Is Life Cycle Assessment in Forestry Still at a Starting Position?

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Abstract

Life cycle assessment (LCA) is one of the most used tools for environmental management, but its application in forestry is still slow. Forestry and wood technology together produce vast amount of different wood products, but the production of timber as raw material is still not included often enough in the LCA process. Production steps have a significant influence on the environmental impact of wood products depending on machinery used, building and maintaining forest roads, management type (clear-cut, even-aged management or selective cut) etc. This paper will show past and present of LCA studies in forestry and its sections: 1) harvesting operations, 2) biomass and 3) forest infrastructure network construction and maintenance.

Keywords: life cycle assessment, energy consumption, environmental management, wood products, environmental impact

1. Introduction

Forestry continues to be a provider for various industries in terms of renewable raw materials, household fuel wood and progressively for biofuels. The development of environmentally friendly technologies, which are basically based on utilization of renewable resources, is still happening slowly, which makes them not-so-cheap replacements to the current fossil fuel technologies and processes while delaying the achievement of sustainable development (Perić et al. 2016). 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 which contributed to higher GHG (Green House Gases) emissions (Berg 1997, Athanassiadis 2000, Berg and Karjalainen 2003).

Trees represent a sink for CO2 by fixing carbon during photosynthesis and storing excess carbon as biomass and net long-term CO2 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 CO2 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). Old-growth managed forests stock more carbon as oppose 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). 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.

International Organization for Standardization (ISO) defines LCA as »compilation and evaluation of the inputs, outputs and potential environmental impacts of a product system throughout its life cycle« (Guinée et al. 2002). Authors conclude that the environmental burden covers all types of impacts upon the environment, including extraction of different types of resources, emission of hazardous substances and different types of land use. LCA project is more than just a study because its results could be used in decision-making by industry, government and non-governmental organisations. Authors summarize with LCA limitations: 1) broad scope of analysing the complete life cycle of a product can only be achieved at the expense of simplifying other aspects; 2) it cannot address localised impacts; 3) it does not have a dynamic rather than steady-state approach; 4) it does not include market mechanisms nor secondary effects on technological development; 5) it is based on linear modelling; 6) environmental impacts are often described as »potential impacts« because they are not specified in time and space and are often arbitrary defined functional unit; 7) it involves a number of technical assumptions and value choices rather than being science-based…and so on.

Nevertheless, LCA is one of the leading and most used tools for overall environmental management (Curran 2016, Finnveden et al. 2009), especially when comparing to carbon footprint calculations in which climate change related greenhouse gases are exclusively considered (EC 2010). Authors continue that initially such limitation is justified, but other relevant impacts such as acidification and eutrophication are very closely and positively related with climate change.

Data from life cycle inventories (LCI) of forest operations provide the forest industry with the input required for assessing its products (Berg and Lindholm 2005). 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 will choose between several alternatives considering differences in environmental effects of the product. This information may be provided by industry, environmental or consumer organisations or by the public sector (Guinée et al. 1992), but also from the scientific community in overall goal of environmental soundness.

Land use and forestry aspects in LCA are complex because of the dynamic nature of forests and long-term production period of the raw material, which is usually corresponding to rotation period. Modelling 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). Environmental system has to be a part of the analysis, characterized by input flows such as CO2, 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 modelling of materials, energy, emission and waste flows (Heinimann 2012).

Most common programs for LCA today are: Bees (NIST – National Institute of Standards and Technology), EcoCalculator (The Athena Institute) ECO-it (Pré Consultants BV), Ecolab version (Nordic Port AB), Gabi 4 (PE Product EngineeringGmbH), PEMS (Pira International), Sima Pro (PRE Consultants BV), Umberto (IFU Institut für Umweltinformatik, Hamburg GmbH), Gemisi (International Institute for Sustainability Analysis and Strategy).

In exploring Ecoinvent multi-product activity datasets, that form the basis for all the other system models, with terms such as: timber, roundwood, oak, spruce, fir or beech, it can be concluded that some of the data regarding timber production (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 to/from environment aspect lacks data. 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 which 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 which was also highlighted by Frühwald (1995), Heinimann (2012), Klein et al. (2015) who stated that inventory analysis is the heart of LCA, taking a considerable amount of time and being extremely data intensive. 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, construction of forest infrastructure network, management type etc.

