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EFO-LCI: A New Life Cycle Inventory Database of Forestry Operations in Europe

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Abstract

Life cycle assessment (LCA) has become a common methodology to analyze environmental impacts of forestry systems. Although LCA has been widely applied to forestry since the 90s, the LCAs are still often based on generic Life Cycle Inventory (LCI). With the purpose of improving LCA practices in the forestry sector, we developed a European Life Cycle Inventory of Forestry Operations (EFO-LCI) and analyzed the available information to check if within the European forestry sector national differences really exist. We classified the European forests on the basis of "Forest Units" (combinations of tree species and silvicultural practices). For each Forest Unit, we constructed the LCI of their forest management practices on the basis of a questionnaire filled out by national silvicultural experts. We analyzed the data reported to evaluate how they vary over Europe and how they affect LCA results and made freely available the inventory data collected for future use. The study shows important variability in rotation length, type of regeneration, amount and assortments of wood products harvested, and machinery used due to the differences in management practices. The existing variability on these activities sensibly affect LCA results of forestry practices and raw wood production. Although it is practically unfeasible to collect site-specific data for all the LCAs involving forest-based products, the use of less generic LCI data of forestry practice is

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desirable to improve the reliability of the studies. With the release of EFO-LCI we made a step toward the construction of regionalized LCI for the European forestry sector.

Keywords Forest Unit · Life cycle assessment · Silviculture · Forest management · Wood

Introduction

About 44% of European land area (including the Russian Federation) is covered by forests and other wooded land, representing approximately 25% of our global forest resources (Forest Europe and UNECE and FAO 2015; Keenan et al. 2015). Forest ecosystems contribute greatly to the provision of several marketed and non-marketed goods and services like construction wood, fuel wood, recreation, fresh water supply, soil protection, and climate regulation. Within the context of this last ecosystem service, forests play an important environmental role as they are estimated to annually remove 719 million tons of CO_2 from the atmosphere, about one-tenth of the European greenhouse gas emissions (Forest Europe and UNECE and FAO 2015). Among the many functions provided, forests produce wood, the main renewable resource used to produce both wood products and energy. With its annual production of 429 million m^3, EU-28 is the largest manufacturer of roundwood within the G20 (Eurostat 2014). Furthermore, wood and other solid biomass are the largest contributors to the mix of European renewable energy sources (Eurostat 2014). According to Eurostat statistics, half of Europe's renewable energy came from wood and wood waste in 2010 (Eurostat 2015). The importance of forest bioenergy in Europe is very likely to increase in the near future due to the momentum created by the European climate and energy policies (EU 2009). The consequent expected increase in demand of wood-based products poses serious concerns about the ecological and environmental consequences of this intensified biomass extraction and use (Schulze et al. 2012). The correct quantification of the eco-environmental impacts from forestry practices is thus crucial to keep management sustainable. While the concept of sustainability gained general acceptance only after the publication of the Brundtland report (WCDE 1987), the principle was already well established and operationally implemented in the forestry sector long before (Wiersum 1995). Life cycle assessment (LCA) is one of the main techniques used to assess environmental sustainability, which consists of three main phases: (i) goal and scope definition, (ii) inventory analysis, and (iii) impact assessment. In the goal and scope the functional unit is defined, i.e., the function fulfilled by the studied system, which provides a reference against which inputs and outputs are related. In this step also system boundaries and the allocation method are defined. The inventory analysis is the phase involving the compilation and the quantification of inputs and outputs between the nature and the system studied (elementary flows) throughout its life cycle. The Life Cycle Inventory (LCI) model for the studied system is built in this phase and typically consists of two components: the foreground model, which is the modeled part whose production can be affected from the commissioner and for which primary data are typically used, and the background model, in which data normally come from generic LCI databases. In the impact assessment the elementary flows are translated into their potential environmental impacts. This is obtained by multiplying the amount of each elementary flow with their characterization factors for the impact categories chosen. The overall environmental load of the system is then obtained summing up the indicator scores calculated for all the flows.

The first LCAs of the European forestry and timber industry already appeared during the early 1990s (EFI 1995; Frühwald and Wegener 1993). Despite this early development of life cycle thinking in the sector, a harmonized, consistent, and accepted methodology has yet to be found (Klein et al. 2015).

Main Methodological Issues in Forestry LCA

Due to the relative complexity of the forestry–wood–paper sector (Sandin et al. 2016; Schweinle 2007), many challenges are posed to the correct implementation of LCA analysis in this context (Bosner et al. 2012; Sandin et al. 2016), namely:

- the long time frame of wood production and use compared to other products studied;
- the spatial variability of forest stands and the site specificity of growth and management;
- the broad variety of joint products arising from forest production and the variety in their usage pathways, e.g., the production of goods coming from thinning activities (roundwood, sawnwood, pulp, chips, etc.);
- the multifunctional nature of forests that leads to the production of an array of services and functions other than timber (e.g., water, non-wood forest products, recreation, carbon sequestration);
- the difficulties in accounting and estimating the effects on growth and biogenic fluxes of natural disturbances and climate change;
- the uncertainty of the end-of-life accounting of long-lived products due to the unpredictable future technological changes.

It has already been shown that the absence of a commonly agreed upon methodological approach, together with the lack of a standardized definition of both the functional unit and the system boundaries, makes the different forest-wood-based LCA studies hardly comparable (Klein et al. 2015; Sathre and O'Connor 2008). Recently, the scientific discussion on the forest LCA methodology has been reinvigorated since the proper accounting of biogenic carbon gained a lot of attention due to the so-called carbon neutrality issue (Johnson 2009; Schulze et al. 2012; Zanchi et al. 2011). The alleged carbon neutrality of forests, namely, the assumption that all removed biomass coming from sustainably managed forests will be entirely sequestered in the future, and hence can be neglected in LCA, has been questioned and disproved (Cherubini et al. 2011; Johnson 2009; Schulze et al. 2012; Wiloso et al. 2016; Zanchi et al. 2011). This change in the traditional paradigm called for a more robust and consistent accounting of biogenic carbon which affects the definition of system boundaries, GHGs to include in the analysis, baselines identification, and the spatio-temporal pattern of CO_2 fluxes. The methodological difficulties briefly presented so far have been extensively discussed in the literature, with several solutions already proposed (Bright et al. 2012; De Rosa et al. 2016; Downie et al. 2014; Helin et al. 2013; Jungmeier et al. 2002ab; Klein et al. 2015; Sandin et al. 2016; Werner et al. 2006). Despite the ongoing research on the methodological issues, it is crucial for any representative LCA of a forest-based production system to carefully consider what happens in the forest by means of a proper identification and description of its characteristics and management. In this work we addressed this need by developing a regionalized LCI of the forest management practices in the European region.

