformation makes the result communication to a broader audience challenging. This issue is tackled by the SQI, which allows to aggregate all LANCA® categories to one number, but does build upon a statistical evaluation for normalization. For the two investigated countries the dropping of the indicator physicochemical filtration (PCF) due to redundancy could not be validated, and therefore the consideration of PCF in the SQI is recommended. The environmental impact categories mechanical filtration and physicochemical filtration run in opposite directions due to the calculation rules. If the result for a given site is high for mechanical filtration, it is low for physicochemical filtration, and vice versa. For this reason, it is always necessary to evaluate all impact categories must always be evaluated and not just one singled out.

While this allows to highlight the relative relevance of the indicators, it does not reflect the relevance of the considered soil functions for the respective land system. For forestry this leads to a focus on occupation – biotic production loss potential. The biotic production loss potential model in LANCA® is not yet regionalized, which is identified as significant update especially for the assessment of forestry systems. Therefore, the biotic production model shall be updated using a GIS based approach. In this report, the HANPP has been evaluated and tested as potential candidate for biotic production.

7.3 Characterisation factor improvement

For the existing LANCA® characterization factors, the suggestions on averaging by Maier et al. (2019) and on regionalisation Bos et al. (2020) for LANCA® are identified as key improvements and will be implemented in the next CF version. Furthermore, the sealing factor approach presented in this work will be included.

Although the use of the SOC indicator in LCAs has been recommended by the Life Cycle Initiative as a mid-point indicator to measure the impact of land use on soil, there are still significant research gaps related to SOC. These are particularly evident in the insufficient data available on the application of this indicator in the forestry sector. Even though De Laurentiis et al. (in preparation) have demonstrated that one can provide a global background database for SOC in LCAs for most EF flows, forestry flows in particular are not adequately covered by the database.

These data gaps relate, among other things, to the existence of SOC maps related to management types as made available by e.g. the EFISCEN Space model for the Netherlands. However, in the absence of data on SOC values under PNV, characterization factors cannot be provided despite the better data available through EFISCEN Space. The IPCC values for change in SOC due to forest management are also inadequate, as this assumes no change compared to natural forests for all forest regimes. Therefore, more research is needed in this area before SOC should be used as an indicator of soil quality for all land use flows in LCA.

Regarding the EFISCEN Space model and management intensity map, the estimation of management intensity in the EFISCEN Space was done merely to demonstrate that it is possible to characterize the different management classes in more detail. Furthermore, this was done to demonstrate the effect of such an assumption on the outcomes. When this approach would be applied "for real", what classes to use (from the management map or otherwise) needs to be discussed with experts and stakeholders, as well as how to characterize these classes in terms of management, harvest systems, etc. Work is underway to validate the outcomes of the time/cost module and the soil carbon module, but we judge the values generally to be in a realistic range. With the estimation of management intensity map from Nabuurs et al. (2019), this can be applied, if needed, extracted regimes to neighbouring countries with similar forest conditions. In this way we have a standardized approach across Europe, independent of national classifications of management. The management patterns per intensity class as extracted from the NFI data do indicate some correlation with the management intensity, i.e. higher harvest probabilities in high intensity management classes. However, the map can certainly be improved in the future by updating the underlying rules and integrating more information layers. It was used in this study to demonstrate a feasible and unified approach for Europe.

In the case study about HANPP in the previous chapter, it shows improvements on HANPP CF which are calculated with grid-specific data. However, there are limited numbers of studies done on gaps in resource-related LCIA methods related to NPPs in the forestry sector. Therefore, it is difficult to compare directly from the other literature. For instance, due to missing data in the database that needs to apply in a method (Alvarenga et al. 2015; Núñez et al. 2013), or more studies focus on the agricultural sectors, excluding forest (Alvarenga et al. 2015; Imhoff et al. 2004). Furthermore, HANPP needs further investigations as many factors affect NPP losses. For example, due to the soil erosion relationship, using HANPP as a single indicator is highly uncertain.

Additionally, further questions would need to be addressed to use it in the scope of this work. For instance, the NPP of potential natural vegetation is used, but what to do with the effects of climate change that may alter conditions and would change the PNV type. Another question that would need to be addressed is whether NPP would be the best metric to use (which is the case in HANPP) or whether for instance Net Ecosystem Productivity would be a better measure, as this would also consider net carbon sequestration (climate mitigation) aspects. Systems with high NPP do not necessarily store large amounts of carbon in the system.

