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Selected Environmental Impacts of Forest Harvesting Operations with Varying Degree of Mechanization

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Abstract

Climate change affects forest ecosystems, impacting timber production and eco-services. Conversely, sustainable forest management has been identified as a means to help mitigate carbon dioxide emissions, a greenhouse gas and contributor to climate change, while also maximizing multiuse benefits through close-to-nature silviculture. In this study, a life cycle assessment was performed on forest harvesting operations at three research sites to provide real-world understanding of the selected environmental impacts associated with harvesting systems typical of Germany: motor-manual (chainsaw and forest tractor), semi-mechanized (single-grip harvester, chainsaw, and forwarder), and fully-mechanized (single-grip harvester and forwarder). Environmental impact categories assessed included greenhouse gas emissions, particulate matter emissions, and non-renewable energy consumption. Results from the three research sites were estimated on a machine basis. The semi-mechanized system resulted in the lowest environmental impact, the majority of which was attributed to felling and processing operations. Next, the environmental impacts were estimated for a complete rotation period and compared amongst the different harvesting systems. According to results, semi-mechanized harvesting systems had the lowest impact over the full rotation period as well as for thinning treatments when compared to motor-manual and fully-mechanized systems. The fully-mechanized system performed the best for final felling treatments. Considering variability between the research sites as well as the system boundary assessed, a diversified approach to harvesting operations may be considered, integrating semi-mechanized and fully-mechanized systems for different treatments throughout the rotation period.

Keywords: forest operations, sustainable forestry, close-to-nature, environmental impacts, greenhouse gas emissions

1. Introduction

With forest ecosystems storing more than 80% of terrestrial aboveground carbon and more than 70% of soil organic carbon, forests can serve as a mitigating agent for increasing carbon dioxide (CO_2) concentrations in the atmosphere, a greenhouse gas (GHG) contributing to climate change (Routa et al. 2011). In some countries, wood is making a revival both as an energy fuel (BMELV 2011a) and in engineered products, substituting non-renewable resources. Historically, technology and the potential for negative environmental impacts associated with wood for energy and product substitution had limited implementation; however, modifications to Intergovernmental Panel on Climate Change (IPCC) accounting for carbon in wood products has shifted perceptions toward wood as a suitable substitute for more energy intensive materials (FAO 2016). On a global level, the FAO provides estimates highlighting the benefits of wood for material and energy uses, with nearly 483 million tonnes of CO_2-equivalent (CO_2-eq.) emissions avoided annually via substitution effects through the use of wood-based building materials, and 25 million tonnes of CO_2-eq. emissions avoided by burning wood at the end of life instead of fossil fuels (FAO 2016). With regard to forestry, forest management is recommended as the best climate change mitigating strategy (compared to reforestation and afforestation) considering its relatively short timeframe and ease of implementation (BMELV 2011b). The optimization of silvicultural treatments and low-impact harvesting are examples of strategies for improving forest stocks (FAO 2016). Harvesting timber for wood products has the potential to store more carbon than conserved forests over the long term given the higher standing tree volume and long-term use of wood products (FAO 2016), with cascading wood use extending the time of storage, which further delays contribution to the greenhouse effect (Höglmeier et al. 2015). Additionally, low-impact harvesting techniques are recognized for mitigating climate change as wood demand grows with an estimated reduction of 6.5 to 12 tonnes CO_2-eq. emissions per hectare over the next 7 to 70 years (FAO 2016).

While studies have shown the environmental benefits of wood products as a carbon sink during their service life as well as a reduction in energy consumption compared to alternative materials, not all environmental impacts are understood (González-García et al. 2013). Wood and wood products are commonly claimed as »carbon neutral«, but perhaps »low GHG emission raw material« is more appropriate as emissions are necessary for the procurement of timber even if the ratio of GHG emissions to carbon content is quite low (Klein et al. 2016). Additionally, while the demand for forest resources grows, it is necessary to recognize that, while it is a renewable resource, it is not infinite (Wolf et al. 2015). This places great importance on identifying the most beneficial and efficient utilization of wood and the forest ecosystem, a task that can be performed by a life cycle assessment (LCA). LCA is a useful analytical tool defined by the International Organization for Standardization (ISO) as the »compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle system« (EN ISO 14040, 2009). LCA in the forestry sector has become an important method for understanding the environmental impacts associated with providing wood (Valente et al. 2011, Klein et al. 2016, Horvat et al. 2017, Proto et al. 2017, Abbas and Handler 2018), despite challenges such as the long time-frame associated with stand establishment; different forest operations and wood products; as well as consideration of non-timber forest services such as water, biodiversity, and tourism (England et al. 2013).

In this study, we focused our assessment on timber procurement from forests under close-to-nature (CTN) management with varying degree of harvest system mechanization. With CTN management, harvest operations are performed on a selective basis to maintain continuous forest canopy coverage, while regeneration occurs through natural processes. While it is difficult to differentiate thinnings from final fellings, and one rotation period from the next in CTN forestry, in this study »thinnings« (TH) are considered as silvicultural treatments that remove trees of smaller diameter to promote the highest value trees in the stand, while »final fellings« (FF) are the removal of those high value trees at their peak value.

The three most common harvesting methods include full-tree (FT), tree-length (TL), and cut-to-length (CTL). The FT method requires only felling of the tree, which is then skidded to the truck accessible road without undergoing any processing in the forest stand. The TL method requires felling, delimbing (removing branches), and topping (cutting the top of the stem at a specified diameter) before transport from the stump to the truck accessible road. The CTL method involves the same processing elements as TL, but adds bucking the stem into assortments (cutting the stem into logs of different specified lengths) before being hauled from stump to truck accessible road. The CTL method, when performed in a fully mechanized system, generally produces higher quality and more consistent timber products than FT and TL methods in a more environmentally conscientious, versatile, and safe manner (Nurminen et al. 2006). Harvesting systems in this study are classified as motor-manual (MM), semi-mechanized (SM), or fully-mechanized (FM). Motor-manual operations commonly use chainsaws operated by loggers to perform felling and processing tasks and then wood is transported to landings with skidders, forwarders, tractors, or animals. Semi-mechanized systems involve the integration of lower mechanized techniques, such as loggers, with machinery, such as a single-grip harvester. Fully-mechanized systems exclusively use machines such as single-grip harvesters (felling, delimbing, processing) or feller-bunchers (felling), forwarders, skidders or clambunks for hauling, stroke delimbers for delimbing, slashers for processing, or chippers for comminution.

Despite the difficulties in comparing LCA studies, literature consistently attributes the greatest emissions and fossil fuel consumption associated with forest management to harvesting machinery. For example, regarding a LCA of Douglas fir (*Pseudotsuga menziesii*) plantation management in Southwest Germany, González-García et al. (2013) identified thinning and logging processes as the major contributors to environmental impacts. Similarly, Klein et al. (2016) calculated that more than 55% of GHG emissions are associated with felling and forwarding in models of raw wood supply chains in Bavaria, Germany. With CTN (»retention«) forestry implemented on more than 50%

of forest lands in Germany (Gustafsson et al. 2012), and utilization of mechanized systems growing over recent years, particularly on public lands (Bayerische Staatsforsten [BaySF] 2015), Germany served as an ideal setting for carrying out this LCA.

The goal of this study was to gain a better understanding of the environmental impacts associated with three forest harvesting systems of increasing mechanization performed under CTN management. This was achieved through LCA of operations at three research sites in Germany implementing MM, SM, and FM systems, respectively, to estimate the GHG emissions, particulate matter (PM) emissions, and non-renewable (NR) energy consumption associated with timber harvesting, from the time of felling until the timber is placed at the truck accessible road. The objectives within the contexts of the three research sites were to:

⇒ estimate the influence of forest operations with varying degree of mechanization on GHG emissions, PM emissions, and NR energy consumption separated by machines

⇒ calculate and compare the environmental impacts of these three harvesting systems over the rotation period of the forest stand

⇒ provide detailed data within the growing field of forestry LCA to compare real-world estimates obtained from CTN forestry to theoretical studies.

The research is innovative in two respects:

⇒ it uses real-world conditions for monitoring live forest operations under a degree of mechanization to allow a comparison to more theoretical LCA's

⇒ it provides recommendations for optimizing harvest system selection, as well as areas for further technological and operational research, in order to mitigate environmental impacts associated with forest harvest operations.