Main Inventory Issues in Forestry LCA

As acknowledged by Werner et al. (2007), the LCI of wood is strongly affected by tree species and forest management. But a detailed description of forestry systems and the inventory of the related material and substance flows is often not easy, as forests are very diverse in terms of species composition, management regime, site productivity, machinery used, and socio-economic conditions (Barbati et al. 2006). Seventy-eight European Forest Types are identified and classified in Europe according to structural, compositional, and functional key factors (Barbati et al. 2014). If one also considers the different harvesting systems within forest types, one gets an even more complex myriad of different forest production systems. González-García et al. (2014) compared the life cycle impact of forest operations in Europe and showed a large variation in terms of biomass productivity and associated environmental impact, even if only seven stands were studied. Despite the described complexity, LCA practitioners commonly base their analysis on Life Cycle Assessment software and their integrated LCI databases (Graedel and Allenby 2010). Also the LCAs of wood-based products typically relies on the generic forest LCI models included in databases like Ecoinvent (Wernet et al. 2016) and GaBi (PE International 2016). Forest LCI models included in the standard LCA software packages are based on a limited number of studies in which only a few forest types and management practices are considered, typically temperate plantations or natural forests in optimal conditions and intensively managed (Newell and Vos 2012). Although these databases represent an important source of information, they are not always able to correctly represent the conditions existing in other European forests (Lewandowska et al. 2008). This lack of sufficiently specific data is mirrored in Ecoinvent, which offers LCI data on hardwood and softwood production for nine systems in total, comprising six species (beech, birch, oak, pine, spruce, and mixed) and only three countries (Germany, Sweden, and Switzerland) for the European region (Wernet et al. 2016). Also GaBi refers to a model developed for forest plantation of central Europe in the wood products models documentation (Frühwald et al. 1997). All these limitations can lead to differences between existing LCI databases and the reality, if these data are not suitable for the local conditions studied (Lewandowska et al. 2008). Much progress has been made to overcome the methodological limitations of LCA when applied to forestry sector (Bright et al. 2012; De Rosa et al. 2016; Downie et al. 2014; Helin et al. 2013; Jungmeier et al. 2002a, b; Klein et al. 2015; Sandin et al. 2016; Werner et al. 2006). The same cannot be said for data quality and availability, for which considerable efforts are still needed (Lippke et al. 2011). With this work we want to contribute to this end and, as such, to a better and more accurate profiling of the LCI of forest operations. We accomplished this through a large survey about the forest management practices in Europe. In this paper, the main findings of this data collection will be presented and the main differences in sivicultural practices found in the European forests will be highlighted to demonstrate the importance of more regional-specific modeling of the management regimes in LCA. The need for better inventories of the sector will not only be claimed by presenting and discussing the results of the survey and their impact on LCA, but has also been operationalized by disclosing and making all the data freely available and usable under Creative Commons Attribution-NonCommercial-ShareAlike (CC BY-NC-SA) license (Creative Commons 2016). With this disclosure, we want to contribute to a more accurate life cycle study of the European forest production systems, and also further stimulate a major level of transparency and reproducibility in LCA studies, for which the importance has been already stressed in several previously published studies (Finnveden et al. 2009; Frischknecht 2004; Pauliuk et al. 2015).

Methods

System Boundaries

The geographical boundary of this analysis consists of 28 countries within the European subcontinent, as shown in Fig. 1, subdivided into the five main eco-regions defined in the State of Europe's Forest report (Forest Europe and UNECE and FAO 2015). The process-based system boundary of the study is from cradle-to-forest road and includes the four mandatory systems (i.e., from PG 1 to PG 4) as defined by Klein et al. (2015). The data collected thus characterize all the activities carried out from site preparation to harvested wood delivery at forest road including all relevant primary (namely, Site preparation: PG 2; Site tending: PG 3; Silvicultural operations: PG 4; and Secondary processes: PG 1) of the entire forest production chain. The "whole rotation approach" (Klein et al. 2015) of the current management of European forests has been followed for the temporal system boundaries identification. Therefore, also from a temporal perspective, the entire forestry system is taken into account by considering the forest over the whole rotation period, and including all age classes and processes over the development of the stand. In this study rotation is defined as the time from regeneration to final exploitation for silvicultural systems 3 and 4, between consequent cuttings (i.e., the cutting cycle) for silvicultural systems 5, 6, and 7 and between consequent selection cuttings for silvicultural system 2 (see Table 1).

Forest Classification: Forest Units (FoUs)

To capture and describe all the possible forest types present in Europe, they had to be first qualitatively clustered and classified in a meaningful way to reduce the number of possible combinations without losing relevant information. We followed the classification adopted in the EU FP7 Project FORMIT (2016), where the forests have been classified on the basis of species composition and silvicultural systems, the two aspects that affect inventory results the most, as will also be shown in the following sections.

The silvicultural systems were combined considering regeneration methods, forest structure, and how the tree

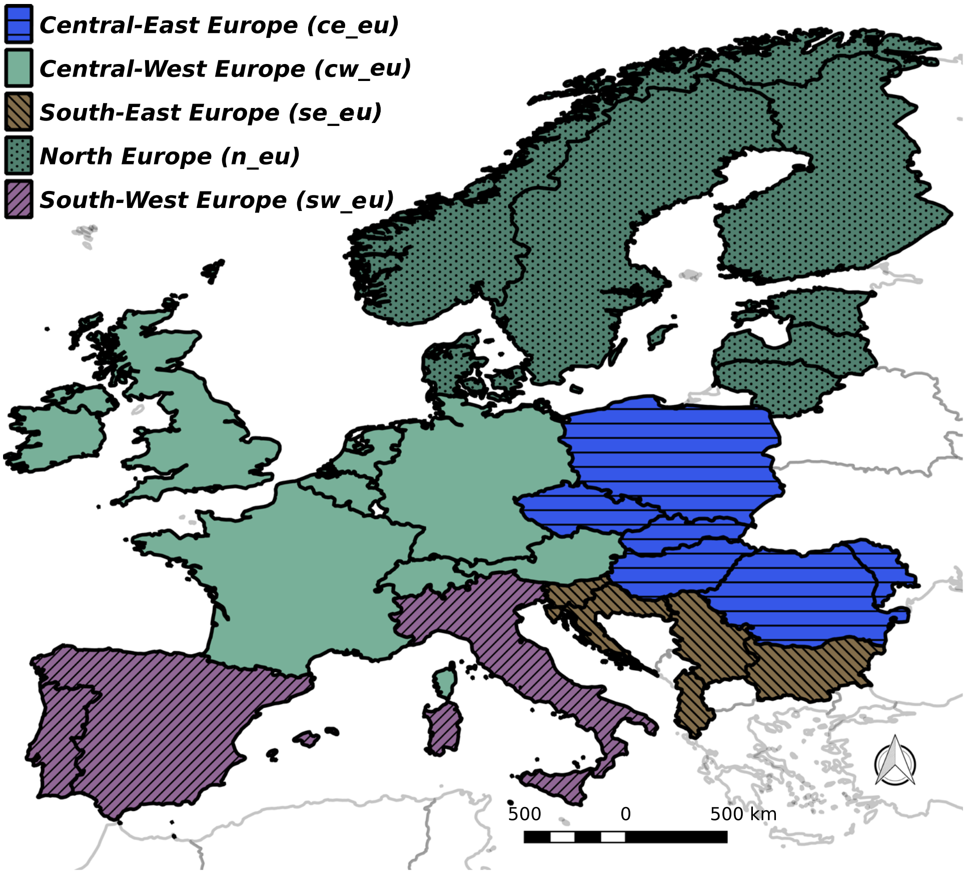

Fig. 1 Surveyed countries grouped by ecoregion

Table 1 Silvicultural systems

Code	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 • Thinnings • 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 • Thinnings • 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