SimaPro 8.2.3 inventory, which includes databases: ecoinvent v3, Agri-footprint, US LCI, ELCD, EU and Danish Input Output, Industry data v.2 and Swiss Input Output, contains term »wood« in many processes. From construction materials (doors, windows), carbon content biogenic materials, paper + board industries, and as a separate entry »wood« where vast number of products from wood chips, raw cork, sawnwood, pulpwood, cleft timber, sawlogs etc. can be found. 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 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 from post-harvest processes (potential forest degradation/deforestation) as well as forest road area which 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.

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

2. 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 fulfil their »cradle to grave« requirement (Heinimann 2012).

Berg (1997) uses LCA techniques in assessing the environmental loads imposed by different types of felling (clear-cut 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 work was not separated from felling. Shelterwood cutting had 10% higher emissions that clear cutting as well as forwarding, which had 20–25% higher emissions in shelterwood management system and it can be expected that in selective forests energy inputs will be even higher. Author concludes that motor-manual felling had lower emissions per cubic meter than mechanized felling and that even heavy deployment of resources for conveying personnel between home and 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.

Most studies in considering harvesting operations actually report on used or invested energy or simply on energy returned on invested (EROI). For example, Athanassiadis (2000) estimated a combined fuel and oil energy use for harvesting and forwarding of 82 MJ/m3, but this did not include the energy used during the production of the 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). 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. Authors state that half of the energy used per cubic metre in Swedish forestry is provided for secondary transport from forests to industries. Enhancing payload per distance, removing return unloaded trips, improving standard of forest roads (road width, curvature and better surfacing as well as »soft« driving) would improve current situation. Type of cutting operation (final felling or thinning) had larger influence on energy input per volume of timber than geographical area of operations. Final feeling consumes less energy (30 MJ/m3) than thinning (48 MJ/m3). Forwarding timber to forest roads in final felling consumed 22–27 MJ/m3 s.u.b. (solid under bark) while in thinning 31–34 MJ/m3 s.u.b. Silviculture operations consumed 11 MJ of energy and seedling production 8 MJ. In conclusion all forest operations in Sweden during one year produced 15 kg/ CO2-equiv./m3 which is a small amount (0.3 Tg C a-1) to national emissions from fossil fuels 18.9 Tg C a-1.

Börjesson (1996) states that the energy required for the production of material embedded in vehicles amounts to average 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) in their paper provide an analysis of the raw materials used in the forestry equipment and energy needed for production of each of the materials. According to their analysis, based on the vehicles mass, Pandur et al. (2015) calculated the total energy consumed in production of materials used in 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 use in the production of forwarders to be related to the mass of the machine, as follows 66.4 MJ/kg.

Klvač et al. (2003) calculated total energy input per unit of wood production (m3) from the fuel and oil consumption and the average mass of machines and replacement materials. The mean energy input was 66.7 MJ/m3 for harvesters and 52.7 MJ/m3 for forwarders, thereby giving a total system energy requirement of 120 MJ/m3 (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/m3 (felling and processing logs) and 31.92 MJ/m3 (felling and processing of one-meter-long firewood), 2) 65.81 MJ/m3 for forwarders and 3) 59.72 MJ/m3 for forest tractor assemblies. For input parameters they used fuel and oil consumption and energy embodied in machines and spare parts (tyres, chains, sprockets and guide bars of chainsaws).

Lindholm (2006, 2010) states that according to several European forestry studies, the energy used in silviculture and logging ranges from less than 60 MJ/m3 timber up to 270 MJ/m3. These findings have been corroborated by the studies of Schweinle and Thoroe (2001), which also considered road building and provide estimates of 170–270 MJ/tonne of dry wood (70–120 MJ/m3). Secondary transport accounts for 90 to 223 MJ, raising total energy use to a level of 180-395 MJ/m3. However, energy use has been shown to be higher in exceptionally difficult terrain conditions (Wegner, 1994), and in long-distance transport of pulpwood (Gonzáles-Garcia et al. 2009; Michelsen et al. 2008) and when silviculture is highly mechanised with a high use of chemicals (Gonzáles-Garcia et al. 2009).

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

Karjalainen and Asikainen (1996) reported that fuel consumption in Finland is 56 l/100 km, while emissions of greenhouse gases (CO2, CH4 and N2O) is 0.03 kg/m3km. According to Svenson (2011) fuel consumption in Sweden is 28 l/100 km, and according to Klvač et al. (2013) in Czech Republic fuel consumption amounts to 2.19 l/m3 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 m3 of wood in lowland forests is 634 MJ/m3, of which fuel amounts to 86% which is similar to Klvač et al. (2003). Of all operations necessary for the production of 1 m3 of wood, energy consumption in timber truck timber transport amounts to 31% of total energy consumption (Pandur et al. 2015.).

