Subject review

LCA Studies in Forestry – Stagnation or Progress?

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Abstract

Today, LCA is one of the leading and most used tools for environmental management, but the application of LCA in forestry is still in an initial phase. Due to a high amount of different wood products which can be produced in forestry sector, production of raw material itself is not included enough in the whole LCA process. Raw wood products and biomass used to be widely declared as »carbon neutral« and renewable, but production steps have a significant influence on the environmental impact depending on machinery used, opening forest with new roads, management type (clear-cut, even-aged management or selective cut), etc. This paper gives a review of LCA studies in forestry based on three segments:

⇒ *harvesting operations*
⇒ *biomass for energy*
⇒ *road construction and maintenance.*

Keywords: life cycle assessment, energy consumption, GHG emission, carbon neutral, wood products.

1. Introduction

Forestry is a traditional supplier for various industries in terms of renewable raw materials, household fuel wood and increasingly for biofuels. Mechanized harvesting systems increased productivity, improved conditions for forest workers and decreased the demand for manpower in forest operations (Holtzscher and Lanford 1997), but have also increased fuel and oil requirements (Athanassiadis 2000, Berg and Karjalainen 2003), which contributed to higher GHG (Green House Gases) emissions (Berg 1997, Athanassiadis 2000). The development of environmentally friendly technologies, which are essentially based on utilization of renewable resources, is still happening at a slow pace, which makes them not-so-cheap replacements of the current fossil fuel technologies and processes and delays the achievement of sustainable development (Perić et al. 2016).

Carbon dioxide is a dominant greenhouse gas and its increasing levels, together with other greenhouse gases (i.e. nitrous oxide, methane, chlorofluorocarbons and tropospheric ozone), may have contributed to the increase in atmospheric temperatures between 0.3 and 0.6 ºC since the late 1800s (Nowak and Crane 2002). Increased atmospheric CO_2 is mostly attributable to fossil fuel combustion (about 80–85%) and deforestation worldwide (Schneider 1989, Hamburg et al. 1997). Atmospheric carbon is estimated to be increasing by approximately 2600 million tons annually (Sedjo 1989) and its present concentration is the highest in the last 650,000 years (Petit et al. 1999, Siegnethaler et al. 2005).

Trees represent a sink for CO_2 by fixing carbon during photosynthesis and storing excess carbon as biomass and net long-term CO_2 source/sink dynamics of forests change through time as trees grow, die, and decay. In addition, human influences on forests (e.g. management) can further affect CO_2 source/sink dynamics of forests through such factors as fossil fuel emissions and harvesting/utilization of biomass (Nowak and Crane 2002). Forest ecosystems cover about 4.1 billion hectares globally (Dixon and Wisniewski 1995) and through forest vegetation and soils about 1240 Pg of carbon is stocked (Dixon et al. 1994). Out of the total

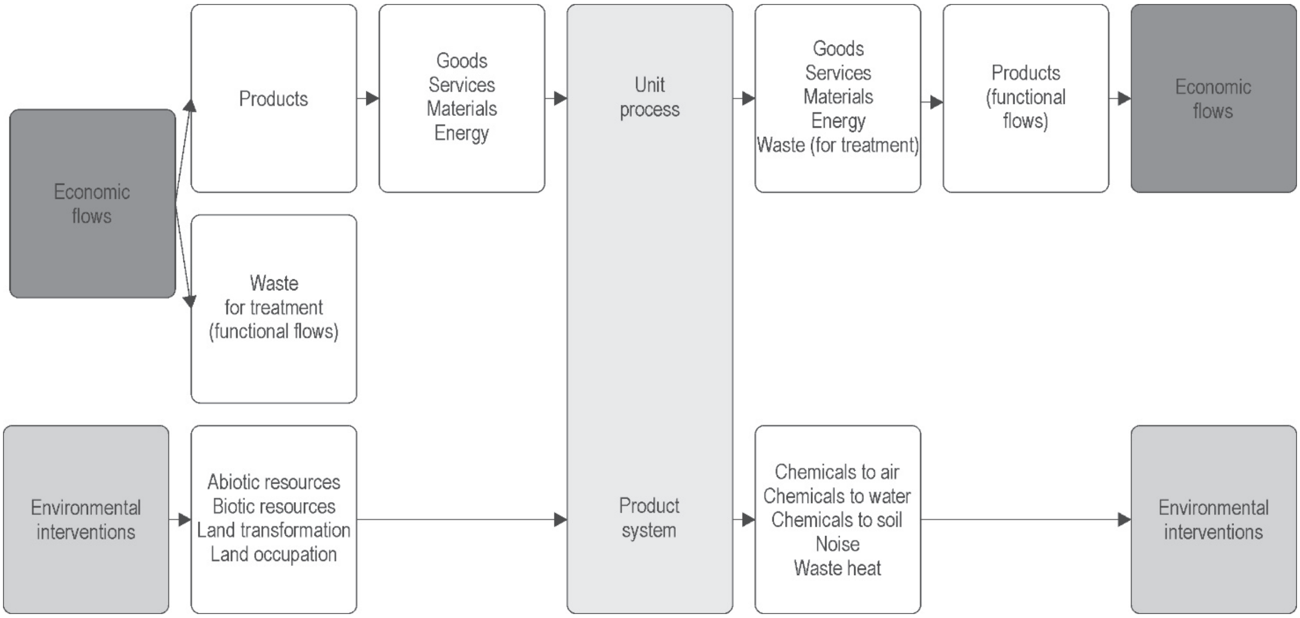

Fig. 1 Data categories by Guinée et al. (2002)

terrestrial carbon stock in forest biomes, 37% is in low latitude forests, 14% in mid-latitudes and 49% in high latitudes. The above-ground plant carbon stock increases with decreasing latitude from tundra to tropical rainforest (Fisher 1995). Old-growth managed forests stock more carbon as opposed to young fast-growing forests and their conversion to young-fast growing forests will not decrease atmospheric carbon dioxide (Harmon et al. 1990). Increase in carbon stock of forest soils can be achieved through forest management including site preparation, fire management, afforestation, species management/selection, use of fertilizers and soil amendments (Lal 2005).

International Organization for Standardization – ISO (2006) defines LCA as a method used for quantification and improvement of possible impacts associated with products by:

⇒ improvement of environmental performance
⇒ design or redesign of manufacturing process
⇒ selecting and quantifying environmental indicators
⇒ establishing environmental soundness for eco-labels for products.

Before defining a system of unit processes, system boundaries should be defined between the product system (Guinée et al. 2006) as a part of the physical environment and the environment (Fig. 1). Authors continue that forestry can be regarded as a part of socio-economic system, but timber extracted from a natural forest will have to be regarded as a critical resource taken from the environment. Likewise, landfill managed without any control measures should be regarded as part of the environment.

Life Cycle Assessment is one of the leading and most used tools for environmental management (Curran 2016, Finnveden et al. 2009). It provides a systematic, holistic and multidisciplinary approach in quantification of environmental burdens and their potential impacts over the whole life cycle of a product, process or activity. Its scope is the entire life cycle of a product, from the extraction of raw materials, through to manufacturing, use, and end of life. Data from life cycle inventories (LCI) of forest operations provide the forest industry with the input required for assessing its products (Berg and Lindholm 2006). Since LCA came into wider application during the 1990s, efforts have been made to make progress with LCI in relation to forest operations with sufficient relevance and quality (Richter 1995, Schweinle 1999, Heinimann 1999, Knechtle 1999). From a production context point of view, LCA is a suitable tool to assess wood supply systems, because it was designed for product systems (ISO 2006). The idea of LCA was to obtain or provide product information from which the consumer would choose between several alternatives considering differences in environmental effects of the product. This information may be provided by industry, environmental or consumer organizations or by the public sector (Guinée et al. 1992), but also from the scientific community whose objective is to provide environmental soundness.

Various databases (European Life Cycle Database – ELCD, U.S. Life Cycle Inventory Database, Ecoinvent Database, Sustainable Product Information Network for the Environment – SPINE, etc.) have been developed to allow communication between different software tools used for practicing LCA such as SimaPro (developed by PRé Consultants), Umberto (developed by IFU Hamburg and IFEU Heidelberg), TEAM (developed by Ecobalance), GaBi (developed by Department of Life Cycle Engineering of the Chair of Building Physics at the University of Stuttgart and PE International GmbH), POLCAGE (developed by De La Salle University, Philippines, and University of Portsmouth, UK) and GEMIS (developed by Öko-Institut) (Perić et al. 2016).