Table 2 Tree species groups

Code	Species group	Species
A	Light-demanding conifers	*Pinus sylvestris, Larix spp., Pinus nigra, Pinus cembra, Pinus heldreichii, Pinus leucodermis, Pinus radiata, Pinus uncinata, Pinus mugo, Pinus contorta, Pinus strobus, Cedrus spp., Juniperus spp.*
B	Shade-tolerant conifers	*Picea abies, Abies spp., Pseudotsuga menziesii, Thuja spp., Taxus baccata, Tsuga spp., Chamaecyparis spp.*
C	Mediterranean conifers	*Pinus pinaster, Pinus halepensis, Pinus pinea, Pinus canariensis, Cupressus spp., Pinus brutia*
D	Fast-growing deciduous	*Betula spp., Populus spp., Alnus spp., Salix spp., Robinia pseudoacacia, Eucalyptus spp.*
E	Slow-growing light-demanding deciduous	*Quercus robur, Q. petraea, Q. cerris, Q. pubescens, Q. faginea, Q. frainetto, Q. macrolepis, Q. pyrenaica, Q. rubra, Q. trojana, Q. hartwissiana, Q. vulcanica, Q. macranthera, Q. libani, Q. brantii, Q. ithaburensis, Q. pontica, Fraxinus spp., Castanea sativa, Rosaceae (Malus, Pyrus, Prunus, Sorbus, Crataegus, etc.), Juglans spp., Cercis siliquastrum*
F	Slow-growing, shade-tolerant deciduous	*Fagus spp., Carpinus spp., Tilia spp., Ulmus spp., Buxus sempervirens, Acer spp. Ilex aquifolium*
G	Mediterranean evergreen trees	*Quercus suber, Quercus ilex, Q. coccifera, Q. lusitanica, Q. rotundifolia, Q. infectoria, Q. aucheri, Tamarix spp. Arbutus spp., Olea europea, Ceratonia siliqua, Erica spp. Laurus spp., Myrtus communis, Phillyrea spp. Pistacia spp. Rhamnus spp. (R. oleoides, R. alaternus), Ilex canariensis, Myrica faya*

canopy is removed (Table 1). Forest tree species have been grouped on the basis of their ecological characteristics and growing strategy, and all the species included in the ICP Forest tree species list (Seidling and Michel 2016) have been considered (Table 2). The combination of a species group and a silvicultural system results in what has been called a Forest Unit (henceforth FoU). Within these 49 FoUs (all possible combinations of species groups and silvicultural systems) it is possible to capture and describe the most typical, currently applied, forest management strategies in Europe. By further combining this information with the geographical location, it is possible to take into account also for their geographical diversity.

Data Collection

The data has been collected through a questionnaire developed in MS Access and consisting of three front end forms each of which linked to a back-end relational database (see Supplementary Material S2 for the link to download it). The questionnaire was organized into four main sections and consisted of a mix of closed-ended drop-down choice and open-ended text box questions. Details on the average silvicultural practices of the forest management were described as follows:

1. FoUs in the Country: A table where the major FoUs present in the country out of the 49 possible had to be indicated.

2. General description: A form where information on the general characteristics and management regime of each FoU were asked for:

(a) Composition (main and secondary species).
(b) Moisture content of green wood and wood density.
(c) Regeneration information of the system, including length of rotation period, type of regeneration, and, if plantation, type of seedlings and density of plantation.
(d) Distance traveled (one way) from forest for harvesting equipments and staff.
(e) Data source.

3. Interventions: A form where all the activities carried out in the FoUs with their relative timing were described in detail for:

(a) Type of intervention.
(b) Year of intervention.
(c) Species concerned by intervention.
(d) Equipment used (main and additional equipment, type, mass, total hours of use during the whole life, productivity, and consumption).
(e) Inputs (type and amount).
(f) Amount and assortment of harvested wood per hectare.

The questionnaire was submitted to all the 12 project partners of the (EU FP7 Project FORMIT 2016). They filled it out for their own country and submitted it to other national forestry experts of neighboring countries. The respondents name has been recorded together with the data source used. An introductory session to the survey was organized with all participants before the launch. A protocol containing all the practical information on how to proceed step-by-step accompanied all the questionnaires and, during the execution, a help desk was provided to clarify all the doubt arising during the completion of the survey. The respondents were asked, first, to point out the FoUs that they considered the most important in their countries and then to describe their current, most representative, average silvicultural management applied. The choice of FoUs was done on the basis of their extension as well as on their ecological and economic importance in the country. All the questionnaires were filled out between October 2014 and May 2015.

Results

FoUs Reported

For the 28 European countries surveyed, a total of 235 FoUs have been reported, with Central-West Europe as the region with the highest amount (95 FoUs). In total 62 FoUs unmanaged (i.e., silvicultural system 1) were reported, especially in Central-East and Central-West Europe (13 and 24 FoUs, respectively). In Central-East, West, and North European regions, even-aged forest management with shelterwood (13, 7, and 11 FoUs, respectively) and clear-cutting system (11, 18, and 16 FoUs), together with the continuous cover forest (2, 12, and 7 FoUs) are the silvicultural systems with the highest amount of FoUs described. Unmanaged and shelterwood FoUs are the ones described for the highest number of species groups (all the seven for both) while coppice with standards only for two. Overall, there is a rather even distribution of species groups reported between ecoregions, except for the North, where conifers are predominant (38 FoUs of species groups A and B vs. 10 of species groups D, E, and F), and the two southern regions with the geographical specificity of the two Mediterranean species groups (Fig. 2).

Data Available in the Database

All collected data were grouped in two tables, one containing the FoUs reported and their general description, and the other one with the detailed description of all their interventions (see “Data collection”). All collected data, their variable name in the spreadsheets, and units are

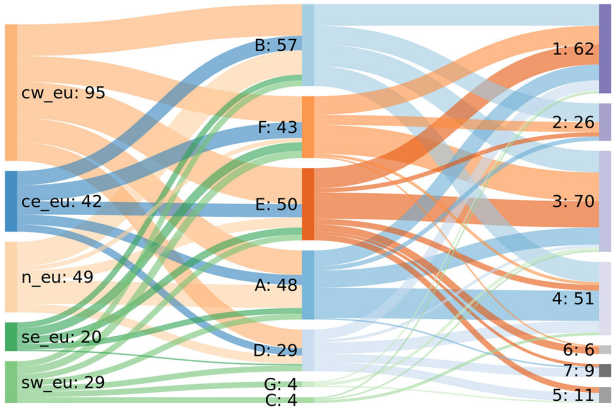

Fig. 2 Alluvial diagram with the distribution of Forest Units between ecoregions, species groups, and silvicultural systems (first, second, and third column, respectively). The width of the node represents the flow quantity (i.e., number of FoUs, also indicated), letters stand for species groups (Table 2), and numbers for silvicultural systems (Table 1), for ecoregion codes (see Fig. 1)

summarized in Tables 3 and 4 and the link to download them is reported in the Supplementary Material S3.