In searching through SimaPro data bases for values on most common harvesting technologies and equipment, only 3 inputs regarding chainsaws (felling and delimbing) are available (not undergone formal validation), regarding diesel consumption of the machinery, hydraulic oils and general lubricants required for the hydraulic systems and moving parts of the harvesting equipment. Harvester can be found in 30 studies, feller buncher in only 2, skidders in 33, forwarders in 60 and for forest skylines or highleads there is no available data.

3. Forest biomass

With the development of the civilization a major shift towards the use of technical properties of wood occurred, but the role of the wood in energy production remained significant since lignocellulosic biomass used to be the main source of energy. (Vusić and Đuka 2015). Because of increasing environmental concerns and energy production towards sustainable sources of energy, forest industry is expected to play a significant role. Among all the available alternative energy sources (hydro, solar, wind, etc.) forest 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.

Past research on environmental burdens of forest biomass production relied mostly on energy analysis, quantifying consumed energy and CO2 or GHG emissions, while recent studies favor LCA and include wider range of environmental impacts (Djomo et al 2011). Klein et al. (2015) state that for the European forestry and wood products sector, the first tangible LCAs 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) (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 environmental 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 been discussed in the forestry sector for 20 years already, there is still a poor amount of information based on scientific research. They name two reasons for this situation; one being the fact that in many cases, forest production is not the main study objective but rather their subsequent products (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 the forest production; and other the overall opinion that their respective processes have only minor environmental impacts, and providing wood for material or energetic purposes is nearly carbon-neutral (Miner and Gaudreault 2013).

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 with the consideration 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 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 CO2-equiv. per m3 o.b. (over bark) mean GWP (Global Warming Potential) from site preparation to forest road, adding 6.3–67.1 kg CO2-equiv. per m3 o.b. for transport processes and in average 20.5 kg CO2-equiv. per m3 o.b. for chipping processes, and 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 land use change effects (LUC – Land Use Change, iLUC – indirect Land Use Change) can be excluded (Klein et al. 2015). In support to their report that the GHG-emissions, even in the worst case of 28 analyzed literature sources, are still low (9 %) compared with 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. Reported results on energy ratios varied 13–79 for the cradle-to-farm gate and 3–16 for cradle-to-plant assessments, and the intensity of GHG emissions ranged 0.6–10.6 g CO2-equiv. per MJ (39–132 g CO2-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).

Heller et al. (2003) in their research of SRWC (Short Rotation Woody Crop) willow for energy stressed the importance of analysing 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’s 23-year lifetime. 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, and that this practice could increases 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 CO2 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. Same authors conclude that in biomass truck transport (40 t total weight) energy consumption was 188.9 MJ/t dry matter with average distance of 96 km, while Pandur et al. (2015) state that energy consumption of wood chips with 35% moisture content with haulier truck on 50 km average distance was 77.35 MJ/t.

Pandur et al. (2015) calculate EROI for wood chips from shelterwood cuttings of lowland oak forests. In calculation they include parameters such as: 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: tyres, 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. Biomass transport by railroad takes up to 0.7 MJ/tkm, twice smaller than by truck, while water transport uses 0.23 MJ/tkm – six times smaller amount on 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 takes from 72.4% for adapted farm tractor to 97.1% for railway, while rest of the 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, modelled 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 perspective. They reported the energy output/input ratio of chips from residues and stumps in the range 21–48, and the greenhouse gas emissions 1.5–3.5 g CO2-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 (CO2) 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 CO2 emission per MWhe (1 MWhe = 2.6136 MWh) of the biomass-fired power generation plant (61.8 kg CO2/MWhe) whit that of coal-fired power generation plants in Japan (960 kg CO2/MWhe) the reduction in the amount of CO2 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 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 the 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 managementactivities because the whole tree is delivered to the landing as part of the primary product harvest. There is no allocation of cost, fuel, and any corresponding environmental burdens required to deliver the tops and limbs to the landing. Those are carried by the primary product. Authors 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.