Land use and forestry aspects of LCA are a complicated issue because of the dynamic nature of forests and long-term production period, which usually corresponds to the rotation period. Modeling carbon, nutrients and energy flows offers a solution that incorporates forestry operations and forest growth in life-cycle inventory without using specific indicators (Wessman et al. 2003). The same authors continue that modeling regarding carbon and nitrogen is usual, while other nutrient flows in the forest are usually ignored. They suggest landscape-related indicators for achieving biodiversity. Environmental system has to be a part of the analysis, characterized by input flows such as CO_2, solar energy, mineral resources and land both occupied and transformed. Inventory analysis consists of mapping the structure and functions of the product system, usually in the form of a process flow diagram that is the basis for the following modeling of materials, energy, emission and waste flows (Heinimann 2012). LCA studies in forestry, however, have a wider context than the ones dealing with machine emissions and fuel consumption and report values of CO_2 and other GHG emissions relative to energy consumed (Cosola et al. 2016).

As Ecoinvent database (Wernet et al. 2016, Frischknecht et al. 2005) highlights, in most cases the production of materials and services creates a mix of burdens and credits to the environment. When the score is positive, like in most cases, the net effect is the damage to the environment. However, in some cases, the score is negative, indicating that the credits are larger than the burdens. While searching through Ecoinvent multi-product activity datasets that form the basis for all other system models with terms such as: timber, roundwood, oak, spruce, fir or beech, it can be concluded that most of the data regarding production of timber (log production, softwood forestry, debarking at forest road, etc.) are based on literature reviews; time aspect (growth of trees) is not included, and very often there are no data related to to/from environment aspect. Timber production is usually referred to as »motor-manual«, without further specifying vehicles used for primary transport and without including primary and secondary forest road infrastructure. Due to high amount of different wood products that can be produced in forestry sector, it seems that the production of raw material itself is not included enough or is even neglected in the whole LCA process. This was also highlighted by Frühwald (1995), Heinimann (2012), Klein et al. (2015), who conclude that inventory analysis is the heart of LCA, taking a considerable amount of time and being extremely data intensive and that it is not properly connected to forestry itself. Raw wood products and biomass used to be widely declared as »carbon neutral« and renewable, but production steps have a significant influence on the environmental impact (Zah et al. 2007, Miner and Gaudreault 2013, Klein et al. 2015) depending on machinery used, opening forests with new roads, management type (clear-cut, even-aged management or selective cut), etc.

SimaPro 8.2.3 inventory, which includes the following databases: ecoinvent v3, Agri-footprint, US LCI, ELCD, EU and Danish Input Output, Industry data v.2 and Swiss Input Output, contains the term »wood« in many processes related to construction materials (doors, windows), carbon content biogenic materials, paper + board industries, and as a separate entry, »wood« can be found in a vast number of products from wood chips, raw cork, sawnwood, pulpwood, cleft timber, sawlogs, etc. However, roundwood, a starting point for many of these products, can be found in 11 inventory processes, where eight of them refer to azobe, eucalyptus, meranti and parana pine and other three to roundwood itself. Datasets on roundwood consider rough estimation of used machinery in European forestry and the associated occupation impact, but do not include wood burning emissions, land transformation and occupation. Datasets of the above mentioned species are more detailed and include harvesting and extraction operations as well as fuel used for forest road construction, but do not include land use of forest roads and gravel, nor logging impacts on further vegetation and environmental impacts of post-harvest processes (potential forest degradation/deforestation) as well as forest road area that is not included in the land use. Majority of these datasets are valid for one specific company and region, so the uncertainty of their further use is rather high and they cannot be assumed to be the standard case. What is even more interesting, not to say ironic, SimaPro 7.1 tutorial

(Goedkoop et al. 2007) is actually based on example »production of planks from a tree«, where tree felling is process 1, and saw mill procedures is process 2. Even though the idea of LCA methodology goes back to 1960s and 1970s (Ayers and Kneese 1969, Hall et al. 1979, Odum et al. 1977), it is still not widely used nor accepted in the forestry community and if it is performed, it is often a »truncated LCA« where environmental burdens of machines and forest road infrastructure are neglected, which results in an underestimation of environmental impacts of forest product systems (Heinimann 2012).

It is predictable that future LCA studies will focus on reducing the uncertainties of the current key issues such as: inclusion in the assessment of indirect effects of land-use-changes and their amortization over time, estimation of bioenergy impacts on biodiversity, better determination of fertilizer induced N emissions, and others (Cherubini and Strømman 2011). Authors continue that standardization in GHG balance accounting (also called carbon footprint) of products is particularly perceived as urgent by policy makers, and the methodological standards provided by consultants and stakeholders try to address this need.

This paper gives a review of scientific literature that used life cycle assessment (LCA) methodology or its parts to estimate sustainability and recycling values and environmental impacts of forestry operations, with the focus on three areas of interest: harvesting operations, biomass for energy and forest road construction and maintenance.

2. LCA studies in harvesting operations

Combustion engines have been the backbone of forest machinery and the quality of the combustion process is crucial for all subsequent results. Machines consume resources through maintenance, which should also be considered in the analysis process. The materials of which a machine is manufactured embody environmental burdens that have to be considered to fulfill their »cradle to grave« requirement (Heinimann 2012).

Klvač et al. (2003) state that energy used in the manufacture and maintenance of machinery contributes to the overall energy use of the system and must be included in any LCA of machines. During calculation of energy embodied in forest machines and vehicles, Pandur et al. (2015) assumed it to be 66 MJ/kg. Börjesson (1996) states that the energy required for the production of material embedded in vehicles amounts to an average of 24 MJ/kg, while manufacturing and assembly of vehicles additionally consumes energy in the amount of 11 MJ/kg for tractors, 9.1 MJ/kg for harvesters, 6.3 MJ/kg for plough, etc. Heller et al. (2003) recorded similar results, where the calculation for agriculture tractor amounted to 26.04 MJ/kg of consumed energy. Engel et al. (2012) provide in their paper an analysis of the raw materials used in the forestry equipment and energy needed for the production of each material. According to their analysis, based on the vehicles mass, Pandur et al. (2015) calculated the total energy consumed in production of materials used for forwarder Valmet 840.2, forwarder Valmet 860.4 and agricultural tractor John Deere 8430, which amounts to 26.79 MJ/kg, 26.79 MJ/kg and 26.56 MJ/kg, respectively. Athanassiadis et al. (2002) estimated the energy used in the production of forwarders to be related to the machine mass, namely 66.4 MJ/kg.

Karjalainen and Asikainen (1996) state that greenhouse gas emissions caused by machinery used in silvicultural and stand preparatory operations, wood harvesting, and timber transportation in Finland were 424.2 Gg carbon dioxide, 10.6 Mg nitrous oxide, 3.5 Gg carbon monoxide, 31.5 Mg methane, 5.6 Gg nitrogen oxide, and 0.7 Gg non-methane volatile organic compounds. Silvicultural and stand preparatory operations accounted for 8% of the total emission, cutting of timber for 13%, primary transport for 18%, secondary (long-distance) transportation for 57% and transportation of machinery for 4%.

Berg (1997) uses LCA techniques in assessing the environmental loads imposed by different types of felling (clear cutting and shelterwood cutting), different level of mechanization (motor-manual felling with chainsaws and mechanized logging with harvesters), timber extraction by forwarders and conveyance of people, machinery and materials to and from the site in northern and southern part of Sweden. Forwarding was not separated from felling. The emissions in shelterwood cutting were 10% higher than in clear cutting and forwarding. The emissions were 20–25% higher in shelterwood management system and it can be expected that in selective forests, energy inputs will be even higher. According to the author, motor-manual felling had lower emissions per cubic meter than mechanized felling and even heavy deployment of resources for transporting personnel to and from work would not be sufficient to balance that difference. Since, shelterwood and clear cutting were performed in different types of stands and terrain, figures presented here cannot be used for straight comparison of felling systems.

Athanassiadis (2000) estimated a combined fuel and oil energy use for harvesting and forwarding of

Table 1 Studies on energy use in forest operations (Lindholm 2006, 2010

Energy use, MJ/m^3	Silviculture and logging	Secondary transport	Total
Germany, saw logs, spruce (transport distance 50 km) (Schweinle 1996)	135	92	227
Switzerland, mechanized logging (Knechtle 1997, 1999)	91	–	–
Switzerland, motor-manual logging (Knechtle 1997, 1999)	111	–	–
Germany, (transport distance 50 km) (Wegner 1994)	62	125	187
Norway (hybrid LCA 3 scenarios from best to worst depending on transport distance) (Michelsen et al. 2008)	–	–	Best 48 Average 162 Worst 390
Spain (Gonzáles-Garcia et al. 2009)	116+155=271	124	395
Sweden (Gonzáles-Garcia et al. 2009)	12+136	223	370

82 MJ/m^3, but this did not include the energy used during the production of oils. The energy consumed during production is reported as ca 4.5 MJ/l for diesel fuel and 15.6 MJ/l for biodiesel (gained from rapeseed).

Klvač et al. (2003) calculated total energy input per unit of wood production (m^3) from the fuel and oil consumption and the average mass of machines and replacement materials. The mean energy input was 66.7 MJ/m^3 for harvesters and 52.7 MJ/m^3 for forwarders, thereby giving a total system energy requirement of ca 120 MJ/m^3 (with fuel accounting for approximately 82% of the total energy use) in Ireland.