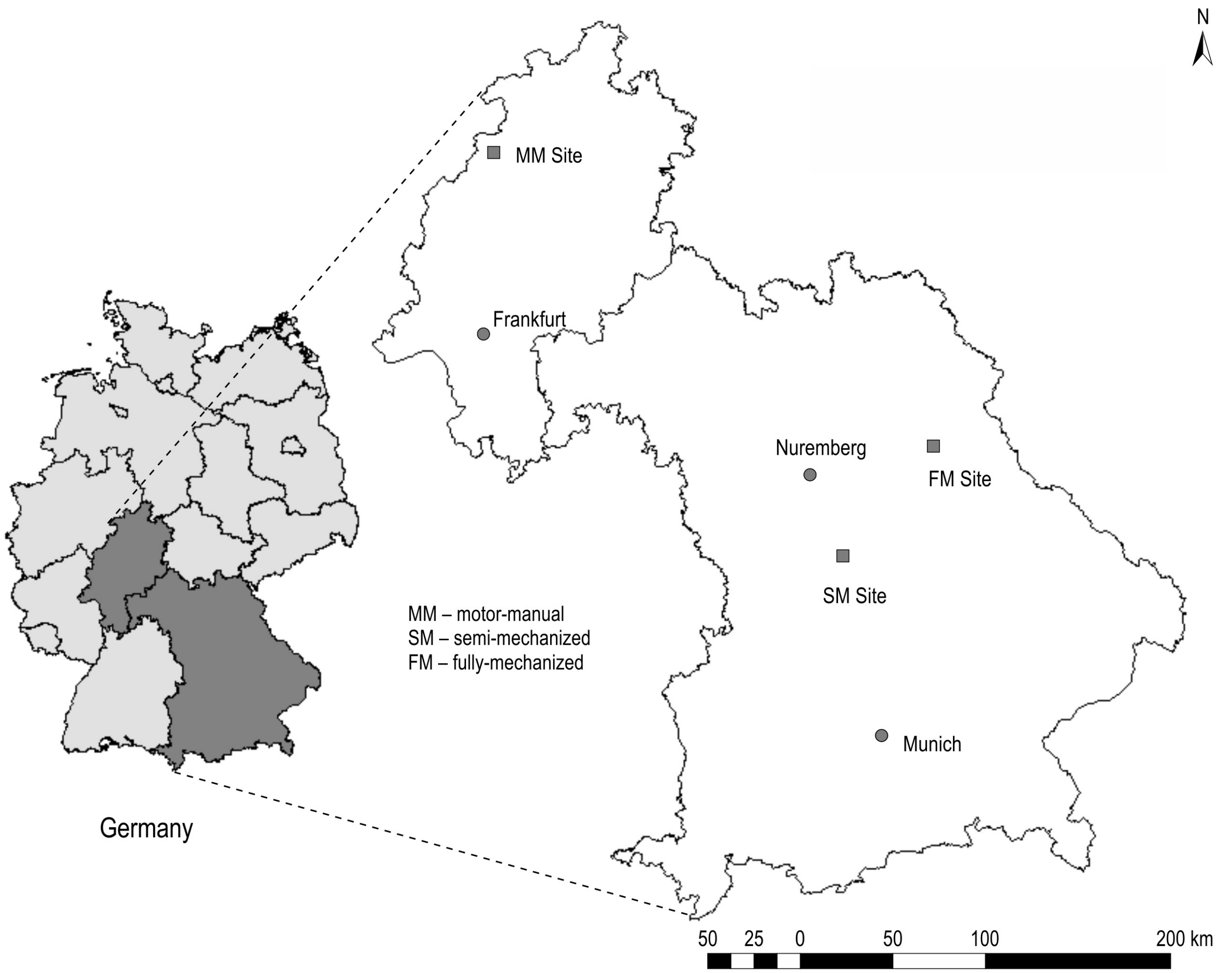

Fig. 1 Map of research sites within Germany

2. Materials and Methods

2.1 Research Site Description

Motor-manual harvesting was performed in northern Hessen, Germany (51°04′39.8″N, 8°32′59.8″E; Fig. 1). The harvest block, composed predominantly of Norway spruce (*Picea abies*), was approximately 3.5 ha with a 20–25% south facing slope at approximately 550 m above sea level (Table 1). Despite remaining in the upper range of acceptable terrain slope for the use of single-grip harvesters and forwarders, MM operations were chosen by the forest management unit. Semi-mechanized harvesting was implemented in central Bavaria, Germany (48°55′45″N, 11°06′01.5″E) at a harvest block of 12.2 ha of undulating terrain with very little slope variation at an elevation of approximately 550 m above sea level. Tree composition was primarily Norway spruce with some European beech (*Fagus sylvatica*). Fully-mechanized harvesting was performed in central Bavaria, Germany (49°36′34.5″N, 11°53′00″E). The harvest block, composed of Scots pine (*Pinus sylvestris*) with some Norway spruce, was pproximately 9.6 ha at an altitude of 350 m above sea level. All three research sites were located in public forests.

Concerning stand characteristics, the SM site had the largest mean tree DBH (45.6 cm, N=428) of the three sites, followed by the MM site (39.6 cm, N=135) and then the FM site (28.6 cm, N=818; Table 1). The difference in mean DBH between the sites was statistically significant (f=496.4, p=0.000) based on a one-way ANOVA with a significance level of 5%. A similar trend was also present for measured tree heights, which varied from 23.4 and 32.3 m as well as standing volume which ranged from 220 to 600 m^3/ha.

2.2 Harvesting Operations and Machine Specifications

The harvesting method chosen at the MM site was TL, where two Husqvarna 562 XP-G chainsaws were used by experienced loggers to fell, delimb, and top trees in the forest stand (Fig. 2A and Table 2). Trees were winched from their felling point within the harvesting block with a Pfanzelt PM Trac 2375 forest tractor at a maximum distance of 75 m (half of the machine operating trail length) to the tractor and then skidded with the tractor mounted grapple along the truck accessible road to the landings (Fig. 2B and Table 2). Bucking was performed at the landings by loggers with a Husqvarna 562 XP-G or by the forest tractor operator using a Stihl 362 chainsaw (Fig. 2C). Stems were bucked to three different assortments with sawtimber cut to lengths as long as possible without exceeding the maximum allowable transport length of 21 m. Table 2 includes manufacturer specifications, of which some data was used for calculations, while other data was included for informational purposes only.

Cut-to-length was the harvesting method used at the SM research site, where a 2016 Ponsse Bear single-grip harvester (Fig. 2D and Table 2) felled, delimbed, topped, and bucked trees that were within boom reach into five different assortments. The eight-wheel harvester had a Ponsse H8 harvesting head mounted on a 10 m long boom. Trees, pre-selected by the district forester within boom reach, were felled and processed by the harvester, and trees located beyond the reach of the harvester boom were felled motor-manually by experienced loggers using chainsaws. Productivity and consumption data was collected for a Husqvarna 560 XP-G chainsaw (Fig. 2E and Table 2). Following harvesting

Table 1 Stand characteristics

Research site	Harvest block area	Species composition[a]	Tree age[b]	Average			
				DBH[a]	Height[a]	Stem volume[a]	Standing volume[b]
	ha		yr	cm	m	m^3/tree	m^3/ha
MM	3.5	Norway spruce, 100%	47–101[c]	39.6[d]	26.8[d]	1.60[e]	450
SM	12.2	Norway spruce, 94% European beech, 6%	55–100	45.6	32.3	2.72	600
FM	9.6	Scots pine, 88% Norway spruce, 12%	89–135	28.6	23.4	0.80	220

[a] Data based on pre-harvest inventory
[b] Data extracted from the forest management stand description
[c] 97% of trees were at least 97 years old with only 3% of trees 47 years old
[d] MM – Average height estimated from measured tree-length with geometric assumptions to account for stump and tree top. Allometry models (Pretzsch et al. 2012) used to calculate a DBH using adjusted tree height
[e] Based on measurements collected during operations. Calculated volumes divided by a factor of 0.8 to approximate the complete stem
DBH – diameter at breast height, MM – motor-manual, SM – semi-mechanized, FM – fully-mechanized