8 Guidance for practitioners and decision makers

8.1 Database development (background LCA)

The results of the case study have shown the importance of the foreground system when evaluating forest products. However, in the further processing steps of wood into e.g. furniture, wood-based materials, wooden toys etc., the influence of background processes such as energy processes is becoming more and more significant. In order to guarantee consistent and comparable results, database developers need rules and guidelines on how to address the impacts on land use to ensure that the background data on forestry products is comparable. Database providers shall rely and explicitly refer to a land use modelling framework that unambiguously specifies land use inventory modelling (see chapter 2 and 4). While the general rules have been specified in the UNEP/SETAC Land Use framework by Koellner et al. (2013b), specific rules for the main land using activities (mainly agriculture, forestry and mining) should be developed in cooperation with experts and stakeholders. For forestry, the modelling principles of Klein et al. (2015) and Cardellini et al. (2018) provide further forestry specific requirements that should be considered.

Addressing occupation effects seems to be consensus in the LCA community: This is the delta of a reference situation to the actual land use. A prerequisite for consistency and comparability is the agreed definition of the reference situation.

The case of transformation, on the other hand, is different: In principle, a distinction is made between reversible and permanent transformation. However, both types of transformation require a different choice of inventory flows. Here a clear and unmistakable modelling framework is missing in order to guarantee comparable and unambiguous results of the applied elementary flows and system boundaries. Giving full transparency and a whole picture of land use impacts reversible and permanent transformation should be modelled.

The modelling framework also shall provide explicit guidance on the functional unit, which could either be an area, a mass or a volume. The functional unit definition should also comprise information on product properties such as the water content and density. Furthermore, the sector specific modelling principles and the assumptions for the chosen input data (which might be based on simulations, production statistics or upscaling of representative systems) shall be made explicit and should be specified to allow for comparable results. This should go in line with the calculation approach of the characterization factors, where also averaging takes place and input data includes similar assumptions and stems from similar models. The chosen approach should be focusing on reliability as well as comparability to ensure representative average data for the background system for a specific land use type.

8.2 Application (foreground LCA)

For LCA practitioners modelling forestry systems the same ambiguities as for background database developers apply. While the Koellner framework (Koellner et al. 2013b) is accepted as basis by most practitioners, some ambiguities still exist. The abovementioned framework for background LCA should therefore also be applicable to foreground modelling.

For occupation and transformation flow choice, the management classification provided in Table 5: should be used. While the flow nomenclature of Koellner et al. (2013a) still is in place the table provides a mapping with the improved nomenclature system. As soon as a flow property system is available and applicable, the use of foreground specific characterization factors is recommended.

The suggestions of Klein et al. (2015) and Cardellini et al. (2018) should be followed for foreground LCA considering the goal and scope specification as well as the inventory structure and system boundaries. In addition to the recommendations provided above, the specific assumptions and the types of input data shall be stated. If applicable in the flow nomenclature, this should include regionalisation level (shall: country, should: specific plot) as well as management intensity and temporal assumptions (full rotation simulations, yield statistics or yield simulations).

8.3 Result interpretation

The SQI currently implemented in software and database systems is very difficult to interpret for the user: the indicator is dimensionless, the bandwidth is not directly communicated, and thus the user does not know how to interpret the result. The provision of an interpretation guideline would be helpful for the user. Furthermore, an integration of the normalization factors into the software systems would give the possibility to conduct a contribution analysis in which the user can determine which of the single indicators contributes the most to the overall result and can further detect the respective origin process where the highest impacts come from.

The extent of the impact of a specific land use activity depends strongly on the country/region/site specific pedoclimatic conditions. Therefore the contribution of a certain soil indicator like erosion resistance or groundwater regeneration to the overall SQI should depend on the site specific prevailing pedoclimatic conditions. At the moment this aspect is not addressed in the calculation of the SQI because all integrated soil quality indicators are weighted with 1. Using a country/region/site specific and land use type specific normalization and weighting could better display the influences of a certain soil indicator to the overall SQI. Therefore, the individual soil quality indicators contributing to the overall SQI should be normalized and weighted depending on the land use type and the country/region/site, creating a set of regionalized normalization factors to be applied to the available elementary flows.

8.4 Policy integration

Given the findings of this report, the current data is not fully prepared for policy integration due to inconsistent data and ambiguities in the framework. The recommendations provided in this report aim to facilitate robust policy integration and decision support through reducing ambiguities.

The LANCA® method on how to calculate and evaluate land use impacts within Life Cycle Assessment is the mandatory method within the PEF/OEF framework. Characterization factors are provided for different countries and land use types which have been normalized and aggregated in the SQI that was developed to improve the applicability of the evaluation of land use impacts in LCA.