Pandur et al. (2015) also calculated total energy inputs for chainsaws, forwarders and forest tractor assemblies, which were: 1) chainsaws 17.46 MJ/m^3 (felling and processing logs) and 31.92 MJ/m^3 (felling and processing of one-meter-long firewood), 2) 65.81 MJ/m^3 for forwarders and 3) 59.72 MJ/m^3 for forest tractor assemblies. For input parameters, they used fuel and oil consumption and energy embodied in machines and spare parts (tires, chains, sprockets and guide bars of chainsaws).

Berg and Lindholm (2005) differentiate seedling production, silviculture, logging and secondary transport to identify the most significant process in terms of energy inputs and output of timber and emissions. The authors state that half of the energy used per cubic meter in Swedish forestry is provided for secondary transport from forests to industries. Enhancing payload per distance, removing return unloaded trips, improving forest roads (road width, curvature and better surfacing as well as »soft« driving) would improve the current situation. The type of cutting operation (final felling or thinning) had greater influence on energy input per volume of timber than geographical area of operations. Final felling consumes less energy (30 MJ/m^3) than thinning (48 MJ/m^3). The energy consumed for forwarding timber to forest roads in final felling was 22–27 MJ/m^3 s.u.b. and in thinning 31–34 MJ/m^3 s.u.b. (solid under bark). The energy consumed in silviculture operations was 11 MJ and in seedling production 8 MJ. In conclusion, in Sweden during one year all forest operations produced 15 kg/ CO$_2$-equiv./m^3, which is a small amount (0.3 Tg C a^{-1}) compared to national emissions from fossil fuels that amounted to 18.9 Tg C a^{-1}.

Lindholm (2006, 2010) states that according to several European forestry studies (Tab. 1), the energy used in silviculture and logging ranges from less than 60 MJ/m^3 of timber up to 270 MJ/m^3. These findings have been corroborated by the studies of Schweinle and Thoroe (2001), who also considered road building and provide estimates of 170–270 MJ/tonne of dry wood (70–120 MJ/m^3). Secondary haulage accounts for 90 to 223 MJ, raising total energy use to a level of 180–395 MJ/m^3. However, energy use has been shown to be higher in exceptionally difficult terrain conditions (Wegner 1994), in long-distance haulage of pulpwood (Gonzáles-Garcia et al. 2009; Michelsen et al. 2008) and when silviculture is highly mechanized and the use of chemicals is high (Gonzáles-Garcia et al. 2009).

Table 2 Energy consumption for lorries of different gross weight. The energy values are based on the lower heating values of diesel fuels (H_D=42.8 MJ/kg diesel)

Transport service	Diesel energy consumption kg/tkm	Final energy consumption MJ/tkm
Lorry 16t	0.072	3.08
Lorry 28t	0.05	2.14
Lorry 40t	0.036	1.54

Spielmann and Scholz (2005) compare LCA of different transporting vehicles in terms of payload used in Switzerland, depending on fuel (kg/tkm) and total energy consumption (MJ/tkm), which is given in Table 2.

The same authors presented the data on CO_2 and NO_X emissions during truck transport with 50% and 100% transport utility i.e. full return trip, and concluded that trucks with 100% full return trips produce 25–30% lower emissions of CO_2 and NO_X.

Pandur et al. (2015) state that energy consumption during timber transport by forest truck assemblies (with a mounted crane) – FTA, at the distance of 53 km, is 199.3 MJ/t of fresh wood. The reason of higher values lies in the fact that loading and unloading of timber with crane is not separated from the driving itself.

In the year 1996, the Croatian state company »Hrvatske šume« Ltd. owned 259 FTAs and participated in total long distance timber transport with a share of 85%. Fuel consumption in all operations necessary for the production of 1 m^3 of wood was 6.96 l/m^3, and fuel consumption in timber truck transport was 2.33 L/m^3 or 33.4% of total fuel consumed (Sever and Horvat 1996).

Karjalainen and Asikainen (1996) report that fuel consumption in Finland is 56 l/100 km, while the emission of greenhouse gases (CO_2, CH_4 and N_2O) is 0.03 kg/m^3km. According to Svenson (2011) fuel consumption in Sweden is 28 l/100 km, and according to Klvač et al. (2013) in the Czech Republic fuel consumption amounts to 2.19 l/m^3 and 67.4 l/100 km.

Klvač et al. (2003) state that in the overall energy audit of mechanized wood harvesting systems in Ireland, fuel consumption was the most significant item (82%), followed by oils (7%) and machine repairs and replacement (11%). Pandur et al. (2015) point out that the total energy consumption in all the operations necessary for the production of 1 m^3 of wood in lowland forests is 634 MJ/m^3, of which fuel amounts to 86%, which is similar to the findings of Klvač et al. (2003). Of all operations necessary for the production of 1 m^3 of wood, energy consumption in timber truck transport amounts to 31% of the total energy consumption (Pandur et al. 2015).

Athanassiadis (2000) states that, during harvesting operations, the type of fuel and oil used by machinery, depending on their origin i.e. whether they are mineral or bio-produced products, significantly affects the environment. The author concludes that the production of RME (rapeseed methyl ester) generates high amounts of CO_2 and NO_X emissions as expected from mineral diesel fuel, and vice versa – in combustion, mineral diesel fuel emissions of HC and CO compounds prevail.

3. LCA studies on biomass for energy

Lignocellulosic biomass was the first and, for many centuries, the main source of energy. With the development of civilization, a major shift towards the use of technical properties of wood occurred, but the role of wood in energy production has remained significant (Vusić and Đuka 2015). In recent years, increasing environmental concerns have resulted in policy measures, strongly shifting the focus in energy production towards sustainable sources of energy. In this respect, forest industry is expected to play a significant role due to the fact that among all the available alternative energy sources (hydro, solar, wind, etc.), biomass is the only carbon based sustainable option (Khan et al. 2009) and, therefore, it can effectively be transformed into different energy carriers (heat, electricity and fuel for transportation) making it the most desirable option for the replacement of fossil fuels.

Different techniques and approaches have been used to assess the environmental effects and energy balance of biomass production and use for energy. Earlier research relied mostly on energy analysis, quantifying consumed energy and CO_2 or GHG emissions in the production system, while recent studies favor LCA and include a wider range of environmental impacts (Djomo et al. 2011). Klein et al. 2015 state that the first tangible LCAs for the European forestry and wood products sector appeared in the 1990s, with the aim to scientifically analyze the impacts arising from nonrenewable inputs into a system.

LCA biomass studies are usually designed either as stand-alone assessments (describing the production system and presenting environmental impacts) or as comparative LCA studies (opposing the environmental impacts of the bioenergy system to the environmental impacts of alternative energy systems, either other renewable or fossil ones) (Djomo et al. 2011). Cherubini and Strømman (2011) state that LCA can be carried out using different methods based on the purpose of the study, and make a distinction between attributional and consequential LCA. The first describes the environmentally relevant flows to and from a life-cycle (and its sub-systems), while the latter describes how environmentally relevant flows will change in response to possible decisions (Finnveden et al. 2009). Although the attributional method is the most used in LCA, in LCA of bioenergy systems the consequential method is broadly applied for comparing the environmental impacts with those of a fossil reference system (Cherubini and Strømman 2011).

Klein et al. (2015) identified a total number of 28 studies where LCAs for forest production were at least one of the main study objectives and supported the statement by Heinimann (2012) that, although LCAs have already been discussed in the forestry sector for 20 years, there is still little information based on scientific research. They name two reasons for this situation. One is the fact that, in many cases, forest production is not the main study objective, while the products of forest production frequently are (e.g. fuel chips or pellets), and environmental impacts of the previous forestry processes are only deduced from literature or calculated starting from the latest stage of the forest product chain (e.g. with the collection of wood residues or chipping), and thereby neglecting important processes of forest production. The other is the general opinion that the respective processes have only minor environmental impacts, and that providing wood for material or energetic purposes is nearly carbon-neutral (Miner and Gaudreault 2013).

Klein et al. (2015) distinguish two central questions related to climate change and forestry; the influence of forest management (and land use change) on carbon stocks of forests and harvested wood products, and GHG-emissions caused by forestry processes mainly originated from non-renewable inputs like fossil fuels or construction material for machineries.

As stated by Cherubini and Strømman (2011), bioenergy systems generally ensure GHG emission savings when compared to conventional fossil reference systems; net GHG emissions from generation of a unit of electricity from biomass are usually 5–10% of those from fossil fuel-based electricity generation (Cherubini et al. 2009, Bhat and Prakash 2009). This ratio will be even lower, if biomass is produced with low energy input (or derived from residue streams), converted efficiently, ideally in CHP (Combined Heat and Power) applications, and if the fossil fuel reference use is inefficient and based on a carbon-intensive fuel such as coal (Cherubini and Strømman 2011).