Data Quality

The data quality was assessed for each FoU following the pedigree matrix approach proposed by Weidema and Wesnaes (1996). While Weidema et al. (2013) was followed for the definition of the indicator scores, the methodology based on the Data Quality Distance (DQD) approach proposed by Lewandowska et al. (2004) was used to assign the overall Quality Class (QC) to each FoU. The lower the DQD, i.e., the differences between the quality requirements (Data Quality Goals) and the actual quality of the inventoried data, the higher the data quality of the indicator considered and consequently its Data Quality Indicator (DQI). The sum of the DQI of all the indicators (tDQI) determine the overall quality of each FoU. All the tDQI were grouped into five QC with decreasing quality from A to E (tDQI ranges: 0–0.5; 0.5–1; 1–1.5; 1.5–2; 2–2.5). In the analysis of the following sections only the results of the FoUs with a QC from A to B will be presented. This decision was taken to remove the bias introduced by the low data quality, in order to guarantee that the observed variability is, in fact, due to real differences in forest management. Of the 235 reported FoUs, the 133 that are actively managed (i.e., silvicultural systems 2–7) and that meet the aforementioned data quality requirements will be presented and discussed in the next sections.

Rotation Length

The average rotation length of the reported FoUs is 86–90 years and varies between 6 and 10 years for the FoU 7-D in Switzerland and Austria, and 196–200 years for the Belgian FoU 4-E (Fig. 3).

When FoUs are grouped per silvicultural system, the following average ranges in rotation lengths are observed: short rotation (16–20 years), coppice (26–30 years), coppice with standards (26–30 years), even-aged forest with shelterwood (86–90 years), and even-aged forest: uniform clearcutting system (116–120 years). A clear trend can also be found if the FoUs are grouped by species group, where the following average ranges in rotation lengths are observed: fast-growing deciduous (41–45 years), Mediterranean conifers (86–90 years), light-demanding conifers (91–95 years), shade-tolerant conifers (96–100 years), slow-growing, light-demanding deciduous (96–100 years), slow-growing, shade-tolerant deciduous (111–115 years), and Mediterranean evergreen trees (111–115 years).

Regeneration of the Stands

Data were collected on how FoUs are established and regenerated (see Fig. 4), as these variables can influence the life cycle impact of forest management (Michelsen et al. 2008). As expected, the type of regeneration is mainly driven by the management, but, remarkably, some differences between ecoregions and species groups are found. Excluding the short rotation, where artificial regeneration is always applied in all reported countries, it can be seen that, broadly speaking, there is a tendency toward natural regeneration in both southern ecoregions (15 FoUs out of 22 in the west and 10 out of 14 in the east). Notable is the widespread adoption of mixed regeneration in the shelterwood systems of the three ecoregions of central and north Europe. This can be explained by the enrichment planting typically used to increase the density of the desired tree species in such a silvicultural system.

Moisture Content of Wood

The moisture content of wood is a very important variable in all forest LCA studies, given its strong effect on both heating value and wood density. Despite this, Klein et al. (2015) found that moisture content is not reported in half of their reviewed studies. In most of the FoUs the moisture content of wood at forest road (dry basis) was reported to be between 35 and 55%, with the highest value ($u = 94\%$) reported in the even-aged forest with shelterwood, light-demanding conifers FoU of Estonia (Fig. 5).

Machinery Used

The overall impact of the management is influenced by the type of machinery used (Berg 1997). Figure 6 shows the data reported in the questionnaire about the machinery used for tree felling (including both thinnings and regeneration fellings). It is clearly visible that heavy forestry machinery is the common choice in almost all types of forests in Central-West and North Europe. This is in contrast with the remaining ecoregions where, with the exception of the short rotation system, the chainsaw is normally used. In short rotation systems the productivity of heavy forestry machinery sensibly increased due to better accessibility and plantation design together with the higher density of the stems. The economic benefits of this high productivity outweigh the burden of the higher cost per hour in comparison to manual harvesting operations making them more economically viable, especially in industrialized countries with higher labor costs (Vanbeveren et al. 2015). The overall impact of felling is not only influenced by the type but also the productivity of the equipment used during the

Table 3 Data available in EFO-LCI on FoUs description

Type of information	Field name	Description	Unit	Comments
General information of Forest Unit	Country	Country name		
	Ec_name	Ecoregion name		
	Eco_code	Ecoregion code		
	Man_syst	Silvicultural system		
	Sp_group	Species group		
	Man_syst_code	Silvicultural system code		
	Sp_gr_code	Species group code		
	FoU	Forest Unit code		
	Itinerary	Short narrative description of the stand and its management		
	Rotation	Rotation length	years	
	Goal_diam	Target diameter (for continuous cover forest management)	cm	
Data quality assessment	Rel	Reliability	$0 \le Rel \le 1$	
	Compl	Completeness	$0 \le Compl \le 1$	
	T_cor	Temporal correlation	$0 \le T\_cor \le 1$	
	G_cor	Geographical correlation	$0 \le G\_cor \le 1$	
	FT_cor	Further technological correlation	$0 \le FT\_cor \le 1$	
	DQD	Data quality distance	$0 \le DQD \le 5$	
	QA	Overall quality assessment for FoU	A, B, C, D, E	
Composition of the stand	Main_sp	Main species in the Forest Unit group		
	Mois_field	Moisture of green wood for main species	%	
	Den_fresh	Density of green wood at for main species	t/m^3	
	Den_dried	Density of dried wood for main species	t/m^3	
	OMS	Other main species		
	OMS-Mois	Moisture of green wood for other main species	%	
	OMS-Den_fre	Density of dried wood for other main species	t/m^3	
	OMS-Den__dri	Density of dried wood for other main species	t/m^3	
	Sec_sp	Secondary species		
	SS-Mois	Moisture of green wood for secondary species	%	
	SS-Den_fresh	Density of green wood for secondary species	t/m^3	
Regeneration	Reg	Type of regeneration		
	Type_seed	Type of seedling		
	Age_seed	Age of seedling		
	Orig_seed	Origin of seedling		

Table 3 (continued)