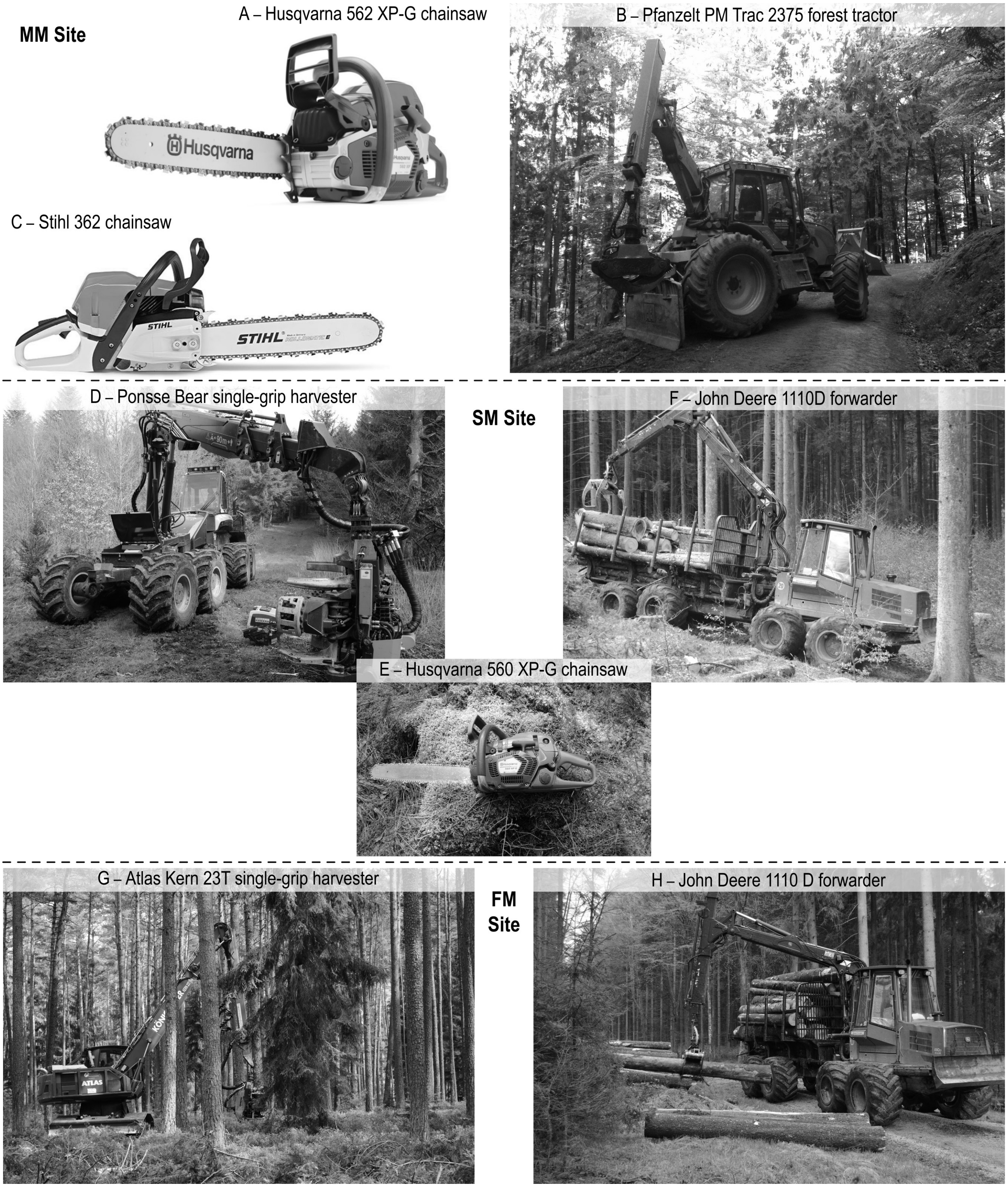

Fig. 2 Machines and equipment used during study

operations, a John Deere 1110D eight-wheel forwarder (Fig. 2F and Table 2) with a load capacity of 12 000 kg was used for log transportation. The CTL harvesting method was used at the FM research site, where an Atlas Kern 23T single-grip harvester (Fig. 2G and Table 2) operated by an experienced operator felled, de-

Table 2 Machine and equipment specifications

	Chainsaws			Harvesters		Extraction	
	Husqvarna 562 XP-G	Stihl 362	Husqvarna 560 XP-G	Ponsse Bear	Atlas Kern 23T	John Deere 1110D Eco III	Pfanzelt PM Trac 2375
Harvesting head	–	–	–	Ponsse H8	Ponsse H6	–	–
Weight, kg	6.1[a]	6.0[a]	5.9[a]	25 250[b,c]	29 050[b,c]	13 670–17 300[c]	12 000
Power output, kW	3.5	3.4	3.5	260	105	121	118
Fuel tank, l	0.65	0.60	0.65	400	264	150	170
Fuel consumption, kg/hr	1.5	1.3	1.7	–	–	–	–
Bar oil, l	0.35	0.33	0.35	–	–	–	–
Hydraulic oil, l	–	–	–	290	180	150	52

[a] Excluding cutting equipment
[b] Including harvester head; excluding rotator
[c] Standard operating weight depends on equipment
Sources: Husqvarna (n.d.a, n.d.b); Stihl (n.d.); Kuratoriums für Waldarbeit und Forsttechnik([KWF],n.d.a, n.d.b); Ponsse (n.d.a, n.d.b); Kern Forstmaschinen (n.d.); John Deere (n.d.); Pfanzelt-Maschinenbau (n.d.)

Table 3 Harvest operations summary

Research site treatment	Harvesting method	Machine	Harvest dates 2016	Harvest intensity m^3/ha	Harvested volume, m^3	Number of trails	Trail spacing m	Trail length m
MM FF	TL	Chainsaw, forest tractor	25–29 April; 11–18 May	50	175	N/A	N/A	150
SM FF	CTL	Chainsaw, single-grip harvester, forwarder	11–19 April	184	2,250	12	15–40	400
FM TH	CTL	single-grip harvester, forwarder	24 June–4 July	78	746	4	30	800

MM – motor-manual, SM – semi-mechanized, FM – fully-mechanized, FF – final felling, TH – thinning, CTL – cut-to-length, TL – tree-length

limbed, topped, and bucked each tree at the stump. The excavator based harvester was equipped with a Ponsse H6 harvesting head mounted on a 14.5 m long boom. Due to trail spacing and long boom reach, all trees were felled and processed with the harvester. Following felling operations, a John Deere 1110 D eight-wheel forwarder was used for log transportation (Fig. 2H and Table 2). A comparison of harvest operations at the three research sites is included in Table 3.

2.3 Data Collection

2.3.1 Felling and Processing

The total volume of fuel and bar oil consumed for the MM system was recorded from the chainsaw fuel tank on a daily basis, along with the number of trees and measurements for those felled and processed in the stand. The amount of consumable materials (e.g. fuel) used for each process were recorded in units available in the field. These data collection units are summarized in Table 4. Stem measurements included total length and the middle diameter before bucking. Lastly, chainsaw working times (including non-productive hours and breaks) were recorded on a daily basis.

MM felling in the SM system was observed for two days of operations, with the tree count, fuel consumption, tank fills, and felling time all recorded. The volume of the fuel cans, both gasoline and bar oil, were documented at the start and finish of the observation period, as well as the total number of trees felled with each refill of the chainsaw tanks. Felling times were measured manually for each individual tree using a stopwatch and marked from the time felling equipment (i.e. chainsaw, axe, and fuel can) was lifted to approach the target tree to the time felling equipment was lifted to transition to the subsequent target tree. Average tree volumes were used to convert consumption rates per tree to consumption rates per cubic meter of timber.

Harvester productivity was recorded with an onboard computer (using Opti4G optimization software), downloaded with a USB memory key, and then imported in the StanForD (Standard for Forest machine Data and Communication) report from the Kuratorium für Wald- und Forsttechnik e.V. (KWF). Within the report, it was possible to acquire such values as trees harvested, number of logs produced, average log diameter and extracted timber volume, and total extracted timber volume per harvest block. The raw data was processed to estimate daily values for trees harvested, extracted volume, and average log volume. In the SM system, harvester diesel consumption values were recorded for four days of operations with estimates for the consumption of transmission oil, head grease, bar oil, and AdBlue (diesel exhaust fluid) provided by the machine operator. In the FM system, diesel consumption and machine hours were recorded from harvester gauges, while other material inputs such as head grease and bar oil were estimated by the machine operator. In all cases, the operator noted the amount of material used during each day in a notebook. Data for all five days of operations was collected.

Table 4 Consumable materials – field data units

Research site	Machine	Data	Units
MM	Chainsaw	Gasoline	liters
		Bar oil	liters
	Forest tractor	Diesel	liters
		Grease	grams
		Hydraulic oil	liters
SM	Chainsaw	Gasoline	liters
		Bar oil	liters
	Harvester	Diesel	liters
		Transmission oil	grams
		Head grease	grams
		Bar oil	liters
		AdBlue (DEF)	liters
		Hydraulic oil	liters
	Forwarder	Diesel	liters
		Grease	grams
		Hydraulic oil	liters
FM	Harvester	Diesel	liters
		Head grease	grams
		Bar oil	liters
		Transmission oil	grams
		Hydraulic oil	liters
	Forwarder	Diesel	liters
		Grease	grams
		Hydraulic oil	liters

MM – motor-manual, SM – semi-mechanized
FM – fully-mechanized, DEF – diesel exhaust fluid

2.3.2 Extraction

Diesel and grease used by the forest tractor in the MM system were recorded on a daily basis along with machine operating hours and distance driven for winching, grapple skidding, and manipulation of timber at the landing. Diesel consumption of forwarders was recorded on a daily basis, while grease input was estimated by the operator. To estimate load volumes, the total number of logs per load was counted and a subset of 15% was subjected to diameter measurements and assortment classification. At the SM research site, forwarder load volumes were calculated for four days of operations and at the FM research site, the load volumes were calculated for two of the five days of operation. Machine operating hours were also recorded on a daily basis.