Klein et al. (2015) state that, considering that all removed biomass from sustainably managed forests will be sequestered again in the future (Helin et al. 2013), and based on the overall opinion that the provision of wood as raw material does not cause high GHG (Green House Gases) emissions, wood and wood products are commonly claimed as »carbon neutral«. They question the »absolute carbon neutrality« of raw wood products, by reporting the results of 28 LCA studies of forestry production (14.3 kg CO_2-equiv. per m^3 o.b. (over bark) mean GWP (Global Warming Potential) from site preparation to forest road, adding 6.3–67.1 kg CO_2-equiv. per m^3 o.b. for transport processes and on average 20.5 kg CO_2-equiv. per m^3 o.b. for chipping processes. They suggest that raw wood products should be described as »low emission raw materials«, if long-term in situ carbon losses by changed forest management or negative direct or indirect effects of land use change (LUC – Land Use Change, iLUC – indirect Land Use Change) can be excluded (Klein et al. 2015). In support to their report, the GHG-emissions, even in the worst case of 28 analyzed literature sources, are still low (9%) compared to the respective carbon content of the harvested wood (the range of C-emitted/C-stored in wood is 0.008–0.09 from forest to plant gate or consumer).

Djomo et al. (2011) synthesized 26 studies on energy and GHG balance of bioenergy production from poplar and willow published between 1990 and 2009. Results reported on energy ratios varied from 13–79 for the cradle-to-farm gate and 3–16 for cradle-to-plant assessments, and the intensity of GHG emissions ranged between 0.6 and 10.6 g CO_2-equiv. per MJ (39–132 g CO_2-equiv per kWh). Although the substantial variation of reported values (caused by different system boundaries and methodological assumptions in reviewed studies) is evident, the review revealed a general consensus that short rotation coppice (SRC) willow yielded 14.1–85.9 times more energy per unit of fossil energy input compared to coal, and that GHG emissions were 9–161 times lower than those of coal (Djomo et al. 2011).

In their research of SRWC (Short Rotation Woody Crop) willow for energy, Heller et al. (2003) stressed the importance of analyzing the whole rotation period with the focus on redistributing the environmental burdens of establishing the plantation over each cutting cycle. They reported the production of 55 units of biomass energy per unit of fossil energy consumed over the biomass crop life cycle of 23 years. The research concluded that inorganic nitrogen fertilizer inputs have a strong influence on overall system performance, accounting for 37% of the non-renewable fossil energy input into the system and that net energy ratio varies from 58 to below 40 as a function of fertilizer application rate. Heller et al. (2003) also suggested substituting inorganic N fertilizer with sewage sludge biosolids, claiming that this practice could increase the net energy ratio of the willow biomass crop production system by more than 40%. They report net greenhouse gas emissions of 0.68 g CO_2 per MJ of biomass produced and point out that, for reasonable biomass transportation distance and energy conversion efficiencies, generating electricity from willow biomass crops could produce 11 units of electricity per unit of consumed fossil energy. The same authors conclude that in biomass truck transport (40 t total weight), energy consumption was 188.9 MJ/t of dry matter on an average distance of 96 km, while Pandur et al. (2015) state that energy consumption in hauler truck transport of wood chips with the moisture content of 35% on an average distance of 50 km was 77.35 MJ/t.

Pandur et al. (2015) calculated EROI (energy returned on energy invested) for wood chips from shelterwood cuttings of lowland oak forests. The following parameters were included in the calculation: energy invested for manufacturing all vehicles, machines and tools used in harvesting operations, road building and maintenance, fuel and lubricant consumption, energy invested in manufacturing of components (spare parts) such as: tires, chains, guidebars, drive spockets, etc. and energy invested for production of pesticides used in forestry.

Börjesson (1996) estimates that total energy consumption during biomass transport by truck is 1.4 MJ/tkm, while for adapted farm tractor energy consumption doubles to 2.9 MJ/tkm. Energy required for biomass transport by railroad is 0.7 MJ/tkm, twice less than by truck, while by water transport it is 0.23 MJ/tkm – six times less energy than required by truck transport, which is, by the way, the most common timber transport in Sweden, Austria, Denmark, Finland, Norway, Germany, Slovenia, Italy, Ireland and Croatia (Schwaiger and Zimmer 2001, Beuk et al. 2007). The largest direct energy input i.e. fuel consumption ranges from 72.4% for adapted farm tractor to 97.1% for railway, while the remaining energy is needed for building infrastructure traffic networks and manufacturing and transporting vehicles.

Lindholm et al. (2010) investigated stumps and logging residues as raw material for energy generation, modeled seven different procurement chains of forest energy in Sweden (variations in geographical location, technology employed and resource use), and calculated their environmental performance from a Life Cycle Assessment (LCA) perspective. They reported the energy output/input ratio of chips from residues and stumps in the range of 21–48, and the greenhouse gas emissions from 1.5–3.5 g CO_2-equiv. per MJ chips.

Results presented in the study by Lindholm et al. (2010) confirmed the conclusions of previous research (Näslund-Eriksson and Gustavsson 2008) that transportation of forest fuel dominates the primary energy use, and that the use of primary energy in transporting forest products varies across different parts of Sweden (Berg and Lindholm 2005) due to different transportation distances as a result of different procurement chain organization. The results for the bundle forest energy supply system show that bundling process has the second highest energy use and environmental impact, but due to the fact that the forest energy systems based on bundles rely on immature technologies, they have the potential to be improved (Lindholm et al. 2010). The primary energy use and environmental impact of the comminution of forest fuel, as the central feature of the forest energy supply chain (Hakkila 2004), strongly depends on the technology used, diesel driven vs. electrical driven (Lindholm et al. 2010), again depending on the design of the procurement chain.

Yoshioka et al. (2005) analyzed the energy balance and the carbon dioxide (CO_2) emission of logging residues from Japanese conventional forestry as alternative energy resources over the entire life cycle of the residues using the method of a life cycle inventory (LCI). They calculated the ratio of energy output to input to be 5.69 and concluded that the production system they researched could be feasible as an energy production system. Comparing the CO_2 emission per MWh_e (1 MWh_e=2.6136 MWh) of the biomass-fired power generation plant (61.8 kg CO_2/MWh_e) with that of coal-fired power generation plants in Japan (960 kg CO_2/MWh_e), the reduction in the amount of CO_2 emission that would result from replacing coal with biomass for power generation could be as much as 3.0 million dry-t/year (Yoshioka et al. 2005).

According to Klein et al. (2015), system boundaries are crucial to identify all relevant processes for a specific LCA. They suggest that the forest system should start with site preparation processes and end at least at the forest road, including all relevant primary and secondary processes of the entire forest product chain (from cradle-to-forest road), and if in some cases, emissions do not appear (for example, if planting processes are not required because natural regeneration occurs), energy balance of this process should be set to zero (Klein et al. 2015). On the other hand, Lindholm et al. (2010), in the study of fuel chip production, set the system boundary starting in the forest after final felling (and including lifting of stumps by harvesters and forwarding stumps and logging residues) and ending when wood chips have been comminuted and delivered to the energy plant. Yoshioka et al. (2005) consider bioenergy as a by-product of conventional forestry, and in this sense set the bioenergy system boundary starting with comminuting logging residues at the landing of the logging site by a mobile chipper accrediting all environmental impacts up to this point to forestry. Similar to Yoshioka et al. (2005), Johnson et al. (2012) in the research of the first thinning by full-tree method, state that the primary products should bear the environmental burdens of the stand management activities because the whole tree is delivered to the landing as part of the primary product harvest. There is no allocation of cost, fuel, nor any corresponding environmental burdens required to deliver the tops and limbs to the landing. Those are carried by the primary product.

It is evident that system boundaries are affected by the raw material characteristics and the place where they are produced/located. This is especially important when analyzing wood energy products, because raw material for their production can be regarded either as waste or product depending on the market situation and cost effectiveness of available harvesting systems. The issue of product/by-product/waste definition was identified by Berg (2001) and its strong influence to allocation procedures was discussed.

Allocation in LCA is carried out to attribute shares of the total environmental impact on different products of a system (Cherubini and Strømman 2011). The allocation of environmental burdens is needed if a process causes several outputs or products (Klein et al. 2015). Allocation concept is extremely important for bioenergy systems, which are usually characterized by multiple products and have a large influence on final results (Cherubini and Strømman 2011).