It is evident that that system boundaries are reflected by the raw material characteristics and the place where it is produced/located. This is especially important when analyzing wood energy products, because raw material for their production can be regarded either as waste or a 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 to the 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 has 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, it’s 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 from conversion processes and type of end-products and in studies which aim 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 the entirety of impacts. Therefore, they suggest that as a default, results should be referred to 1 m3 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 enable a calculation of 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 the 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 the 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 for the quantitative comparison (Klein et al. 2015).

Furtula (2014) in his model for defining factors that affect energy consumption and GHG emission during the production of solid wood fuels, concludes that firewood has the lowest energy consumption and CO2-equiv., however it has a high raw material consumption per unit of produced thermal energy. A production of wood chips has a bit higher energy consumption and GHG emission effect than firewood, and the lowest raw material consumption per unit of produced thermal energy. Pellet has the highest energy consumption and CO2-equiv. emission among the respective solid wood fuels, however, it is possible to reduce the consumption of thermal energy by natural drying of raw material, and to reduce GHG emission effect by deploying the process of cogeneration (CHP) in production process. Wood pellet has a lower consumption of raw material per unit of produced thermal energy compared to firewood, which makes it more preferable for use in household furnaces and boilers. Figure 1 and 2 show environmental impact (calculated in SimaPro program) regarding firewood, pellets and chips with varying moisture content, and chip production (mobile diesel driven chipper or stationary electric driven chipper). Relations were conducted according to energy unit (MWh) of lower heating power.



**Fig. 1** The impact of the production of firewood and pellets on the environment (Source: Furtula 2014)

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**Fig. 2** The impact of the production of firewood and chips on the environment (Source: Furtula 2014)

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 the question of efficient land use (bioenergy vs. carbon sequestration) and predict that future LCA studies will focus on reducing the uncertainties of these current key open 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).

4. Forest infrastructure network construction and maintenance

Environmental impact studies in forestry usually exclude forest transport infrastructure impact, which is according to Treloar et al. (2004) correlated 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.

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 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 permanent forest road in Finland is 3290.74 kg CO2, 0.0826 kg N2O, 27.50 kg CO, 0.2374 kg CH4, 39.648 kg NOx 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 to 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, same authors according to another study of Häkinnen and Mäkelä (1996) 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 in advance adopted strategy.

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 to study 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. All analysis was based on following average values of forest road parameters in hilly-mountainous parts of Switzerland: 1) a roadbed width of 4.2 m, 2) a cut slope angle of 1:1, 3) a fill slope angle of 4:5, 4) a thickness of the base course of 0.3 m, 5) a thickness of the surface course of 0.08 m, and 6) a transport distance for base course materials of 10 kilometers. Authors concluded as follows:

* On moderate slopes 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 emitted greenhouse gas.
* 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.
* 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 by increasing it from 4.2 m to 6.2 m.

Above stated results and conclusions were later again 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 depending on the side slopes and CO2 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 CO2 emissions. Authors, similarly to Heinimann and Maeda-Inaba (2003), estimate that required diesel fuel for roads constructed on slopes up to 50%, while using a cut-fill construction method, was 1400 l/km, with emitting 3777.59 kg of CO2/km, while on slopes higher than 50% with 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 CO2/km was emitted. It is evident that fuel consumption and CO2 emissions were 5.5 times greater on slopes higher 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 CO2-equiv. km-1 road. It should be mentioned that understanding of road maintenance operations as environmental burden is even more difficult to find in scientific studies, such data is usually ignored due to lack of data bases 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 the necessity of further investigation into the actual extent and frequency of forest road maintenance regarding 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. To maintain 1 km of road requires 102 GJ and 9000 kg CO2-equiv. Authors, further divide forest roads to 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 operations.

Furthermore, authors state that over the full forest rotation period, road maintenance requirements exceed that 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 CO2-equiv., while 1912.2 MJ ha a-1 of energy is required and 129.9 kg ha a-1 CO2-equiv.is emittedduring forest road maintenance operations.

5. Conclusions

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 possibility to compare the research results and provide solid ground for coherent conclusions.

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 is 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 either skidders and processors on the landing or cable yarders with processing heads concentrate the logging residues at the landing site and setting the system boundaries from comminution phase onwards.

Production in forestry, as oppose to wood processing industry, can be roughly divided to: 1) roundwood, 2) long-meter firewood, long stackwood and 3) slash; therefore, results should be based to 1 m3 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. Information about the moisture content and wood density should be given in order to enable a calculation of 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 to specific research area included in the LCA study due to high differences in data of previous research and overall complexity.

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

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