Type of information	Field name	Description	Unit	Comments
	Dens	Density of plantation	plants/ha	
Forest transport	Equip	Distance (one way) to forest for silvicultural equipment	km	
	Staff	Distance (one way) to forest for silvicultural staff	km	
	Harv_equip	Distance (one way) to forest for harvesting equipment	km	
	Harv_staff	Distance (one way) to forest for harvesting staff	km	
	Road	Forest road density	m/ha	
	Trail	Skidding trail density	m/ha	
Interventions rules. Description of the general rules on which thinnings and regeneration fellings are based (regeneration fellings are clearcuts, selection fellings in continuous cover and preparatory, seedling, secondary and final fellings in shelterwood)	Rul__thn	Rule on which the thinning is based (e.g., achievement of a certain standing stock, basal area, age, density, etc.)		This is reported for four thinnings and the value of *n* indicates the chronological order (e.g., Rul_th1, Rul_th2, Val_th1, etc.)
	Val_thn	Value (of standing stock, basal area, age, density, etc.) when the thinning is applied		
	Typ_thn	Type of thinning		
	Targ_thn	Target value (of standing stock, basal area, age, density, etc.) after the thinning is applied		Clearcutting, coppice, and short rotation
	Un_thn	Unit of target value (of standing stock, basal area, age, density, etc.)		
	Com_thn	Comments		
	Rul__cle	Rule on which the felling is based (e.g., achievement of a certain standing stock, basal area, age, density, etc.)		
	Val_cle	Value (of standing stock, basal area, age, density, etc.) when the felling is applied		
	Com_cle	Comments		
	Rul__sel	Rule on which the selection felling is based (e.g., achievement of a certain standing stock, basal area, age, density, etc.)		Continuous cover forest
	Val_sel	Felling intervals		
	Targ_sel	Target value (of standing stock, basal area, age, density, etc.) after the selection felling is applied		
	Un_sel	Unit of target value (of standing stock, basal area, age, density, etc.)		
	Com_sel	Comments		

Table 3 (continued)

Type of information	Field name	Description	Unit	Comments
	Rul__x	Rule on which the type of felling is based (e.g., achievement of a certain standing stock, basal area, age, density, etc.)		This is reported for preparation (pre), seedling (sed), secondary (sec), and final (fin) felling. The value in parenthesis is used in place of *x* to indicate which one (e.g., Rul_pre, Rul_sed, Val_pre, etc.)Shelterwood
	Val_x	Value (of standing stock, basal area, age, density, etc.) when the type of felling is applied		
	Age_x	Target value (of standing stock, basal area, age, density, etc.) after the type of felling is applied		
	Targ_x	Unit of target value (of standing stock, basal area, age, density, etc.)		
	Com_x	Comments		
	Rul__grad	Rule on which the wood grading is based (e.g., achievement of a diameter, volume, quality standard, etc.)		
	Val_grad	Value need		
	Com_grad	Comments/additional info and brief description on how the wood is graded		
Data source	DS_rot/goal	Data source for rotation length/target diameter		
	DS_comp	Data source for composition of the stands		
	DS_reg	Data source for regeneration		
	DS_transp	Data source for forest transport		
	DS_int/rul	Data source for the description of rules applied in the interventions		
	DS_equip	Data source for the equipment used in the inverventions		
	DS_inpu	Data source for the inputs used in the inverventions		
	DS_harv/ha	Data source for harvesting volumes of the interventions		

Table 4 Data available in EFO-LCI on FoUs interventions

Type of information	Field name	Description	Unit	Comments
General information of Forest Unit	Country	Country name		
	Ec_name	Ecoregion name		
	Eco_code	Ecoregion code		
	Man_syst	Silvicultural system		
	Sp_group	Species group		
	Man_syst_code	Silvicultural system code		
	Sp_gr_code	Species group code		
	FoU	Forest Unit code		
General information on interventions	Interv_num	Cronological number of intervention		
	Timing_of_interv	Timing of intervention (relative to regeneration or previous selection felling)	years	
	Type_of_interv	Type of intervention		
	Sp_interv	Species concerned by the interventions		
	Pre_int_stock	Stock of the stand before the intervention		
	Pre_int_BA	Basal area of the stand before the intervention		
Equipment used	Equip_n	Equipment used in the intervention		This is reported for three machines (1st, 2nd, 3rd) and the value of *n* indicates them (e.g., Equip_1, Equip_1, Power_1, etc.)
	Power_n	Power of the main equipment used (if motorized)	CV	
	Mass_n	Mass of the main equipment used	tons	
	Consum_n	Consumption of motorized machine	l/h	
	Hrs_use_life_n	Hours of use during whole life for equipment	h	
	h/ha_n	Average productivity of the equipment used during the intervention	h/ha	
	m3/h_n		m^3/h	
	fresh_t/h_n		tons/h	
Input used	input_n	Type of input used (fertilizer, herbicide, etc.)		This is reported for two inputs and the value of *n* indicates which one (e.g., input_1, input_2, active_pr1, etc.)
	active_prn	Active principle		
	Amount_n	Amount applied	kg/ha	
Wood removal	Stem	Tick boxes indicating the type of wood removed (if)		
	Stem_and_res			
	Stumps			
	m3_ob_x	Amount of wood removed during the intervention	m^3/ha (over bark)	This is reported for three assortments (Logs, Firewood, and pulp) and the value of *x* indicates it (e.g., m3_over_bark_Logs, etc.)
	m3_ub_x		m^3/ha (under bark)	
	dry_t_x		tons/ha	
	St_m3_Firewood	Firewood removed during intervention	m^3/ha (stacked)	
	m3_chips	Chips removed during intervention	m^3/ha	
	Loose_m3_x	Amount of wood removed during the intervention	m^3/ha (loose)	This is reported for chips and stumps the value of *n* indicates the one (dry_t_pulp, etc.)
	dry_t_x		tons/ha	

operation, which in turn depends on many factors like accessibility and structural characteristics of the stand. Figure 7 shows the distribution of the average harvesting productivities of different machinery reported in each FoU for thinning and regeneration felling. It is interesting to note that while between machinery there are clear differences in terms of productivity, for the same machinery the differences between the type of intervention are minor. For chainsaw a median productivity of one cubic meter harvested per hour (m^3/h) for both thinning and regeneration felling is observed, for feller buncher 5 and 7 m^3/h and for harvester 6 and 12 m^3/h, respectively.

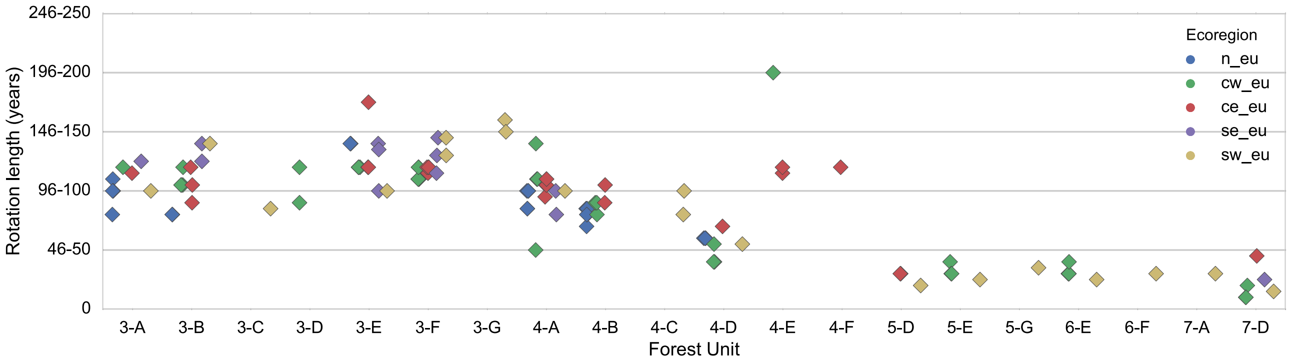

Fig. 3 Rotation length reported as a function of Forest Units and ecoregions. Letters stand for species groups (Table 2) and numbers for silvicultural systems (Table 1), for ecoregion codes (see Fig. 1)