The functional unit is the unit to which all LCA results of a system are referred to and, therefore, its clear definition is essential (Klein et al. 2015). Cherubini and Strømman (2011), in their literature analysis, identify four types of functional units: input unit related (mass or energy unit, where the results are independent of conversion processes and type of end-products and in studies aimed at comparing the best uses for a given biomass feedstock); output unit related (unit of heat or power produced or km of transportation service is usually selected by studies aiming at comparing the provision of a given service from different feedstocks); unit of land (hectare of land needed to produce the biomass feedstock as the first parameter to take into account when biomass is produced from dedicated energy crops); and year (used in studies characterized by multiple final products, since it allows avoiding an allocation step). Klein et al. (2015) argue that calculating the impacts only on a hectare or annual base without any product-based unit would not be helpful, due to the fact that the raw wood product is usually the base for different final products, and its inherent ecological impacts represent just a part of all impacts. Therefore, they suggest that, as a default, results should be referred to 1 m^3 o.b. as the most common functional unit in forestry. They also state that, in addition to the default functional unit, information about the moisture content and wood density should be given in order to be able to calculate additional functional units like 1 t biomass o.d. (oven dry), 1 t of carbon, 1 MJ (lower heating value), or 1 ha, depending on subsequent use of the wood. Moisture content is not important only for calculating conversion efficiency but also for understanding results of the transportation processes. Lindholm et al. (2010) take the calculations one step further accounting for dry matter losses and the ash content of harvested stumps and logging residues as parameters affecting the mass balance of the systems. It can be concluded that the functional unit depends on the goal of the study and on further use of the raw wood and that, as a consequence, different study objectives result in different functional units, which in some cases causes difficulties in making quantitative comparisons (Klein et al. 2015).

Cherubini and Strømman (2011) state that, in the light of the future expected competition for fertile land, one of the important research questions will be that of efficient land use (bioenergy vs. carbon sequestration). They predict that future LCA studies will focus on reducing the uncertainties of these current key issues (inclusion in the assessment of indirect LUC effects and their amortization over time, estimation of bioenergy impacts on biodiversity, better determination of fertilizer induced N emissions, and others).

LCA studies are crucial to understand and quantify environmental impacts and to avoid possible negative effects of increasing wood use as energy source (Klein et al. 2015). The use of different input data, functional units, allocation methods, reference systems and other assumptions complicates comparisons of LCA bioenergy studies (Cherubini and Strømman 2011). Some authors recognized that different accuracy levels and reliability of the input parameters have a strong influence on the final results, and therefore tried to solve this problem by applying sensitivity analyses, modeling different productivity levels (Johnson et al. 2012), energy requirements (Lindholm et al. 2010), or biomass-fired power generation plant parameters (Yoshioka et al. 2005). When analyzing 28 different literature sources of LCA in the forestry sector, Klein et al. (2015) concluded that the results of the GWP varied considerably between studies, depending on the processes included and decisive assumptions (like productivity rates and fuel consumption of machineries), but also stated that, compared with the carbon stored in wood, the GWP actually varies on a low scale.

4. LCA studies in forest road construction and maintenance

Forest traffic infrastructure gives access to forests and forest land and, therefore, it is today an essential

Table 3 Environmental loadings caused by road construction and maintenance (Mroueh et al. 2000)

Environmental loadings	Construction	Maintenance
CO_2, kg/km	263,000 – 562,000	33,900
SO_2, kg/km	280 – 610	4.1
NO_x, kg/km	2600 – 3800	140
CO, kg/km	600 – 1100	20
Violatile organic compounds (VOC), kg/km	550 – 980	210
Fuel consumption, l/km	63,000 – 100,000	18,200
Energy consumption, kWh/km	790,000 – 1,470,000	183,300

part of intensive forest management (Šikić et al. 1989, Potočnik 1996, Gucinski 2001, Loeffler et al. 2009, Stampfer 2010, Whittaker et al. 2011, Bosner et al. 2012, Pentek and Poršinsky 2012, Sokolović and Bajrić 2013, Papa et al. 2015). Enache and Stampfer (2014) state that significance of forest traffic infrastructure as environmental burden is actually two-sided, because in forests with poor accessibility, the environmental footprint of forest operations is significant due to long timber extraction distances. Improving the environmental performance of forest operations requires a well-developed forest infrastructure, specifically the density and quality of roads. Even though forest traffic infrastructure and long-distance transport have a share of about 60% in the overall environmental burden of timber procurement process, environmental performance of silviculture operations, timber harvesting and transport are extensively addressed in the literature, while forest roads are kept aside from the analyzed system boundaries except a few recent studies (Berg and Karjalainen 2003, Whittaker et al. 2011, Bosner et al. 2012, Heinimann 2012).

Karjalainen and Asikainenen (1996), in their extensive study made in Finland, conclude that the highest GHG emissions in silvicultural and forest improvement work were caused by building of permanent forest roads. Building of one kilometer of permanent forest road requires nearly 47 h of work with an excavator, 4.25 h with a bulldozer, 6.8 h with a loader, and 24 h driving materials with a truck to complete the upper structure of the road, giving a total fuel consumption of 1236.2 l km^{-1}. Respectively, GHG for building one kilometer of permanent forest road in Finland is 3290.74 kg CO_2, 0.0826 kg N_2O, 27.50 kg CO, 0.2374 kg CH_4, 39.648 kg NO_x and 5.646 NMVOC.

Mroueh et al. (2000), in a study of life cycle assessment of road construction, analyze numerous factors (environmental loadings) and divide them into five categories: 1) resource use, 2) effluents to soil and waters, 3) emissions to air, 4) wastes, and 5) other loadings. According to the study of Häkinnen and Mäkelä (1996), the same authors estimate the environmental burdens that arise during maintenance and repair of roads in Finland in the period of 50 years. The frequency of repairs is determined by a preset strategy (Tab. 3).

Heinimann and Maeda-Inaba (2003) developed a model that evaluates environmental burden of forest road construction based on an input-output model of the underlying process network. This approach enabled the study of the influence of 6 road construction parameters: 1) roadbed width, 2) cut slope, 3) fill slope, 4) thickness of base course, 5) thickness of surface course, and 6) transport distance of base course materials. The entire analysis was based on the following average values of forest road parameters in hilly-mountainous parts of Switzerland: 1) roadbed width of 4.2 m, 2) cut slope angle of 1:1, 3) fill slope angle of 4:5, 4) thickness of the base course of 0.3 m, 5) thickness of the surface course of 0.08 m, and 6) transport distance for base course materials of 10 kilometers. Authors concluded as follows:

On moderate slopes of up to 40%, construction of one meter of forest road consumes about 350 MJ of energy, while emitting about 20 kg of greenhouse gases;

Energy consumption is equivalent to the heating value of about 10 l of diesel fuel per meter of road length, and about 10 kg of wood mass that has to be grown to sequestrate the amount of emitted greenhouse gases;

Transport distance of base course materials is the most sensitive factor of influence. Compared to on-site preparation of aggregates, a 50-kilometer transport increases energy consumption by a factor of about five;

Table 4 Breakdown of energy requirements and GHG emissions for forest road construction and maintenance (Whittaker et al. 2011)

Stage	Energy requirement MJ/km	Emissions			
		kg CO_2/km	kg CH_4/km	kg N_2O/km	kg CO_2 eq/km
Road construction – diesel fuel					
Loading roadstone	48,867.96	3,376.73	0.925	0.026	3,407.59
Haulage	99,545.84	6,878.53	1.883	0.053	6,941.38
Spreading roadstone	25,338.94	1,750.90	0.479	0.013	1,766.90
Grading	2,714.89	187.60	0.051	0.001	189.31
Rolling	1,680.64	116.13	0.032	0.001	117.19
Material inputs					
Roadstone (blasted)	127,509.70	7,605.12	32,075	39,175	20,081.00
Roadstone (crushed)	51,657.34	3,416.85	5,226	5,369	5,147.44
Machine manufacture					
Excavator	9,003.75	668.96	0.982	0.039	705.21
Haulage	25,725.00	1,911.31	2.806	0.112	2,014.87
Bulldozer	9,261.00	688.07	1.010	0.040	725.35
Grader	1,194.38	88.74	0.130	0.005	93.55
Roller	422.63	31.40	0.046	0.002	33.10
Machine maintenance					
Excavator	180.08	13.38	0.020	0.001	14.10
Haulage	514.50	38.23	0.056	0.002	40.30
Bulldozer	185.22	13.76	0.020	0.001	14.51
Grader	23.89	1.77	0.003	0.000	1.87
Roller	8.45	0.63	0.001	0.000	0.66
Total	403,834.19	26,788.09	45.745	44.841	41,294.33

Slope is the second important factor that shows a nonlinear influence on energy consumption and greenhouse gas emissions. Increasing slope to about 50% doubles energy consumption and greenhouse gas emissions, while a slope of 70% almost triples them;

Roadbed width is the third important factor of influence. Energy consumption doubles when the roadbed width is increased from 4.2 m to 6.2 m.