However, the application of the integration and evaluation of land use impacts within LCA studies needs to be improved in order to obtain consistent and comparable results of the land use impacts of different studies. A guideline shall be provided on how to conduct LCA studies on forestry systems including:

1. How to collect and integrate the inventory data and
2. How to interpret the results.

The software and database developers must also be considered in this guideline that defines and specifies the integration of inventory data for background systems, e.g. regarding the choice of the reference system, regeneration times and regarding the integration of permanent and/or reversible transformation.

This is explicitly important for forests and cultivation areas as these land use types are most often responsible for large areas of land use. Therefore products from renewable resources as wood or other biomass often tend to have a large land use impact with associated large spreads in the results. It is therefore very important to improve the reliability and robustness of the applied method as well as its consistent and comparable application.

The SQI needs to be revised taking into consideration all five LANCA® indicators as well as the improvements regarding the individual soil quality indicators highlighted in this report. Besides, a weighting depending on the specific land use type and the respective country/region/site should be applied for the different individual soil quality indicators contributing to the SQI.

Glossary

Areas Of Protection (AoP)	Four areas of protection (valuable in themselves or to humans) were identified by Udo de Haes et al. (1999): Human health, man-made environment, natural environment, and natural resources. Natural resources as a protection area reflect the concern of availability to future generations. Natural resources may be any part of the natural environment, but the protection area is only affected if availability to future generations is affected, i.e. Through irreversible depletion. In contrast, natural environment as a protection area is defined in terms of its current value (to humans or in itself), and may be affected both by reversible and irreversible depletion (Guinée et al., 2002).
Background	Refers to those processes or system in the product life cycle for which no direct access to information is possible. For example, most of the upstream life-cycle processes and generally all processes further down steam will be considered part of the background processes.
Average Data	Refers to a production-weighted average of specific data
Biotic Production Potential	The ability of an area to produce biomass
Cause-Effect Chain	Impact pathway as an environmental mechanism including system of physical, chemical and biological processes for a given impact category, linking the life cycle inventory analysis result to the common unit of the category indicator (ISO 14040) by means of a characterisation model (Sala et al. 2012).
Characterisation	Calculation of the magnitude of the contribution of each classified input/output to their respective EF impact categories, and aggregation of contributions within each category. This requires a linear multiplication of the inventory data with characterisation factors for each substance and EF impact category of concern. For example, with respect to the EF impact category "Climate change", CO2 is chosen as the reference substance and kg CO2-equivalents as the reference unit.
Characterisation Factor (CF)	Factor derived from a characterisation model which is applied to convert an assigned Resource Use and Emissions Profile result to the common unit of the EF impact category indicator (based on ISO 14040:2006).
Classification	Assigning the material/energy inputs and outputs tabulated in the Resource and Emissions Profile to EF impact categories according to substance's potential to contribute to each of the EF impact categories considered.

Ecological Zones	FAO developed so called FRA 2000 provided a mandate to incorporate biodiversity indicators into the assessment and as a response FAO developed the first Global Ecological Zones (GEZ) classification and maps to enable the presentation of some of the FAO forest statistics to be shown by a set of classes that have some ecological meaning and more generally understood as broad forest types (e.g. Tropical rain forests, boreal forests etc.).
Ecosystem Services	The benefits people obtain from ecosystems. These include such as food and water provisions, flood and disease control, cultural services like recreational benefits, and nutrient cycling.
Endpoint impact	Impact category, also known as the damage-oriented approach, translates environmental impacts into issues of concern such as human health, natural environment, and natural resources.
Environmental Footprint (Ef)	Framework aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product (based on ISO 14044:2006). The EF impact assessment methods provide impact characterisation factors for elementary flows to aggregate the impact to a limited number of midpoint and/or damage indicators.
Erosion Resistance	The ability of a soil to prevent erosion beyond the natural erosion rate.
Foreground system	Refers to those processes or system in the product life cycle for which direct access to information is available. These processes are called foreground processes (Clift et al. 1998)
Goal And Scope	Specifying the objectives, contents, and pertinent choices of the LCA study (Schenck et al. 2014)
Groundwater Recharge Capacity	The ability of a soil to contribute to groundwater recharge.
Human Appropriation Of Net Primary Productivity (HANPP)	A metric developed to quantify how land use alters energy flows in ecosystems via land conversions and biomass harvest that the human impact on the environment (Haberl et al. 2007)
Land Occupation	EF impact category related to use (occupation) of land area by activities such as agriculture, roads, housing, mining, etc. Land occupation considers the effects of the land use, the amount of area involved and the duration of its occupation (changes in quality multiplied by area and duration). The current type of land use of an area per functional unit within a certain duration that affects the quality of the soil