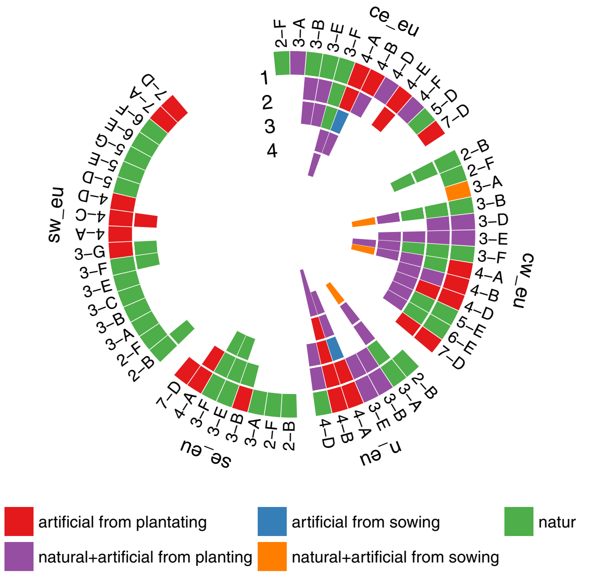

Fig. 4 Type of regeneration reported by FoU and grouped by ecoregion. Letters stand for species groups (Table 2) and numbers for silvicultural systems (Table 1), for ecoregion codes (see Fig. 1)

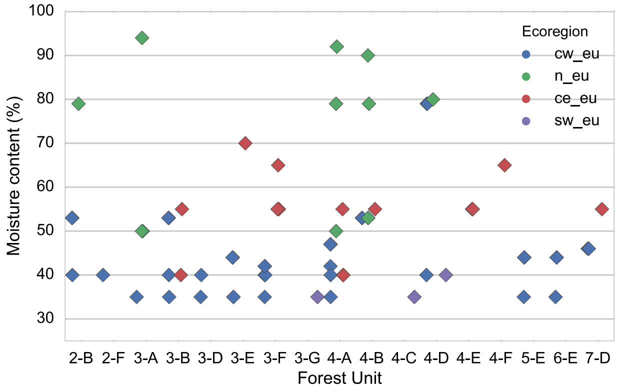

Fig. 5 Moisture content of green wood. Letters stand for species groups (Table 2) and numbers for silvicultural systems (Table 1), for ecoregion codes (see Fig. 1)

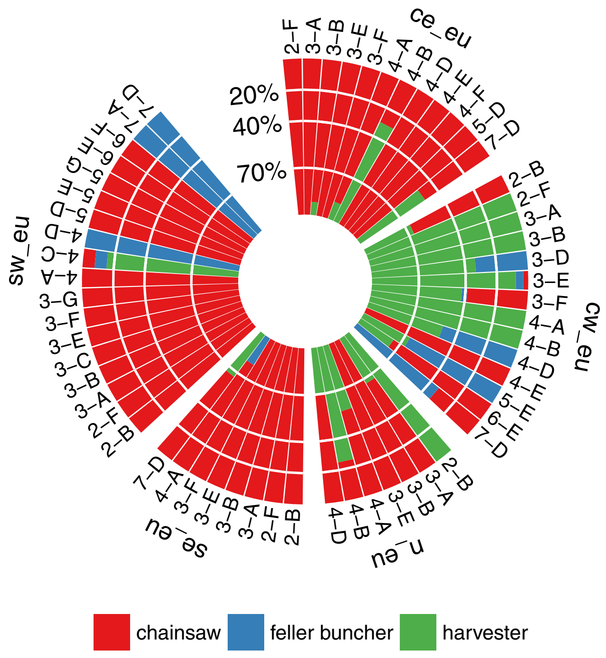

Fig. 6 Type of machinery used in the thinning and felling reported in percentage per FoU and grouped by ecoregion. Letters stand for species groups (Table 2) and numbers for silvicultural systems (Table 1), for ecoregion codes (see Fig. 1)

Harvesting Volumes and Assortments

While ISO 14040 and 14044 on LCA recommend to avoid allocation whenever possible, the partitioning of burdens for multi-outputs processes is often necessary in the forestry context due to the high number of co-cycled, by-cycled, and re-cycled products produced and used along the chain. Despite this widespread application of allocation in LCA of forestry systems, the description of the procedure followed in many cases is not described (Klein et al. 2015). Following the suggestions of Klein et al. (2015) about allocation that should be based on mass or volume, we asked to report the volume of wood extracted during felling and thinning operations specifying the assortment (Fig. 8). This distinction is important for the allocation of the impacts of forestry operations to the different products produced. The first thing to note is that, despite what is considered to be good management practice in silvicultural guidelines, thinnings are often not applied at all, and this is almost the standard practice in both southern ecoregions. This is because in these two ecoregions productive forests are typically in mountainous areas with high mobilization cost. When thinnings are applied, the sum of all wood removals by thinnings over the rotation period consists of an amount of wood that is often sensibly lower than the amount removed by regeneration fellings. Clearly visible is the higher wood production along the rotation for the clear-cut system compared to the other systems. With regard to the grading, it is interesting to note the biggest share of firewood produced in deciduous forests (species groups D, F, and G). Overall, the assortments of products from harvesting exhibit a high variation also between silvicultural systems and countries. This variability is due to local market conditions and the relative demand for each assortment.

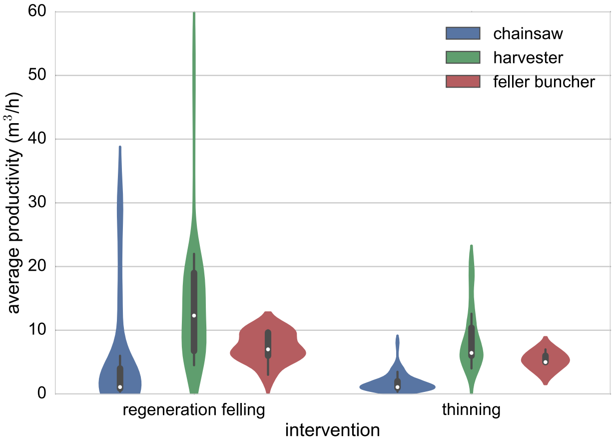

Fig. 7 Violin plot showing the distribution of the average harvesting productivities of different machinery reported in each Forest Unit for regeneration felling and thinning