The above stated results and conclusions were later confirmed by Heinimann (2012), who reported that during construction and maintenance of forest roads, embodied energy rates of 315 MJ m^{-1} to 735 MJ m^{-1} depend on the side slopes and CO_2 emission rates between 19 and 47 kg m^{-1}

In the mountains of the United States, Loeffler et al. (2009) study the actual excavation of road paths in »extreme terrain conditions« with regard to energy consumption and CO_2 emissions. Similarly to Heinimann and Maeda-Inaba (2003), authors estimate that diesel fuel required for roads constructed on slopes of up to 50%, while using a cut-fill construction method, was 1400 l/km, with emitting 3777.59 kg of CO_2/km. On slopes of more than 50%, by using a full bench road construction method, between 7680 and 18,800 l/km diesel fuel was consumed and between 20,974.06 and 51,504.86 kg of CO_2/km was emitted. It is evident that fuel consumption and CO_2 emissions were 5.5 times greater on slopes of more than 50%.

Whittaker et al. (2011) state that forest road construction is a highly energy-intensive operation, where operations such as grading, rolling and hauling stone requires approximately 4.7 l diesel for 1 m of road and, in total, road construction requires 404 GJ and emits 41 t CO_2-equiv. km^{-1} road. Detailed analysis of energy requirements and GHG emissions are given in Table 4.

It should be mentioned that it is even more difficult to find understanding of road maintenance operations as environmental burden in scientific studies, such data usually being ignored due to lack of databases or due to its overall complexity. This is confirmed by Schwaiger and Zimmer (2001), who collected data from 11 European countries regarding LCA of forestry and forest products, Berg and Karjalainen (2003) who analyzed emissions during harvesting operations in Finland and Sweden, Loeffler et al. (2009), all without including estimates of fuel consumption or emissions for road reconstruction, grading and maintenance. In the following year, Whittaker et al. (2010) emphasize that the actual extent and frequency of forest road maintenance should be further investigated in terms of environmental burdens. Whittaker et al. (2011) state that road maintenance operations are less energy intensive due to the smaller quantities of aggregate used per km, and fewer machinery operations. 102 GJ and 9000 kg CO_2-equiv. are required to maintain 1 km of road. Authors, further divide forest roads into two groups depending on the necessity of road maintenance:

Type A roads, which are maintained once a year,

Type B roads, which are maintained before each harvesting operation.

Furthermore, authors state that over the full forest rotation period, road maintenance requirements exceed those of the original road construction. In the study area, where road density of type A roads was 0.008 km/ha and type B was 0.007 km/ha, over a 50-year forest rotation period with six felling periods, original road construction required 120 MJ ha a^{-1} of energy and emitted 8.0 kg ha a^{-1} CO_2-equiv., while 1912.2 MJ ha a^{-1} of energy is required and 129.9 kg ha a^{-1} CO_2-equiv. is emitted during forest road maintenance operations.

In forestry, environmental impact studies usually exclude forest transport infrastructure impact, which is correlated, according to Treloar et al. (2004), to road construction, maintenance and use, due to its high complexity, where a complete LCA of forest roads is difficult and time consuming, and it depends on the system boundaries and on the number of inputs in the process analysis. Treloar et. al (2004) and Sharrard (2007) state that a hybrid based process and input-output based LCA approach is recommendable for estimating project specific environmental impacts of forest roads.

5. Final remarks

LCA is still not adequately applied in forestry because of broad variations of wood products originating from the forestry sector, and because the production of raw material is usually not included or is ignored in LCA process, together with the fact that LCA for forestry usually takes substantial amount of time (productions phase correlates to rotation period) and is highly data intensive (land use). The main study objectives are usually based on forestry by-products (chips, pellets, etc.), and environmental impacts of the previous forestry processes are derived from literature or calculated, but starting from the latest stage of the forest product chain.

It can be concluded that the nature of a raw material (being the starting point of a process) or a product (being the ending point of a process) and allocation of environmental burdens are strongly influenced by the applied harvesting system and harvesting method. For example, in cut-to length harvesting, pulp wood designated for energy use should be burdened with environmental load from the beginning of the production (silvicultural processes), whereas logging residues used for energy generation should bear environmental load from forwarding onwards. Opposed to that, full-tree systems, employing skidders and processors on the landing or cable yarders with processing heads concentrate the logging residues at the landing site, setting the system boundaries from comminution phase onwards.

Production in forestry can be roughly divided into: 1) roundwood, 2) long-meter firewood, long stackwood and 3) slash. Therefore, the results should be based on 1 m^3 o.b. as the most common functional unit in forestry for roundwood or 1 t biomass for long-meter firewood and slash, thus creating system boundaries that were quite vague before. Information about the moisture content and wood density should be given in order to be able to calculate additional functional units. Also, other nutrient flows, besides carbon and nitrogen, should be included in the whole life cycle assessment process. Data on road construction and maintenance should be taken from a higher level (forest administration office or region) on a yearly basis and divided into specific research areas included in the LCA study due to high differences in data of previous research and overall complexity.

Total energy invested in the whole production process of three major forestry products is usually not available or not reliable enough, and fuel consumption increased by 20% can be used as energy inputs since it is an easily measurable parameter not to mention the most influential one. This way it is possible to simplify future LCA processes primary based on forestry.

Based on the number of published studies and different approaches used (raw material definition, system boundaries, allocation procedures, functional units), future trends in the LCA research of forestry production and use will need substantial harmonization (and maybe simplification) of rules and procedures to reduce the variability and enable the comparison of research results and provide solid ground for coherent conclusions.

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6. References

Athanassiadis, D., 2000: Energy consumption and exhaust emissions in mechanized timber harvesting operations in Sweden. Science of the Total Environment 255(1–3): 135–143.

Athanassiadis, D., Lideslav, G., Nordfjell, T., 2002: Energy use and emissions due to the manufacture of the forwarder. Resources, conservation and recycling 34(3): 149–160.

Ayers, R.U., Kneese, A.V., 1969: Production, consumption and externalities. The American Economic Review 59(3): 282–297.

Berg, S., 1997: Some aspects of LCA in the analysis of forestry operations. Journal of Cleaner Production 5(3): 211–217.

Berg, S., 2001: Problems with terms and definitions in inventories for forest sector LCS. In: Energy, Carbon and Other Material Flows in the Life Cycle Assessment of Forestry and Forest Products; Achievements of the Working Group 1 of the COST Action E9. European Forest Institute Discussion Paper 10: 23–26.

Berg, S., Karjalainen, T., 2003: Comparison of greenhouse gas emissions from forest operations in Finland and Sweden. Forestry 76(3): 271–284.

Berg, S., Lindholm, E.L., 2005: Energy use and environmental impacts of forest operations in Sweden. Journal of Cleaner Production 13(1): 33–42.

Beuk, D., Tomašić, Ž., Horvat, D., 2007: Status and development of forest harvesting mechanisation in Croatian state forestry. Croatian Journal of Forest Engineering 28(1): 63–82.

Bhat, I.K., Prakash, R., 2009: LCA of renewable energy for electricity generation systems – A review. Renewable and Sustainable Energy Reviews 13(5): 1067–1073.

Börjesson, P.I.I., 1996: Energy analysis of biomass production and transportation. Biomass and Bioenergy 11(4): 305–318.

Bosner, A., Poršinsky, T., Stankić, I., 2012: Forestry and life cycle assessment. P. 139–160 in Global perspectives on sustainable forest management, C.A. Okia (Ed.). InTech, ISBN: 978-953-51-0569-5.

Cherubini, F., Bird, N.D., Cowie, A., Jungmeier, G., Schlamadinger, B., Woess-Gallasch, S., 2009: Energy- and greenhouse gas-based LCA of biofuel and bioenergy systems: key issues, ranges and recommendations. Resources Conservation and Recycling 53(8): 434–447.

Cherubini, F., Strømman, A.H., 2011: Life cycle assessment of bioenergy systems: State of the art and future challenges. Bioresource Technology 102(2011): 437–451.

Cosola, G., Grigolato, S., Ackerman, P., Monterotti, S., Cavalli, R., 2016: Carbon Footprint of Forest Operations under Different Management Regimes. Croatian Journal of Forest Engineering 37(1): 201–217.

Curran, M.A., 2016: Life Cycle Assessment. John Wiley & Sons, Inc., Kirk-Othmer Encyclopedia of Chemical Technology: 1–28.

Dixon, R.K., Brown, S., Houghton, R.A., Solomon, A.M., Trexler, M.C., Wisniewski, J., 1994: Carbon pools and fluxes of global forest ecosystems. Science 263(5144): 185–190.

Dixon, R.K., Wisniewski, J., 1995: Global forest systems: an uncertain response to atmospheric pollutants and global climate change. Water Air Soil Pollution 85(1): 101–110.

Djomo, S.N., Kasmioui, O.E., Ceulemans, R., 2011: Energy and greenhouse gas balance of bioenergy production from poplar and willow: a review. Gcb Bioenergy 3(3): 181–197.

Enache, A., Stampfer, K., 2014: Environmental performance of forest roads due to construction, maintenance and use – case study analyses in Romanian mountain forests. 37th Council on Forest Engineering Annual Meeting. Moline, Illinois, 10 p.