Land Transformation	EF impact category related to conversion (transformation) of land area by activities such as agriculture, roads, housing, mining, etc. Land transformation considers the extent of changes in land properties and the area affected (changes in quality multiplied by the area). The change in the quality between two specific types of land use
Impact Category	Class of resource use of environmental impact to which the Resource Use and Emissions Profile data are related.
Inventory	The collection of the input and output data
Life Cycle Assessment (LCA)	Compilation and evaluation of the inputs, outputs, and the potential environmental impacts of a product system throughout its life cycle (ISO 2016)
Mechanical Filtering Capacity Of Groundwater	The ability of a soil to filter a suspension by mechanically binding pollutants to soil particles
Midpoint impact	Measured in specific impact category units, or problem-oriented approach, translates impacts into environmental themes such as climate change, acidification, human toxicity, etc.
Net Primary Productivity (NPP)	An indicator of the biomass produced by green plants in an ecosystem in a defined period of time, usually 1 year, usually represented by amount of dry matter (DM) or carbon (C) per unit of land occupation (Alvarenga et al. 2015).
Normalisation	Results are multiplied by normalisation factors that represent the overall inventory of a reference unit (e.g. A whole country or an average citizen). Normalised impact assessment results express the relative shares of the impacts of the analysed system in terms of the total contributions to each impact category per reference unit. When displaying the normalised impact assessment results of the different impact topics next to each other, it becomes evident which impact categories are affected most and least by the analysed system. Normalised impact assessment results reflect only the contribution of the analysed system to the total impact potential, not the severity/relevance of the respective total impact. Normalised results are dimensionless, but not additive.
Permanent Transformation	The quality of land between different types of land use
Physicochemical Filtration Capacity Of Groundwater	The ability of a soil to absorb dissolved substances from the soil solution and thus prevent them from entering the groundwater
Potential Natural Vegetation (PNV)	The vegetation that could be expected to occur in areas where there are no human activities (Chiarucci et al. 2010).

Reference Situation	A baseline as a starting point against to the quality of the land under a particular type of land use is currently measured so called reference state as well. Several definition for the reference situations in LCA are available by Koellner et al. (2013)
Regeneration Time	The impacts of occupying the land during the time it takes to return it to the quality under the prior land use, with the time taken referred (Koellner, De Baan et al. 2013)
Reversible Transformation	The quality of abandoned land during its regeneration
Goal And Scope	The product or service to be assessed is defined, a functional basis for comparison is chosen and the required level of detail is defined.
Soil Organic Carbon	An indicator of soil quality. SOC is used as a way to approach the productive capacity of the soil, which in turn affects the AoP 'natural resources' and 'natural environment'. Unlike the previous version of the land use framework (Milà i Canals et al., 2007)
Soil Sealing	The covering of the soil surface with impervious materials as a result of urban development and infrastructure construction. The term is also used to describe a change in the nature of the soil leading to impermeability including compaction by agricultural machinery. In LANCA®, soil sealing indicates artificial materials that covers the surface.
Weighting	Weighting is an additional, but not mandatory, step that may support the interpretation and communication of the results of the analysis. EF results are multiplied by a set of weighting factors, which reflect the perceived relative importance of the impact categories considered. Weighted EF results can be directly compared across impact categories, and also summed across impact categories to obtain a single value overall impact indicator. Weighting requires making value judgements as to the respective importance of the EF impact categories considered. These judgements may be based on expert opinion, social science methods, cultural/political viewpoints, or economic considerations

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Land using practices are at the core of many human activities with an impact on the environment. Its consideration in methods such as Life Cycle Assessment (LCA) is complex and oftentimes requires experts to perform studies and understand results.

This report focuses on land use impact assessment methods in LCA studies applied to forestry. It presents an in-depth investigation of the state of the art in forestry modelling and LCA, considering the EFISCEN space forest model, the UNEP/SETAC land use framework, the European Commissions' Environmental footprint, and the Fraunhofer LANCA® framework. Building on these, recommendations are provided for the modelling framework, the improvement of existing and the introduction of new indicators. Improvements for LANCA® are presented and Soil Organic Carbon (SOC) as well as Human Appropriated Net Primary Production (HANPP) are introduced as new in-dicators. The improved framework is applied to an exemplary case study using different modelling approaches based on EFISCEN space. The indings are inally condensed in a recommendation section for developers, practitioners, stakeholders, and policymakers.

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