LCA Impact

To evaluate the LCA impact of the variations presented above, the climate impact for the production of 1 m^3 of overbark (m3 ob) raw wood was calculated. The analysis considered the GHG emissions of all inputs and management operations occurring along the aforementioned process-based system boundary (see “System boundaries”). All the foreground data used to model the emissions were taken from EFO-LCI. Specifically, from the database were used the data about: (i) distances traveled from staff; (ii) forest road density; (iii) regeneration type and, in case of artificial regeneration; (iv) number of seedling per hectare; (v) type of intervention; (vi) if wood was harvested during the intervention, its amount (in m^3/ha); (vii) type and (viii) operational productivities (in m^3/h or h/ha) of the equipment used; (ix) type and (x) amount of inputs used (e.g., fertilizer) plus (xi) rotation length. Ecoinvent 3.3 and Agribalyse

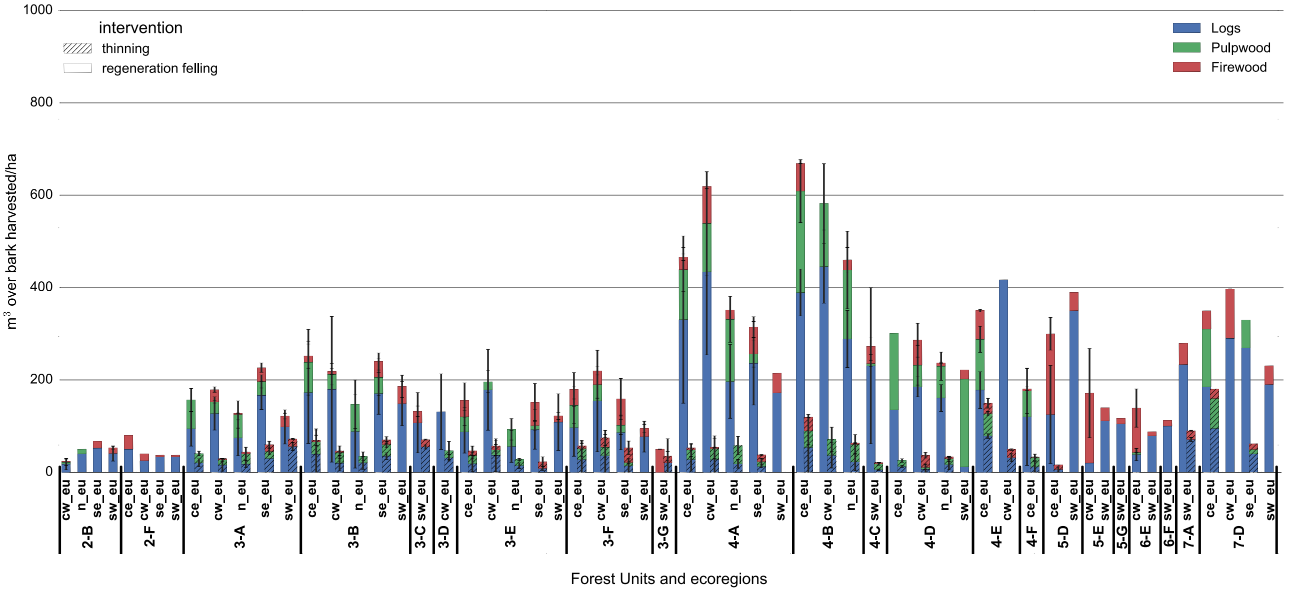

Fig. 8 Clustered stacked bar chart showing average harvesting volume for thinning (hatched bars) and regeneration felling (solid bars) and their standard deviation (error bars) for each ecoregion grouped by FoU. Letters in main *x*-axis category stands for species (Table 2) and numbers for silvicultural systems (Table 1), for ecoregion codes in secondary *x*-axis category (see Fig. 1). In case of thinning values are calculated summing all the thinning interventions. For shelterwood, regeneration felling values are calculated summing preparation, seedling, secondary and final fellings

1.3 (Colomb et al. 2015) were used for the background LCI data about the GHG emission per hour of use of the machinery, unitary seedling production, and material used for road maintenance and fencing (see Table S1). All management interventions reported in EFO-LCI were distinct into general and specific as reported in Table S2. In the former are included the activities that are not related to the amount of timber harvested, being dependent on the area of forest regenerated (e.g., ripping), and for which the emissions were calculated on a per hectare basis. For the latter (e.g., primary felling) the emissions were directly estimated from the m3 ob of wood harvested in that intervention for 1 ha. Based on the operational productivity of the machinery, their total demand per hectare over one rotation (in h of use or km for manual activities) was calculated for all general and specific interventions occurring over a single rotation in each FoU, as shown in Eq. 1.

$$D = \begin{cases} C * \frac{P_{\mathrm{h/ha}}}{8}, & \text{if manual in generic} \\ C * \frac{\frac{W}{P_{\mathrm{m^3/h}}}}{8}, & \text{if manual in specific} \\ \frac{P_{\mathrm{h/ha}}}{W}, & \text{if generic} \\ \frac{W}{P_{\mathrm{m^3/h}}}, & \text{if specific} \end{cases} \tag{1}$$

with D = total use of machinery (in h/ha or km/ha) for the intervention under consideration over one rotation. $P_{\mathrm{h/ha}}$ = operational productivity (in h/ha) of the machinery for the intervention under consideration. $P_{\mathrm{m^3/h}}$ = operational productivity (in $\mathrm{m^3/h}$) of the machinery for the intervention under consideration. $W = \mathrm{m^3ob/ha}$ of wood harvested over one rotation for the intervention under consideration. C = commuting distance for staff (km).

Continuing with the example above, when in a FoU the intervention "ripping" is reported and the machinery used is "ripper", the operation productivity in h/ha is used. The total hours of use of the ripper is derived from third case in Eq. 1. In manual activities only the transport of worker is considered, assuming a working day of 8 h and that the task is performed from two workers. Knowing the daily distance traveled from staff and the operational productivity of the intervention (both from EFO-LCI) the total distance traveled is calculated using first and second cases in Eq. 1. Forest road maintenance was modeled based on the skidding trail and road densities reported in EFO-LCI and assuming that overhauling measures take place every 15 years. Impacts from both generic and specific interventions over a single rotation were then scaled to 1 $\mathrm{m^3}$ based on the ob volume of wood harvested over one rotation. The Supplementary Material contains also the Jupyter notebook (Shen 2014) with the LCA analysis.