Engel, A.M., Wegener, J., Lange, M., 2012: Greenhouse gas emissions of two mechanized wood harvesting methods in comparison with the use of draft horses for logging. European Journal of Forest Research 131(4): 1139–1149.

Finnveden, G., Hauschild, M.Z., Ekvall, T., Guinée, J., Heijungs, R., Hellweg, S., Koehler, A., Pennington, D., Suh, S., 2009: Recent developments in Life Cycle Assessment. Journal of Environmental Management 91(1): 1–21.

Fisher, R.F., 1995: Soil organic matter: clue or conundrum? W.W., McFee, J.M., Kelly, (Eds.), Carbon Forms and Functions in Forest Soils, Soil Science Society American, Madison, WI, USA, 1–12.

Frischknecht, R., Jungbluth, N., Althaus, H.-J., Doka, G., Dones, R., Heck, T., Hellweg, S., Hischier, R., Nemecek, T., Rebitzer, G., Spielmann, M., 2005: The ecoinvent database: Overview and methodological framework. International Journal of Life Cycle Assessment 10(1): 3–9.

Frühwald, A., 1995: LCA – A Challenge for Forestry and Forest Products Industry. Proceedings of the International Workshop organised by the European Forest Institute and the Federal Research Centre for Forestry and Forest Products, 3 – 5 May. Hamburg, Germany, 9–14.

Goedkoop, M., De Schryver, A., Oele, M., 2007: SimaPro 7.1 Tutorial. Report version 3.2, PRé Consultants, Netherlands, 79 p.

González-García, S., Berg, S., Feijoo, G., Teresa Moreira, M., 2009: Environmental impacts of forest production and supply of pulpwood: Spanish and Swedish case studies. International Journal of Life Cycle Assessment 14(4): 340–353.

Gucinski, H., 2001: Forest roads: a synthesis of scientific information. DIANE Publishing, Portland, OR, USA, 103 p.

Guineé, J.B., Gorée, M., Heijungs, R., Huppes, G., Klejin, R., de Koning, A., van Oers, L., Wegener Sleeswijk, A., Suh, S., Udo de Haes, H.A., de Brujin, J.A., van Duin, R., Huijbregts, M.A.J., 2002: Handbook on Life Cycle Assessment: Operational Guide to the ISO Standards. Kluwer Academic Publishers, 692 p.

Guineé, J.B., Huppes, G., Lankreijer, R.M., Udo de Haes, H.A., Wegener Sleeswijk, A., 1992: Environmental life cycle assessment of products. R. Heijungs (final editor), B&G, Netherlands, 97 p.

Guineé, J.B., van Oers, L., de Koning, A., Tamis, W., 2006: Life Cycle Approaches for Conservation Agriculture, Part I: A definition study for data analysis. CML report 171, June 2006, University of Leiden, Netherlands, 1–67.

Hakkila, P., 2004: Developing technology for large-scale production of forest chips – Wood energy technology programme 1999–2003. Technology programme report 6. Final Report. TEKES, Helsinki, Finland, 58 p.

Häkkinen, T., Mäkelä, K., 1996: Environemtal adaption of concrete. Environmental impact of concrete and asphalt pavements. VTT Research Notes 1752, Espoo, Finland, 61 p.

Hall, C., Lavine, M., Sloane, J., 1979: Efficiency of the energy delivery systems: I. An economic and energy analysis. Environmental Management 3(6): 493–504.

Hamburg, S.P., Harris, N., Jaeger, J., Karl, T.R., McFarland, M., Mitchell, J.F.B., Oppenheimer, M., Santer, S., Schneider, S., Trenberth, K.E., Wigley, T.M.L., 1997: Common questions about climate change. United Nation Environment Programme, World Meteorology Organization (1997), Nairobi, Kenya, 24 p.

Harmon, M.E., Ferrell, W.K., Franklin, J.F., 1990: Effects on Carbon Storage of Conversion of Old-Growth Forests to Young Forests. Science 247(4943): 699–702.

Heinimann, H.R., 2012: Life cycle assessment (LCA) in Forestry – State and Perspectives. Croatian Journal of Forest Engineering 33(2): 357–372.

Heinimann, H.R., 1999: Okobilanzierung von forstlichen Produktionssystemen—Beziehungen zu Umweltmanagementsystemen und Ubersicht uber das methodische Konzept. Schweiz Z Forstwes 150(3): 73–80.

Heinimann, H.R., Maeda-Inaba, S., 2003: Quantification of Environmental Performance Indicators Epis for Forest Roads. High Tech Forest Operations for Mountainous Terrain, Austro2003, October 5–9, Schlaegl – Austria, 13 p.

Helin, T., Sokka, L., Soimakallio, S., Pingoud, K., Pajula, T., 2013: Approaches for inclusion of forest carbon cycle in life cycle assessment—a review. BCB Bioenergy 5(5): 475–486.

Heller, M.C., Keoleian, G.A., Volk, T.A., 2003: Life cycle assessment of a willow bioenergy cropping system. Biomass and Bioenergy 25(2): 147–165.

Hohle, A.M.E., 2011: Energy consumption by energy wood supply. FORMEC 2011 – Pushing the boundaries with research and innovation in forest engineering, October 9–13, Graz, Austria, poster presentation.

Holtzscher, M., Lanford, B., 1997: Tree diameter effects on cost and productivity of cut-to-length systems. Forest Products Journal 47(3): 25–30.

ISO 2006: ISO 14040 Environmental management – Life cycle assessment – Principles and framework (2nd ed.). Geneva, Switzerland, 20 p.

Johnson, L., Lippke, B., Oneil, E., 2012: Modeling Biomass Collection and Woods Processing Life-Cycle Analysis. Forest Products Journal 62(4): 258–272.

Karjalainen, T., Asikainen, A., 1996: Greenhouse gas emissions from the use of primary energy in forest operations and long-distance transportation of timber in Finland. Forestry 69(3): 215–228.

Khan, A.A., de Jong, W., Jansens, P.J., Spliethoff, H., 2009: Biomass combustion in fluidized bed boilers: Potential problems and remedies. Fuel Processing Technology 90(1): 21–50.

Klein, D., Wolf, C., Schulz, C., Weber-Blaschke, G., 2015: 20 years of life cycle assessment (LCA) in the forestry sector: state of the art and a methodical proposal for the LCA of forest production. The International Journal of Life Cycle Assessment 20(4): 556–575.

Klvač, R., Kolarik, J., Volona, M., Drapela, K., 2013: Fuel Consumption in Timber Haulage, Croatian Journal of Forest Engineering 34(2): 229–240.

Klvač, R., Ward, S., Philip, M.O., Owende, P.M.O., Lyons, J., 2003: Energy Audit of Wood Harvesting Systems. Scandinavian Journal of Forest Research 18(2): 176–183.

Knechtle, N., 1997: Materialprofile von Holzerntesystemen – Analyse ausgewählter Beispiele als Grundlage für ein forsttechnisches Ökoinventar. Graduate thesis, ETH Zürich, Department of Forest and Wood Research, Switzerland, 65 p.

Knechtle, N., 1999: Materialprofile von Holzerntesystemen als Ausgangspunkt für Ökoinventare. Schweizerische Zeitschrift für Forstwesen 150(3):81–87.

Lal, R., 2005: Forest soils and carbon sequestration. Forest ecology and management 220(1): 242–258.

Lindholm, E.L., Berg, S., Hansson, P.A., 2010: Energy efficiency and the environmental impact of harvesting stumps and logging residues. European Journal of Forest Research 129(6): 1223–1235.

Lindholm, E.L., 2006: Energy use in Swedish forestry and its environmental impact. Licentiate thesis, Uppsala, Sweden, 28 p.

Lindholm, E.L., 2010: Energy Use and Environmental Impact of Roundwood and Forest Fuel Production in Sweden. Doctoral Thesis, Swedish University of Agricultural Sciences, Uppsala, Sweden, 1–81.

Loeffler, D., Jones, G., Vonessen, N., Healey, S., Chung, W., 2009: Estimating Diesel Fuel Consumption and Carbon Dioxide Emissions from Forest Road Construction. 2008 Forest Inventory and Analysis Symposium, US Department of Agriculture, Forest Service, Rocky Mountain Research Station, United States of America, 11 p.

Michelsen, O., Solli, C., Hammer Stromman, A., 2008: Environmental Impact and Added Value in Forestry Operations in Norway. Journal of Industrial Ecology 12(1): 69-81.

Miner, R., Gaudreault, C., 2013: A review of biomass carbon accounting methods and implications. National Council for Air and Stream, improvement. Technical bulletin 1015, 33 p.

Mroueh, U.M., Eskola, P., Laine-Ylijoki, J., Wellman, K., Juvankoski, E.M.M., Ruotoistenmäki, A., 2000: Life Cycle Assessment of Road Construction. Finnra report, 17/2000, Helsinki, Finland, 59 p.