2.4 Life Cycle Assessment

2.4.1 System Description

This study focused on timber harvesting operations, including felling, processing, and extraction from the stand to forest road, using three different harvesting systems. Harvesting is a process in a larger system of forestry activities typically identified in cradle-to-gate LCA for timber procurement. A common system boundary for the three harvesting systems is displayed in Fig. 3, while the machinery and methods within that boundary vary. This system boundary excludes the upstream environmental processes and forest management as well as downstream operations such as long-distance transportation and secondary processing at a mill. The database from which impact conversion factors were taken does consider upstream and downstream functions associated with machines and materials implemented for timber harvesting, such as equipment manufacturing, fuel production, and lubricant disposal, in addition to the impacts directly attributed to material consumption. This is an important consideration, as energy incorporated into the harvesting machinery can equal 40–50% of the direct process energy (Knechtle 1997). However, the impact conversion factors taken from the database do not include moving and transportation of equipment or personnel between sites.

To obtain a comparable field of reference to other LCA studies, impact categories calculated for the specific events were also extrapolated over a common timeframe i.e. one rotation period. Lastly, non-merchantable residual wood and the potential changes in the carbon content of the forest soils are not included in this study. As stated in Klein et al. (2016), even if the harvesting of residual wood less than 7 cm in diameter is becoming more popular, it is not common. It is controversial in Bavaria as it can affect soil fertility and therefore forest growth, thus it is viewed as an unsustainable forest practice for the majority of harvest sites (Klein et al. 2016).

2.4.2 Functional Units

Functional units are applied in order to normalize the system inputs and compare the impact categories between the harvest systems and with other studies. Consumption rates and impact categories are reported per cubic meter of extracted timber over bark (m^3 o.b.) with a stem diameter greater than 7 cm. Materials consumed and allocated machinery usage have been converted to kg when necessary, using the appropriate material properties and machine hours. In the cases when temporal or spatial comparisons are required, functional units of productive machine hour (PMH), estimated working hour (EWH) or machine operating hour (MH), as available, and hectares were used, respectively.

Impact categories allow for the measurement and comparison of the relationship between resource consumption and emitted pollutants per functional unit (Heinimann 2012). This study focuses on both emission-related (GHG and PM) and energy-related (NR energy consumption) impact categories as these are representative of influences on global climate change and are readily compared with existing studies from a range of geographical areas implementing similar forest operations. Other site-specific categories such as water impacts, soil impacts, and biodiversity, as well as economic and social evaluations were excluded since these impact categories can be affected by regional and environmental factors, for which data was not available. GHG emissions are reported in kilogram of carbon dioxide equivalent (kg CO_2-eq). As defined by IPCC (2007), »CO_2-equivalent emission is the amount of CO_2 emission that would cause the same

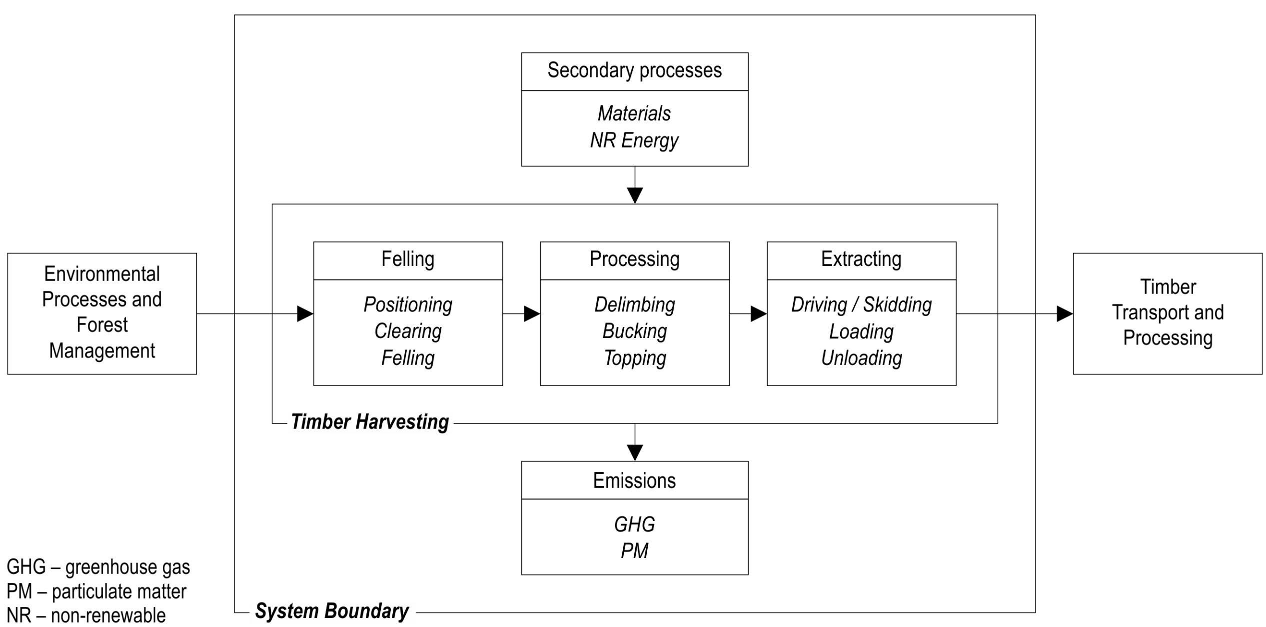

Fig. 3 System boundary for the three case studies

time-integrated radiative forcing, over a given time horizon, as an emitted amount of a long-lived GHG or a mixture of GHGs«. PM emissions are reported in kilograms of particulate matter with an equivalent diameter of 2.5 micrometers (kg $PM_{2.5}$-eq). According to the World Health Organization (WHO 2000), particulate matter from diesel is almost pure carbon with aerodynamic diameters of around 0.1 micrometers (mm) making this an impact category of particular interest in the context of forest harvesting operations with the associated diesel-operated machinery. NR energy consumption is reported in mega joule lower heating value (MJ LHV). While the higher heating value represents the maximum potential energy recoverable from a fuel, the LHV is more appropriate to report as it excludes the latent heat contained in the water vapor, which cannot be used effectively (McKendry 2002).

2.4.3 Inventory Analysis

Input and output flows were estimated using field data, operator experience, and literature review. Forestry LCA studies, such as that by Werner et al. (2007), identified machine use and energy input as the two input flows for harvesting. This section describes the method for estimating the allocation of harvesting equipment implemented in each of the three harvesting systems along with data processing for the calculations of material consumption by this equipment.

Production of harvest machinery is a central factor in assessing the environmental impacts of timber production. As this research monitored operations covering a short period of the overall machine service life, a portion of the impacts associated with the production and lifespan of the machinery used must be allocated appropriately. The machine hours (i.e. productive, estimated, and operational) are calculated from field data or recorded from on-board meters or computers, then multiplied by the weight of the machine and divided by the expected machine lifespan. Productive working hours of 1350 (chainsaw), 18 650 (harvester), 15 000 (forest tractor), and 17 200 (forwarder) were used for the expected lifespan of the respective machines (Engel et al. 2012). The resulting allocated weight of machinery dedicated to the research site operations can then be normalized by the extracted timber volume.

In addition to the machinery used, an understanding of the materials consumed is required to estimate the impact categories for each harvesting system. Recorded values such as fuel, bar oil and grease were converted to the appropriate units to calculate impact category using material densities (i.e. liters to kilograms) and divided by the corresponding harvested timber volume in cubic meters.