Climate was chosen as impact category due to the relevant role played by biogenic carbon and its importance in the carbon neutrality issue. For the anthropogenic emissions due to forestry operations the Global Warming Potential over 100 years (GWP-100) is calculated (IPCC 2013) while for biogenic carbon the impact is assessed using the GWPbio (Cherubini et al. 2011) over a time horizon of 100 years (GWPbio-100). This climate impact has been calcualted for all FoUs and compared with the climate impact of the nine European unit processes available in Ecoinvent 3.3 for raw wood production (Fig. 9). The variability of results in EFO-LCI is higher then when using Ecoinvent. The antropogenic impact ranges from 11.1 to 16.4 $\mathrm{kgCO_2eq/m^3}$ in Ecoinvent and from 0.4 (FoU 5-D in ce_eu) to 73.1 (FoU 3-F in sw_eu) $\mathrm{kgCO_2eq/m^3}$ in EFO-LCI while the biogenic impact ranges from 143.6 to 73.1 $\mathrm{kgCO_2eq/m^3}$ in Ecoinvent and from 1.6 (FoU 7-D in cw_eu) to 451.9 (FoU 4-E in cw_eu) $\mathrm{kgCO_2eq/m^3}$ in EFO-

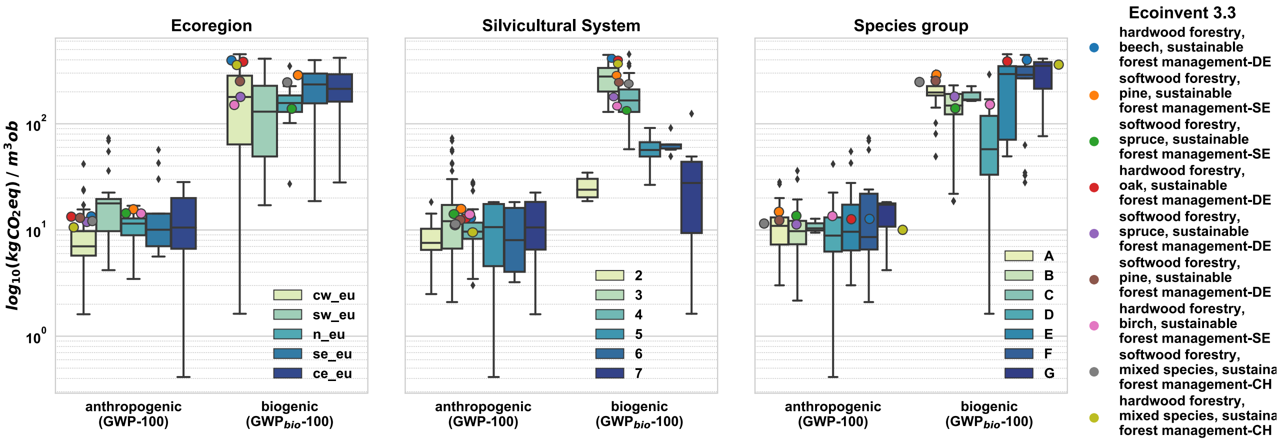

Fig. 9 Boxplots of the climate impact (log10 scale) per $\mathrm{m^3}$ over bark of raw wood harvested in the Forest Units measured as GWP-100 for anthropogenic emissions (left) and GWPbio-100 for biogenic carbon fluxes (right) and compared with Ecoinvent 3.3 (dots). EFO-LCI results are grouped by ecoregion (see Fig. 1 for codes), silvicultural system (see Table 1 for numbers), and species group (see Table 2 for letters). Ecoinvent results are plotted against the relative ecoregion and species group while for the silvicultural system they are placed at the center being an average between silvicultural systems 2 and 3

LCI. The total climate impact (GWPbio-100 + GWP-100) in Ecoinvent and EFO-LCI is, respectively, in the range from 158.7 to 421.8 $kgCO_2eq/m^3$ and from 7.6 (FoU 7-D in cw_eu) to 471.0 (FoU in 3-F sw_eu) $kgCO_2eq/m^3$. In EFO-LCI a higher number of ecoregions are covered in comparison to Ecoinvent, which has data only for two of them. Furthermore, when the results are disaggregated by silvicultural systems and species groups, their intra-group and extra-group variability can be quite important. Ecoinvent processes are averages of different management styles and the silvicultural system applied is not explicitly mentioned but, from the description, it seems to be an average between silvicultural systems 3 and 4. While for these two systems the order of magnitude of the biogenic impacts is similar, for all the other systems impacts are systematically lower in EFO-LCI, especially in silvicultural systems 2 and 7 due to their shorter rotation period. Also when looking at species group, biogenic impacts in EFO-LCI tend to be lower than in Ecoinvent. For both species groups and silvicultural systems the median anthropogenic impacts of the FoUs are spread around the impacts found in Ecoinvent processes.

Conclusions

The present study shows that there is a remarkable variation in rotation length, type of regeneration, amount and assortments of wood products harvested, and machinery used in interventions, depending on tree species and management practices applied, as well as on the specific country where the production takes place. All these differences are important and significantly affect the life cycle impact of raw wood production. Although we have shown how climate impact assessment of wood production would benefits from the use of regionalized inventory, how these improvements are translated into better LCA of wood-based products is difficult to estimate. The relative role played by raw wood production obviously depends on the product studied, but also on the type of environmental impact considered and the methodological choices made. For example in González-Garca et al. (2009) the abiotic depletion potential of hardboard manufacturing is solely due to raw wood production but, on the opposite, its relative contribution to human toxicity and photo-oxidant formation is only about 2% of the overall impacts. In Martnez-Alonso and Berdasco (2015) the relative contribution of raw wood production to the carbon impact of sawn timber manufacturing ranges from 8 to 34% depending on whether the wood is kiln or air dried. Those are just two examples of how the choice of impact assessment method and technological assumptions can change the relative importance of forestry when put in a broader perspective. Also other methodological aspects like the system boundary of the analysis (e.g., cradle-to-gate vs. cradle-to-grave) and the allocation used can be of crucial importance. With regard to the system boundary, as we have also shown, the relative contribution of biogenic carbon to the total climate impact is rather important and, in our case, relatively higher than the anthropogenic ones. Considering that many of the wood-based products LCA's in the literature assumes the climate neutrality of wood, the relative role played by forestry, at least for what the climate impact is concerned, can be higher than expected. It is realistically unfeasible to collect site-specific data for all the LCAs involving forest-based products. Despite this, a higher level of disaggregation and regionalization of inventories would improve the accuracy and credibility of life cycle studies of forest production systems. The difficulty of acquiring site-specific data is one of the main challenges faced when trying to build regionalized inventories (Hellweg and Milà i Canals 2014). We tried to address this problem by collecting and disclosing FoU-specific data on the management practices of European forests with the final goal of reducing the uncertainty of forestry LCA. In collecting this information, we tried to follow as much as possible the methodological guidelines proposed by Klein et al. (2015), with the goal of continuing the process of harmonization proposed by the authors. While EFO-LCI include only part of the information necessary to develop forestry LCI (namely, on management and harvesting practice), the missing information on forest growth and carbon sequestration can be taken from the study of Neumann et al. (2016), where the same FoU classification is used.

The choice of disclosing all the data collected under the CC BY-NC-SA 4.0 license has been taken to further stimulate transparency and reproducibility in LCA and to fight the so-called "reproducibility crisis" (Baker 2016; Peng 2015). The use of open science is seen as one of the main instruments to increase scientific integrity and minimize the two aforementioned problems (McNutt et al. 2016; Nosek et al. 2015; Ram 2013; Wicherts et al. 2012), and we hope that in the near future this will become the standard practice in the LCA world, as it is already for other sectors with high scientific standards (Anonymous 2016). Our final hope is that the database developed, being conceived as a collaborative one, will not only be used but also integrated and improved by other researchers and practitioners.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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