Näslund-Eriksson, L., Gustavsson, L., 2008: Biofuels from stumps and small roundwood – costs and CO_2 benefits. Biomass and Bioenergy 32(10): 897–902.

Nowak, D.J., Crane, D.E., 2002: Carbon storage and sequestration by urban trees in the USA. Environmental pollution 116(3): 381–389.

Odum, H.T., Kemp, W., Shell, M., Boynton, W., Lehman, M., 1977: Energy analysis and the coupling of man and estuaries. Environmental Management 1(4): 297–315.

Pandur, Z., Šušnjar, M., Zorić, M., Nevečerel, H., Horvat, D., 2015: Energy Return on Investment (EROI) of Different Wood Products. Precious Forests – Precious Earth, M., Zlatić, (Ed.), Intech, Rijeka, Croatia, 165–184.

Papa, I., Pentek, T., Lepoglavec, K., Nevečerel, H., Poršinsky, T., Tomašić, Ž., 2015: Metodologija izradbe detaljnog registra primarne šumske prometne infrastrukture kao podloge za planiranje i optimizaciju radova održavanja šumskih cesta. Šumarski list 139(7–8): 311–328.

Pentek, T, Poršinsky, T., 2012: Forest Transportation Systems as a Key Factor in Quality Management of Forest Ecosystems. Forest Ecosystems – More than Just Trees, J.A., Blanco, L., Yueh-Hsin, (Ed.), InTech, Rijeka, Croatia, 433–464.

Perić, M., Komatina, M., Bugarski, B., Antonijević, D., 2016: Best Practices of Biomass Energy Life Cycle Assessment and Possible Applications in Serbia. Croatian journal of forest engineering 37(2): 375–390.

Petit, J.R., Jouzel, J., Raynaud, D., Barkov, N.I., Barnola, J.M., Basile, I., Bender, M., Chappellaz, J., Davisk, M., Delaygue, G., Delmotte, M., Kotlyakov, V.M., Legrand, M., Lipenkov, V.Y., Lorius, C., PÉpin, L., Ritz, C., Saltzman, E., Stievenard, M., 1999: Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica. Nature 399(6735): 429–436.

Potočnik, I., 1996: Mnogonamenska raba gozdnih cest kot kriterij za njihovo kategorizacijo. Disertacija, Biotechnical faculty University of Ljubljana, 241 p.

Richter, K.,1995: Life cycle assessment of wood products. In: Life cycle analysis – a challenge for Forestry and Forest Industry. Proceedings of the International Workshop, European Forest Institute and the Federal Research Centre for Forestry and Forest Products, 3–5 May, Hamburg, Germany, 69–79.

Schneider, S.H., 1989: The changing climate. Scientific American 261(3): 70–79.

Schwaiger, H., Zimmer, B., 2001: A comparison of Fuel Consumption and Greenhouse Gas Emissions from Forest Operations in Europe. Energy, Carbon and Other Material Flows in the Life Cycle Assessment of Forestry and Forest Products. Achievements of the working group 1 of the COST action E9, European Forest Institute, Discussion paper 10, 952-9844-92-1, Joensuu, Finland, 33–53.

Schweinle, J., Thoroe, C. 2001: Vergleichende Ökobilanzierung der Rundholzproduktion in verschiedenen Forstbetrieben. Mitteilungen der Bundesforschungsanstalt für Forst- und Holzwirtschaft. Nr. 204, Kommissionsverlag Buchhandlung Max Wiedebusch, Hamburg, Germany.

Schweinle, J., 1999: Analyse und Bewertung der forstlichen Produktion als Grundlage für weiterfuhrende forst- und holzwirtschaftliche Produktlinien – Analysen. Mitteilungen der Bundesforschungsanstalt für Forst- und Holzwirtschaft, No. 184., Kommissionsverlag Buchandlung Max Wiedebusch, Hamburg, Germany.

Sedjo, R.A., 1989: Forests to offset the greenhouse effect. Journal of Forestry 87(7): 12–15.

Sever, S., Horvat, D., 1996: Razvoj i organizacija hrvatskoga energetskog sektora, Knjiga 6 Gospodarenje šumama u Hrvatskoj – Proizvodnja i potrošnja energenata i energije. Coauthors: Anić, I., Fabijanić, G., Figurić, S., Hodić, I., Krpan, A.P.B., Matić, S., Meštrović, Š., Oršanić, M., Polaček, M., Poršinsky, T., Puljak, S., Risović, S., Tomljanović, S., 1996: Energy Institute Hrvoje Požar. Zagreb, Croatia, 1–76.

Sharrard, A.L., 2007: Greening Construction Processes Using an Input-Output-Based Hybrid Life Cycle Assessment Model. PhD thesis, Carnegie Mellon University Pittsburgh, Pennsylvania, 343 p.

Siegenthaler, U., Stocker, T.F., Monnin, E., Luthi, D., Schwander, J., Stauffer, B., Raynaud, D., Barnola, J-M., Fische, H., Masson-Delmotte, V., Jouzel, J., 2005: Stable carbon cycle-climate relationship during the Late Pleistocene. Science 310(5752): 1313–1317.

Sokolović, Dž., Bajrić, M., 2013: Otvaranje šuma. Forestry Faculty University of Sarajevo, 248 p.

Spielmann, M., Scholz, R.W., 2005: Life Cycle Inventories of Transport Services. The International Journal of Life Cycle Assessment 10(1): 85–94.

Stampfer, K., 2010: Forest Engineering – Course Script. Institute of Forest Engineering, Department of Forest and Soil Sciences, University of Natural Resources and Life Sciences – BOKU, Vienna, Austria.

Svenson, G., 2011: The impact of road characteristics on fuel consumption for timber trucks. In P., Ackerman, H., Ham, E., Gleasure, (Ed.) Proceedings of 4th Forest Engineering Conference: Innovation in Forest Engineering – Adapting to Structural Change. Stellenbosch University, 172 p.

Šikić, D., Babić, B., Topolnik, D., Knežević, I., Božičević, D., Švabe, Ž., Piria, I., Sever, S., 1989: Tehnički uvjeti za gospodarske ceste. Scientific Traffic Board of Yugoslav Academy of Science and Art, Zagreb, Croatia, 78 p.

Treloar, G.J., Love, P.E.D., Crawford, R.H., 2004: Hybrid lifecycle inventory for road construction and use. Journal of construction engineering and management 130(1): 43–49.

Vusić, D., Đuka, A., 2015: Repositioning of Forest Biomass as a Renewable Source of Energy – Implications to Harvesting Operations in Croatia. Proceedings of the Conference CROJFE 2015: Forest Engineering – Current Situation and Future Challenges. 18th–20th March 2015, Zagreb – Zalesina, Croatia.

Wegener, G., 1994: Der positive Beitrag der Holznutzung zur CO_2 Bilanz. In: Scientific conference »Holz im Rahmen der Internationalen Grünen Woche«, F.W. Bröker (Ed.). Mitteilungen der Bundesforschungsanstalt für Forst- und Holzwirtschaft, Kommissionsverlag Buchhandlung Nr. 176, Max Wiedebusch, Hamburg, Germany, 187–197.

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., Weidema, B., 2016. The ecoinvent database version 3 (part I): overview and methodology. The International Journal of Life Cycle Assessment, [online] 21(9), 1218–1230. Available at: <http://link.springer.com/10.1007/s11367-016-1087-8> [Accessed 15.11.2016.].

Wessman, H., Alvarado, F., Backlund, B., Berg, S., Hohenthal, C., Metsäteho, S.K. Lindholm, E.L., 2003: Land use in eco balance and LCA of Forest products. Report summarize of subprojects 2–5 of Land and Geography project of Nordic Industrial Fund, 25 p.

Whittaker, C.L., Mortimer, N.D. Matthews, R.W., 2010: Understanding the Carbon Footprint of Timber Transport in the United Kingdom. North Energy Associates Limited, Northumberland, United Kingdom, 66 p.

Whittaker, C.L., Mortimer, N.D., Murphy, R., Matthews, R.W., 2011: Energy and greenhouse gas balance of the use of forest residues for bioenergy production in the UK. Biomass and bioenergy 35(11): 4581–4594.

Yoshioka, T., Aruga, K., Nitami, T., Kobayashi, H., Sakai, H., 2005: Energy and carbon dioxide (CO_2) balance of logging residues as alternative energy resources: system analysis based on the method of a life cycle inventory (LCI) analysis. Journal of Forest Research 10(2): 125–134.

Zah, R., Boni, H., Gauch, M., Hischier, R., Lehmann, M., Wager, P. 2007: Life cycle assessment of energy products: environmental assessment of biofuels. Final Report, EMPA—technology and society Lab, Auftrag des Bundesamtes für Energie, des Bundesamtes für Umwelt und des Bundesamtes für Landwirtschaft, Bern, Switzerland, 20 p.

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