2.4.4 Impact Assessment

Assuming linearity of the relationship between the flow of commodities and the environmental impacts (Heinimann 2012), the GHG and PM emissions, and NR energy consumption could be estimated from the harvest machinery usage and material consumption rates using impact conversion factors found in the Ecoinvent 2.2 database (Frischnecht et al. 2005). Factors used for the study were in units (i.e. kg CO_2-eq/m^3 o.b., kg $PM_{2.5}$-eq/m^3 o.b., and MJ LHV/m^3 o.b.) per kilogram of material (e.g. per kg of machine or per kg of diesel). Impact conversion factors were taken from the Ecoinvent 2.2 database for chainsaws and heavy machinery, and used to calculate the impacts associated with production of the respective machines, chainsaws and heavy machines (i.e. harvester, tractor, forwarder). In addition to the consumption of materials, the contribution to impact categories from the provision and

Table 5 Assumed silvicultural treatments for the research sites

Research site Treatment	Rotation period[a] years	Number of treatments[a]		Treatment effect factor[b] Final felling → Thinning
		Thinning	Final felling	
MM, final felling	100	4	3	1.52[c]
SM, final felling	100	4	3	0.56[d]
FM, thinning	135	5	3	2.48[d]

[a] Rotation period and number of treatments correspond to typical forest practices in Germany for the respective species composition

[b] Treatment effect factor applied to impact categories for converting final felling values to thinning values

[c] MM treatment effect factor based on fuel consumption for motor-manual felling and tractor extraction during thinning and final felling treatments (Berg and Karjalainen 2003). Assumed fuel consumption is representative of GHG emissions, PM emissions, and NR energy consumption

[d] SM and FM treatment effect factor based on data from subject review comparing the CO2 emissions associated with felling and extraction for TH and FF used under varying degree of mechanization (Cosola et al. 2016). Assumed CO2 emissions are representative of GHG emissions, PM emissions, and NR energy consumption

MM – motor-manual, SM – semi-mechanized, FM – fully-mechanized disposal of these materials were estimated using the impact conversion factors. The Ecoinvent 2.2 database was accessed using GaBi 6 software (GaBi 2012).

2.4.5 Impact Category Extrapolation

With the impact categories calculated, it was possible to compare the emissions of GHG and PM, and the consumption of NR energy amongst the three research sites. However, as these were discrete harvest operations and the three research sites were at different phases of the stand rotation period, the impact categories must be adjusted to compare the impacts of harvesting timber between the harvest systems, as well as to values calculated within other LCA studies.

The impact categories were, therefore, extrapolated over the whole rotation period typical of forest management in Germany to account for prescribed thinnings and final fellings. Table 5 includes the assumed silvicultural treatments based on plans for the full rotation of the stands along with a treatment effect factor for converting impact categories from final felling to thinning treatment. We assumed that the properties of the stand and harvesting operations are consistent throughout the full rotation for the treatment associated with each system. Converting between final felling and thinning treatments was based on calculated ratios from literature review studies (Berg and Karjalainen 2003, Cosola et al. 2016). The treatment effect factor was applied to the research site results to convert from one treatment to another, as appropriate. A weighted average of the impact category was then calculated corresponding to the number of thinning and final felling treatments. At the MM research site, impact categories associated with the thinning treatment were multiplied by four (number of events) and added with the values associated with the final felling treatment times three (number of events) then divided by seven (the total number of events). In doing so, a more representative number for the harvesting of timber products from stump to truck accessible road over the complete rotation period for each system was calculated. Continuing one step further, the impact category was then divided by the rotation period and harvest block area to calculate an annual emission value per m^3 o.b. per year and an area emission value per m^3 o.b. per hectare. It is also important to note that no change in efficiency or productivity of the machines or equipment used was assumed over the rotation period.

3. Results

3.1 Resource Consumption

Material consumption rates are presented in Table 6, with a comparative bar chart of fuel consumption rates (l/m^3 o.b.) for each machine at the different research sites displayed in Fig. 4. The SM system had the lowest combined fuel consumption (0.736 kg/m^3 o.b.) with values for the MM system and FM system of 0.775 and 0.969 kg/m^3 o.b., respectively (Table 6). Similarities in values for felling between the SM and FM system can be observed, while forwarding within the FM system was noticeably higher than that of the SM system. Extraction using the forest tractor contributed to the majority of fuel consumption within the MM system.

Table 6 Material consumption rates (kg/m^3 o.b.) for three research sites separated by machine

Research site Treatment	Machine	Fuel[a]	Bar oil	Grease	AdBlue	Transmission oil	Hydraulic oil
MM final felling	Chainsaw	0.100	0.065	–	–	–	–
	Tractor	0.675	–	0.0009	–	–	0.0105
	Total	0.775	0.065	0.0009	–	–	0.0105
SM final felling	Harvester	0.398	0.004	0.0011	0.038	0.0004	0.0065
	Chainsaw[b]	0.014	0.009	–	–	–	–
	Forwarder	0.324	–	0.0005	–	–	0.0034
	Total	0.736	0.013	0.0016	0.038	0.0004	0.0099
FM thinnning	Harvester	0.404	0.0074	0.0011	–	0.0007	0.0070
	Forwarder	0.565	–	0.0005	–	–	0.0087
	Total	0.969	0.0074	0.0016	–	0.0007	0.0157

[a] Chainsaw fuel was a gasoline-oil mixture. All other machines were diesel operated

[b] A factor of 0.65 was applied to the raw field data to account for the number of trees manually felled

SM – semi-mechanized, MM – motor-manual, FM – fully-mechanized

Table 7 Recorded machine times for three research sites

Research site Treatment	Machine	Time consumption hr/m^3 o.b.
MM final felling	Chainsaw[b]	0.426
	Tractor[d]	0.174
	Total	0.600
SM final felling	Harvestera	0.024
	Chainsaw[b,c]	0.017
	Forwarder[a]	0.023
	Total	0.073
FM thinning	Harvester[d]	0.042
	Forwarder[d]	0.058
	Total	0.100

[a] Values based on productive machine hour (PMH15)
[b] Values based on estimated working hour
[c] A factor of 0.65 was applied to the raw field data to account for the number of trees manually felled
[d] Values based on machine operating hour
MM – motor-manual, SM – semi-mechanized, FM – fully-mechanized

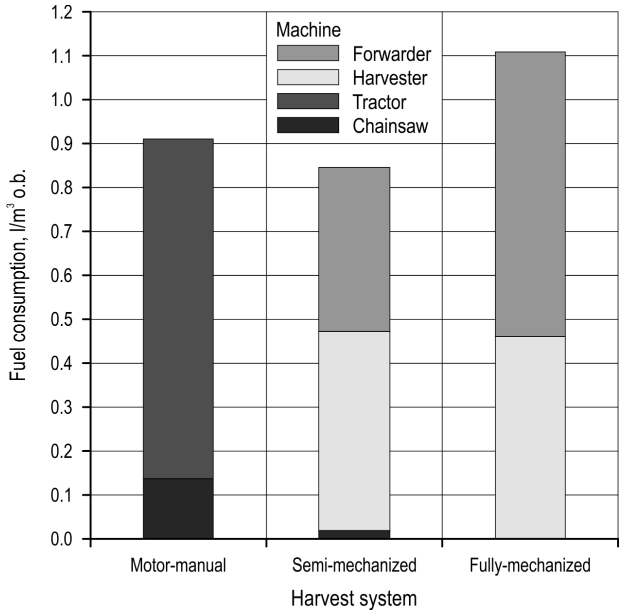

Fig. 4 Fuel consumption rates (l/m^3 o.b.) of three research sites separated by machine

Time is a resource of utmost importance in forest operations and is a critical parameter in productivity studies. Additionally, it was necessary to allocate environmental impacts associated with the lifespan of machinery to the time frame of operations. The MM system had the highest time consumption rate with 0.6 hr/m^3 o.b., of which 0.426 hr/m^3 o.b. are attributed to felling and processing by chainsaw. The SM system had the lowest time consumption rate with 0.073 hr/m^3 o.b. and the FM system had a consumption rate of 0.1 hr/m^3 o.b. as detailed in Table 7. The values are difficult to compare between the SM and FM systems, as the heavy machinery are reported in both PMH_{15} and MH. MH is the time when the machine engine is run-

Table 8 Impact categories for three harvest systems calculated by silvicultural treatment, annual impact, and unit area

Impact category	Harvesting system	Thinning treatment[a]	Final felling treatment[a]	Full rotation[b]	Annual impact[c]	Area impact[d]
					per yr	per ha
GHG emissions kg CO_2-eq/m^3 o.b.	MM	5.172	3.412	4.418	0.044	1.262
	SM	1.643	2.937	2.197	0.022	0.180
	FM	3.962	1.598	3.076	0.023	0.320
PM emissions kg $PM_{2.5}$-eq/m^3 o.b.	MM	0.00519	0.00343	0.00444	0.000044	0.00127
	SM	0.00191	0.00342	0.00256	0.000026	0.00021
	FM	0.00463	0.00187	0.00359	0.000027	0.00037
NR energy consumption MJ LHV/m^3 o.b.	MM	72.730	47.986	62.125	0.621	17.750
	SM	23.221	41.522	31.064	0.311	2.546
	FM	56.237	22.691	43.657	0.323	4.548

[a] See Table 4 for assumed rotation periods, number of silvicultural treatments during rotation, and treatment effect factor used in calculations
[b] Impact categories associated with harvest operations over the full rotation are a weighted average of the thinning and final felling treatments
[c] Assumed rotation periods (Table 4) used to calculate annual impact
[d] Harvest block area (Table 1) used to calculate area impact
MM – motor-manual, SM – semi-mechanized, FM – fully-mechanized

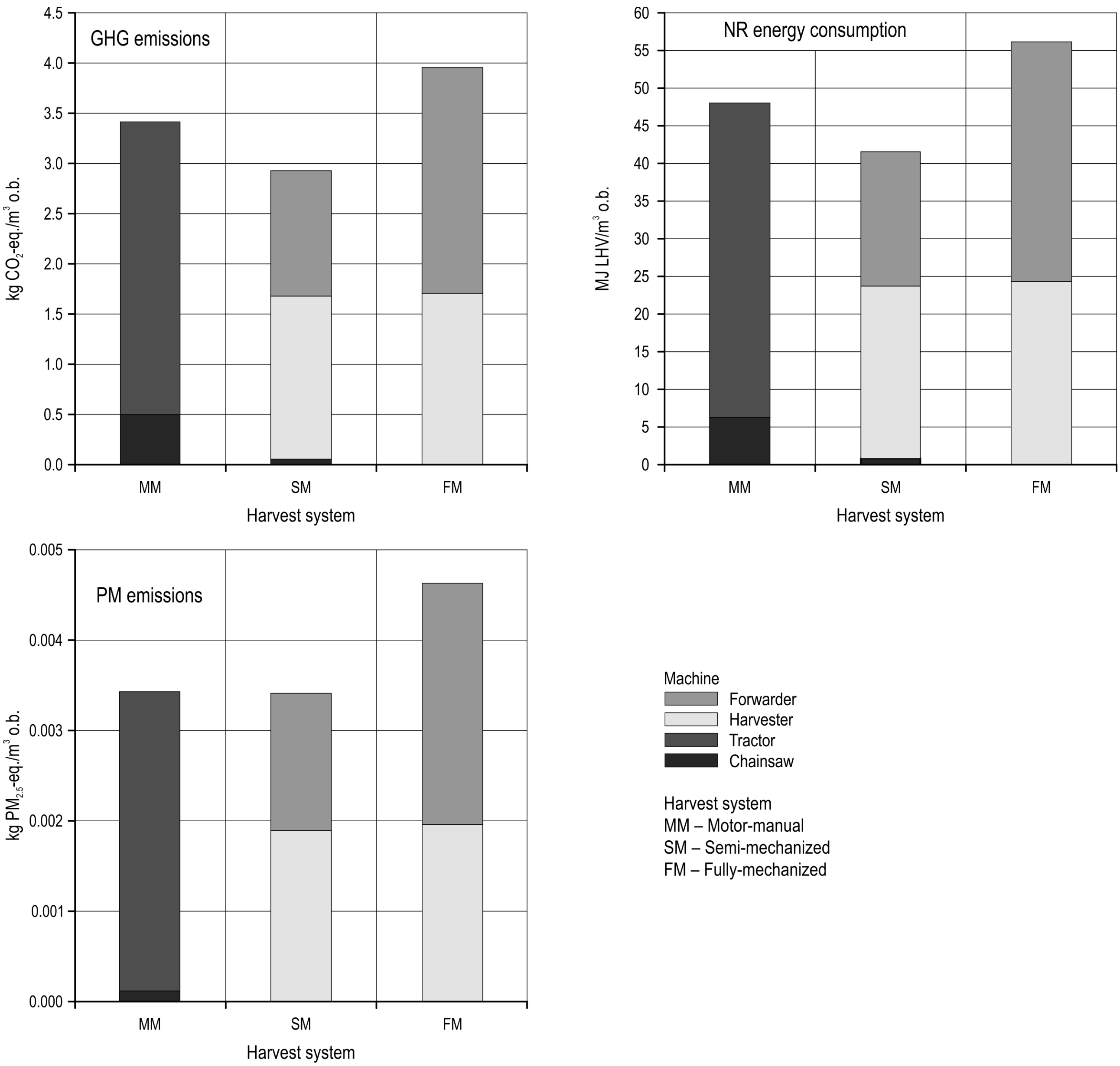

Fig. 5 Impact category results for three research sites separated by machine

ning, while PMH_{15} has all delays greater than 15 minutes removed, thus reducing the time per extracted timber volume. Whether the times presented are based on PMH, MH, or EWH, as noted in the table, depends on the data available for the research site and machine.

3.2 Calculated Impact Categories

3.2.1 Research Sites

Of the three research sites, the SM system had the lowest environmental impact, with GHG emissions of 2.937 kg CO_2-eq/m^3 o.b., PM emissions of 0.00342 kg $PM_{2.5}$-eq/m^3 o.b., and NR energy consumption of 41.522 MJ LHV/m^3 o.b. The calculated impact categories associated with each machine for the different research sites are displayed in Fig. 5. The trends were similar amongst the three impacts and appear to be linked to the fuel consumption as displayed in Fig. 4.

3.2.2 Stand Rotation

Understanding the effects of different silvicultural treatments (i.e. thinning and final felling), as well as stand management (i.e. rotation period) and characteristics (i.e. area), the impact categories calculated for

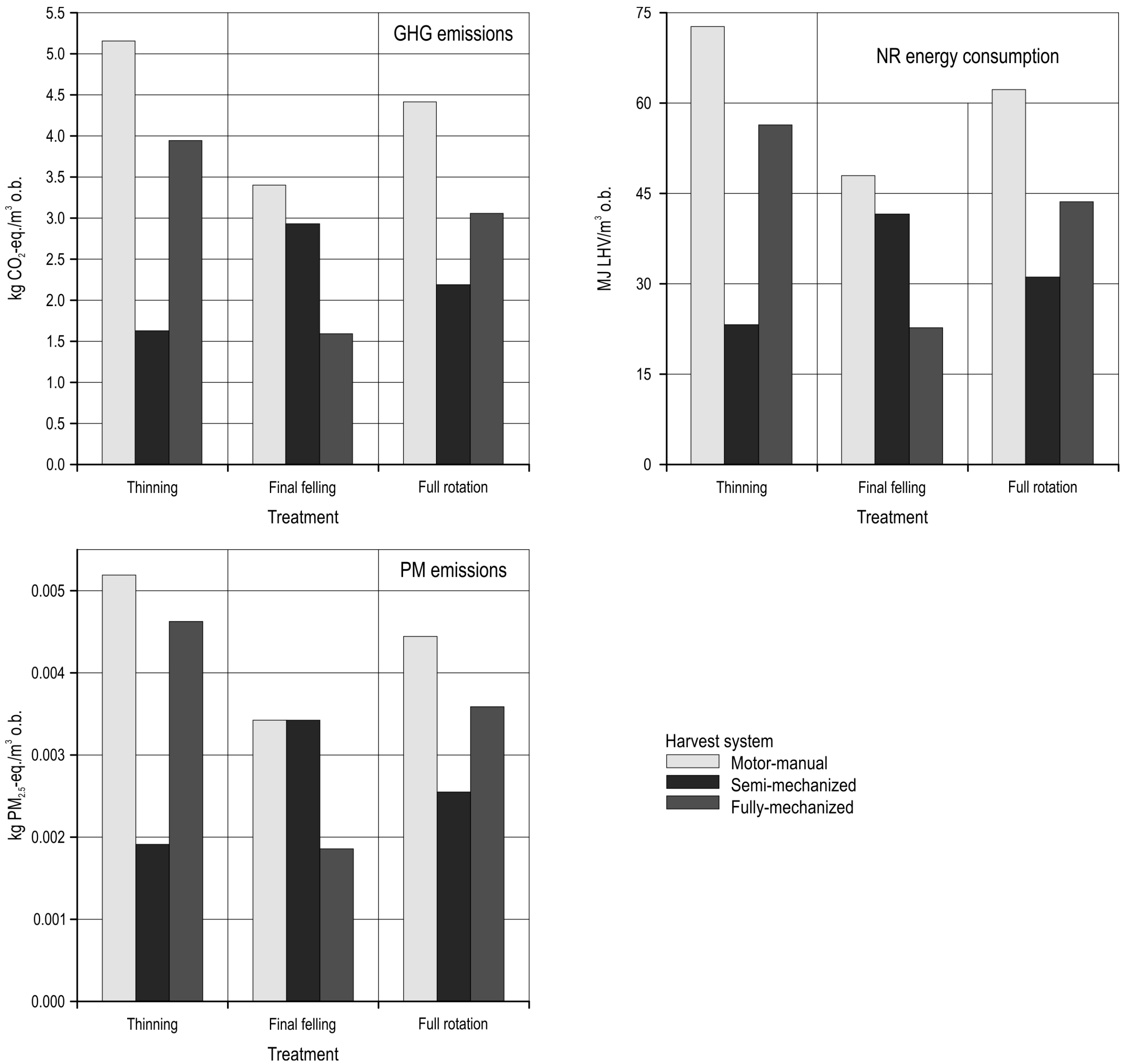

Fig. 6 Impact categories of silvicultural treatments using different harvest systems

the research sites were extrapolated to harvesting operations over the full rotation period for the corresponding harvesting system. This allowed for a more representative comparison between the research sites, which were then evaluated on an annual and area basis (Table 8). Impact categories associated with the silvicultural treatments and harvesting operations over the full rotation period using the different harvest systems are displayed in Fig. 6. The SM system resulted in the lowest impacts for both thinning treatments and harvest operations over the full rotation period, while the FM system had the lowest impacts for final felling treatments. The motor-manual system resulted in the highest impacts for thinning treatment, final felling treatment, and harvest operations over the full rotation.

4. Discussion

Study results are discussed within the context of the three research sites. Variability between the research sites limited the ability to make conclusive comparisons between the three systems and machines used. That is to say, differences between the harvest blocks such as tree diameter, standing volume, machines, and trail length, although observed, were not normalized into the LCA results. Such differences are expected to affect results, and thus are discussed on a qualitative basis but a complete quantitative assessment was not possible. Additionally, assumptions were required to evaluate the three harvest systems on a treatment basis and over a full rotation period, as described in the materials and methods.

4.1 Fuel Consumption

Fuel consumption contributed to a large portion of the overall environmental impacts compared to other resources consumed. It was the most consumed material during harvesting operations, while the emission factors associated with the combined provision and consumption of diesel and gasoline were among the highest in comparison with other inventory categories. Regarding forest machinery, although manufacturing is intensive, the impacts associated directly with their construction are allocated over several years of harvested timber. In this study, the production of forest machinery contributed anywhere from one to 15% of the total environmental impact, depending on the harvest system, machine, and impact category assessed; however, this was not a focus of the study.

The results were less than the 2.5 and 1.75 l/m^3 from a literature survey by Smidt and Gallagher (2013) for machine fuel consumption, using both a feller-buncher and grapple skidder for thinning and clear-cutting operations, respectively. However, as noted in the study, the sum of 90% confidence intervals could sum to 70% or more of the mean total fuel consumption (Smidt and Gallagher 2013). Additionally, the harvest systems evaluated in Smidt and Gallagher (2013) were quite different from those in our study. In another study based on survey data of foresters in the United States, Kenney et al. (2014) provided fuel consumption rate ranges for felling (lower limit [LL]=0.38 l/m^3; upper limit [UL]=1.7 l/m^3) and skidding (LL=0.57 l/m^3; UL=1.3 l/m^3). Although these two processes differ from the systems in our study, results were in general agreement with these ranges, excluding felling with a chainsaw, which was not included in Kenney et al. (2014).

Considering machine specific data, harvester fuel consumption rates at both the SM and FM research sites were outside the range of the Smidt and Gallagher (2013) study (LL=0.666 l/m^3; UL=2.210 l/m^3), while the forwarder result for the SM site was outside the range and for the FM site within the range (LL=0.413 l/m^3; UL=0.833 l/m^3). In Ackerman et al. (2017), mechanized clear-felling CTL harvest operations of *Pinus patula* resulted in harvester and forwarder diesel consumption rates of 0.64 and 0.38 l/m^3, respectively. Harvester fuel consumption rates at both the SM and FM research sites were below this result. The forwarder fuel consumption rate at the FM research site was noticeably higher than the Ackerman et al. (2017) result, while the SM research site was comparable. Differences in harvester fuel consumption rates can be linked to varying tree dimensions and form characteristics, machines configurations, terrain conditions, and operator experience, among others. Harvester fuel consumption at the SM and FM research sites were comparable to each other, with the larger consumption rate in the FM system potentially explained by the decrease in productivity associated with a thinning treatment of smaller diameter pine and, therefore, a smaller standing volume harvested at a lower intensity. Additionally, a brand new machine was used at the SM site. The fact that approximately 65% of trees were felled by chainsaw at the SM site would reduce the fuel consumed by the harvester. In fact, the combined fuel consumption rate of the harvester and chainsaw at the SM site were greater than that of the harvester alone at the FM site, 0.474 l/m^3 o.b. compared to 0.462 l/m^3 o.b.

Chainsaw fuel consumption rates were substantially lower than those of harvester data, as would be expected, in spite of the lower harvest yield at the MM research site, which would increase the fuel consumption rate per extracted timber volume. This is consistent with Berg and Karjalainen (2003), in which fuel consumption of motor-manual felling was approximately 21% and 30% of mechanized felling in Finland and Sweden, respectively. Chainsaws were used only for felling at the SM site. This was reflected in the results with a fuel consumption rate of an order of magnitude less than that at the MM research site, where chainsaws were used for all felling and processing.

Forwarder results at the SM and FM research sites were quite different, 0.370 l/m^3 o.b. compared to 0.646 l/m^3 o.b., respectively. As the same machine was used in the two case studies, this difference may be attributed to influences on productivity from such characteristics as silvicultural treatment, average extraction distance, pile size, assortments, and terrain (Nurminen et al. 2006). Tree size also has an impact on loading productivity, but grapple and pile size have been shown to be potentially even more important (Nurminen et al. 2006). These influencing factors were not evaluated in detail as part of this study; however, considering the harvest operations summary (Table 3), the trail length at the SM site was half that of the FM site, so the driving distance per load can be expected to have been greater in the FM system, thus increasing the fuel consumption per load. Additionally, of the logs counted, over 50% were 5-meter saw wood assortment at the SM research site, with less than 5% 4-meter saw wood and the remainder pallet, particle, and pulpwood. In contrast, only 1% of logs from the FM site were 5-meter long saw wood assortment, with approximately 33% 4-meter saw wood and over 65% pallet, particle, and pulpwood. A higher frequency of shorter logs as compared to logs of longer length require more manipulation and boom movement during loading and unloading (Nurminen et al. 2006), which is expected to increase fuel consumption per load.

The forest tractor used at the MM site resulted in the highest fuel consumption rate of all other machines used at the three research sites. In fact, the tractor had a fuel consumption rate of 0.771 l/m^3 o.b., which is more than 90% of the whole fuel consumption rate of the SM system. This may be attributed to the high diesel requirements of the tractor in comparison to the low timber volume extracted from the MM research site harvest block and small average load volume achieved with a winch and grapple skidder.

Concerning the consumption rate of other materials (e.g. bar oil and diesel exhaust fluid) the SM system consumed more than the other two systems on the whole; however, this does not seem to be the critical factor in the calculation of overall impact categories. The quantity of material consumption could be attributed to the higher harvest intensity and average tree DBH. Also, the new harvester used diesel exhaust fluid associated with new clean emission technology in addition to other materials.

4.2 Time Consumption

Harvesting productivity studies are typically performed on a basis of m^3/hr (the inverse of time consumption rate in this study) and can serve as a useful comparison and explanation of the three research sites. As harvesting productivity increases, time consumed per cubic meter decreases. Time consumption results in this study were less than the converted harvesting productivity results from Berg and Karjalainen (2003), but within an order of magnitude, the exception being the MM system of chainsaw and tractor, which were nearly the same. Harvesting productivity can be impacted by the silvicultural treatment, with thinning productivities compared to final felling of approximately 62% for motor-manual felling, 46% for mechanized felling, 67% for forest tractor operations, and 70% for forwarder operations (Berg and Karjalainen 2003). Thus, we would expect the time consumption to be higher for the FM system, which was used for a thinning treatment. However, when comparing the harvesting productivity of thinning with final felling in Berg and Karjalainen (2003), it should be considered that final fellings (Sweden and Finland) included both clear-cutting and shelter-wood cutting. In our study, final fellings did not involve clear-cutting, which is a highly productive means of felling and would impact the effect of silvicultural treatment on productivity. Increasing harvesting intensity through higher tree removal rates has also been shown to decrease time consumption (Nurminen et al. 2006), potentially explaining the difference between the SM and FM systems, of which the SM system has the greater harvesting intensity.

Additionally, harvester productivity increases with increasing stem size as modern machines are so effective that they do not require significantly more time to process larger volume trees (Nurminen et al. 2006), which is especially true for softwood trees. This may further clarify reasons for the lower time consumption of the SM system compared to the FM system, of which the SM research site has the larger average tree DBH. Studies have shown that this increase in productivity is not linear and may eventually begin to decrease as the stem diameter becomes too large for the harvester head resulting in the so-called »sweet-spot« (Visser et al. 2009).

4.3 Impact Assessment

Environmental impacts associated with the MM system were approximately 16% greater than the SM system, with the exception of PM emissions, which were nearly identical (0.2% greater), while the FM system resulted in environmental impacts approximately 35% greater than the SM system. In both cases (MM and FM systems), the higher calculated environmental impacts can likely be attributed to the lower productivity previously discussed. The timber volume harvested with the MM system was substantially lower than that with the SM system and was performed at a lower harvesting intensity (Table 3), while at the same time the forest tractor used in the MM system had the highest fuel consumption rate per extracted timber volume compared to other machines. Harvesting productivity at the FM research site appears to be more affected by the tree size and treatment, as well as the hauling distance and assortments. Also of note were the low PM emissions associated with the MM system compared to other impact categories, perhaps because all felling was performed with a chainsaw, which consumes less fuel and uses a gasoline and oil mixture rather than diesel.

Evaluating the impacts of individual machines at each of the three research sites provides insight into which major contributors may be within a specific set of site conditions, but may also guide where improvements to the harvesting systems can be focused. The forest tractor contributed to the majority of emissions within the MM system, with 85% GHG emissions, 96% PM emissions, and 89% NR energy consumption. Within the SM system, approximately 55% and 43% of impact categories were attributed to the harvester and forwarder, respectively, with approximately 2% contributed by the chainsaw. The exception was PM emissions, for which less than 0.5% was created by the chainsaw. In contrast to the SM system, in which the harvester made up the majority of environmental impacts, impacts associated with the FM system were primarily from the forwarder with an average contribution of 57% compared to 43% within the SM system. However, Fig. 5 shows that harvester impacts in the two mechanized systems were similar, thus indicating that substantial differences between impact categories lie with the forwarder. A productivity study by Nurminen et al. (2006) observed that forest haulage has been studied less than felling, potentially due to a perceived maturation of technology. However, with more complicated working conditions developing in the last couple decades (i.e. more wood products and scattered wood piles), improved forwarding efficiencies may be possible.

Perhaps it is more interesting to analyze the estimated impact categories over an assumed rotation period for the harvest block than the individual research site results. Trends for the three impact categories were similar when looking at the different treatments using the three harvest systems, with the SM system resulting in the lowest impacts for thinnings, and the FM system resulting in the lowest impacts for final fellings. Under thinning treatments, the environmental impacts associated with the MM system ranged from 172 to 215% greater than the SM system, while the FM system was approximately 140% greater. Regarding final felling treatments, environmental impacts associated with the MM system ranged from 84 to 113% more than the FM system, with the SM system approximately 83% greater than the FM system.

In a subject review researching the CO_2 emissions in felling, extraction, comminution, and transport operations of CTN and plantation forestry, Cosola et al. (2016) reported average thinning and final felling values for SM systems in CTN forestry of 2.69 and 4.81 kg/m^3, respectively, and for FM systems 12.07 kg/m^3 (thinning) and 4.87 kg/m^3 (final felling). Comparing SM systems to FM systems, the reversed trend in emissions for thinning and final felling was attributed to more difficult working conditions associated with SM systems, pointing to emissions from extraction operations in particular (Cosola et al. 2016). Although these results were for CO_2 only, they do serve as a comparison to GHG emissions calculated for SM and FM systems in this study. For the SM system, thinning values were below those found in Cosola et al. (2016), but within the same order of magnitude, while the final felling value was within the range of the study (lower limit [LL]=2.32 kg/m^3; upper limit [UL]=11.91 kg/m^3). GHG emission calculated for thinning treatments with the FM system were well below the average CO_2 emissions of 12.07 kg/m^3 in Cosola et al. (2016), but within the range (LL=3.14 kg/m^3; UL=76.94 kg/m^3), while for final felling, GHG emissions were just under the range (LL=1.94 kg/m^3; UL=11.76 kg/m^3).

If the same harvest system was to be used for the harvest block throughout the rotation period, the SM system would result in the lowest GHG emissions (2.197 kg CO_2-eq/m^3 o.b.), PM emissions (0.00256 kg $PM_{2.5}$-eq/m^3 o.b.), and NR energy consumption (31.064 MJ LHV/m^3 o.b.). The FM system had the second lowest environmental impacts with 40% more GHG and PM emissions, and 41% more NR energy consumption. The MM system had the highest environmental impacts with approximately twice the GHG emission and NR energy consumption, and 73% PM emissions more than the SM system.

Estimated GHG emissions for the full rotation period were lower, yet comparable, to similar research considering variability between studies (site conditions and assumptions). Within an intensive timber harvesting system, Klein et al. (2016) calculated 5.044 kg CO_2-eq./m^3 for felling and forwarding, compared to 3.434 kg CO_2-eq./m^3 for an extensive system. The subject review by Cosola et al. (2016) estimated CO_2 emissions associated with the felling and extraction of timber under CTN management to be 3.94 kg/m^3 for semi-mechanized systems and 6.69 kg/m^3 for fully-mechanized systems.

In Klein et al. (2016), PM emissions and NR energy consumption were calculated for provisiding different wood assortments from common Bavarian tree species (from stand to truck accessible road), including site preparation, site tending, felling, forwarding, and loading onto trucks. PM emissions of 0.001 to 0.026 kg $PM_{2.5}$-eq/m^3 and NR energy consumption from 80 to 390 MJ/m^3 were calculated (Klein et al. 2016). As the results from the research sites included only felling and forwarding, it would be expected that these would represent approximately 55% of the values from Klein et al. (2016) based on GHG emission results (for which emissions are separated for different processes). While there is a large variation, PM emissions and NR energy consumption results from our study are comparable to 55% of the theoretical results from Klein et al. (2016). PM emissions associated with all three systems and NR energy consumption for the MM system are within the expected range, while NR energy consumption associated with SM and FM systems are less than the lower limit (LL) of the range (71% and 99% of the LL, respectively).

5. Conclusion

Forest management in Germany features CTN silvicultural practices and low-impact harvesting, maintaining high profits, supporting multi-functional ecosystems, and minimizing environmental impacts. This study assessed the selected environmental impacts associated with common harvesting systems (i.e. MM, SM, and FM) by performing LCAs on live operations at three research sites with results in general conformance with other comparable LCA studies. The environmental impacts assessed were GHG emissions, PM emissions, and NR energy consumption.

Results of the three research sites indicated that over the full rotation period, a SM harvesting system produced the lowest environmental impacts (GHG, PM and NR); however, when considering different silvicultural treatments separately, the SM system had the lowest environmental impacts for thinnings, while the FM system generated the lowest environmental impacts for final fellings. A diversified approach to harvesting could be considered, integrating SM systems for thinnings with FM systems for final fellings, while also considering site conditions. Benefits of highly productive harvesting and forwarding machinery associated with FM systems can be maximized under final felling conditions when a higher timber volume per area is harvested, thereby offsetting the high consumption of diesel. Conversely, a SM system may be more appropriate for selection thinning of smaller diameter trees, taking advantage of motor-manual felling.

With felling and processing receiving so much attention in the recent decades as harvesting methods and systems transition, and technology advances, extraction still contributes significantly to the environmental impacts associated with harvesting operations. Even with variability between the research sites, the effects of longer extraction distances (e.g. 800 m vs. 400 m) and shorter log assortments (e.g. 2.0–3.5 m vs. 4.0–5.0 m) on the environmental impacts associated with forwarding were evident when evaluating the SM and FM systems. This places great importance on forest infrastructure planning (i.e. truck accessible road and machine operating trail layout) as well as strong operational coordination (e.g. log pile organization). There may also be room for operational or technological development (fuel efficiency improvement aside) to meet changing market demands for wood assortments and reduce environmental impacts.

Although there are signs that motor-manual systems are used less frequently than in the past, they still play a significant role in many European countries, specifically in small-scale operations and difficult terrain. The forest tractor clearly had the greatest environmental impact, thus steering the direction of future improvements. Improving fuel efficiency, optimizing productive hours, and increasing extraction volume are some examples.

Regarding LCA, as the forestry sector comes to embrace this analytical tool, the LCA community is advancing to meet the demands of a sustainability-conscious society, and taking into consideration the three pillars – environment, economy, and society. Lifecycle sustainability analysis, taking the so-called »triple bottom line« approach, provides a holistic perspective leading to balanced decision making. In forestry, for example, further considerations could be given to timber revenue, labor opportunities, or recreation in conjunction with environmental impact analysis, which may be of particular interest in considering the multi-functional approach of CTN forest management.

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